A Synthesis of the Hydrogeology of the Table Mountain Group - Formation of a Research Strategy

Kevin Pietersen and Roger Parsons
(Editors)

TT 158/01

Water Research Commission

"The supply of water produced by fountains tells not only of water which has fallen as rain on higher-lying land, and which was lost and buried, but has been raised again from the grave, as living water restored to man for use - but it awakens a suspicion that much more has been interred to await a resurrection by other means - or to remain for ages in the depths of the earth, until by some great convulsion the fountains of the great deep be broken up; and much, it may be, to escape by an underground course to the sea, which never says - 'It is enough!' "

In:

Water Supply of South Africa and Facilities for the Storage of It

compiled by John Croumbie Brown (1877)

formerly Government Botanist at the Cape of Good Hope, and
Professor of Botany in the South African College, Cape Town

A Synthesis of the Hydrogeology of the Table Mountain Group - Formation of a Research Strategy

Prepared for the Water Research Commission

by

Kevin Pietersen and Roger Parsons (Editors)

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Cover photograph: Tight second-order folds in the Nardouw Subgroup of the Table Mountain Group at Cogmanskloof west of Montagu.

Photograph courtesy of Council for Geoscience, Bellville.

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Introduction and Background

Preface

Groundwater by its very nature will always remain with some aura of mystery. However, vision, good science and responsible advocacy can go a long way to turn this around.

This is exactly what happened over the last few years for groundwater found in the Table Mountain Group aquifers. I am thrilled that I could play a little part in spreading the message of the "hidden treasure" with my speech at the November 2000 Congress of the International Association of Hydrogeologists in Cape Town. A year later I remain convinced that this unique water resource of the southern and western Cape will offer unique solutions to the growing water problems of this area.

But many uncertainties remain, considering that we want to move groundwater exploration in this country an order of magnitude deeper, from 100 m to 1 000 m. A major challenge in the utilisation of this resource is that we want to maintain the natural harmony of water and vegetation in our treasured Cape mountain ecosystem. Leaps of faith will be required, underpinned by the best possible science.

I am therefore very encouraged to see the scientific community sharing their knowledge and experience in this synthesis of the Hydrogeology of the Table Mountain Group groundwater. The role of the Water Research Commission and of the Department of Water Affairs and Forestry must obviously be acknowledged in initiating, guiding and supporting much of the research as well as the co-ordination to this. At the same time the Cape Metropolitan Council took the leap of faith to invest substantially in a feasibility study of this source as potential bulk water supply for Cape Town. They could not have hoped for a better scientific platform and a more ready core of South African hydrogeologists to become modern pioneers in search of the deep hidden treasure.

Greater potential rewards such as what we wish to achieve here, are usually associated with greater risk. Therefore, it is essential that research and development work is stepped up to reduce the risks related to TMG groundwater development and I am happy to see that the Water Research Commission has already initiated a new phase of research. I believe that such supporting research investment, with particular focus on Integrated Water Resource Management, could have benefits far beyond the Cape. In fact, I see that this undertaking could produce outputs of global significance.

Ronnie Kasrils

(signed)
Mr Ronnie Kasrils
Minister of Water Affairs and Forestry

The Need for Appropriate Research of the Table Mountain Group Aquifer Systems

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Abstract

The Table Mountain Group (TMG) aquifer system is exposed along the west and south coasts of South Africa. It has the potential to be a major source of water to these regions. To realise this potential, many uncertainties and barriers need to be overcome, including: understanding of the occurrence, attributes and dynamics of TMG Aquifer systems; lack of understanding of environmental impact of exploitation; and uncertainties about how best to manage the resource within a multi-objective environment. Research within a multi-disciplinary environment is thus needed to find appropriate answers to questions concerning the water resource potential and optimal management of TMG Aquifers, in the interest of furthering integrated water resource management in the region.

Introduction

The Water Research Commission (WRC) is a statutory body, mandated to find appropriate solutions to the water management challenges in South Africa. Groundwater is an important research field in the WRC, attracting the fourth largest funding allocation in the organisation. The following aims (problem areas) for groundwater research to be addressed over a 5-year time frame, have been identified:

- To refocus groundwater characterisation towards integrated water resource management in line with national needs and priorities.
- To manage groundwater quality with emphasis on the prevention of contamination/pollution.
- To support activities that develops appropriate professional, institutional and management practices to achieve integrated water resource management.
- To encourage innovative and imaginative research (lateral thinking) with the potential to contribute to meeting the identified vision of groundwater research.

Accordingly a programme orientated approach to addressing both the short and long term needs of sustainable use and management of groundwater resources in South Africa is under development. Currently, the groundwater research field comprises of the following research programmes:

- Groundwater Reserve Programme
- Fractured Rock Aquifer Research Programme
  - Karoo Aquifer System
  - Basement Aquifer System
  - Table Mountain Group (TMG) Aquifer System
- Community Groundwater Supply and Sanitation
- Groundwater Quality and Protection.

This paper outlines the need for an appropriate research programme on the occurrence, attributes and dynamics of groundwater systems in the TMG.

Research programme rationale

The TMG aquifer system is a regional aquifer with potential to be a major source for future water supply in the Western and Eastern Cape. TMG Aquifer consists mainly of sandstone, shale and quartzite units and is exploited extensively for agricultural purposes. The largest groundwater supply from a fractured rock aquifer system in South Africa is taken from the Vermaaks River wellfield found in the TMG aquifer systems. To date however, there has been limited research into the aquifer system.

The Coordinating Committee for Geohydrological Research (CCGR), an advisory body to the WRC recommended in 1999, that attention be given to investigating the TMG aquifer system for water supply purposes (including aspects of resource evaluation and sustainable development). The committee recommended a workshop be held with various role players to identify research needs to formulate a research programme.

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At the workshop held in Cape Town the following overall goal for the research programme was identified "**To develop and further enhance, within the Department of Water Affairs and Forestry and the broader scientific community, the capabilities to manage TMG Aquifers in a sustainable manner focussing on issues such as system dynamics, community water supply needs and water volumes required to sustain sensitive ecosystems**". Using this as basis, the workshop participants went through a process of identifying and ranking research needs for the TMG aquifer system (Table 1). The outcome of this ranking was that, preparation of a synthesis of current hydrogeological knowledge and understanding of the TMG aquifer system was needed to form a "coherent" and "logical" framework for future research activities in the TMG aquifer system. Preparation of this volume is a direct result of the workshop and represents the first attempt to document current knowledge of the TMG aquifer system.

Table 1
Key issues to be addressed in a research programme on TMG Aquifers

1. Status of current knowledge of TMG aquifer systems.
2. The influence of structural geology on flow dynamics and groundwater occurrence.
3. Impact of groundwater abstraction on ecosystems.
4. Management scenarios for groundwater abstraction.
5. System dynamics (flow conditions, boundary conditions, yield potential, groundwater/surface water interaction).
6. Technology transfer.
7. Resource quantification methodologies.
8. Recharge (including artificial recharge).

Challenges

There are many uncertainties and barriers to overcome before large volumes of groundwater can be abstracted in a sustainable manner from the TMG aquifer system. Furthermore, there are many definitions and varied understanding of the concepts of sustainable development and integrated water resource management. However, the main goal for water management is a balance between protection (conservation) of dependent ecosystems and development of the resource. The concept of sustainability has a number of implications for the management and use of groundwater resources, including:

- The sustained provision of a basic quantity of water for domestic purposes, i.e. to meet normal household and health requirements.
- The potential contribution to economic development and poverty alleviation.
- The maintenance of aquifer system integrity (e.g. prevention of subsidence and salinisation).
- The protection of the groundwater resource from contamination.
- The proper functioning of ecosystems which are dependent on the groundwater resource.

To address the challenges of sustainable water use and management, an integrated framework is required. There is now wide recognition that a holistic, systematic approach based on IWRM principles must replace the current fragmentation when managing water resources and supplies. The interaction and connection (including inter-dependencies) of three complex and rapidly changing systems provide the rationale for adoption of an IWRM approach. These are:

- The environmental system, of which water is a vital part and a constituent of all living things.
- The hydrologic system, which governs the flow and regeneration of water.
- The human socio-economic system of which can have significant impacts on the environmental and hydrological system

Planning and management of water resources are closely associated with societal development and progress. However, this needs to take place within the context of sustainable development, which requires planning over a prolonged temporal and spatial scale. This further increases the complexity of the decision-making process.

Prior to 1998, the use of groundwater was beyond the regulatory jurisdiction of the state. The National Water Act (Act No 36 of 1998) corrected this situation and considers groundwater as an integral part of the hydrologic cycle. The Act provides the legal framework for groundwater management in South Africa. The Act includes:

- Formal recognition of the unity of the hydrologic cycle.
- Provision for resource protection and sustainability.
- Confirmation of water as a national resource under national management.
- Special status to meet rights of and obligations to neighbouring states.
- Decentralisation of water management within a national framework.
- Limitation of rights into perpetuity.
- Water allocation specifically to achieve socially and economically optimal water use.
- A formal requirement for water conservation and demand management.
- Economic pricing of water.

The focus of groundwater management in South Africa, at least for the foreseeable future, will be on equitable allocation for economic development, resource integrity and meeting basic human needs. The challenge remains to implement these principles in reality. Management strategies will need to be developed to address the unique characteristics and roles of groundwater. This needs to take place within the context of a socio-economic development paradigm.

To be able to meet the challenges, a proper understanding of TMG aquifer system is required. To date, research of the TMG aquifer system has been limited and of an ad hoc nature. It is aimed that the research programme provide information required to ensure groundwater from the TMG aquifer system can be used to meet the challenge of supplying water to the region in a sustainable manner.

Conclusion

The TMG aquifer system has the potential to be a significant source of water. The resource needs to be used within the context of IWRM and sustainable development principles (including understanding environmental requirements). A research programme to find solutions to the challenges posed by using the TMG aquifer system sustainably will be based on the current level of knowledge and understanding revealed in the remaining chapters of this document.

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Part 2:

Geology

The Stratigraphy, Lithology and Structure of the Table Mountain Group

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Abstract

The dominantly arenitic Table Mountain Group (TMG) is well-exposed within the Cape Fold Belt, which straddles the west and south Coasts of South Africa. This thick succession of well-indurated rocks displays some variation with regard to both lithological and bedding characteristics, which influence their hydrogeological potential. As most of these rocks have low primary porosities, they only become good aquifers where fractured. The most favourable targets are faults and strongly folded strata, where the rocks have been fractured sufficiently to create secondary porosity. Continued deformation produces cataclasites in quartz arenites and clayey, non-porous material in impure arenites, resulting in a drastic reduction of pore space volumes.

Introduction

The sediments of the Cape Supergroup were deposited from early Ordovician to early Carboniferous times, approximately between 500 and 340 million years ago. This predominantly siliclastic sequence is exposed along the entire length of the Cape Fold Belt (CFB), the 280-220 million year old orogenic belt straddling the west and south coasts of South Africa. The succession of quartz arenites, shales and siltstones, with minor conglomerate and a thin diamictite unit, has been subdivided into the Table Mountain, Bokkeveld and Witteberg Groups (Du Toit, 1954; Rust, 1967; Theron, 1972; Theron and Loock, 1988; Broquet, 1992). Maximum thickness of the Cape Supergroup amounts to 5 300 m and 9 600 m, respectively for the western and eastern Cape (SACS, 1980). These sediments were deposited in shallow marine environments under tidal, wave and storm influences, as well as in non-marine, braided-fluvial environments. The medium to coarse grain size and relative purity of some of the quartz arenites, together with their well-indurated nature and fracturing due to folding and faulting in the fold belt, enhance both the quality of the groundwater and its exploitation potential.

Table Mountain Group

The cratonic sheet sandstones (Rust, 1967; Tankard et al., 1982) of the TMG in the lowermost part of the Cape Supergroup form the backbone of the Cape Fold Belt from Vanrhynsdorp in the west to Port Elizabeth in the east (Fig. 1). Due to the low deformational intensity, most of the stratigraphic and sedimentological research on these rocks was done along the West Coast and in the southwestern Cape (Rust, 1967; Vos and Tankard, 1981; Thamm, 1988; Fuller and Broquet, 1990; Turner, 1990). Although intense deformation (Hälbich, 1983) makes sedimentological studies and thickness determination formidable tasks (Broquet, 1992), Rust (1973) and Johnson (1976) concluded that the sequence thickens eastward (Fig. 2). The TMG is subdivided into eight formations, with the upper three contained within the Nardouw Subgroup (Table 1). The TMG consists of 95% quartz arenite with medium to coarse grain-size and variable amounts of feldspar and clay minerals. However, these quartz arenite beds often are separated by partings and thin beds of siltstone. The presence of the latter is often masked by talus and soil cover.

Lithostratigraphy

The lowermost unit of the TMG, the *Piekenierskloof Formation*, consists of conglomerate, quartz arenite and minor mudrock that are confined to the West Coast (Rust, 1967). It unconformably overlies phyllites and quartzites of the Neoproterozoic Malmesbury Group, and red terrestrial sediments of the early Palaeozoic Klipheuwel Formation. The Piekenierskloof Formation was deposited by alluvial-fan and braided-river complexes on uneven topography created during folding and uplift of the Neoproterozoic Pan-African mountain belts along the West Coast prior to about 500 Ma ago. This valley and ridge palaeotopography caused considerable lateral and vertical variation in both composition and thickness of the Piekenierskloof Formation. Along the coast (Fig. 1), the sequence is dominated by clast- and matrix-supported vein-quartz conglomerates

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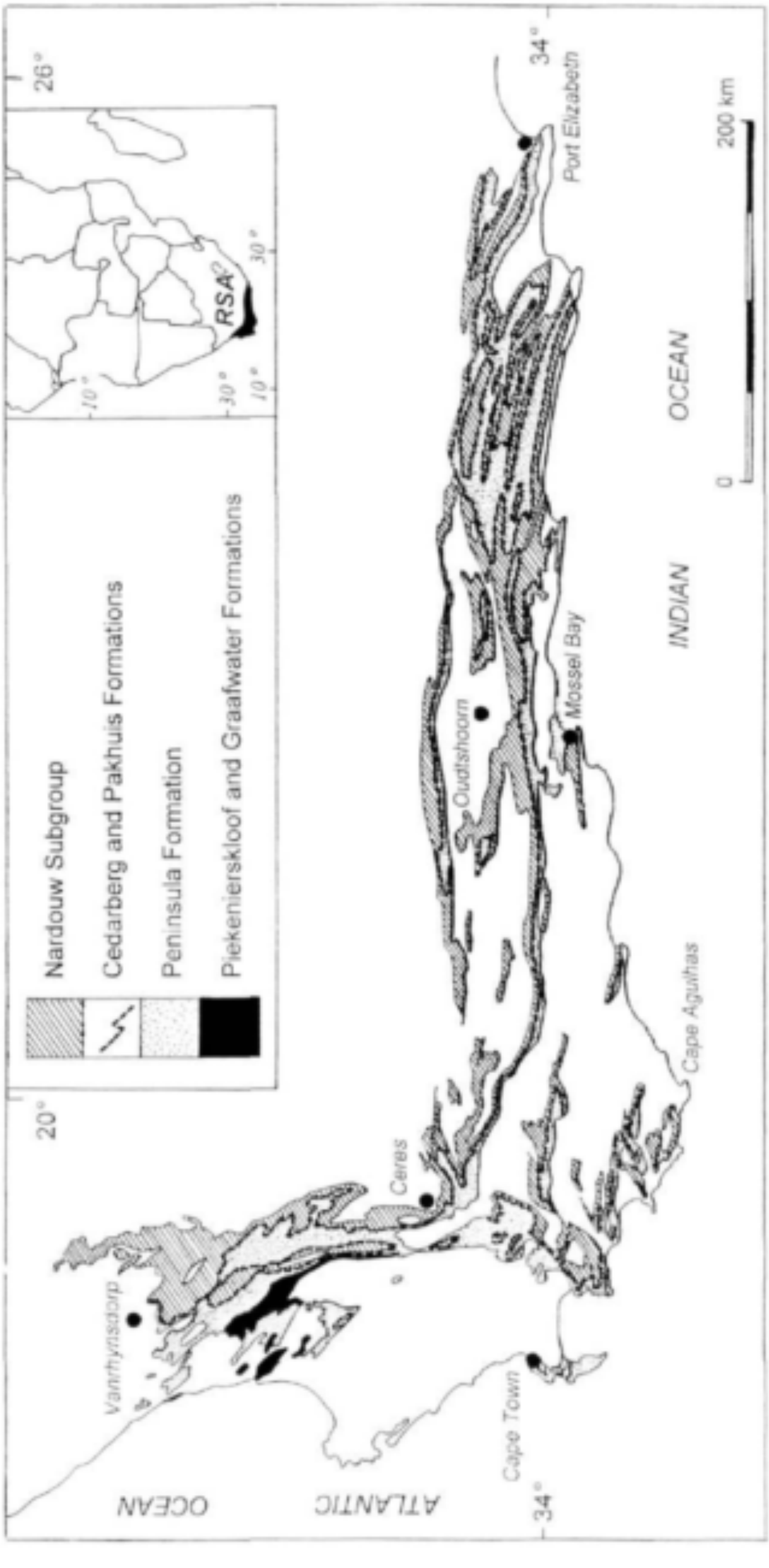

Figure 1
Distribution of the Table Mountain Group

that are interbedded with coarse- to medium-grained, cream-weathering, cross-bedded quartz arenite. Reported maximum thicknesses for the Piekenierskloof Formation vary between 900 m northwest of Citrusdal (Rust, 1967) and 390 m at Piketberg (Thamm, 1993). A thin (1-2 m thick) discontinuous unit of conglomerate with mainly quartzite clasts sporadically occurs at the base of the TMG in the Eastern Cape (I.C. Rust, pers. comm.). At Piketberg (Fig. 4), the formation consists of quartz arenite (De Hoek Member of Rust, 1967) very similar in appearance to the Peninsula Formation and considered a lateral, distal equivalent of the conglomerates along the West Coast. In areas of little topographic relief where faulting, erosion or sand cover result in the non-exposure of the underlying and overlying lithostratigraphic units, it may be difficult to distinguish between arenites of these two formations, especially when there are no associated conglomerates. As it is important from a hydrogeological viewpoint to know where you are in relation to hydrologically less favourable lithostratigraphic units such as the Graafwater Formation and the Malmesbury Group, distinction between these quartz arenite types is imperative. Distinguishing features under these conditions are the general tendency of Piekenierskloof Formation quartz arenites to weather to cream, rather than buff colours, and total absence of trace fossils ("worm tubes") or other biogenic structures.

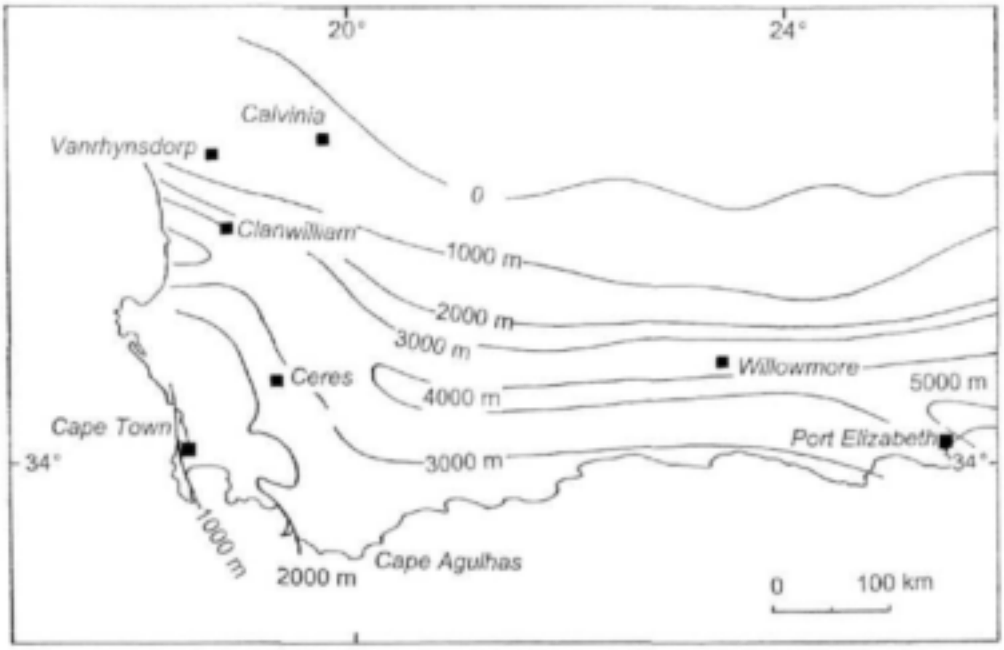

Figure 2

Table Mountain Group basin isopachs (according to Rust, 1973)

Table 1
TMG lithostratigraphy (thickness values mostly apply to southwestern outcrops)

Subgroup	Formation	Lithology	Bed thickness (m)	Maximum thickness (m)
Nardouw	Rietvlei/Baviaanskloof	Feldspathic sandstone	0.5 - 1	280
	Skurweberg	Quartz arenite	1 - 2	390
	Goudini	Silty sandstone, siltstone	0.3 - 0.5	230
	Cedarberg	Shale, siltstone	0.1 - 0.3 in siltstone	120
	Pakhuis	Diamictite, shale	variable	40
	Peninsula	Quartz arenite	1 - 3	1800
	Graafwater	Impure sandstone, shale	0.1 - 0.5	420
	Piekenierskloof	Quartz arenite, conglomerate, shale	0.3 - 1.5	900

Additionally, siltstones and shales within the Piekenierskloof Formation are usually green, but some thin beds of purple sandstone and shale occur at Piekenierskloof Pass. The Piekenierskloof Formation thins rapidly towards the south and east, because southwest of Vanrhynsdorp, it is represented by only a thin veneer of angular quartz fragments, and the formation is absent south, southwest and east of Villiersdorp. The upper boundary of the formation is taken at the first purple siltstone of the Graafwater Formation.

The *Graafwater Formation* is characterised by purple, thin-bedded, ripple-marked and mudcracked sandstone, siltstone and shale beds. These features, together with the presence of trace fossils, prevent confusion with any other unit within the TMG. Rust (1967) subdivided it into four distinct members and calculated a maximum thickness of 424 m in the type area west of Clanwilliam (Fig. 2), where the basal shale is 180 m thick, the next unit comprise 180 m of sandstone and above that lies 30 m of white sandstone, followed by fine pinkish, often bioturbated sandstone at the top. The formation shows severe lateral facies and thickness changes, is only about 30 m thick south of Ceres, and probably continues to occur as a shale unit below the Peninsula Formation for some unknown distance to the east. The upper contact with the well-sorted, thicker-bedded, white quartz arenites of the Peninsula Formation is relatively abrupt, reflecting a major change in depositional conditions. The Sardinia Bay Formation (Shone, 1983), a succession of conglomerate, sandstone and shale exposed on the coast about 15 km west of Port Eliza-

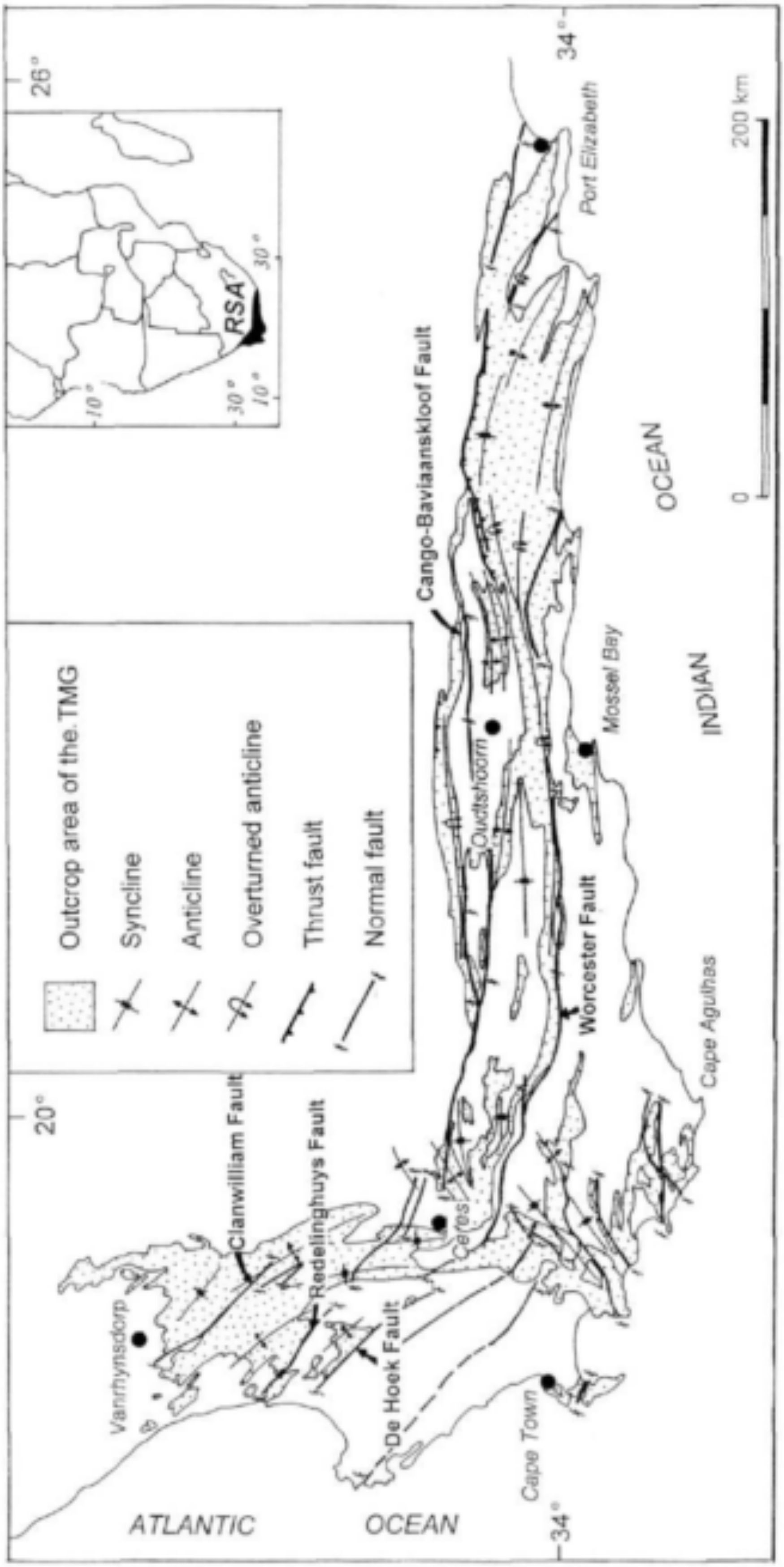

Figure 3
Major structures of the Cape Fold Belt

beth, could be the lateral equivalent of the Graafwater Formation in the Eastern Cape (I.C. Rust, pers. comm.).

The name of the *Peninsula Formation* is derived from the Cape Peninsula (Rust, 1967), where the full succession (550 m) is exposed against Table Mountain. It comprises a succession of coarse-grained, white quartz arenite with scattered small pebbles and discrete thin beds of small-pebble, matrix-supported conglomerate. The pebbles are normally vein quartz, but sometimes (Rust, 1967) consist of black, oolitic chert. Compared to their abundance in the Graafwater Formation, trace fossils are generally very rare within the Peninsula Formation, but two distinct zones of vertical biogenetic tubes occur along the West Coast (Rust, 1967). In this area, these "tube zones" are useful to distinguish between the quartz arenites of the Peninsula Formation and the De Hoek Member of the Piekenierskloof Formation where these are faulted or overlying strata have been eroded away (Fig. 4). The formation reaches a thickness of about 1 800 m at Clanwilliam in the west (Rust, 1967), but is reportedly much thicker (Rust, 1973; Johnson, 1991) in the Eastern Cape. However, thickness measurement is hampered by the severe folding and unknown amounts of thickening due to thrusting (Booth and Shone, 1992) within the formation. The determination of formation thickness is also impeded by the general lack of marker beds. In the

Cape Peninsula. Fuller and Broquet (1990) identified two informal members within the formation that are separated by 1 m of clast-supported conglomerate (probably equating with the Slanghoek Member of Rust, 1967).

The *Pakhuis Formation* occurs above the Peninsula Formation and comprises about 40 m of glacially derived sediments, but is restricted to the southwestern Cape (Broquet, 1992; Rust, 1967). It displays two interfingering facies variations, namely a gritty quartz arenite with small angular clasts (Steenbras Member) and varvites with dropstone argillite (Kobé Member). The southern, arenaceous diamictites are erratic in their distribution, being often only present within synclinal folds in the "Fold Zone" (Rust, 1967), a zone of soft-sediment deformation, which itself, is not present everywhere.

The monotonous arenitic character of the TMG is interrupted by an important marker unit, the *Cedarberg Formation*, which is a thin (maximum 120 m), but remarkably continuous unit, consisting of black silty shale at the bottom, grading into brownish siltstone and fine sandstone at the top. According to Broquet (1992), the Cedarberg Formation was probably deposited when the basin was depressed glacio-isostatically, leading to a rise in sea-level and a decrease in sediment influx. It is best exposed within the southwestern Cape, but continue along the whole length of the southern Cape Fold Belt, where it is often shows extreme tectonic thinning. Its confining character makes the Cedarberg Formation very important in a hydrogeological sense.

The *Nardouw Subgroup*, with its three subdivisions, the *Goudini, Skurweberg* and *Rietvlei* (*Baviaanskloof* in the Eastern Cape)Formations, is another thick (maximum 1 200 m) unit of sandstone that varies between quartz arenite, silty and feldspathic arenites, accompanied by some very minor interbedded conglomerate and shale. This lithological diversity, together with textural, grain size and bedding thickness differences, lead to pronounced differences in weathering, structural and hydrogeological characteristics. The basal unit, the Goudini Formation, is characterised by reddish weathering, thin sandstone beds with common shale intercalations, which are less resistant to weathering than the thick-bedded, arenitic Skurweberg Formation. The topmost unit, the Rietvlei Formation (Baviaanskloof Formation in the Eastern Cape), is easily recognised by finer grain size, common high feldspar contents and resultant more dense vegetation cover, which is visible on aerial photographs as darker tones of grey, compared to the lighter Skurweberg Formation. The contact with the overlying dark shales of the Bokkeveld Group is usually abrupt.

Structure

Introduction

The presently exposed structure and thickness of the TMG rocks are the result of initial deposition within an east-trending basin (Rust, 1973) along the southern and southwestern Cape regions, as modified by two major tectonic events, namely the Permo-Triassic Cape Orogeny and the fragmentation of southwestern Gondwana during the Mesozoic. The Cape Orogeny had the effect of tectonically thickening the sequence in areas of high strain like the Southern Cape, whilst the later extensional faulting disrupted the initially continuous exposures. The CFB consists of two branches forming a mountain chain of about 1 200 km along the south coast and part of the west coast of the Republic of South Africa (De Villiers, 1944; Söhnge and Hälbich, 1983). The Cape Orogeny deformed a basement of previously deformed and metamorphosed Neoproterozoic rocks and the Cape Granite Suite, together with its cover sequence of Ordovician to Triassic rocks (Cape Supergroup and part of the Karoo Sequence). The exposed width of the southern branch is about 200 km, and of the western branch, about 150 km. Both branches are arcuate in plan view and convex towards the Karoo Basin, merging with northeast-trending folds in the syntaxis of the southwestern Cape.

The western branch

The western branch ("Cedarberg Fold Ranges" of Du Toit, 1954) differs in two major aspects from the southern branch (De Villiers, 1944; Söhnge, 1983). The first one is its much lower shortening intensity and the second, its northwesterly fold trend. The large-scale structure (Fig. 3) of the resistant TMG and resultant topography was determined by the physical properties of the competent units, which usually display monoclinal folds (De Villiers, 1944) that are often arranged in conjugate pairs, forming mega-box folds (De Beer, 1995). A tendency for parts of the Nardouw Subgroup (especially the Goudini Formation) to display similar monoclinal, kink-like folds, is helpful to identify this group of rocks where the Cedarberg Formation is not exposed. The fine-grained rocks display no cleavage, except for weak solution types in Cedarberg shale towards the south (De Swardt and Rowsell, 1974; De Beer, 1989) and strong shear cleavages in shaly interbeds within tight folds, but fracture cleavage is rare. However, joints are ubiquitous in most of the more competent beds. Faults of the western branch trend northwesterly, the major ones being the De Hoek Fault, the Redelinghuys Fault and the Clanwilliam Fault, all of which display wide breccia zones and sometimes manganese-iron hydrothermal deposits formed by solution of detrital heavy minerals. Numerous subsidiary splays and sets of transverse northeast-trending minor faults are also present.

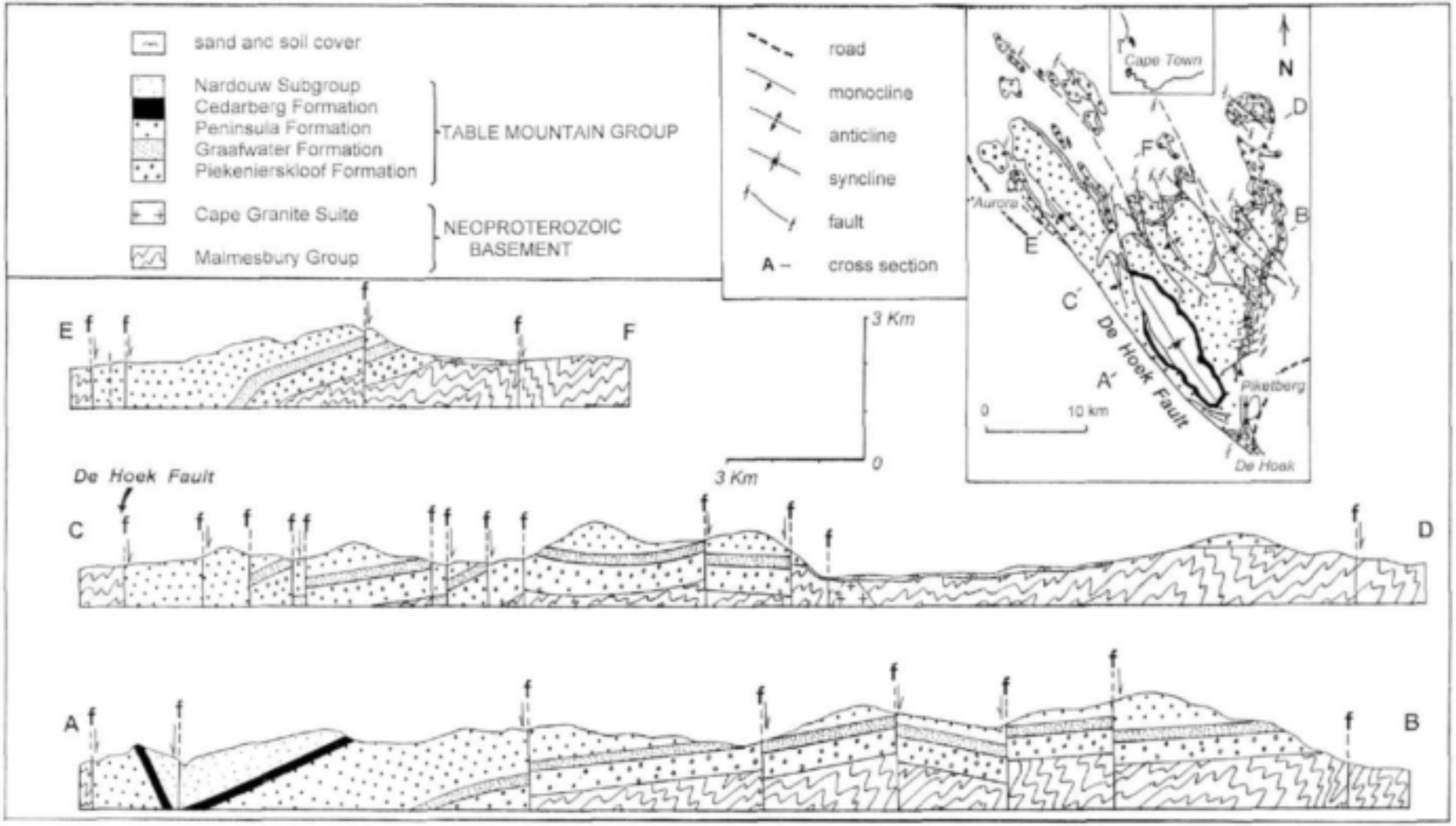

Figure 4

Structure of the TMG in the Piketberg outlier

The Piketberg outlier (Fig. 4) serves as an example of fault and fold geometry in the western branch. The outlier represents a half-graben bounded on the southwestern side by the De Hoek fault, which has a northeast-down displacement of at least 400 m and a breccia zone some tens of metres wide. All of the faults are near-vertical normal faults with minor transtensional components and varying damage zone widths, while fold wavelength is about 5 km.

The southern branch

The southern branch displays northerly-verging, often overturned first-order folds, sliced by a few thrusts (Theron, 1962; Booth and Shone, 1992) and normal faults, with strong fracture cleavage in the quartz arenites and slaty cleavage in the Cedarberg Formation. The transect along 22°E (Söhnge and Hälbich, 1983) serves to illustrate the most important features of the southern branch (Fig. 5). The two most important regional fold structures are the Swartberg and the Outeniqua anticlinoria. There are abrupt changes in style and intensity of deformation in the cover rocks across the CFB, with the least deformed *Zone 1* north of the Swartberge having fold wavelengths of 1-2 km and limb inclinations of less than 5°. Excepting leading edges of small listric thrusts, cleavage is generally absent and horizontal shortening amounts to only a few percent. *Zone 2* displays open symmetric and upright flexural slip folding with wavelengths of 1-2 km and limb inclinations less than 25°. A spaced axial plane cleavage is developed in fine pelites only and buckle shortening is about 8%. *Zone 3* is characterised by asymmetric and inclined folds with wavelengths of 5-7 km, for which 30% shortening was calculated. A well-developed, fanning axial plane cleavage is often accompanied by a steeply south-dipping solution or crenulation cleavage. This was followed by compressional kinking around 230 Ma ago. Complex quartz microstructures displaying multiple sets of deformation lamellae with c-axis fabrics that are asymmetric towards the mesofabric indicate pulsating, cold working conditions and excessive strain hardening. Temperatures remained below 300°C. *Zone 4* has, additionally to the features of Zone 3, second-order "cascade folds" on overturned limbs, profuse evidence of bedding decoupling and local thrusting. Bulk horizontal shortening is slightly higher at 35%, with steep thrusts contributing little to this figure. Two recrystallised cleavages developed in fine-grained pelites. Illite crystallinity indicates temperatures of about 300°C, while fluid inclusions in quartz found along thrusts indicate temperatures up to 360°C. These higher temperatures are reflected in TMG quartz arenites by recrystallised zones of a few microns wide.

Hälbich (1983) ascribes the sudden inception of intense folding in the cover rocks of the third and fourth zones to relatively sudden stratigraphic thickening of the Table Mountain Group. The "explosive stage" of folding was reached from here southwards with sequential folding triggered by basement weaknesses in the deep crust, basement and cover rocks alike. The southern edge of the SCCB crustal anomaly (approximately coinciding with the Cango-Baviaanskloof Fault) forms the northern boundary of *Zone 5* (Fig. 1) between the inland Swartberge and the coastal Outeniqua Range, and consists of Bokkeveld Group in a wide synclinorium, overlain at Oudtshoorn by the post - Cape Fold Belt, terrestrial conglomerate of the Enon Formation. Strain markers indicate up to 30% internal longitudinal strain and the folds are open structures with an intense axial plane cleavage. The metamorphic grade approaches epizonal conditions (±300°C).

The coastal Outeniqua Range of *Zone 6* (Fig. 5) contains tight to isoclinal folds with flat south-dipping axial planes, slaty cleavage, crenulation cleavage, kinks and a prominent downdip mineral elongation lineation. Quartz grains in the TMG arenites are completely annealed to a stable polygonal (foam) structure. Horizontal shortening is estimated at around 70% and epimetamorphic greenschist facies conditions (with biotite) reached at approximately 350°C. Thrust faulting with important displacements (Theron, 1962; Shone and Booth, 1992) is common towards the eastern part of the CFB, especially in the vicinity of the north trending "Willowmore High" (Rust, 1973), a linear Cape Basin floor positive element.

The major faults trend easterly (Fig. 3), but is accompanied by a transverse set of minor, approximately penecontemporaneous northeast-trending transfer faults, suggesting elements of transtension. The major ones are the Worcester Fault and the Kango-Baviaanskloof Fault Zone, both of which remain seismically active to this day. All of these faults display zones of brecciation a few tens of metres wide, cataclasm and numerous minor splays, as well as horse-tailing.

The syntaxis

Fold axial traces of the western and the southern branches form open arcs in the Western Cape Province where they merge with the broad zone of northeast trending structures of the syntaxis. Based on differing fold trends and shortening intensity, the syntaxis may be divided into two separate domains lying north and south of the Hex River anticline. Cleavage is restricted to cover pelites of the southern domain.

The northern domain is characterised by north, northwest, northeast and minor east trending folds, while the southern domain contain only east and northeast trending folds. The curvature of both branches to form oroclinal arcs in the syntaxis which merge with an intermediate trend, suggests their formation by roughly simultaneous northeast-southwest and northwest-southeast directed shortening (De Villiers, 1956; Newton, 1975; De

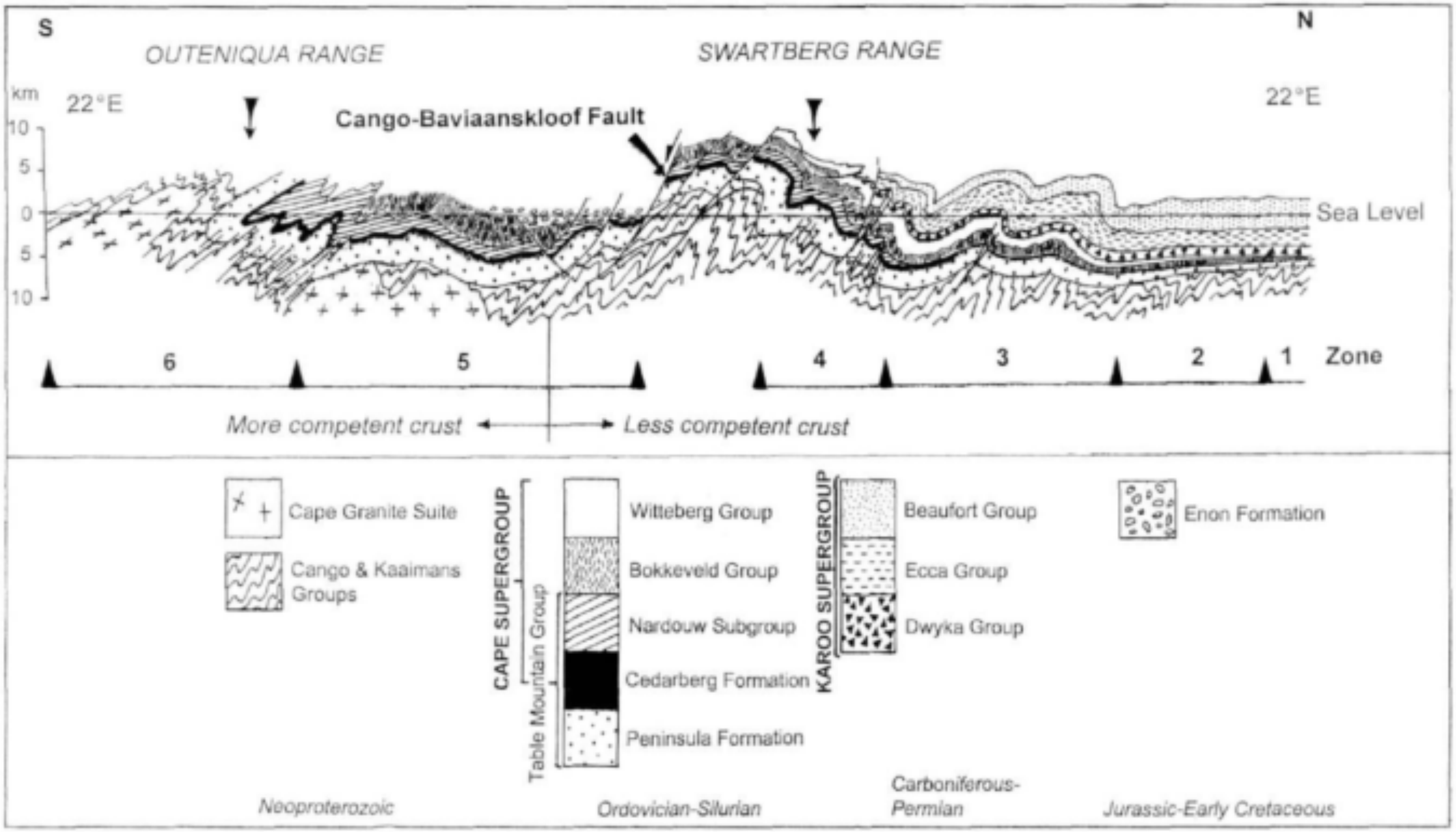

Figure 5

Schematic crustal section through the Southern Cape Fold Belt (modified from Söhnge and Hälbich, 1983)

Beer, 1990; De Beer, 1995). The syntaxis is the most fractured part of the CFB, with components of the western and southern branch faulting both being present. The Worcester Fault changes trend from easterly to northwesterly and the area south of it is dominated by numerous large northeasterly-trending faults. The latter set of fractures must have formed contemporaneously with the Worcester Fault or slightly later, because they end against this major fracture, which attains its maximum displacement of more than 5 km in the syntaxis.

Effects of deformation on target selection

Sedimentary features such as grain size, matrix composition, sedimentary structures and formation thickness are inevitably modified by folding and faulting processes, the end result of which will ultimately determine the structure and resultant hydrogeological potential of these rocks. Apart from changing porosity values, regional thickness estimates for formations in areas of high strain could be grossly exaggerated (Fig. 2) and meaningless (see Booth and Shone, 1992), if the amount of tectonic thickening by folding and thrusting is unknown. For example, thickness determinations from maps without structural information about the position of fold axial planes could easily give values two or three times the original thickness. Such calculations become even more inaccurate where the presence of intraformational thrust faults goes unnoticed.

Internal features of depositonal units, such as grain size distribution and primary porosity, may change substantially during deformation, while on the visible scale, cross-bedding laminae, bedding planes and formation boundaries are folded and disrupted. Thrusting could also play an important, often relatively unknown, role in this process. Intuitively, all of these processes should lead to an increase in fracture density and aquifer capacity within the competent quartzose rocks of the TMG. Thin section studies often prove that even in pure quartz arenites from unfolded beds, intergrain pore spaces are completely filled by secondary quartz overgrowths, making these rocks nearly impermeable. It is only where they are fractured by folding, cleavage formation and/or faulting that the rocks develop a secondary porosity and become aquifers. Deformation of less pure arenites, like the feldspathic and silty varieties encountered within parts of the Nardouw Subgroup, commonly transforms and mobilises the impurities to fine micaceous or clay material, which has a negative effect on the permeability of fractures and the aquifer ability of breccias (Table 1).

Too much deformation, especially within pure quartz arenites, is also not beneficial to hydrogeological potential. Greeff and Hälbich (2000) recently pointed out that strong cataclasm, especially when accompanied by silicification, greatly reduces the aquifer potential of quartz arenites in the TMG of the Kammanassie Mountains (east of Oudtshoorn). This one example is typical of aspects noticed during several drilling programmes in the past and serves as a clear reminder that highly folded beds and fault breccias are not always good aquifers and that detail structural investigation should always form part of a borehole siting programme, because these aspects will also influence the capacity of a major aquifer to be replenished from contributing sources such as fault splays.

Faults themselves may be grouped into two end-members, namely compressional reverse/thrust faults with dips below 45° and extensional to transtensional normal faults with dips in excess of this. Within the TMG of the CFB, breccias associated with all of these faults generally look alike. In principle, therefore, a narrow breccia zone at the surface is no guarantee that a borehole will continue to encounter breccias for long when it is a thrust fault with low dip. In the CFB, the possibility of encountering such flat dipping faults is probably low within most of the southern branch and almost zero in the western branch. The fact that on a crustal scale, most normal faults are listric in shape (see Fig. 5), is not relevant to the depth range within which boreholes are normally drilled, especially where sited within a wide breccia zone.

Although major faults with well-developed breccia zones are normally the best aquifers, fold hinges with strongly developed fracture cleavage, joint sets (see Coetzee, 1983) and axial-planar faults can be good targets as well, especially where capped by impervous beds. Such situations are likely to be encountered at contacts between the Piekeniers-kloof Formation and the Graafwater Formation, between the upper Peninsula Formation (especially where the glacial fold zone - see Rust, 1967 - is developed) and the Cedarberg Formation, as well as within the Nardouw Subgroup and specifically at its contact with the confining Bokkeveld Group shales. Large springs in the Cape Fold Belt are often located where large faults are capped by the Bokkeveld Group, for example the hot springs at Brandvlei (south of Ceres) and Warmwaterberg (west-southwest of Oudtshoorn). These faults are generally large fractures connected to other major faults of divergent trend and usually traverse areas of mountainous terrane with high rainfall.

Conclusions

Large fracture systems within the arenites of the TMG have the potential to be important water resources in future. However, borehole siting and resource strategies should take cognisance of a variety of aspects such as detail lithological variation and structural setting. A better understanding of these aspects could save time and prevent money from being being wasted on unsustainable sources, as well as aid in the planning of large groundwater projects.

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Use of Structural Geology and Remote Sensing in Hydrogeological Exploration of the Olifants and Doring River Catchments

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Abstract

Structural geology and remote sensing is used in hydrogeological exploration of the Olifants and Doring river catchments to accurately quantify the boundaries and internal structures of the Table Mountain Group (TMG) fractured-rock aquifers; to map the principal hydraulically conductive structures (hydrotects); and to determine regional and localised patterns of fracture orientation and spatial density. Use of Landsat and SPOT images in quantitative structural analysis involved satellite-based remote sensing techniques, aerial photographic interpretation (API) of selected well-exposed terrains, follow-up fieldwork and stereographic analysis of the data. Accurate structural data was obtained for modelling of the 3D fold and fault geometry of the TMG Aquifers and their fracture patterns. The major features of hydrogeological significance are:

(1) *Large aquifer volumes are located up to 3 km below sea-level in the boxfold-like Olifants River Syncline (ORS).*
(2) *There is a close kinematic relationship between approximately N/S fold-axial trends and the dominant NW/SE faulting.*
(3) *There are five principal joint sets and major fault traces.*
(4) *Four major "megafault" or "hydrotect" systems trend in a NW/SE directions, linked to each other by connecting splay- and cross-faults.*
(5) *Fracture spatial density (FSD) and connectivity relationships indicate that the fault-fracture systems constitute a percolating network for deep geofluids movement.*
(6) *Aeromagnetic survey data supports the correlation of certain megafault zones across areas of no, little, or poor bedrock exposure. Incorporation of physiographic data, geological contacts and fracture-fault traces, into a common geographic information system (GIS) with advanced geospatial analytical capabilities provides a future platform for aquifer management and groundwater resource development.*

Introduction

Objectives and methodology

Aims

The principal aims and uses of structural geology and remote sensing were:

- To define accurately and quantitatively the geological boundaries and internal structures of the deep TMG fractured-rock aquifer that supplies a strong locally focused groundwater flow to thermal springs along the Olifants River valley, seep zones, springs, and vleis along the coast, and provides an artesian flow to some boreholes for agricultural and municipal water supply in the Citrusdal area.
- To locate and map on a regional scale within the study area the principal, hydraulically conductive, tectonic structures - "hydrotects" (Umvoto, 1997) - along which the deep artesian groundwater flow is channelled;
- To undertake localised structural mapping to determine quantitatively the patterns of fracture orientation and fracture spatial density over a range of characteristic length scales on one particular hydrotect.

The contribution of fractures (faults and joints) to the permeability of fractured, sandstone aquifers depends on the nature of the fractures themselves, i.e. aperture, presence/absence of fault gauge, preferred flow channels. It also depends on the nature of the fracture system as a whole, i.e. orientation

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and length distributions, geometry and connectivity (Odling 1997).

In the TMG Aquifer, three fracture components exist which can significantly contribute to water flow, viz. bedding-fractures, joints and faults. The geometrical and hydraulic characteristics of these three structures may be different, so that all must be investigated. Fieldwork in support of remote sensing is aimed at characterising the remotely mapped fault and joint systems in terms of the factors listed above.

In the case of the joint systems:

- Good exposures are sought to map the joint systems on the surface of bedding planes at a range of joint densities
- Cliff sections are examined to investigate joint persistence and the influence of bedding on the system, and to estimate fracture aspect ratios
- Line samples are taken to obtain data on orientation and length distributions, and spacing on the field outcrop scale
- The nature of fracture apertures and the presence of mineralisation and preferred flow channels is investigated.

In the case of the fault systems:

- Good exposures are sought to investigate the nature of the 'damage zone' of increased fracture density near major faults
- The relation between faulting and jointing in terms of fracture orientation and density approaching major faults is investigated
- The nature of mineralisation in fractures in and adjacent to fault zones is recorded.

Data analysis

To determine the nature of the fracture system over a range of scales, in terms of geometry, the role of mechanical layering, connectivity, and the relation to the concept of a "percolation threshold", data collection in the Olifants/Doring region involved satellite imagery, digital elevation models (DEMs) and their derivative products, and the local interpretation of conventional aerial photography. This analysis is used to build conceptual models of the fracture system for use in hydrogeological flow modelling. Furthermore, the following analyses are possible:

- Length distributions from satellite imagery, aerial photos, and field mapping to determine the nature and scaling of the fracture length distributions (lognormal or power law)
- Maps of joint systems for the relation between fracture density and connectivity
- Orientation distributions at different scales are compared in order to detect scale ranges of different sizes of fracture
- Information on fracture apertures to build a model for the relationship between apertures, chemical activity (mineralisation, dissolution), orientation, age, and location (proximity to major faults).

Previous mapping and structural work by the South African Geological Survey and other workers has focused mainly on descriptions of the stratigraphy, sedimentology, and fold structures of the region (e.g. Visser and Theron, 1973; De Beer, 1989, 1999). From the perspective of this study, the descriptive aspects of the folding are less significant than those related to rock fracturing, except in relation to the major synclinal structure that have down-folded large volumes of TMG Aquifer rocks.

Use of remote sensing techniques

Apart from a pioneering study by Newton (1975) on air-photo interpretation (API) for structural analysis in other parts of the CFB to the south and east of the study area, there has been remarkably little attention to the use of remote sensing methods in TMG hydrogeological exploration.

In this study, digital images obtained from the Landsat and SPOT satellite platforms have been combined with and, in the SPOT image case, even superimposed upon a high-resolution DEM to obtain quantitative spectrometric data and also quantitative 2D directions and 3D orientations of various features.

In the structural analysis of folding over the whole region, the study mainly relied on previous and present conventional API and selective follow-up field mapping of the main fold axial traces. In an area covered by one SPOT scene (118/415) centred roughly over the main Cederberg range, northeast of Citrusdal, the "Geospatial Analysis" capabilities of the TNTmips software was used to obtained bedding measurements and the regional fold-axis orientation from georeferenced superimposition of the SPOT scene on the DEM.

Techniques of combining maps, or aerial and satellite images with DEMs for the extraction of three-dimensional orientation data are well documented in remote sensing literature (Morris, 1991; Chorowicz et al., 1991; Mahon et al., 1993). Although the petroleum industry has developed some expensive, proprietary software that implements these documented algorithms, no inexpensive software for use in regional mapping applications was available prior to 1995. Locally developed software was used to collect structural data for the Olifants-Doring catchment hydrogeology study and represents the first time the method has been used on an operational basis in this region.

The method is especially suited to areas underlain by folded rock strata, combined with large variations in topographic elevation. In this respect, the Olifants-Doring study area and, in fact, the entire TMG terrain is ideal for application of the technique. The software involves use of accurately co-georeferenced image and digital elevation data. The image data have to be of a sufficiently high resolution in order to accurately trace and position geological contacts, fracture trace lines and bedding traces. The on-screen interpretation phase of the method requires input from an experienced structural geologist and photo-interpreter, since recognition of actual structural features and correct placement of sampling points is crucial to the success of the method. The method is therefore intensely interactive and knowledge-based.

This remote sensing method represents an important departure from the normal "lineament tracing" methods of structural interpretation commonly employed in remote sensing. Such simplistic 2D "lineament analysis" methods are prone to errors in areas with significant topography, where lineaments (outcrop traces of geological surfaces) can change direction across ridges and valleys because of the relationship between trace-line orientation, axial planar orientation, and topography. Few analyses undertaken in 2D account for topographically induced apparent changes in orientation of the traces of bedding, fractures or faults. Because this Image + DEM method is intrinsically three-dimensional, effects of topography are accounted for and structural orientations obtained for features are true 3D orientations. These orientations can reliably be analysed using conventional methods of structural analysis (stereonets, histograms or eigenvector statistical analysis), whereas it is unwise to submit the results of 2D lineament interpretation to such rigorous analysis, except in topographically flat areas, or where supporting 3D structural information has confirmed the vertical/near-vertical orientation of the structures being analysed.

SPOT imagery with a 10 m resolution was used in conjunction with a 30 m resolution DEM (maximum height error of ±10 m) derived from minimum curvature surface fitting to 1:50000 digital elevation contours. The method provides structural information that was statistically the same as that obtained during concurrent field surveys. These results, together with other field validation studies of the method conducted in the Cape Fold Belt (Millad, 1993; Slabber, 1996) have demonstrated that it is reliable, and suitable for application throughout the CFB. Given the high costs of field work, and difficulties encountered in accessing many mountainous terrains, this application of remote sensing provides the most cost and time-effective tool for capturing the large amounts of accurate structural data required for realistic modelling of the three-dimensional geometry and fracture patterns in TMG and Witteberg Group aquifers.

Olifants-Doring fold structures

Cedarberg folding and Hex River syntaxis zone

A convergent fold bundle in the Ceres District swings from ENE/WSW trend in the Hex River Mountains at the far southern end of the E drainage region (De Beer, 1999) to N/S trend in the Kouebokkeveld ranges in the southwestern part of the study Area. The structurally controlled high topography of this "syntaxis zone" forms the southern boundary divide between the Olifants/Doring Basin and the Breede River catchments. In the headwaters of the Doring River the main fold axes trend NE/SW around a major syncline exposing Karoo formations, although at a smaller scale a complicated pattern of NW/SE cross-folding is also evident (De Beer, 1999).

Kouebokkeveld fold bundle

The Kouebokkeveld and Olifantsrivierberge ranges are part of the N/S-trending Cedarberg fold-belt; the structure-controlled topography of which forms the southern boundary divides of the E10 (Upper Olifants) drainage region.

In the E10 headwaters zone, there are four contiguous major fold structures (Fig. 1). The westernmost is the Olifants River Syncline (ORS), extending north past Citrusdal and Clanwilliam (blue dotted line in Fig. 1). To the east of the ORS, three major folds terminate or change shape northwards along a NW/SE-striking fault system. From east to west, these are shown as:

(a) **Hansiesberg Anticline** (orange-dotted line marked HBA)
(b) **Agter-Witzenberg Syncline** (blue dotted line marked AWS)
(c) **Kouebokkeveld Anticline** (orange dotted line marked KBA).

The zone of generally west-dipping strata between the HBA and AWS is no longer evident on the northern side of a NW/SE fault system that controls part of the upper Olifants river course. The KBA continues northwards, but the AWS and HBA folds terminate along this fault zone and two structures located farther to the northwest in the fold bundle replace them, namely:

(d) **Leeu River Syncline** (blue dotted line marked LRS)
(e) **Sneeukop Anticline** (orange dotted line marked SKA).

These three fold structures (KBA, LRS, and SKA) are replaced by the single anticlinal structure along the axis of the Cederberg range (Fig. 1). They apparently terminate near or along another NW/SE-striking fault that crosses the eastern limb of the Citrusdal Trough.

Olifants River syncline

The most important major fold structure of the whole region is the roughly N/S-striking **Olifants River Syncline** (blue dotted line marked ORS; Fig. 1). It is divided by a hinge-zone culmination around Kriedouwkrans, ~35 km north of Citrusdal, into two distinct axial troughs, namely the Citrusdal Trough and the Clanwilliam Trough, both down-folding rocks of the Bokkeveld Group. Here the ORS is obliquely transected by a major NW/SE-striking fault system (TLM in Fig. 1 and Fig. 4). An oblique fault system of similar orientation abruptly truncates the syncline just north of Clanwilliam, and another NW/SE fault system (GVM in Fig. 1 and Fig. 4) transects it in the Tharakamma area. At each of these localities, the profile shape and sense of asymmetry of the ORS is notably changed, which implies a close kinematic relation between the faulting episode and at least the later phases of fold development.

The southern trough segment of the ORS syncline reaches a maximum width in the Citrusdal area, where there is a ~10 km separation between the Cedarberg Formation on the opposite limbs. In the southern part of the same area, the syncline is also at its deepest, because the Boplaas Formation is locally exposed here within the Bokkeveld Group, as the highest stratigraphic unit seen within this particular section of the fold.

Quantitative structural analysis of part of the ORS and adjacent Cederberg Anticline, using a combination of SPOT imagery and DEM was undertaken in order to improve the database from accurate

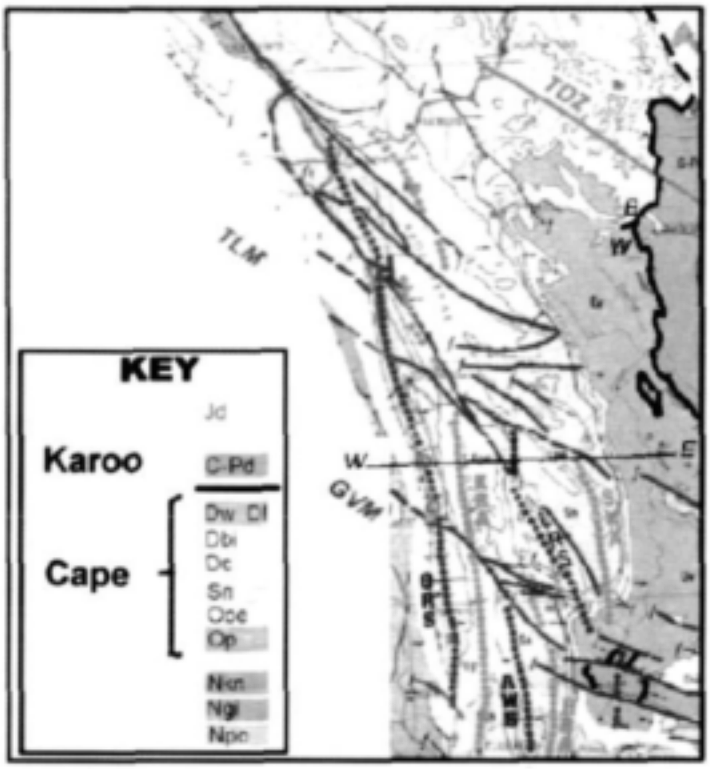
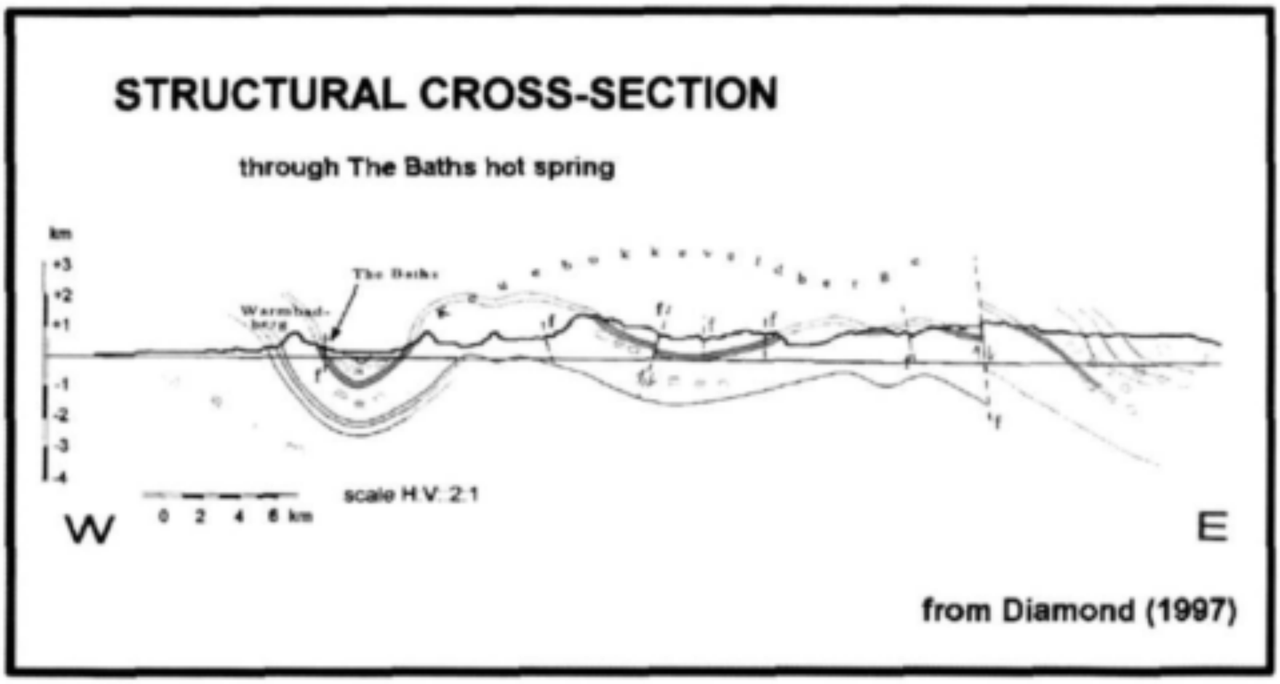


Figure 1

Grey-tone geological map showing the main fold axes (blue and orange dotted lines) and other important structural features (green and red lines for major faults and dykes, respectively) in the south-eastern part of the Olifants-Doring study area. Fold, fault and other annotations are explained in the text. Black line marked W-E represents trace of structural profile (Fig. 2) through The Baths hot spring (red circle on ORS trace).



from Diamond (1997)

Figure 2

Structural profile across the ORS and adjacent Kouebokkeveld folds, drawn along line W-E in Fig. 1

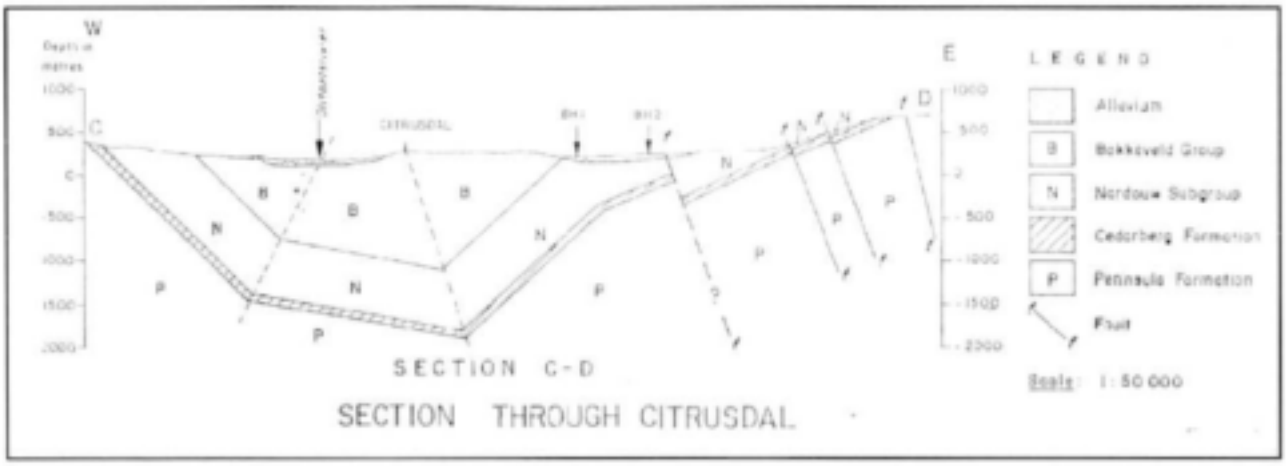


Figure 3

Detailed structural cross-section through the Citrusdal portion of the ORS. Note that only the top of the ~1 300 m thick Peninsula Aquifer (P) is shown in the synclinal hinge area.

construction of fold profiles normal to the local fold-axial direction. Most previous structural cross-sections (e.g. Fig. 2: after Diamond, 1997) are schematic and vertically exaggerated.

For the recent CAGE study, four accurate "balanced" cross-sections of the ORS were constructed across a critical deepest path of the ORS in the Citrusdal area. The fundamental premise is that folding within the TMG occurred through a flexural slip (deck-of-cards) mechanism in which the "orthogonal thickness" (normal to bedding) was preserved across the fold. As actually observed in the field, the structural geometry of the ORS consists of planar limbs and discrete kink-like hinge zones. In these profile constructions (e.g. Fig. 3), the base of the Peninsula Aquifer may reach depths around 3 km below sea level in the flat-bottomed or "box-folded" ORS structure.

Olifants-Doring fault systems

Previously little attention was given to the details of faulting and fracturing in the rocks of the Olifants-Doring area, although rock fracturing appears as one of the most striking aspects of the geology and geomorphology. It is also the principal controlling factor in TMG hydrogeology. The faults, fractures and joints in the quartzitic Peninsula Formation and the similarly quartzitic Nardouw Subgroup are of main interest for long-term groundwater supply, because they impart to the otherwise relatively impermeable rock a "secondary" permeability.

NW/SE-striking faults crossing the area form sub-parallel, continuous, interconnected systems, extending over distances of more than 100 km (Fig. 4). Together these systems constitute four "megafault" zones (Fig. 4), i.e.:

Saron-Aurora Megafault (SAM);
Gydo-Verlorevlei Megafault (GVM);
Twee Riviere-Liepoldtville Megafault (TLM);
Krakadouw-Klawer Megafault (KKM).

A megafault is defined as a structure having such great surface length and displacement that it is presumed to extend to considerable depth, at least equal to the upper brittle layer (~10-15 km) if not the entire thickness (~40 km) of the continental crust. At the largest of tectonic scales, namely that of the whole CFB, the megafaults of the Olifants-Doring area appear to constitute a system of splays off the even larger Cango Megafault, which extends between the Tulbagh–Ceres area in the west to beyond Port Elizabeth in the east (see De Beer, 2001, Fig. 3 in this volume).

All previously mapped fault structures (thin red lines on Fig. 4) have been digitised from the published 1:250 000 geological maps (e.g. Visser and Theron, 1973). During the course of the recent CAGE study and groundwater prospecting from 1995, the traces of a number of these faults have been extended and others have been added from field mapping, conventional API, and satellite (Landsat and SPOT) photogeological interpretation (Fig. 4, blue lines). There is undoubtedly scope for even more refinement of the fault mapping in many parts of the area, including the addition of displacement attributes (sense and amount) for different segments

In the western part of the area (Fig. 4), the larger faults appear to be normal faults across which the hanging-wall is downthrown to the northeastern side, e.g. the major fault between Aurora and Piketberg. In the eastern and northern parts, the larger, apparently normal faults generally show downthrown blocks on the southwestern side, e.g. the major fault near Clanwilliam. These generally NW/SE to WNW/ESE-directed, slightly arcuate, structures are crossed or connected by straighter, apparently more steeply dipping faults along NW/SE to NNW/SSE directions, and others which have E/W to NE/SW directions. The latter structures are interpreted as strike-slip or transcurrent faults of sinistral and dextral shear sense, respectively. In a few instances, thrust faults of roughly N/S to NNW/

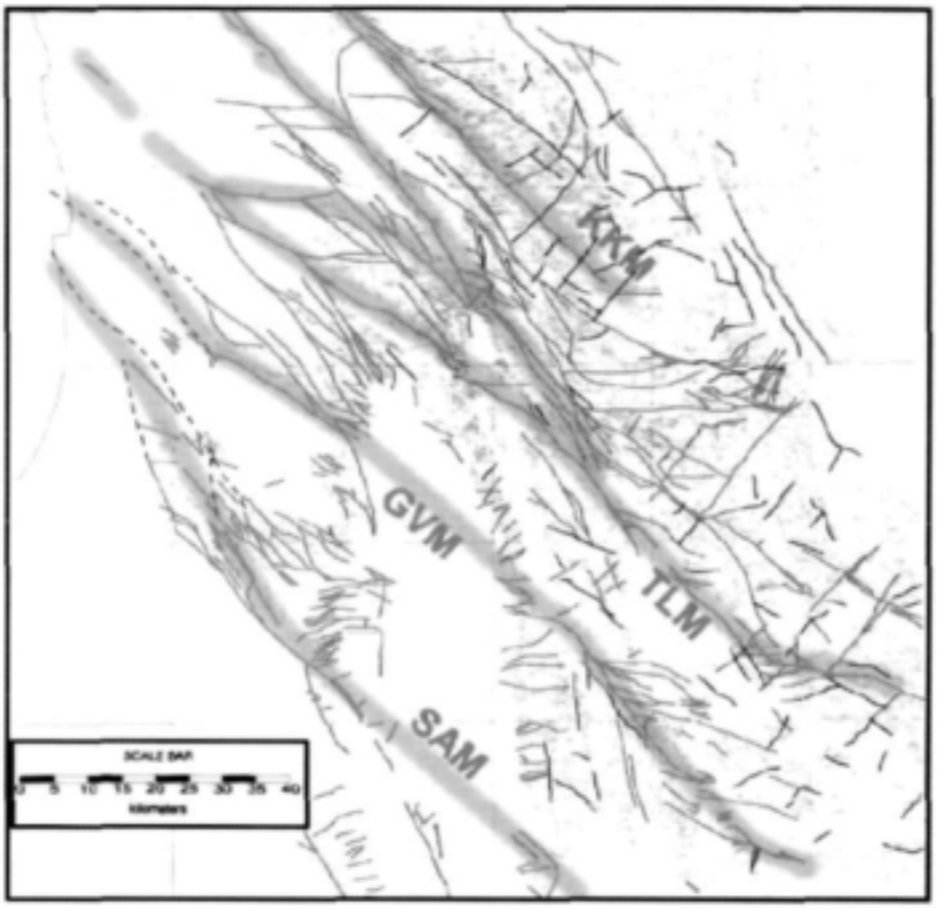


Figure 4
The four major mega-fault zones (pink overlay) superimposed on a fault and (Landsat) fracture trace map of the study area

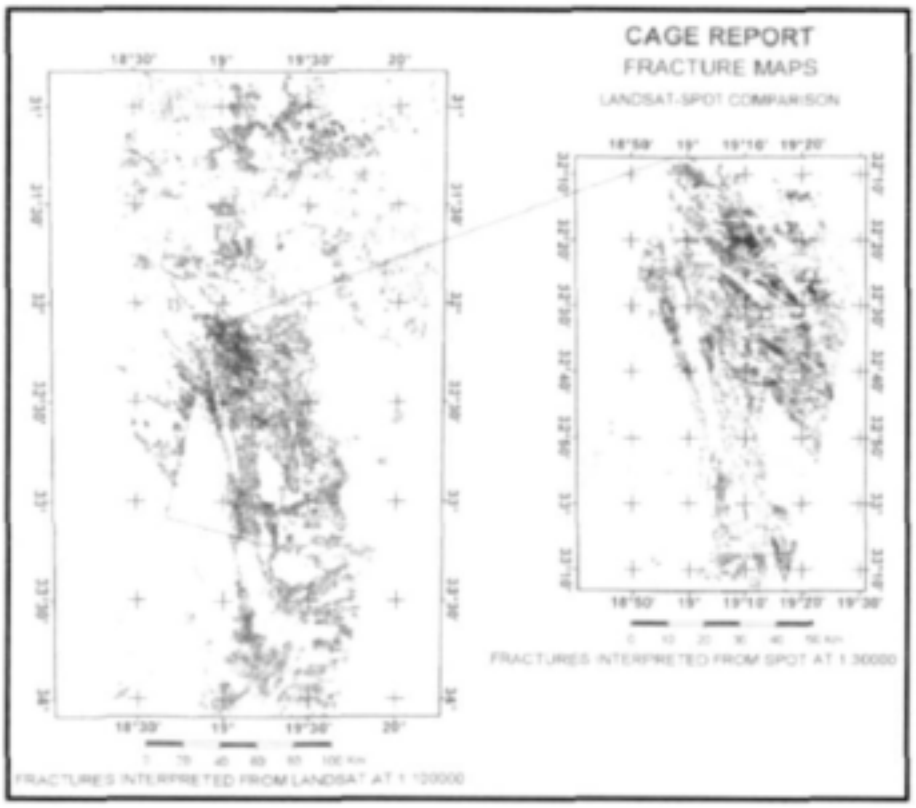


Figure 5
Maps of all fracture traces compiled from Landsat (left) and SPOTTM imagery (right)

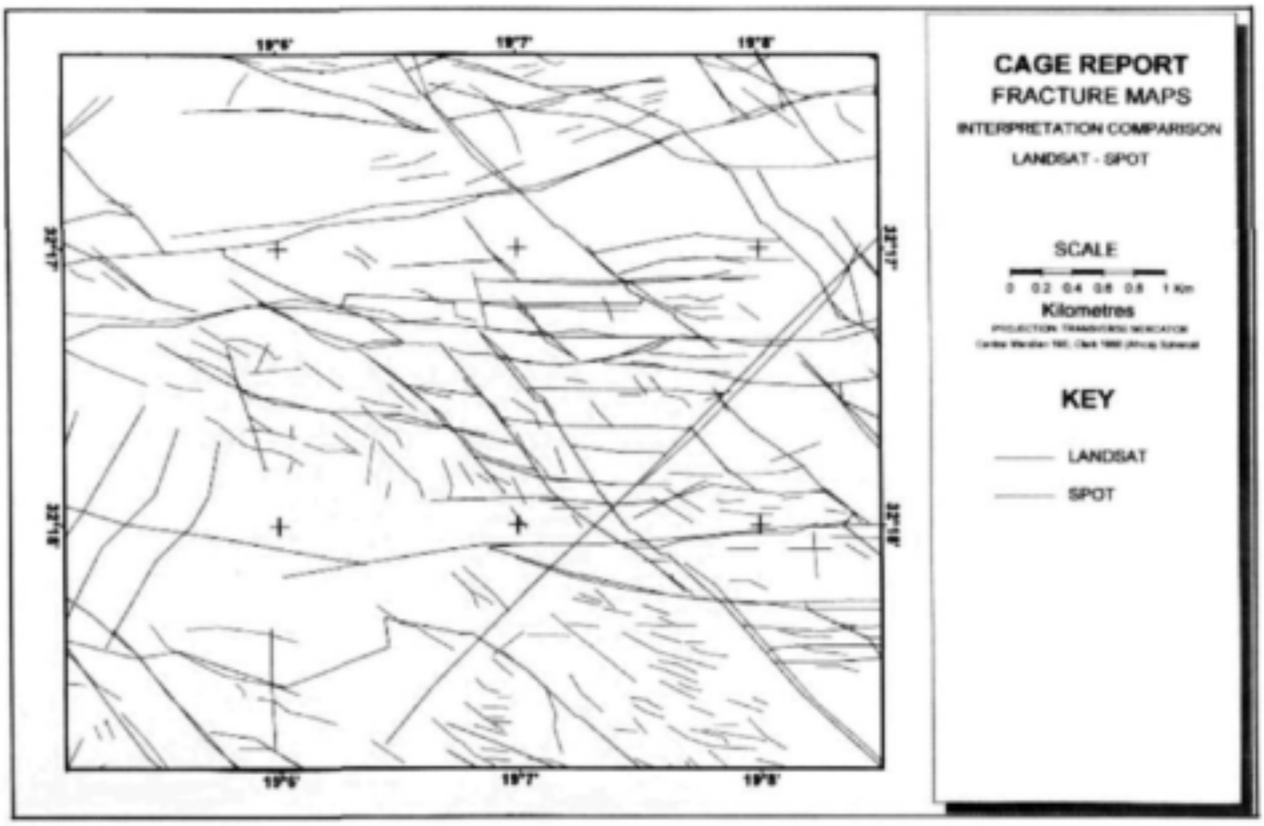


Figure 6

Fracture map detail from a small part of the study area showing both Landsat-derived (black) and SPOT-derived (red) traces

SSE strike were discovered during earlier groundwater prospecting.

In dynamic terms, the full range of the fault-kinematic pattern described above is consistent with a WNW/ESE- to NW/SE-directed axis of maximum horizontal compressive stress in a strike-slip regime within the upper crust or lithosphere. During Gondwanaland break-up and Lafonia block rotation (Ben-Avraham et al., 1993; 1994), another "microplate" comprised of the southwestern part of the region probably experienced some several kilometres of sinistral strike-slip translation in a south-easterly direction, relative to the African mainland in the north-eastern part of the area. Where individual component parts of this sheared zone were rotated from NW/SE into more E/W directions, a local stress regime of upper-crustal extension (normal faulting) was established. In contrast, where individual parts were bent into more N/S directions, the local stress regime corresponded to crustal compression (thrust faulting and fault-bend or fault-propagation folding).

The late-stage (Jurassic-Cretaceous) origins postulated for fault-and fold development in this area may be an important factor in the preservation of relatively high hydraulic conductivity along the main fracture zones. If these developments post-dated the main stages of the Permo-Triassic Cape Orogeny, and also the deepest burial and metamorphism of the TMG sequences, then the hydraulically conductive structures will have been less prone to later sealing, i.e. by silica deposited from hydrothermal fluids mobilised during the peak of metamorphism.

Pervasive joint sets

Accurately georeferenced Landsat images (175/82 and 175/83) covering most of the southwestern Cape were digitised on-screen for apparent fracture traces, using the TNTmips Geospatial Analysis software package at a viewer scale of 1:100 000 (1 mm = 100 m). A total population of 36 982 fracture segments was recorded (Fig. 5). Georeferenced SPOT images were digitised on-screen for fracture traces at a viewer scale of 1:30 000 (1 mm = 30 m). For both Landsat and SPOT images digitiser operators were instructed to concentrate on exposed rock areas, to mark only lineaments which have clear and definite topographic expressions but not river courses, and to take special care to avoid man-made or artificial linears (roads, property boundaries, fences, power lines, etc.).

River and stream courses can, of course, be structurally controlled, but such lineament information can also be extracted from a digital

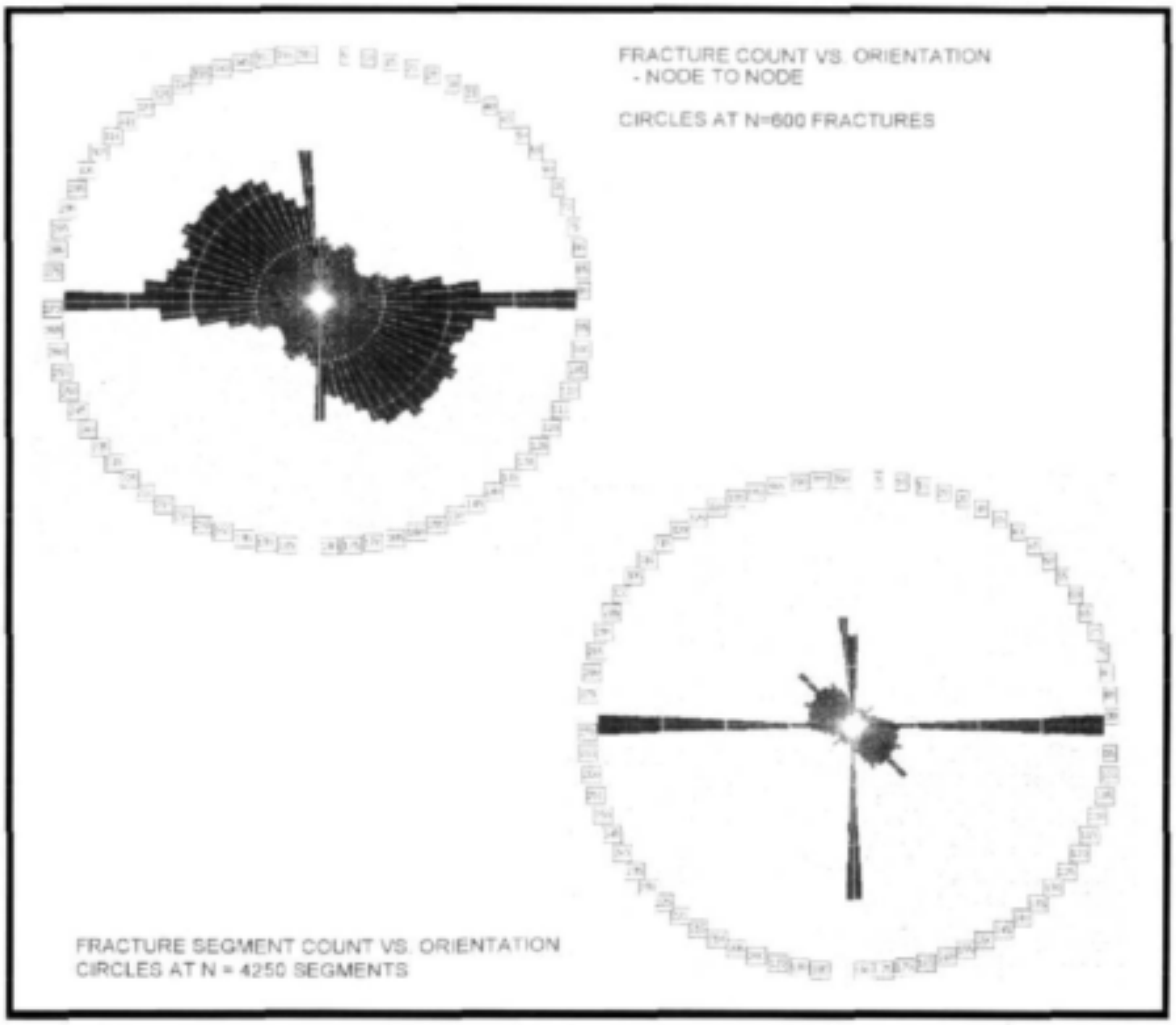


Figure 7
Rose diagrams for Landsat fractures

elevation model (DEM). Furthermore, many of the major mapped faults are closely followed by stream or river courses. Discriminating against these longer linear features on the satellite imagery can therefore bias the digitised data set towards the shorter fractures showing lesser degrees of connectivity.

In practice there is an observed tendency for the digitising operator to truncate shorter lines some distance, of the order of 50 m or less, before their possible nodal connection with other lines at high angles (e.g. Fig. 6). The TNTmips Geospatial Analysis software allows the ends ("dangling nodes") of such disconnected fractures to be "snapped" to the nearest line within given distance limits. When the original digitised data set was "snapped" in this manner for a node-to-line distance of 50 m or less, the number of resolved connections was 3 324.

On the basis of their orientation distribution (Figs. 7 and 8), five systematic sets of fracture traces, corresponding to NW/SE-, E/W-, N/S-, NE/SW-, and ENE/WSW-trending joint sets are identified in this satellite photogeological interpretation (SPI). These five sets correspond well with the three main lineament sets, i.e. NW/SE-, E/W, and NE/SW-trending traces - previously identified from conventional aerial photogeological interpretation (API), undertaken for borehole-siting purposes (unpublished Umvoto Africa cc reports, 1994-1997).

A three-dimensional analysis of a combined SPOT image and DEM was also undertaken for four of these fracture sets, i.e. the NW/SE, NE/SW, E/W, and N/S sets. A total of 365 new orientation measurements were extracted from this analysis in a relatively short space of time (about three days).

The stereographic projection shows that the NW/SE fractures have bimodal dips in both NE and SW directions. The NE/SW and E/W fracture sets dip dominantly to the SW and S, respectively. The satellite and DEM results compare well with the products of a regional field-based structural survey.

In general the fracturing is similarly orientated in both Peninsula and the Nardouw formations, but

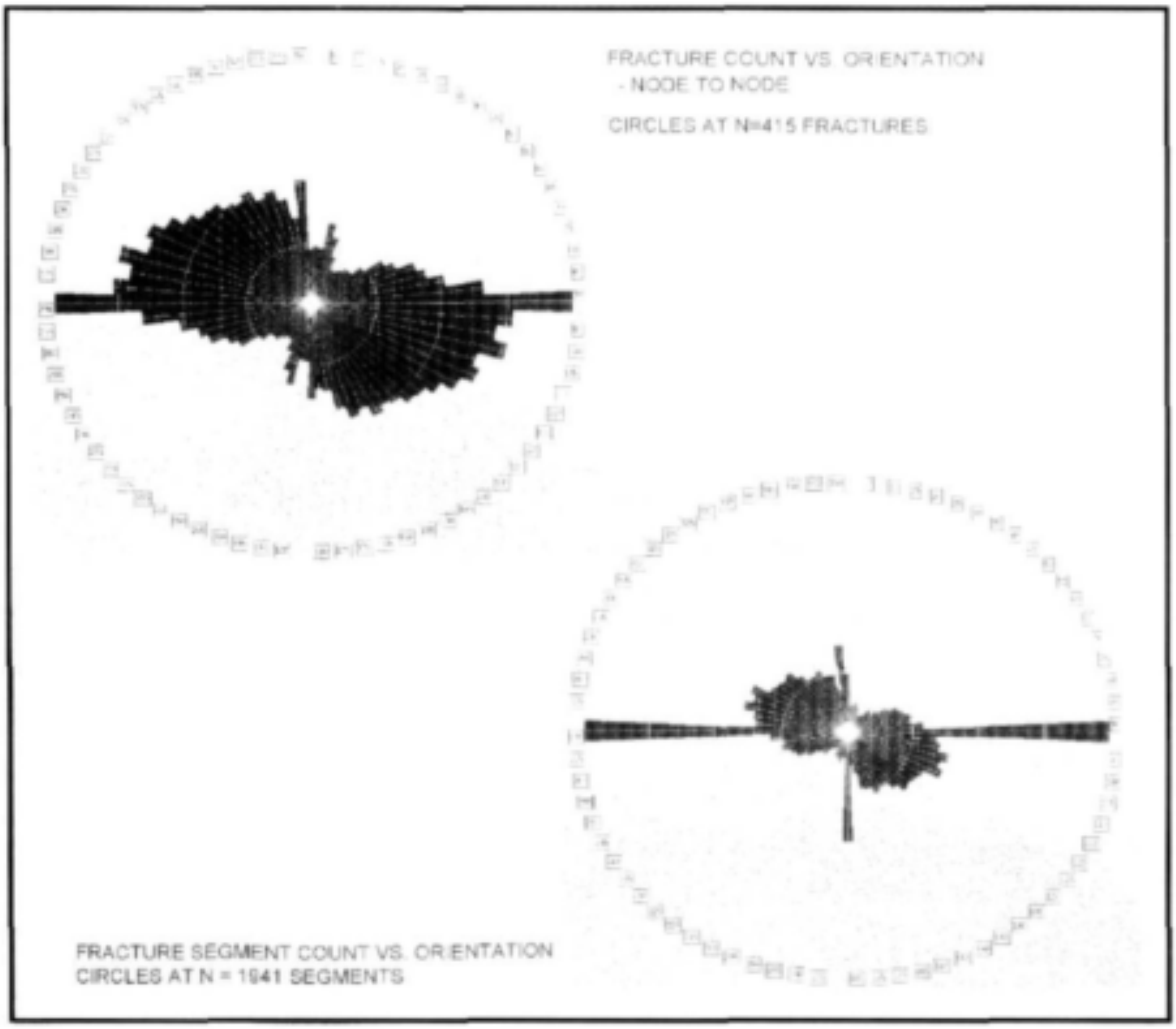


Figure 8
Rose diagrams for SPOT fractures

there is variability in fracture spacing, depending on bedding thickness differences and proximity to major fault zones. In parts of the study area, the more thinly bedded Nardouw Formation is intensely fractured by closely spaced but relatively discontinuous structures. Large-scale, continuous, widely spaced master joints are characteristic of parts of the more massively bedded Peninsula Formation. Sub-horizontal or steeply dipping bedding planes and formational contacts (against the relatively impermeable Cedarberg Shales, for example) can contribute to the secondary permeability and can, in combination with local structures and topography, control the occurrence and flow rate of springs.

On both the Landsat and SPOT imagery, the length-frequency distribution of fractures of all orientations appears to follow a power-law distribution (Figs.9 and 10).

NW/SE fracturing

Landsat fracture traces in the entire NW/SE set fall within the azimuth range N290°E to N350°E, with a distinct mode at N315°E. On a Rose diagram of narrow (5°) bandwidth, this set shows a relatively wide angular dispersion with possible subordinate mode at N295°E (Fig. 7). On SPOT imagery the mode at N295°E is confirmed and one at N305°E appears (Fig. 8).

In the entire area covered by the Landsat images a total of 12 166 fracture segments was digitised in this particular set, ranging in length from a minimum of 5 m to a maximum of 16 424 m, measured from node (intersection or termination) to node. The mean length is 1 035 m (± 1 015 m standard deviation) and cumulative total fracture length is 12 592 km.

As a first approximation to a spatial density of fracturing, the area distribution of fracture number within 5 × 5 km grid elements is plotted for elements covering zones of bedrock exposure within the study

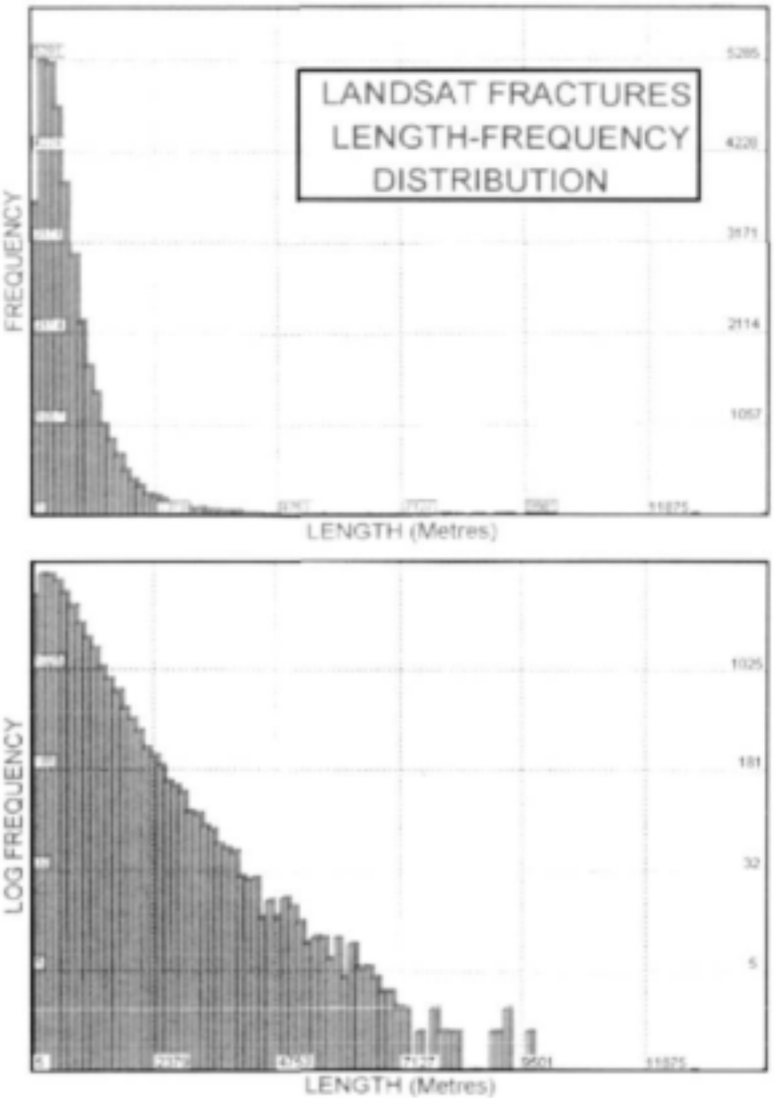


Figure 9

Length frequency histograms for Landsat fractures

area and its immediate surroundings on the two merged Landsat images. It is notable that the areas of higher number also tend to follow NW/SE trends.

E/W fracturing

Landsat fracture traces in the entire E/W set fall within the azimuth range N250°E to N290°E. This fracture set has a most conspicuous Rose diagram mode at N270°E, especially on a "line segment" plot (Fig. 7), showing little angular dispersion outside a 10° band. It is equally conspicuous in the SPOT imagery analysis (Fig. 8).

In the Landsat image areas 7 962 fracture segments were digitised in this particular set, ranging in node-to-node length from a minimum of 5 m to a maximum of 9 919 m. Mean length is 1 053 m (± 957 m) and total fracture length in this set is 8 384 km.

Over the Olifants-Doring region and its immediate surroundings, the areas with Landsat fracture-number density above the mean plus two standard deviations (8.86 + 2 × 8.12 fractures/element) are mainly clustered around the northern Cedarberg and to the northwest of the Citrusdal trough on the ORS. The area containing a number density above the mean is again locally elongated along NW/SE-trending corridors, in both these areas.

The NW/SE spatial trends in the geographic distribution of E/W fracture density are evidently controlled by topography over the erosionally resistant TMG outcrops. The zones of mountainous topography are in turn controlled by the NW/SE strike orientations of the major fault zones, especially the megafaults.

The maximum horizontal compressive stress is most probably oriented E/W, accordingly to analyses of focal mechanisms of the 1969 and 1970 Ceres earthquakes (Zoback, 1992). The closely spaced E/W fracturing developed throughout the study area may therefore represent, in part at least, a "neotectonic jointing". If this assumption is correct, then it suggests that the fracture sets striking N/S or nearly N/S will tend to be closed by the contemporary stress regime, whereas those with a more E/W strike direction may be elastically dilated, and therefore suitably open conduits for groundwater.

NE/SW fracturing

Landsat fracture traces in the entire NE/SW set fall within the azimuth range N015°E to N055°E. The set shows a relatively broad mode around N030°E on a "node-to-node" Rose diagram, but a small well-defined mode at N045°E on a "line segment" plot (Fig. 7). In the more restricted area covered by SPOT imagery, there is a conspicuous node-to-node peak at N015°E (Fig. 8).

In the Landsat images 3 063 fracture segments were digitised in this particular set, ranging in node-to-node length from 10 m to a 9 823 m. The mean length is 1 130 m (± 982 m) and total fracture length in this set is 3 460 km.

When the geographic distribution of NE/SW-orientated fracture length within a 5 × 5 km grid element is plotted over the study area, the blocks of higher relative fracture number tend to be grouped along roughly NW/SE alignments.

In the entire area covered by the Landsat images a total of 3 033 fracture segments were digitised in this particular set, ranging in node-to-node length from 5 m to 15 187 m. The mean length is 948 m (± 945 m standard deviation). Total fracture length in this set is 2 875 km. Along this direction some conspicuously long digitised linears may represent bedding or formational contacts, e.g. the Cedarberg contact on the Olifantsberge range west of Citrusdal.

ENE/WSW fracturing

Landsat fracture traces in the entire ENE/WSW set fall within the azimuth range N055°E to N070°E, but show little or no mode in a Rose diagram (Fig. 7). This set could therefore be regarded as an asymmetric tail on the E/W fracture distribution. However the SPOT image analysis reveals a slight clustering along this trend (Fig. 8).

In the entire area covered by the Landsat images a total of 1 335 fracture segments - the smallest number in the five sets - were digitised in this particular set. They range in node-to-node length from 10 m to 8 297 m. The mean length is 1 093 m (± 947 m standard deviation). Total fracture length in this set is 1 460 km.

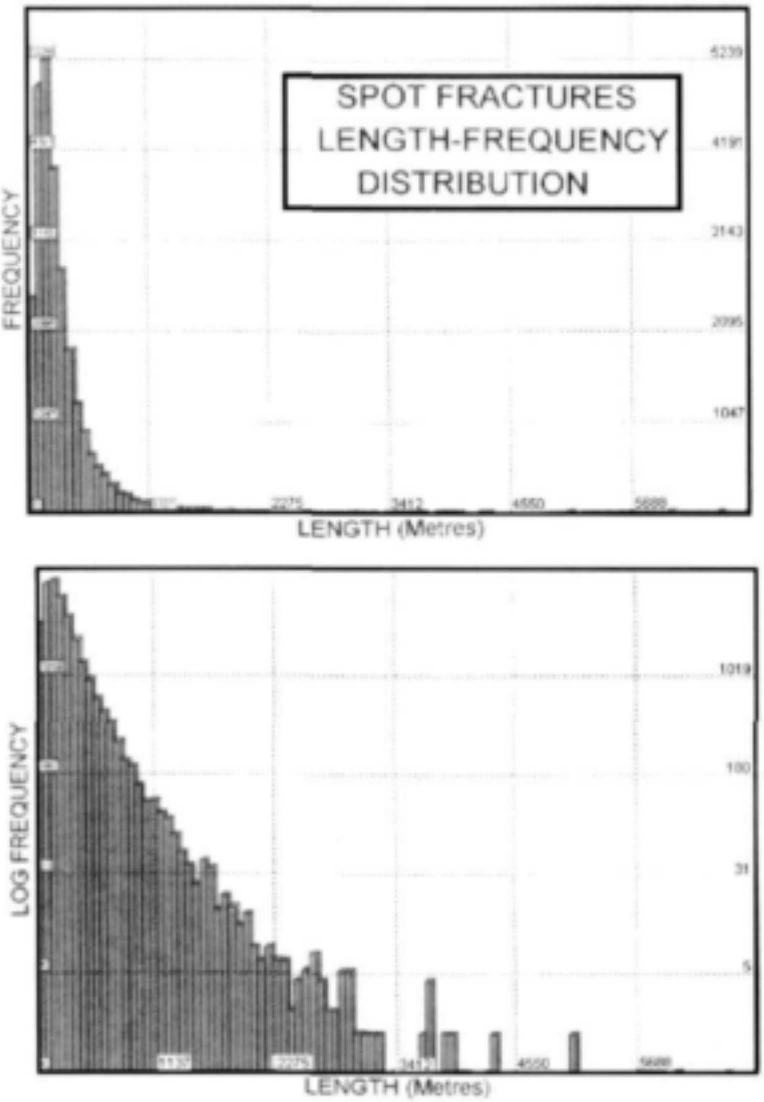


Figure 10
Length frequency histograms for Spot fractures

Intrusives

Tankwa dolerite dyke zone

Dolerite intrusions that cut through the Karoo and pre-Karoo basement rocks over long distances (of the order of 100+ km) are possible crust- or lithosphere-penetrating feeder dykes to the abundant sill complexes in the Karoo basin. Such major vertical feeders are actually rarely encountered. The Tankwa Dyke Zone (solid red line marked TDZ in Fig. 1) is one such noteworthy structure.

Hydrogeologically the TDZ could act as a lateral barrier to the horizontal migration of deep thermal waters in the TMG and other sub-Karoo aquifers. Its marginal fracture systems could also provide vertical migration channels of relatively high hydraulic conductivity, which may locally breach the basal Karoo (Dwyka) aquiclude, and promote a substantial leakage of deep artesian water across the Cape-Karoo stratigraphic boundary.

Other aeromagnetic features

Several conspicuous, NW/SE- to WNW/ESE-trending, narrow lineaments are evident on the Magnetic Fabric map (Council for Geoscience, 1997). One of these features crosses the wide anticlinal structure of Malmesbury basement between Piketberg and Citrusdal. It is also represented as a ~50 km-long "aeromagnetic lineament" on the recent Structure Map of South Africa (Council for Geoscience, 1995). On the basis of its trend and apparently post-Cape age, it is probably a prominent, although hitherto unmapped, late- to post-Karoo dyke. Its southeastern end lies in the TMG formations of the Olifantsberge, close to the location of The Baths hot spring. In its northwesterly extension across the pre-Cape basement, this aeromagnetic anomaly may trace the link between the southern and northern parts of Gydo-Verlorevlei Megafault (GVM, Fig. 1 and 4).

Conclusions

From a hydrogeological perspective, the major structural features of the study area are as follows:

- There is a close kinematic relationship between folding along slightly N/S axial trends and the dominant NW/SE faulting, such that the TMG Aquifers are compartmentalised within fold and fault-bounded blocks.
- The structural geometry of major folds, such as the ORS, is such that large volumes of aquifer formations are located at depths up to 3 km below sea-level in box-fold configuration.
- Four major "megafault" systems cross the area along roughly NW/SE directions, and are linked to each other by numerous connecting splay- and cross-faults.
- Fracture-trace analysis on Landsat and SPOT imagery (locally incorporating 3D analysis to reference DEMs) reveals five principal joint sets, covering the exposed areas of the TMG and other formations between the (generally eroded and superficially covered) major fault traces.
- Evidence from aeromagnetic surveys supports the correlation of certain megafault zones across areas of no, little or poor bedrock exposure, on the premise that the main magnetic anomalies are produced by major fault zones soon after the main episode of fault displacement.

Acknowledgements

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Part 3:

Aquifer Description

Hydrogeological Characteristics of the Table Mountain Group Aquifers

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Abstract

The Table Mountain Group (TMG) occurs within the Western and Eastern Cape Provinces of South Africa, extending from just north of Nieuwoudtville to Cape Agulhas and then eastwards to Algoa Bay, a linear outcrop distance of over 900 km. A large percentage of its total thickness of >2 000 m consists of quartzitic sandstones. These sandstones are of Ordovician to Silurian age (500 My) and because of their age, essentially possess zero primary hydraulic conductivity. However, due to a combination of favourable factors such as structure and climate, they form one of the major fractured rock aquifers in South Africa.

The physiographic setting of the TMG Aquifer is extremely varied. The northern outcrops border on desert areas with <150 mm/a of precipitation, while around Worcester and Ceres, precipitation is >2 000 mm/a. In the latter mountainous areas, elevations reach >2 000 m, while at Eland's Bay, the Cape Peninsula and along the Southern and Eastern Cape coast, wave-cut platforms occur at sea level.

Over 30 major users of the TMG Aquifer have been identified, ranging from municipalities to agriculture and it has major direct and indirect beneficial impacts on the hydrogeology of the Western and Eastern Cape. Borehole blow-out yields of up to 120 ℓ/s have been recorded and hot-spring flows of 127 ℓ/s.

Introduction

At the International Association of Hydrogeologists symposium held in Cape Town in November 2000, the South African Minister of Water Affairs and Forestry, Mr Kasrils, described a large aquifer discovered in the Western and Eastern Cape as being, "A Great Hidden Treasure". He went on to say, "In human life terms, the Aquifer may in the long run be more valuable than the country's gold and diamond wealth, for nothing can compare to clean water for the wellbeing of our people and the sustainability of our economic development".

Stirring words indeed and the aquifer being referred to was the TMG Aquifer. This paper provides an overview of its hydrogeological characteristics.

Hydrogeological setting

The TMG occurs within the Western and Eastern Cape Provinces, extending from just north of Nieuwoudtville to Cape Agulhas and then eastwards to Algoa Bay, a linear outcrop distance of over 900 km (see Fig. 1). A large percentage of its total thickness of >2 000 m consists of quartzitic sandstones. These sandstones are of Ordovician to Silurian age (500 My) and because of their age and mild regional metamorphism, essentially possess zero primary hydraulic conductivity. However, due to a combination of favourable factors, such as structure and climate, they form one of the major fractured rock aquifers in South Africa.

The physiographic setting of the TMG Aquifer is extremely varied. The northern outcrops border on desert areas with <150 mm/a of precipitation, while around Worcester and Ceres, precipitation is >2 000 mm/a. In the latter mountainous areas, elevations reach >2 000 m, while at Eland's Bay, the Cape Peninsula and along the Southern and Eastern Cape coast, wave-cut platforms occur at sea level.

Some general characteristics of the TMG Aquifer are discussed first before introducing the differing hydrogeological domains and their main characteristics.

Hydraulic conductivity and transmissivity

Characterising the hydraulic conductivity, transmissivity and storativity of a fractured rock aquifer, such as the TMG, is a bit like characterising wind speeds in the Cape Peninsula, i.e. zero to hurricane force. So it is with the TMG; unfractured rock possessing zero hydraulic conductivity and highly fractured rock or single, large fractures having very high hydraulic conductivity. Lithology and tectonic/structural controls mean that these parameters will vary considerably from place to place.

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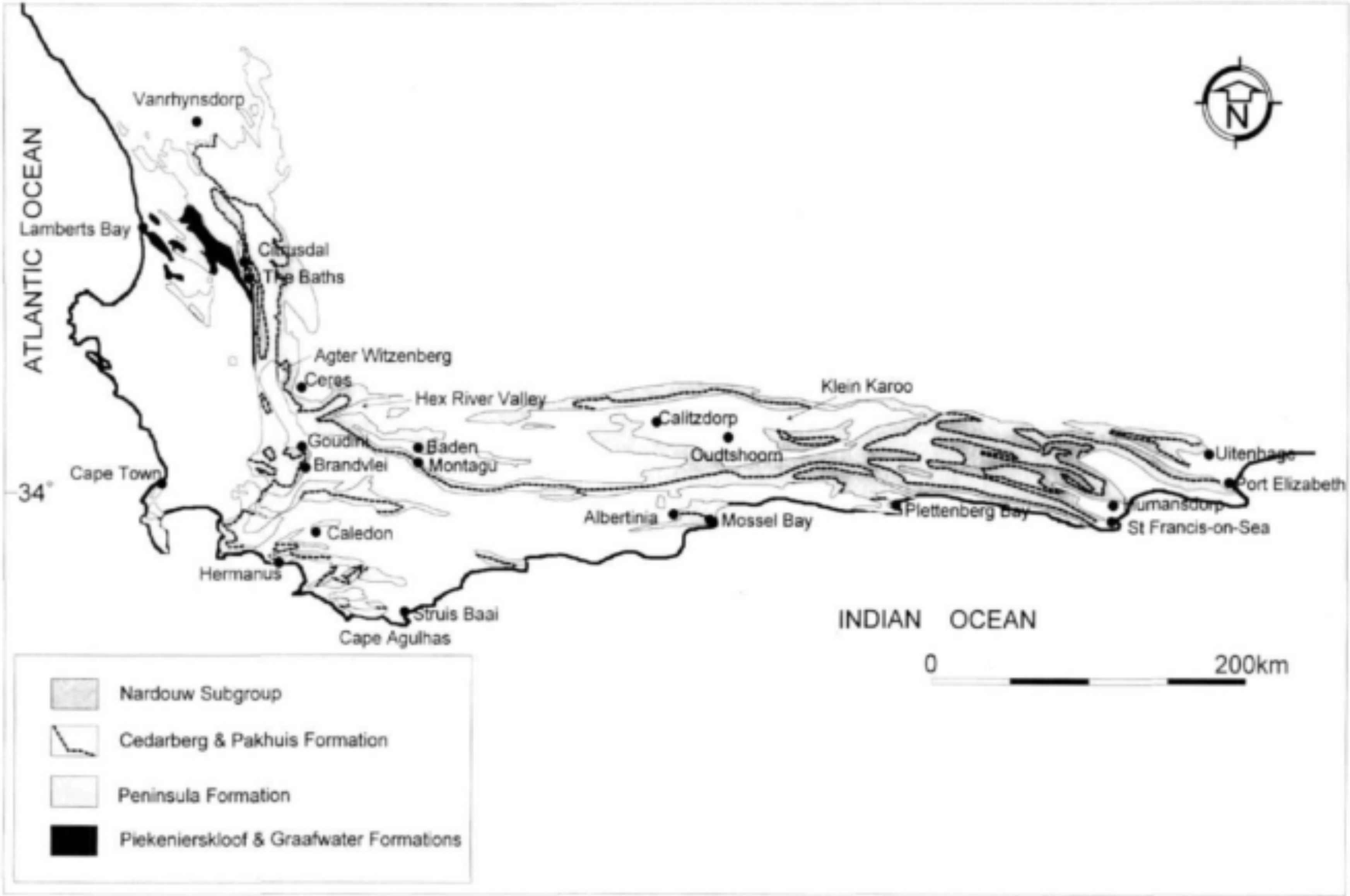

Figure 1

Distribution of the Table Mountain Group (after De Beer, 2001)

There is also the question of applicability of the various analytical methods for test pumping analysis and the relationship between hydraulic conductivity and transmissivity in a fractured rock environment. Discussion of these two aspects is beyond the scope of this paper but means that much of the data on transmissivity (and storativity) in the local literature may be suspect.

Packer or pressure head testing is the most reliable method of obtaining hydraulic conductivity values for specific sections of test boreholes. However, there is not much information on the TMG in the literature in this respect. The only source found relates to dam foundation investigations (Brink, 1981) and the data are reproduced in Table 1.

The wide range of the above figures tends to support the opening statement of this section. Drilling depth is largely unrecorded but was a maximum of 50 m at the Lakenvalley site. This means that the above figures do not reflect the main production zone of the TMG, which is usually >100 m below ground surface (see section on Deep Groundwater Circulation).

Some individual examples of hydraulic conductivity estimates include:

- Based on theoretical considerations and borehole logs and Darcy analysis of The Baths spring flow, Umvoto (2000) calculated a range of hydraulic conductivity of 1.99 m/d to 1.99 x 10^{-3} m/d.
- A tracer test in the Nardouw Subgroup in the Villiersdorp area yielded a hydraulic conductivity figure of 0.30 m/d (Rosewarne, 1991).
- Weaver (1999) developed a conceptual model of the Agter-Witzenberg area and assigned a K value of 0.05 m/d to the Nardouw Subgroup.

Table 1
Hydraulic conductivity measurements from dam foundation investigations

Dam	Hydraulic conductivity (m/d)			Formation
	Min	Max	Mean	
Paul Sauer	0	0.43	0.07	Nardouw Subgroup
Roode Elsberg	0.17	0.86	0.26	Peninsula
Lakenvalley	0.09	1.73	0.26	Skurweberg
Elandskloof	0.04	0.52	0.17	Peninsula

Transmissivity values calculated by various workers, covering the main aquifer formations and a varied selection of type areas over the TMG outcrop area, are given in Table 2.

The figures in Table 2 suggest that T values of a few hundred m²/d are associated with productive fracture zones, while <10 m²/d corresponds to matrix zones. The upper value for St Francis-on-Sea is considered to be a spurious figure. This is reinforced by throughflow calculations that were used to guide safe yield predictions for the St Francis-on-Sea wellfields. A T of 100 m²/d was used and the performance of the wellfields over 10 years of continuous use indicates that this was the right order of magnitude.

Storativity

A storativity of <0.001 is generally assigned to the TMG Aquifers on the WRC "Saturated Indices" map (Vegter, 1995). In a discussion on water supply potential of the TMG, Weaver (2000) quotes a number of estimates of storativity favoured by various researchers, as follows:

Table 2
Transmissivity and storativity values for various TMG formations and areas

Area	Formation	Reference	Transmissivity (m²/d)	Storativity	Analysis method
Citrusdal	Peninsula	Umvoto-SRK (2000)	<10 to 200	1 x 10^{-3} to 1 x 10^{-4}	FC*
Struisbaai	Peninsula/Nardouw	Weaver (1999)	15 to 200	8.6 x 10^{-3}	Jacob
Uitenhage	Peninsula/Nardouw	Maclear (2001)	<10 to 400	2 x 10^{-4} to 5 x 10^{-2}	Unknown
Kleinmond-Bot River	Nardouw	Parsons (2001)	70 to 320	1 to 5 x 10^{-4}	Jacob and FC
Klein Karoo	Peninsula/Nardouw	Kotze (2000)	10 to 200	10^{-4} to 10^{-2}	FC
Hex Valley	Rietvlei/Gydo Shale	Rosewarne (1989)	55	-	Gringarten & Witherspoon
St Francis-on-Sea	Nardouw	Rosewarne (1989)	165 to 2485	1.8 to 3.3 x 10^{-3}	Gringarten & Witherspoon

* Flow characteristic method

- Weaver uses a storativity of 10^{-2} to estimate groundwater reserves as 66 billion m^3 in the TMG within a 200 km radius of Cape Town (Weaver, 2000).
- Hartnady and Hay (2001, in Weaver et al., 2001) support a storativity of 10^{-1}.
- Kotze supports 10^{-2} to 5 x 10^{-2} (Kotze, 2000).

Looking at the range of values in Table 1 and the above, it would appear that a figure of 0.001 or $1x10^{-3}$ is a fair estimate for a bulk storativity of the Peninsula and Nardouw formations.

Using a rough dimensional analysis of the TMG outcrop area and thickness gives a rock volume of 47 000 billion m^3. A significant percentage of this volume will be above the regional water table but there are also significant volumes of sub-outcrop beneath the Bokkeveld Group not included. In the light of the above storativity values, it is not unreasonable to conclude that there are tens of billions of cubic metres of groundwater in storage in the TMG Aquifer. By comparison, there is of the order of 1.5 billion m^3 of storage available in all existing (including the proposed Skuifram Dam) dams sourcing TMG runoff water at full supply capacity.

Hydrogeological domains

The TMG Aquifer outcrop and sub-outcrop area can be broadly divided into two hydrogeological domains:

- Intermontane
- Coastal.

Except where there may be natural barriers to flow, such as the Cedarberg Formation or faults, the two domains are interconnected. The domains are, however, inhomogenous in that the major formations within the TMG have different hydrogeological properties and potential. This is discussed briefly in this paper under appropriate sections but is dealt with more fully in a separate section in this volume, "Targets for Drilling in TMG Aquifers." The stratigraphy, lithology and structure of the TMG is discussed in detail by De Beer (2001).

Intermontane domain

This domain covers all of the inland outcrop and sub-outcrop area and, in the opinion of the author, the main characteristics of the domain are the following:

- Deep groundwater circulation
- Enhanced groundwater potential in adjacent formations
- High direct recharge from both rain and snowmelt
- There are visible targets for borehole siting
- Occurrence of hot springs
- Free-flowing boreholes are common
- Associated alluvial deposits are important for direct groundwater supply and indirect recharge
- Associated groundwater has very low electrical conductivity (EC) and is corrosive.

An additional aspect, viz. groundwater management, is also covered as the winter rainfall area offers a unique approach to optimising groundwater yields.

Several specialist aspects of TMG Aquifer hydrogeology are dealt with in full papers by other authors, eg recharge, pumping tests and environmental isotopes and these aspects are only briefly mentioned or omitted from this paper.

Deep groundwater circulation

The main groundwater intersections in the TMG Aquifer are commonly at depths of >100 m below ground surface and geothermal evidence from hot springs, such as Brandvlei and Calitzdorp, indicates that groundwater circulation to depths of up to 2 000 m can occur. This characteristic feature goes against conventional geological/structural theory that joint/fracture openings will close-up with increasing depth due to the pressure of the overlying rock mass. Some of the reasons for deep groundwater circulation are put forward as follows:

- The TMG consists mainly of a thick sequence of fairly uniform, brittle quartzitic sandstones which would tend to fracture readily under stress.
- These rocks have been involved in a continental scale orogeny which lead to the formation of the Cape Fold Belt, providing ample levels of stress to produce widespread and deep fracturing.
- The associated groundwater is usually acidic and low in dissolved solids, lessening the likelihood of blocking of fractures by deposition of minerals. Deposition of iron and manganese oxides has/does occur but this is usually at or near surface in response to changing equilibria at spring discharge points or by pumping.
- TMG sandstones are predominantly composed of silica and so weathering products are less likely to lead to blocking of fractures.

Figure 2 illustrates the increase in yield with depth commonly shown by boreholes in the TMG Aquifer.

At Boschkloof near Citrusdal, the main groundwater strikes occurred at depths of 150 to 300 m, with total blow-out yields of up to 120 ℓ/s (Umvoto-SRK, 1998).

In the Klein Karoo area, environmental isotope signatures of groundwater from springs indicates that recharge takes place at much higher altitudes than occur locally and it is postulated that recharge takes place in the mountains and deep groundwater

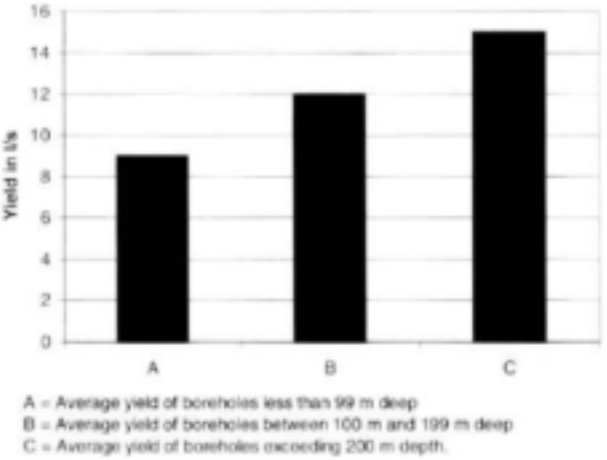

Figure 2

Yield increase with depth in the TMG Aquifer: Grabouw-Villiersdorp area (from Weaver, 1999)

flow along regional faults transports groundwater to its current discharge points (Kotze, 2000).

In the Hex Valley, many boreholes tapping the Bokkeveld Aquifer yield artesian flow in the winter months. This is considered to be in response to recharge to the TMG Aquifer of the Hex River Mountains and indicates that groundwater has circulated to depths of at least a few hundred metres.

In 1908, a 1 103 m deep borehole was drilled in the Swartkops area north-east of Port Elizabeth, with an initial artesian flow of 13 ℓ/s. It subsequently became known as the Swartkops Spa but the borehole has since been destroyed (Lomberg et al., 1996).

Enhanced groundwater potential in adjacent formations

The main geological formations bounding the TMG are the Cape granites and the Bokkeveld and Malmesbury Groups. In their own right they are usually regarded as low yielding aquifers and, in the case of the latter two formations, often contain poor quality groundwater. However, adjacent to the TMG, this picture changes dramatically, particularly in the Western Cape. This is due to enhanced recharge due to the high rainfall on the TMG mountains and the transmission of this water into the adjacent rocks along cross-cutting structures. This low EC groundwater also flushes out and dilutes soluble salts. Particularly good examples of this effect are seen in the Ceres and Hex Valleys and at Erinvale near Somerset West.

At Ceres, drilling and test pumping (SRK, 1995) showed that the main aquifer in terms of borehole yield, quality and economics is the Bokkeveld Group, not the TMG. The subject is dealt with in detail in the Ceres case study (Rosewarne, 2001). Bokkeveld boreholes yield twice as much water (~20 ℓ/s) from half the depth (~70 m) and at half the cost of installation (R50 000).

In the Hex Valley, recharge from precipitation on the Hex River Mountains controls the quality of groundwater in the main Bokkeveld Aquifer and determines the extent of irrigable groundwater. Figure 3 shows the fluctuation in the position of the 80 mS/m (guideline upper limit electrical conductivity for irrigation of vines) iso-contour line with time, with northward and south-westerly incursions indicating lower and higher recharge from the Hex River Mountains, respectively.

In both of the above areas the main aquifer being directly exploited is the Bokkeveld Group, not the TMG Aquifer. To the north and east of these two areas the Bokkeveld becomes progressively more argillaceous and acts more as an aquitard than an aquifer.

High direct recharge

Mean annual precipitation on the higher mountain peaks of the TMG in the Western Cape exceeds 1 000 mm and over much of the catchment exceeds 600 mm, except in the areas north of Clanwilliam. Intuitively, therefore, it can be expected that recharge will be high in some of these areas. In most years a significant part of this precipitation falls in the form of snow, especially in the Hex and Ceres Valleys, the slow melting of which adds considerably to the total recharge. In the Hex Valley, farmers maintain that good snowfalls in winter mean that groundwater supplies will be more sustained towards the end of the summer irrigation season. The surface of the TMG is also conducive to infiltration, comprising a sponge-like jointed and blocky rock with minimal soil cover.

Recharge is dealt with in detail in a separate paper but some examples of estimates are given here as an overview. Rosewarne (1984) estimated recharge to the TMG/Bokkeveld formations of the Hex River Valley at 12% of MAP in 1979, using the argument that water levels in boreholes in 1978 and 1979 were very similar, indicating that recharge was equivalent to pumpage during the intervening irrigation season.

Kotze (1998) obtained recharge estimates for the mountainous catchment inland of Hermanus of 11 to 30% based on area related, cumulative departure from the mean annual precipitation and chloride mass balance methods.

Kotze (2000) calculated recharge of 16% for the Peninsula Aquifer and 5% for the Nardouw Aquifer of the Kammanassie Mountains, in the Little Karoo.

Meyer (1999) states that recharge rates of 15% or more are not unrealistic for certain areas of the Eastern Cape TMG.

Maclear (1996) determined a recharge rate of 25% for the Uitenhage Springs, using the chloride mass balance method.

Weaver (1999) used Cl and $\delta^{18}O$ data to investigate groundwater flow in the Agter Witzenberg area and obtained estimates of recharge as high as 50%.

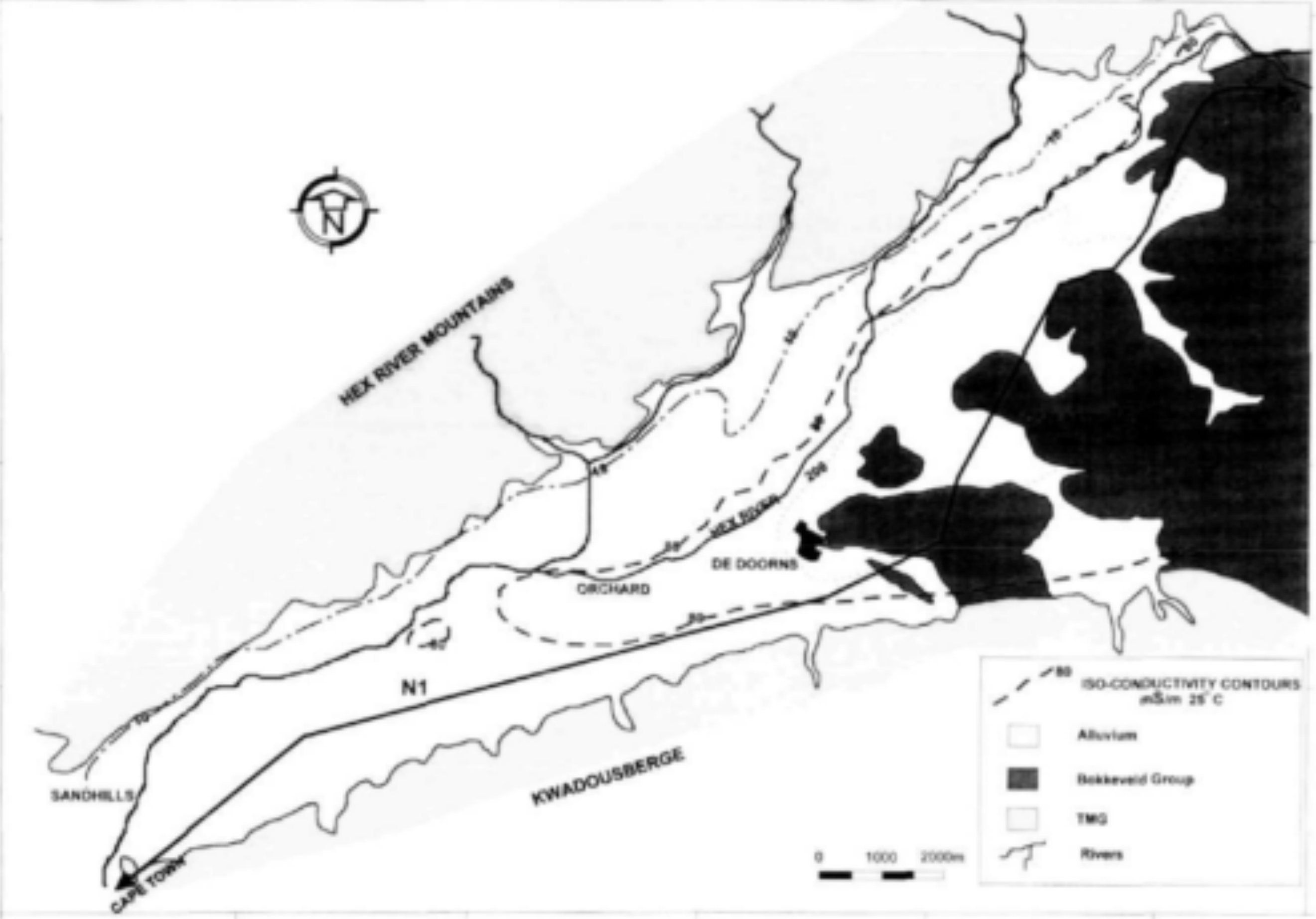

Figure 3

ISO-conductivity map: Summer 1980

Associated alluvial deposits

During the detailed hydrogeological study carried out by Rosewarne (1981) in the Hex River Valley, three types of alluvium were recognised based on the source rocks, i.e. TMG sandstones, Bokkeveld shales and sandstones and a mixture of the two (see Fig. 1 of the Hex River Valley case study). The most important of these is the TMG alluvium. Apart from the Hex Valley, important aquifers associated with this alluvium occur in the Breë River Valley, particularly around Rawsonville (BRGM, 1976 and Rosewarne, 1981).

Close to the source areas, ie mountain fronts, the alluvium consists of thick (~ 60 m), coarse fan type deposits grading from silt through sand and gravel to cobbles and boulders. In flood- plain areas the alluvium is finer grained.

The importance of the alluvium and its role in the groundwater regime varies from area to area. In the Hex Valley it is an indirect source of groundwater recharge, with only a few shallow wells, or "putte" as they are known locally, tapping this resource. The main contribution is by leakage of groundwater from the alluvium into the underlying TMG/Bokkeveld Aquifer when the piezometric level in the latter is drawn-down below the water table in the alluvium.

Rosewarne (*op cit*) calculated this contribution to be of the order of 5 million m^3/a, which is approximately 25% of the total annual groundwater abstraction in the Hex Valley. This leakage means that boreholes in areas overlain by TMG alluvium show smaller seasonal drawdowns and more rapid recoveries, even during times of below average rainfall (see Fig. 3 in the Hex River Valley case study).

In the Breë River Valley around Rawsonville, the TMG alluvial aquifer is exploited directly and some 25 million m^3 are abstracted annually for irrigation of vines (BRGM, 1976).

Groundwater quality

Groundwater associated with the TMG Aquifer in mountainous regions is characterised as being amongst the purest occurring in South Africa in terms of EC/TDS. At Ceres, ECs as low as 4 mS/m were measured for production boreholes at the base of the Skurweberg and in pristine mountain catchments is typically <10 mS/m. However, this purity comes at a price and the unbuffered groundwater can have a pH as low as ~3 and be very corrosive and aggressive. PVC and/or stainless steel piping and fittings are essential for all associated reticulation.

The macro-chemical character of TMG Aquifer groundwater in this domain reflects the origin of the precipitation recharging the aquifer rather than the rock type. Precipitation is predominantly derived from frontal systems originating in the Atlantic and Indian Oceans and the groundwater is therefore a NaC1 type. Figure 4 is a Piper diagram showing chemical analyses of groups of groundwater samples from various localities in the TMG Aquifer.

The diagram shows a concentration of analyses, in the NaC1 field for both intermontane and coastal domain samples and for the various geographic localities in the TMG outcrop area. However, there is quite a spread of analyses into the Ca/Mg HCO_3 and Ca/$MgSO_4$/$C1_2$ fields as well, particularly among the Citrusdal samples. Some of the latter may possibly represent lithologies other than the TMG.

Although the bulk of the TMG Aquifer rock composition consists of silica, large amounts of iron and manganese compounds are associated with joints and fractures and disseminated within the rock. The low pH of circulating groundwater means that these minerals are readily dissolved and TMG groundwater often contains high iron and manganese concentrations, i.e. >1 mg/ℓ. Problems associated with this groundwater are discussed in Jolly (2001).

Smart and Tredoux provide a detailed overview of groundwater quality (2001).

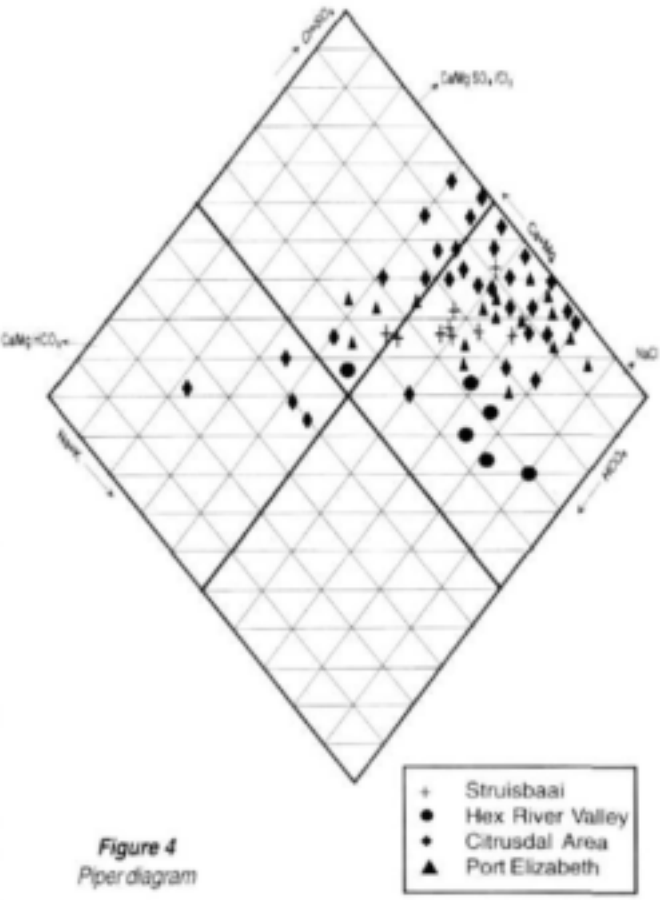

Figure 4
Piper diagram

Visible targets for borehole siting

The Intermontane areas of TMG are usually sparsely vegetated and have thin or no soil cover. Accordingly, fractures, faults and joints show up well on air photographs and satellite imagery. In the field, major features are often picked out by lines of green vegetation cutting across the contrasting grey sandstone outcrop. Good examples of the latter can be seen on the Skurweberg at Ceres. However, there is often no associated anomally when electromagnetic traverses are run over such features.

A drawback of exploiting the TMG Aquifer of the Intermontane Domain is that much of the area is inaccessible for borehole siting or drilling. Large areas are also nature conservation areas and this poses problems of access and potential impact of groundwater abstraction on vegetation. This has caused delays and refusal of access to prime target areas at Hermanus and Porterville, for example.

Groundwater management

The winter rainfall area of the Intermontane Domain offers a unique opportunity to maximise/optimise groundwater yield from the TMG Aquifer. This area is characterised by reliable precipitation in the range 600 to >1 000 mm/a, which is mainly concentrated during the period June to September. Even in a 'dry' winter such as 2000 started out being, there were still the highest snowfalls in 40 years in many areas of the Intermontane Domain. Whether global warming/climatic change will lead to a significant reduction or loss of this winter precipitation in decades to come is beyond the scope of this paper.

The main demand for irrigation water is in the dry summer months and for peak domestic supplies, over the Christmas and Easter holiday periods. The management scenario advocated (Weaver, 2000 and Rosewarne, in Weaver et al., 2001) is for new boreholes/wellfields to be developed in the TMG Aquifer for increased abstraction during the summer months - even exceeding average recharge estimates - in the knowledge that there will be sufficient winter precipitation to recharge the aquifer.

This approach acknowledges that there will be increased drawdown in groundwater levels and decreased surface water low flows but that the dynamic use of groundwater storage and recharge will produce a higher catchment yield than the *status quo*. It is proposed that this groundwater management approach be termed **Summer Overdraft**.

In many parts of the Intermontane Domain there are catchments where water allocations/availability from springflow or surface water low flows are regarded as 'cast in stone', e.g. the lower Hex Valley and Klein Karoo. Any perceived interference in such flows is met with swift recourse to litigation. However, springflow and surface water low flows or baseflow represent gravity overflow of groundwater from compartments and is a minimum catchment yield. This can be increased significantly by pumping boreholes to exploit groundwater in storage and creating increased reservoir volume to absorb excess precipitation.

This type of groundwater management is practised in areas such as the Hex River Valley and the Agter-Witzenberg (Weaver, 1999). However, problems of partial recovery and saline water intrusion can occur in 'dry' years because many boreholes tap the Bokkeveld Aquifer, away from the main recharge zone.

The quantity and rate concept of aquifer yield applies here, where total recharge to a catchment may be equal to or exceed the annual groundwater abstraction but the rate at which the water moves into the area of withdrawal does not (Rosewarne, 1981). Because of this, the summer overdraft approach to groundwater management will only work consistently where the following conditions collectively exist:

- Exploitation is directly from the TMG Aquifer
- Intermontane Domain of the TMG Aquifer
- Winter rainfall area
- Mean annual precipitation 600 to >1 000 mm.

The new Water Act also allows for a more dynamic approach to catchment water management rather than the blinkered approach of the past, although Cape Nature Conservation policies appears to be in direct conflict with the abovementioned approach.

Coastal plain

This domain is mainly developed along the Southern Cape Coast between Cape Hangklip and Mossel Bay and from Oyster Bay to Port Elizabeth and comprises a wave-cut platform, bounded inland by foothills of coastal mountain ranges or differing geological formations. The characteristics of this domain are as follows:

- Comprises a wave-cut platform
- There is usually a covering of Quaternary sands and calcrete
- Shallower groundwater occurrence
- Lack of visible targets for borehole siting
- Possibility of seawater intrusion
- Moderate to poor groundwater quality
- Indirect recharge
- Associated with cold springs.

Shallower groundwater occurrence

The seaward boundary of the Coastal Plain is the discharge zone of this domain, with the saline/freshwater interface basically being an impermeable boundary. The upper boundary is a wave-cut platform, which implies that the previously overlying rock mass has been eroded away, as discussed above. The presence of saturated sands overlying the TMG Aquifer in many areas also gives rise to shallow groundwater occurrence. It is therefore likely that groundwater circulation will be shallower than in the Intermontane Domain. Evidence from various localities in the Coastal Plain points to this being the case.

At St Francis-on-Sea boreholes were drilled to 200 m in an initial exploration drilling programme. In the later main drilling programme, the optimum depth was found to be ~90 m, with equivalent or higher yields being obtained when compared to the initial drilling programme (see St Francis-on-Sea case study).

There is also a psychological reluctance to drill deep boreholes on the Coastal Plain if the topographic elevation above sea level is only a few tens of metres.

Borehole siting

The covering of sand and calcrete means that targets for borehole siting such as faults, fractures and joints are often not visible. Location by means of geophysics below 20 to 40 m of overburden is also problematical, especially given that such features do not necessarily produce an anomaly even when exposed at surface.

This problem was encountered at St Francis-on-Sea when developing a wellfield to supply up to 60 ℓ/s to the town (Rosewarne and Lomberg, 1989). After consideration of various options and after several trial holes had been drilled, it was concluded that boreholes could be sited virtually anywhere within the sub-outcrop of the Nardouw Subgroup and strike exploitable quantities of groundwater. This was attributed to bedding planes being the main conduits for groundwater flow and storage. With a dip of ~50° to the NE, every borehole was virtually guaranteed to intersect a number of water-bearing features. In this way, 15 boreholes were drilled with only one failure and the rest giving long-term yields of between 2 and 11 ℓ/s.

The situation at St Francis-on-Sea seems to be fairly unique and borehole siting at places such as Port Elizabeth and Gansbaai has not been as successful, even when using aids such as electromagnetics surveys. These sites are developed on sandstones of the Peninsula Formation, which tend to be more massively bedded.

Seawater intrusion

In coastal TMG Aquifers, fractures/bedding planes extend into the sea and there is free interconnectivity between fresh groundwater inland and seawater. The risk of seawater intrusion, or deterioration in groundwater quality, is therefore a function of management practices rather than simply the distance of a borehole from the sea and whether the water table is drawn-down below sea level.

In areas susceptible to seawater intrusion, continuous pumping at relatively low rates from a number of widely spaced boreholes is the recommended management scenario. On-off pumping of single boreholes at high rates creates turbulence and is potentially a much greater threat than drawing the water table/piezometric surface below sea level as a result of decreased borehole efficiencies and/or chemical encrustations.

In this respect, the peak season overloading of the water supply systems of coastal resort towns is of concern. There is a great temptation to increase borehole pumping rates and duration rather than face the wrath of holidaymakers and ratepayers if the water supply runs out over Christmas or Easter.

Weaver (1999) investigated sources of salinity in the Struisbaai Aquifer and concluded that salinity in the old wellfield is probably due to a degree of seawater intrusion.

Lomberg et al. (1996) report that boreholes within 200 m of the beach at Summerstrand in Port Elizabeth show a rapid change from fresh to saline water during pumping. Owners report that when the boreholes are next pumped, fresh water is again obtained initially.

In 1991, sixteen boreholes were drilled on the main refinery site at Mossgas for insertion of cathode protection equipment. These boreholes all penetrated the TMG Aquifer to depths of up to 150 m and, in all cases, the driller reported the groundwater as brackish (J Myburgh, pers. comm.). There are only a few windpumps in the area, although there are some high yielding boreholes a few kilometres away. The TMG is tightly interfolded with Bokkeveld rocks which may be a source of salinity. Residual salinity could also remain from the marine transgression that formed the wave-cut platform in this area, with the intercalated Bokkeveld shale aquicludes retarding flushing and dilution.

Groundwater quality

Groundwater in the Coastal Domain is postulated to have a generally longer residence time than that associated with the Intermontane Domain. This is certainly true of the throughflow component, which may have travelled many tens of kilometres along the axis of the feeder mountain chain, e.g. St Francis-on-Sea. There is also the component of indirect recharge from the overlying sediments. These factors combine to give a higher level of dissolved solids and a different chemical character to the Intermontane Domain groundwater.

Electrical conductivity is normally in the range 50 to 100 mS/m and the chemical character of the groundwater is more of a mixed type, with a $CaHCO_3$ component derived from calcrete and shell material and NaCl from throughflow (originating as intermontane domain recharge).

The Port Elizabeth Municipal area is an exception to this generalisation. Research into groundwater use within the municipal area (Lomberg *op. cit.*) showed groundwater quality was atypical for the TMG Aquifer. Although the two water types previously mentioned are also found here, i.e. $CaHCO_3$ and NaCl, there is a far greater range in EC of from 50 to 819 mS/m. There are also often very large variations in groundwater quality in boreholes a few streets apart. Since this is the only instance of a major city being sited on the TMG Aquifer it was concluded that a combination of point source contamination from leaking sewers, industrial sites, old waste disposal sites, informal housing, irrigation and other such activities was the cause of this situation.

Indirect recharge

Where the sand cover is saturated it acts as a source of indirect recharge, as with the TMG alluvium of the Intermontane Domain. Apart from lessening the effects of drought, this recharge also changes the chemical character of the TMG Aquifer groundwater due to dissolution of calcrete and shell material. The basic recharge is derived from throughflow from the inland Intermontane Domain.

Vulnerability of TMG Aquifers to contamination

Over its entire outcrop area, the upper formations of the TMG Aquifer can be regarded as being unconfined. Fractures, joints and bedding planes are open at surface and any 'soil' covering tends to be permeable aoelian sand with calcrete layers, or alluvium.

Much of the TMG Aquifer recharge area is inaccessible and occurs outside of areas of urbanisation. However, there are many large towns and one city, Port Elizabeth, located on or partially on the lower-lying areas of the aquifer. Ceres, Villiersdorp, Hermanus, Caledon, St Francis-on-Sea and Port Elizabeth, for example, all have waste disposal sites situated on the TMG Aquifer.

The first four towns are all in areas classified as having a water surplus or B+ according to DWAF's Minimum Requirements for Waste Disposal by Landfill Document, i.e. they will produce leachate. The waste site at Ceres is known to be contaminating the TMG Aquifer and is dealt with in detail elsewhere in this volume as a case study. The site is close to borehole sites for future expansion of the existing wellfields at Ceres (SRK, 1993) and one or possibly two of these sites would probably not be developed because of the threat of contamination.

In Port Elizabeth, the current main waste site at Arlington is not contaminating the underlying Recent sediments or TMG Aquifer because it is in a water deficit or B- area. However, urbanisation has led to the development of atypical groundwater quality beneath the main city area, as described previously. This is described in more detail in the case study on Port Elizabeth in this volume.

Groundwater use

Over 30 major users of the TMG Aquifer have been identified, ranging from municipalities to agriculture and it has major direct and indirect beneficial impacts on the hydrogeology of the Western and Eastern Cape. Borehole blow-out yields of up to 120 ℓ/s have been recorded and hot-spring flows of 127 ℓ/s.

To give an indication of the importance of the TMG Aquifer, the major towns using groundwater from this source are listed in Table 3, along with estimated daily usage. Table 4 lists the major springs emanating from the TMG, with flow rates. Locations are all shown on Fig. 1.

Some examples of other groundwater use and estimates of reserves gives further indications of the importance and potential of the TMG Aquifer:

- It was conservatively estimated by Umvoto-SRK(*op. cit.*) that 60 Mm^3/a could be abstracted from the CAGE catchment area centred on Citrusdal without impact on the environment.
- Modelling of the catchments of the Amandel and Sandrif Rivers in the lower Hex Valley indicates that there could be an additional 20 Mm^3/a of groundwater available.
- Regional areas where significant abstraction of groundwater occurs either directly or indirectly from the TMG Aquifer include the Agter-Witzenberg, Hex Valley and Klein Karoo areas.

Table 3
Major towns using TMG Aquifer groundwater

Town	Daily usage (m^3)
Albertinia	700
Caledon	280
Ceres	4150
Hermanus	950
Humansdorp	1850
Jeffreys Bay	2200
Lamberts Bay	360
Plettenberg Bay	780
Steytlerville	200
St Francis-on-Sea	2000
Uitenhage	4320

Table 4
Major springs emanating from the TMG

Spring	Flow rate (ℓ/s)
Baden	38
Brandvlei	127
Caledon	9.4
Calitzdorp	8
Goudini	11
Montagu	38
The Baths	29
Uitenhage	47

(from Meyer, 2001)

Conclusions

The TMG Aquifer is one of the most important regional aquifers occurring in South Africa. This can be attributed to the following:

- Large aereal extent
- Great thickness
- Development of an extensive network of fractures
- High orographic precipitation.

Two hydrogeological domains are recognised, viz. Intermontane and Coastal Plain. Their characteristics are:

Intermontane Domain

- Deep groundwater circulation up to thousands of metres
- Enhanced groundwater potential in adjacent formations
- High direct recharge up to 30% and possibly 50% in places
- Visible targets for borehole siting
- Occurrence of hot springs flowing at up to 127 ℓ/s
- Free-flowing boreholes common
- Associated alluvial deposits are important for direct groundwater supply and indirect recharge to underlying aquifers
- Associated groundwater has very low EC, is a NaCl type and is corrosive. Iron precipitation is often a problem.

Coastal Plain Domain

- Comprises a wave-cut platform
- There is usually a covering of Quaternary sands and calcrete
- Lack of visible targets for borehole siting
- Shallower groundwater occurrence
- Indirect recharge
- Possibility of seawater intrusion.

Within these domains, the differing formations of the TMG have differing hydrogeological properties and targets for exploitation vary from area to area.

Being essentially unconfined, the TMG Aquifer is vulnerable to contamination in the lower lying areas of the Intermontane Domain and the Coastal Plain. This is particularly seen in the atypical groundwater chemistry developed beneath the main urbanised areas of Port Elizabeth.

The high winter rainfall of the Intermontane Domain lends itself to heavy pumping during summer peak irrigation and domestic demand times. The new water laws also allow for a less blinkered approach to catchment water use than in the past. The more dynamic use of groundwater storage and recharge, termed summer overdraft in this paper, will produce a higher catchment yield than the *status quo*. The TMG and associated Bokkeveld Aquifers are unique in this respect and offer an exciting opportunity to increase and optimise catchment water management.

Over 30 major users of the TMG Aquifer have been identified and it is estimated that there are tens of billions of cubic metres of groundwater in storage. This groundwater is indeed a "Great Hidden Treasure".

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Part 4:

Exploration

The Role of Remote Sensing in Exploration for Deep Artesian Groundwater Within the Table Mountain Group

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Abstract

Remotely-sensed data includes all forms of spectral and geophysical data collected from air or space, which require integration with data sets obtained from the ground for meaningful interpretation. Data sets are acquired in digital format or can be converted by scanning or digitisation. Geographic information systems (GIS) allow these data sets to be easily viewed in any combination as overlays on reference maps. In the Table Mountain Group (TMG) fractured-rock aquifers, the quantitative mapping of the three-dimensional folded and faulted geometry of aquifers and aquitards, and the location, spacing and density of fracturing, is of paramount importance. Analysis of the orientation and geometry of key hydrotectonic features requires three-dimensional remote sensing techniques, supported by ground-truth field observations, in conjunction with a digital elevation model (DEM) of the same area. In TMG terrain structural interpretation should be carried out at various scales between Landsat (1:250 000 to 1:100 000), SPOT (1:30 000), and aerial photography (>1:10 000) to establish the scaling relationship between the fault and fracture arrays and hydraulic connectivity. Quantitative processing of DEM imagery is useful for mapping fracture and lineament patterns that can be obscured in spectral images, but are etched in the topography. This facilitates automated mapping of fracture traces, production of surface texture models as aids to lithological mapping, precise delineation of watersheds, drainage basins and flow lines, and accurate determination of aquifer volumes in three-dimensions. Landsat data and night-time thermal imagery can be processed to enhance vegetation patterns for identification of springs, seeps and wet-lands in recharge/discharge areas. "Change vector analysis" (CVA) of winter and summer imagery also has hydrogeological applications. Ground controlled classification methods on multispectral or hyperspectral datasets can produce reliable digital maps showing the distribution of various vegetation covers and exposed bedrock areas, which, when linked to DEM-derived slope and aspect models, are invaluable for runoff simulation and groundwater recharge modelling. The MODIS instrument on the new Terra satellite has been designed for direct sensing of environmental parameters such as temperature and surface moisture, and will soon provide researchers with key climatic variables for recharge modelling, at high temporal and moderate spatial resolution. The possibility now exists to develop methodologies and tools for integrated water resource management (IWRM) using a map-centric knowledge system from a variety of disciplines.

Introduction

The interpretation of remotely sensed data is a subject that covers a wide range of data types, scales and applications, and is highly specialised. Remotely-sensed data includes, by definition, all forms of spectral and geophysical data collected from air or space. These data need to be integrated with all data sets obtained from the ground, such as geological and topographic data, in order to achieve the most meaningful interpretation.

Data and interpretative methodology

Airborne data typically includes photography, radar and radiometrics. Satellites detect electromagnetic radiation (EMR) within specific bands of wavelength in which there are "windows" of atmospheric transmission, which are not absorbed by gases in the atmosphere. Windows occur throughout most of the EMR spectrum, ranging from ultraviolet, through visible light, reflected infrared, thermal (emitted) infrared and microwave (radar). No single satellite is capable of covering the entire range of these windows in the spectrum but the various satellites in orbit, as a group, cover most of it. Every natural or synthetic object reflects and emits EMR over a range of wavelengths and therefore has its

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own spectral signature. If these wavelengths match up with a window of atmospheric transmission they will be transmitted through the atmosphere and can be detected by one or other satellite with the appropriate frequency bandwidth.

Most data sets are in digital format and those that are collected in any other form, such as aerial photography, topographic contours and geological map data are commonly converted into digital form by scanning or digitisation. These data sets are then easily viewed on computer in any combination as layers (files) that are stacked on top of each other. The different data sets can also be processed; for example, a total field magnetic data set can be processed into vertical and horizontal derivatives, to enhance structural features.

Vegetation is of prime importance for hydrological exploration as vegetation changes between the dry and wet seasons can indicate where spring flow and seasonal seep zones (inter alia) supporting ephemeral aquatic systems occur (Le Maitre et al., 2001). This can be determined by comparing satellite images taken in winter and summer months for a given area. This use of remote sensing techniques shall be most useful in both reserve determinations, identification of recharge and discharge sites as well as recharge calculations. The latter is more fully discussed in this paper (Le Maitre et al., 2001).

Rock types of differing weathering patterns have different "texture" in satellite images. For example, the resistant sandstones of the TMG form high mountains and are deeply incised by river courses, whereas granites or shales tend to weather negatively and are generally covered by soil or alluvium. Contacts between contrasting lithologies can be seen on most satellite images, and this upgrades geological mapping.

Interpretation of remotely sensed data can be carried out either on hard-copy plots or on screen. Before embarking on an interpretation for any given area, careful consideration should be given to the types of data sets that need to be interpreted, processing, extent of the map area, scales of interpretation, and usefulness of the finished product.

In terms of deep artesian groundwater exploration the interpretation should highlight lithology, fracturing, faulting and folding so as to model or predict the form and geometry of the Peninsula and Nardouw aquifers at depth, areas of recharge, flow along faults and fractures, and discharge along aquitards such as the Cedarberg Formation. This interpretation of the key components of the regional flow path patterns should be based on detailed published and unpublished geological maps as well as remotely sensed data with delineation of faults and fractures at various scales from all data sources.

Scale and resolution

Landsat TM satellite data should be interpreted at scales of 1:250 000 to 1:100 000 as the resolution of this data is approximately 30 m only. Faults and fractures delineated at these scales would define the larger and deeper structures in the crust. Panchromatic Landsat 7 ETM data can be interpreted at 1:50 000 as its resolution is 15 m. Interpretation at this scale would give more detail on the smaller faults and fractures. SPOT Panchromatic has a resolution of 10 m and can be interpreted at a scale of at least 1:30 000, offering more detail on these structures. Aerial photographs have a scale of greater than 1:10 000 and a resolution of less than 5 m and consequently offer the most detail.

The interpretation should be carried out at various scales in order to determine the scaling relationship between fault and fracture arrays and hydraulic connectivity. It should preferably be started at a scale of 1:250 000 to 1:100 000 to delineate the regional faults and fractures, and a regional cross-section should be drawn through the area of interest to check that the interpretation is compatible both in plan and cross-section. As in the mapping of lithological contacts this process upgrades geological mapping.

Any interpretation can then be checked in the field in terms of bedding, structural measurements and lithology. Interpretation in specific target areas should then be carried out at scales of 1:50 000 to 1:30 000 for actual drill target sites and these target areas should also be field checked. The final interpretation should include a set of maps at different scales and a set of sections, which are all compatible and useful for exploration for deep artesian groundwater.

Structural geology

The mapping and analysis of geological structure is of paramount importance in the TMG aquifers, in that a good understanding is required of the three-dimensional folded and faulted geometry of both aquifers and aquitards, and the location, spacing and density of fracturing in the fractured rock aquifers (see paper titled "Use of structural geology and remote sensing in hydrogeological exploration of the Olifants and Doring River Catchments" in this volume). Construction of three-dimensional models and cross-sections requires a considerable amount of structural information to be gathered, including a statistically significant number of readings of strike and dip of units where statistical methods of structural analysis are to be applied, such as in determining cylindrical domains for the construction of down-plunge projections.

Acquiring these amounts of data by field collection is time-consuming, costly and sometimes dangerous in the TMG outcrop area. Regional mapping of geological contacts as an input to these models can be readily and accurately undertaken using remote sensing in the TMG (see Fig. 1). Given the contrasting composition of the units concerned in terms of quartz and clay-mineral content, false colour RGB combinations of Landsat TM bands 3, 5, 7 and 1 are ideal for lithological discrimination and contact mapping. Newer satellite sensors such as the ASTER instrument aboard the TERRA AM 1 satellite (15 to 30 m resolution) present further opportunities for lithological mapping in the TMG, by virtue of this intrument's enhanced capability for distinguishing carbonates from clays, and for better classification of various weathered products.

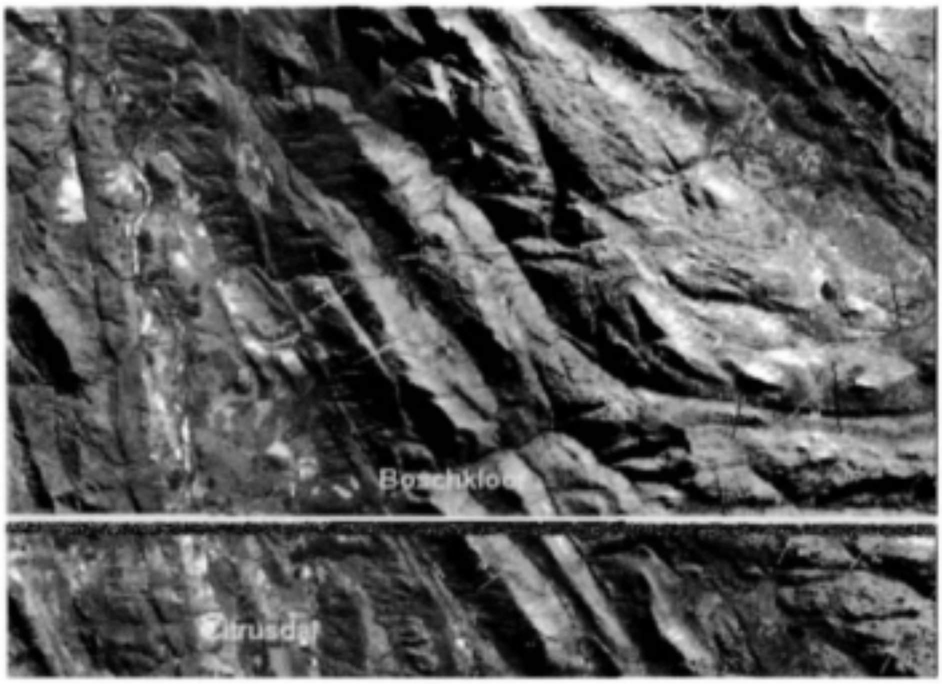

Figure 1A

Digitally mapped fracture/master joint orientations covering part of the CAGE project area. Different fracture sets shown in separate colours.

Collecting large amounts of structural information to support the construction of reliable three-dimensional models is possible using remote sensing. New techniques of image analysis allow for the interpretation of ortho-rectified, high resolution satellite images such as SPOT, IKONOS, or Landsat 7 Panchromatic band images, or aerial photographs, in conjunction with a digital elevation model of the same area.

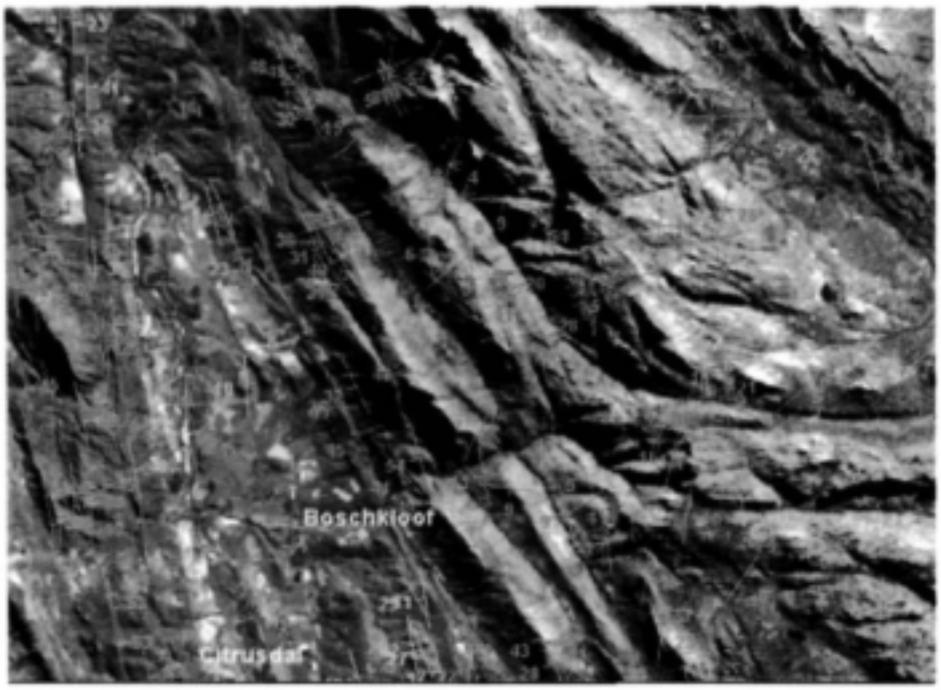

Figure 1B

Digitally mapped bedding orientations over same area as Fig. 1A. Different colours denote separate stratigraphic units (Dark blue = Peninsula Fm; Red = Cedarberg Fm; Light Blue = Nardouw Sgp; Orange = Bokkeveld Gp)

By interactively identifying three points visible on any planar feature on the imagery, such as contacts, faults, bedding traces, fold axial planes and fractures, it is possible to compute three-point solutions for the orientation (strike and dip) of the planar feature. At any specific point on the image where an orientation has been computed, it is also possible to compute a local thickness value, provided both the top and bottom of a unit are visible on the image.

The TMG outcrop area, with its variable topography and deeply incised valleys, is ideal for the application of this technique, which facilitates the collection of massive amounts of structural data in a relatively short time. These data allow for the plotting of stereographic diagrams of various structural components, facilitating further in-depth, three-dimensional analysis of the geometry of folds, faults and fractures.

Conventional methods often ignore the role of topography and involve two-dimensional interpretations of fracture and lineament patterns using satellite and aerial imagery. Although useful for fracture density studies and basic mapping of these patterns, these methods need to be applied with caution in the area of the TMG aquifers, especially when undertaking orientation analyses. Given the topography of the area, the construction and interpretation of two-dimensional rose diagrams of the orientations of lineaments and fractures can be erroneous, since the trace orientations of these features as reflected in an image are dispersed by topography if the fractures and lineaments being analysed are not vertical.

Shallow-dipping faults and fractures are known to occur throughout the Cape Fold Belt, and non-vertical radial and conjugate joints related to the fold structures are pervasive and important as water-transfer and permeability-enhancing structures. Correct analysis of the orientation and geometry of these key hydrological features requires the application of three-dimensional techniques, supported by field observations to ground-truth the data acquired from images.

Digital elevation models

Processing of digital elevation models (DEMs) should be an integral part of any remote sensing study of the TMG aquifers. These data are useful for mapping fracture and lineament patterns, especially in areas affected by human activities where the traces of major lineaments, faults and fractures tend to be obscured in spectral images, but are preserved in the topographic record stored in a DEM.

Integration of DEMs with image data for vegetation and structural analyses has already been discussed. DEMs are essential in order to apply shadow removal techniques to enhance images in areas of pronounced topography, enabling a better product for mapping and interpretation. DEMs are necessary for the production of ortho-rectified imagery and, since it is desirable that all mapping and interpretation be based on map-corrected images, they are indispensable where researchers do not have access to ortho-images created by a third party. DEMs are useful for automated mapping of fracture traces, for identifying slope breaks and nick points, for mapping watersheds, drainage basins and flow lines, to produce surface texture models as an aid to automated lithological mapping, and for determining aquifer volumes in three dimensions.

Sun-shaded DEMs enhance subtle topographic features, and when digitally combined with transparent satellite, geophysical or other imagery, become powerful aids in interpretation, such as, for example, locating the surface expression of a geophysical anomaly (See Fig. 2A-D). First order trend filters of a DEM provide models of the regional topographic gradient, whilst higher order trend filters supply information on local topographic gradients, all of which can assist in determining regional to local groundwater flow directions.

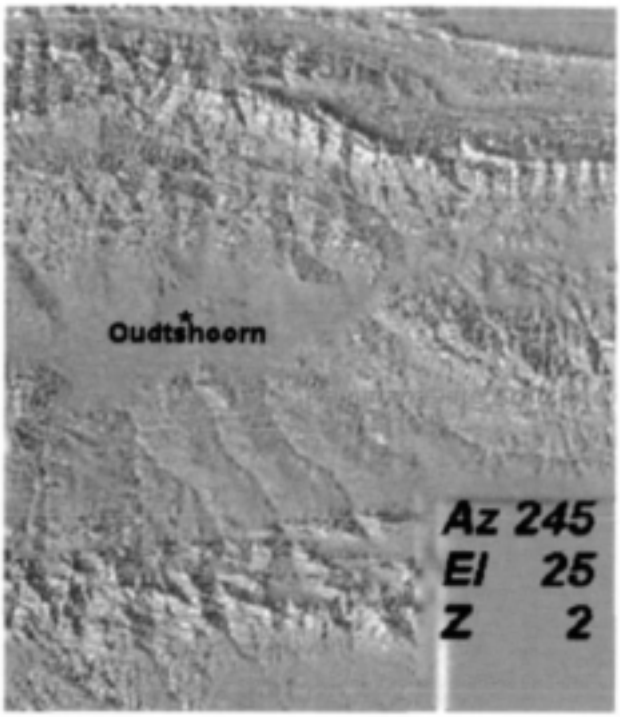

Figure 2A

Digital elevation model (DEM) sunshaded from the south-west (Sun Azimuth 245°SW, Sun Elevation 25° and vertical exaggeration 2x) at the Oudtshoorn and Kammanassie Mountains.

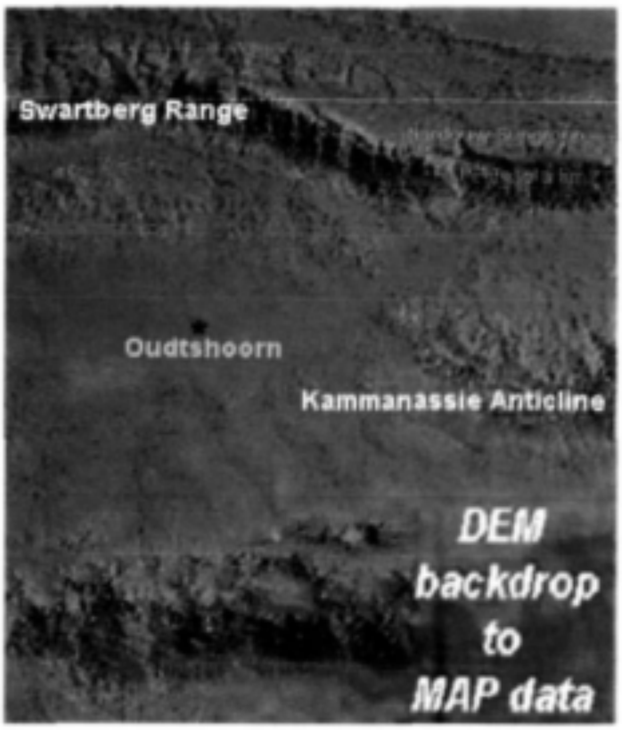

Figure 2B

Mean annual precipitation (MAP) overlain on the sunshaded DEM reveals the disparity in rainfall over the Peninsula and the Nardouw Aquifers of the Table Mountain Group.

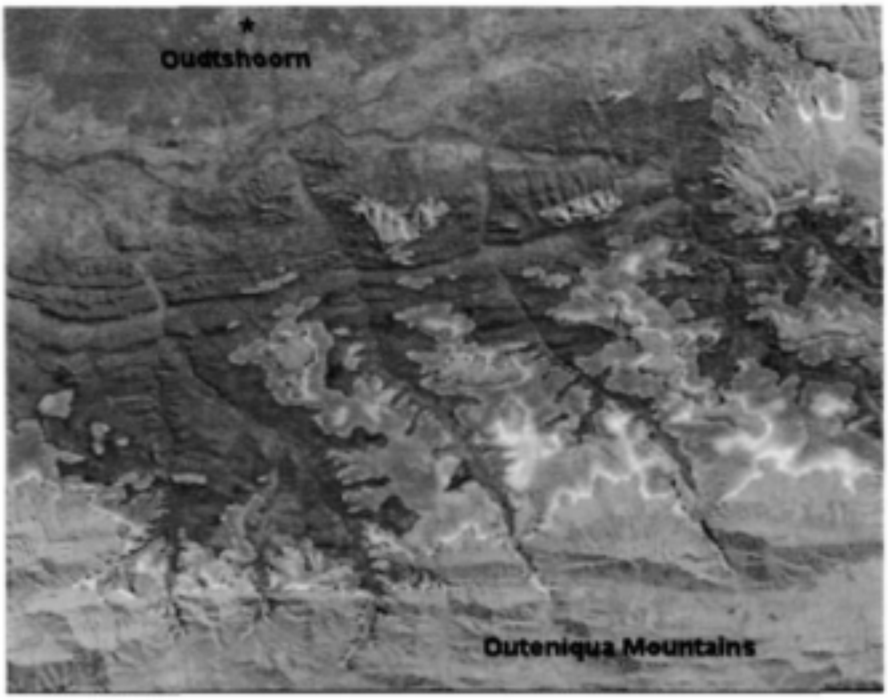

Figure 2C

Colour DEM of area including Oudtshoorn and Outeniqua range, overlain on Landsat panchromatic background. Elevations < 480 m in violet and > 550 m in red. Blue – orange rainbow colour scale emphasises high-level tertiary land surface on northern slopes of Outeniquas.

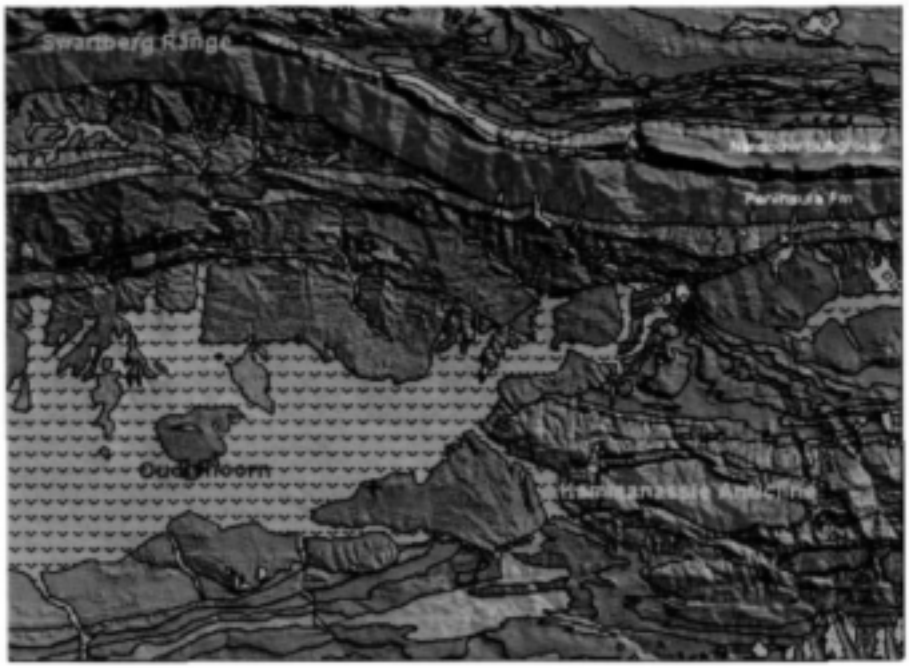

Figure 2D

GIS based geology overlain on the sunshaded DEM in Figure 3A showing clearly how the Table Mountain Group dominates the pronounced high-lying topography and is overlain by rocks of the Uitenhage group in the synclinal valley of the Olifants River in the Gouritz water management area (WMA).

A DEM enables a researcher to examine the area of interest in a three-dimensional simulated model. This entails digitally draping imagery or a digital geological map on the DEM, with the capability of flying over (See Fig. 3) or around the area so as to examine the area from any vantage point. Besides the obvious benefits for enhancing presentations and making the area more understandable to those unfamiliar with the terrain, these models can be invaluable in the interpretation process. For example, the validity of interpreted structural lineaments can be assessed, since geological lineaments have a topographic expression, whereas man-made lineaments incorrectly mapped as part of the interpretation do not have topographic expression on a vertical scale that will be detected in a three-dimensional simulation.

By setting a vantage point so as to place the viewer looking down the plunge of fold structures, the cross-sectional geometry of exposed fold structures can be seen, and used as control for the geometry reflected in geological sections. In the case of the TMG, the geometry of thrust and other fault structures can be readily assessed using these simulated models.

Mapping of vegetation springs and seep zones

Specific problems are encountered when examining the TMG aquifers, which are most cost-effectively resolved through the use of remote sensing data. The regional extent of the aq-

Figure 3

Simulated 3D view looking northwest towards Citrusdal, along the strike of a major geotect. The simulation was created by draping a Landsat natural colour composite over a digital elevation model in flight simulation mode.

uifer, and the inaccessible mountainous terrain arising from the resistant nature of the main aquifer units pose special problems for field investigators.

The identification of springs, seeps and wetlands in recharge areas, is best undertaken in these areas by employing techniques used by botanists to process Landsat data for enhancing vegetation patterns. Landsat RGB false colour infrared composites (432) can give a visual depiction of where lush vegetation is concentrated along water-bearing fractures, at the intersections of fractures or along the contacts between aquifers and aquitards. Since the bulk of the TMG occurs within the winter rainfall of South Africa, examination of summer false colour infrared imagery is recommended, because this will highlight vegetation with high biomass that is supported by ground moisture or root systems tapping groundwater, whereas winter images show vegetation patterns related more to rainfall distribution and agricultural activity.

To further enhance the mapping of vegetation, specifically for the identification of springs and seeps, ratios of images in the very near infrared (VNIR) to red wavelengths can be produced (e.g. Landsat bands 4/3 ratio). Alternatively, standard normalised vegetation index images (NDVI) can be produced from a variety of satellite data sets (Landsat, NOAA-AVHRR, SPOT XS, and Modis), depending on the scale of the vegetation anomalies being sought (see Fig. 4).

It has been demonstrated in the CAGE project (Hartnady and Hay, 2000) that the identification of vegetation anomalies associated with springs and seeps in the TMG is further enhanced by undertaking a multi-temporal analysis of Landsat TM data, or vegetation change mapping. The seasonal response of vegetation in this area varies significantly for the different vegetation biomes, and the combined processing of winter and summer imagery enhances these effects, and also aids in discriminating natural vegetation from agricultural crops.

Vegetation image products (change maps, ratios or indices) can be processed further, for example by image thresholding, to identify only those areas of anomalous vegetation biomass. A shortfall of using only remote-sensing data to identify vegetation anomalies that are representative of springs and seeps, is that such processing also enhances vegetation along river courses or associated with agricultural activity.

More rigorous identification of significant anomalies requires a knowledge-based analysis of vegetation ratios and indices in relation to variables such as proximity to slope breaks, location on concave slopes or within topographic depressions, proximity to fractures known to be hydraulically conductive, proximity to fracture intersections, and loca-

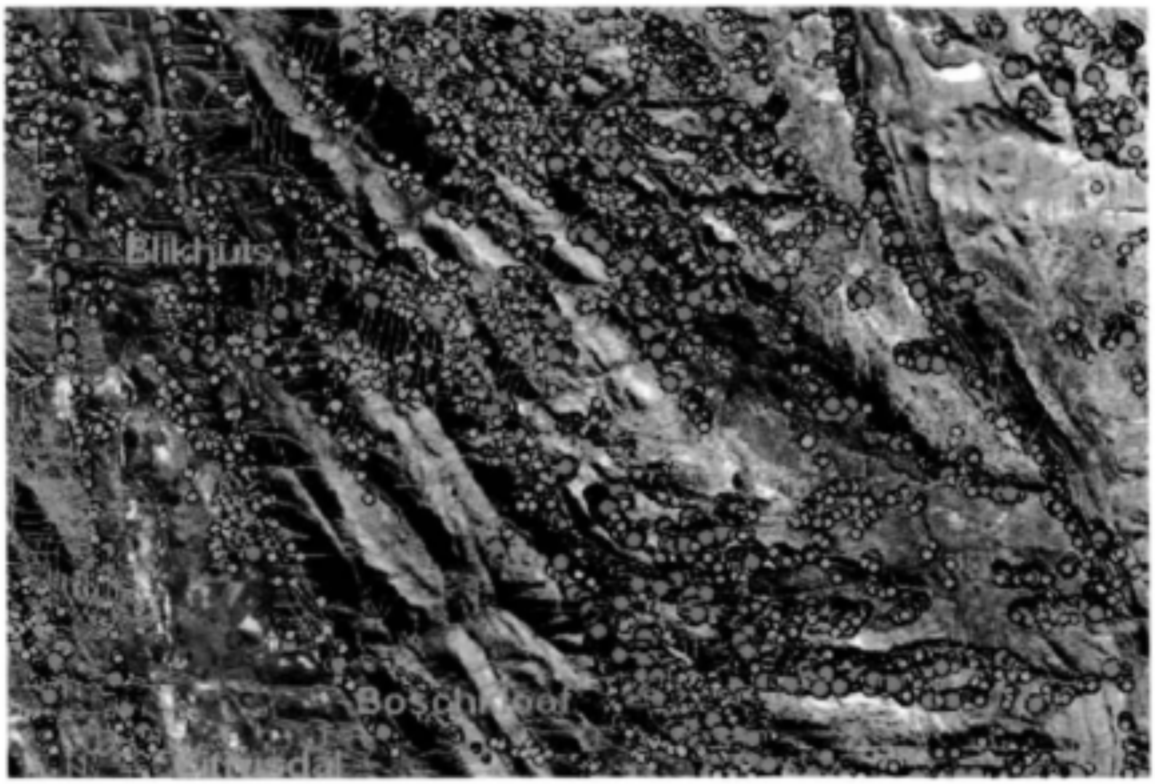

Figure 4

Vegetation anomalies (Rank 4-5 = green; Rank 6 = yellow; Rank 7 = red) and all fractures interpreted from Landsat TM image overlain on a portion of the DEM for the CAGE study area. Two well-field sites, Boschkloof and Blikhuis are shown.

tion of anomalies along or close to contacts between aquifers and aquitards. Such filtering of the remote sensing data is best accomplished by integrating remote sensing data with other spatial datasets (such as digital elevation models and digital geological maps), and careful design of knowledge-based queries based on field experience of the area under investigation.

Direct identification of areas of higher moisture content could be made using night-time thermal imagery. Whilst Landsat thermal bands can be used to identify areas of enhanced surface moisture, these day-time thermal images suffer from pronounced shadow and thermal equilibration effects, and are not ideal. Specific acquisitions of night-time Landsat-7 thermal data can be requested, and this data would be more suitable.

Ideally, however, application of thermal imagery to hydrological studies of the TMG would require commissioning of costly airborne surveys. The same applies to radar wavelengths, which by virtue of the attenuation of radar by water or water-bearing soils and sands, also presents an opportunity for mapping and identifying seeps, springs and aquatic systems. Radar image interpretation is more complex, and within the TMG area layover and radar-shadowing effects are likely to be pronounced, making the identification and separation of low returns related to high moisture content extremely difficult.

Groundwater recharge

Remote sensing has a role to play in providing information for recharge and infiltration calculations (See paper titled "Towards 'map-centric' simulation modelling of TMG recharge" in this volume). Vegetation density maps, produced from NDVI models or vegetation band ratios, serve as one input to these calculations (areas of reduced runoff , but possibly higher abstraction through transpiration losses). By using ground controlled supervised classification methods on multispectral or hyperspectral datasets it is possible to produce reliable vegetation maps at scales of up to 1:100 000, which, when linked to a GIS system, can contain information such as variable transpiration rates, root depths and runoff retardation factors for each vegetation type mapped, and for each 30 × 30 m area of ground.

Using standard methods employed by geologists for regolith mapping, which entails use of DEM data in conjunction with multi-spectral or hyper-spectral imagery and supervised classification methods, it is also possible to map soil types, alluvium, and colluvium, and to separate these from exposed bedrock. A digital map showing the distribution of these various cover types and exposed bedrock, and containing linked information as to their relative areal extents, is invaluable when estimating infiltration recharge parameters. Slope and aspect models de-

Figure 5

Slope model for the Citrusdal area, created from a Digital Elevation Model. Each 30 x30 m image cell stores a local slope value, useful as input into runoff - infiltration modelling algorithms

rived from a DEM are further aids in runoff/infiltration modelling (see Fig. 5).

More recent satellite sensors such as the Terra MODIS instrument have been designed for direct sensing of environmental parameters such as temperature and surface moisture. These new sensors will, in the future, provide researchers with key climatic variables for recharge modelling, at high temporal and moderate spatial resolution.

Conclusion

The possibility now exists to develop methodologies and tools for integrated water resource management (IWRM) using map-centric knowledge systems from a variety of professional disciplines. This step requires a paradigm shift from multidisciplinary to interdisciplinary understanding, appreciative of the variety of interpretations and overlays implicit in the digital data sets. The concurrent development of user-friendly visualisation tools for near-real time access to and display of multilayered geospatial data sets data sets will lead to improved professional management of water resources and, ultimately, a more informed public, enabling decision-makers to better assess the consequences of actions in both the short and long term.

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Geophysical Techniques Appropriate for Exploration of Table Mountain Group Aquifers

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Abstract

The geophysical techniques that can be applied to groundwater exploration in general in South Africa include the seismic reflection and refraction, gravity, magnetic, electromagnetic and electrical resistivity methods. Most of these techniques have been applied to groundwater exploration of the Table Mountain Group (TMG) Aquifer. The electrical resistivity method are widely used and accepted as the most reliable method for exploration of the TMG Aquifer. The electrokinetic and magnetic resonance sounding techniques are recently developed techniques that can directly detect the presence of groundwater in the subsurface. These two methods have been applied to fractured aquifers in South Africa, but the feasibility of applying these two methods to the TMG Aquifer should be investigated. The mountainous terrain associated with the TMG rocks makes most geophysical surveying impractical and difficult to interpret and most prominent geophysicists in South Africa agree that geophysical exploration in the TMG has been insufficient. Geophysics is still a cost-effective and efficient tool to minimise risk associated with randomly drilling boreholes.

Introduction

Geophysical surveying involves the measurement of a physical property of the subsurface, at the earth's surface, that can then be interpreted in terms of the subsurface geology. Geophysical investigations in groundwater exploration are used as a non-invasive tool to identify drilling targets prior to (exploratory) drilling. Several different geophysical methods are used in groundwater exploration, including seismic reflection and refraction, gravity, magnetic, electromagnetic and electrical resistivity methods. Most of these techniques have been applied to groundwater exploration in the TMG rocks; either directly through exploration of the TMG Aquifer or indirectly through investigation of the overlying sediments. The electrokinetic and magnetic resonance sounding techniques are fairly recent developments in geophysics that can directly detect the presence of groundwater. These have not been applied to exploration of the TMG Aquifer.

The mountainous terrain associated with the TMG rocks, makes most geophysical surveying impractical and difficult to interpret. The different geophysical techniques that can be applied to groundwater investigations are introduced below in terms of their application to groundwater exploration in the TMG rocks. More detailed information regarding the different geophysical techniques can be obtained from the publications noted in the bibliography at the end of this paper.

Interviews and previous work

All the major geophysicists (and prominent users of geophysics) in South Africa were contacted with regards to geophysics in the TMG. The interviewees include Johan de Beer, Reinhard Meyer, John Weaver, Jeff Jolly, Edgar Stettler, Mike Smart, Schalk Meyer and Peter Rosewarne. The following general comments about geophysics in the TMG are significant:

- Everybody agreed that insufficient geophysics has been done in the TMG.
- The conventional techniques that can be successful in the TMG are the resistivity and electromagnetic methods. Microseismicity has been applied to the Worcester fault (pers comm. Mike Smart).
- Geophysical data related to the TMG rocks were acquired in areas where the investigation target overlies the TMG, e.g. seismic velocities of the TMG rocks in the Breë River valley were determined during an investigation of the overlying alluvium (pers. comm. Reinhard Meyer).
- Aeromagnetic and regional gravity data can be used to delineate large-scale structures in the TMG (pers. comm. Johan de Beer; Rosewarne, 2001). These methods are, however, only use-

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ful where dolerite dykes have intruded into the structures (Hartnady and Hay, 2001). The data are regional and should be used for remote sensing only. The field positions of the structures should be accurately delineated using field geophysics. It should also be noted that the aeromagnetic and gravity anomalies do not provide direct information about the groundwater associated with the structures (pers. comm. J de Beer).

- The typical targets in the TMG are linearly extensive fractures that are connected to other water bearing fractures. Traversing will thus be highly successful as an exploration tool (pers. comm. Peter Rosewarne)
- If the geophysical surveying applied to a certain study area is not based on theory and a clear understanding of the method and results, then geophysical surveying is used as a divining tool.
- Geophysical surveying should be calibrated using available borehole information (groundtruth) and/or correlation between several different geophysical methods.

Seismic method

During seismic surveying pulsed acoustic energy is generated at the earth's surface. This energy is then propagated into the subsurface and reflected or refracted at an acoustic impedance interface in the subsurface. The two-way travel time of the reflected or refracted events, measured at the earth's surface, can then be interpreted in terms of the geology of the subsurface if velocity (and density) information is available for the subsurface. Seismic data can be used to accurately delineate linear structures in hard rock terrains (e.g. fault structures) as well as determine depth of weathering (depth to bedrock) if velocity data and/or groundtruth is available for the study area.

TMG quartzites have a significantly higher velocity than the argillaceous lithologies of the TMG, the underlying Malmesbury Group rocks and the overlying Bokkeveld Group rocks. The velocity of the granite of the Cape Granite Suite is comparable to that of the quartzites. The fact that the quartzites have a higher velocity than the interbedded shales and underlying Malmesbury rules out the use of seismic refraction techniques (because critical refraction can only occur when the velocity of the overlying layer is lower than the velocity of the underlying layer). The seismic reflection technique in general is only successful where the sedimentary strata are flat-lying or have a low dip. The mountainous terrain that typifies the TMG strata will make reflection studies logistically difficult and very costly. In the highly folded areas reflection data also will be very complex and difficult to interpret.

Electrokinetic sounding method

The electrokinetic sounding (EKS) technique is an electroseismic method that relies on the presence of groundwater in the subsurface for the generation of the electrokinetic signal. The surfaces of mineral grains in rocks have net charges and groundwater is electrolytic in nature. Thus in saturated rocks, an electric charge are produced at the contact between the water and solid, resulting in an electrically double-layered fluid. A mechanical disturbance (seismic) propagating through this water-saturated medium will result in relative movement between the solid and fluid phase. This relative movement will induce electric current to flow in the water saturated medium with an associated electromagnetic field generated (electro). This electromagnetic field is then measured at the earth's surface (Fourie et al., 2000).

The EKS technique has been applied to the Karoo rocks in South Africa. This technique might be successful in similar hard rock environments, where a high permeability contrast exists between the fracture zones and surrounding rock (Fourie et al., 2000). It has however not been applied to the TMG rocks. The feasibility of applying the EKS method to groundwater exploration in the TMG should be investigated.

Gravity method

The gravity method entails measuring small local variations in the gravitational field of the earth that are caused by changes in the density of the subsurface. The density changes are in turn related to subsurface geology. However, gravity data do not have wide application in groundwater exploration: regional data can be used to model gross structures and to follow out trends but gravity data will not be very useful to study specific water-bearing features.

The prominent fault structures in the TMG can be mapped using gravity surveying, but it is expensive and time-consuming and does not provide information directly related to the groundwater associated with the specific structures.

Magnetic method

During magnetic surveying, local variations in the earth's magnetic field are measured. These variations are mostly caused by local magnetic mineralisation. Most magnetic mineralisation is magmatic in origin and the magnetic method is thus not very useful in sedimentary terrains without magmatic intrusions. In exceptional cases the weathered products of fault zones can be mineralised and have a magnetic signature. Then such features could be traced on magnetic data.

However, hydrous ferric oxide ($Fe_2O_3nH_2O$), commonly known as iron oxide, precipitates and deposits in the fault zones and fractures of the TMG. This mineral is not magnetic and will not give a magnetic signal – i.e. a fault zone with iron oxide will not be detected by a magnetometer. It is important to note that if the geophysical method used for a specific study is not based on sound theory and a clear understanding of the method and the results, then geophysical surveying is used as a divining tool. The magnetic method is often used as a divining tool.

Aeromagnetic surveys have been used with success in certain areas where the major fault zones have been intruded by dolerite dykes, e.g. in the Olifants and Doring River catchments in the Southern Cape (Hartnady and Hay, 2001).

Magnetic resonance sounding method

The magnetic resonance sounding (MRS) method is a fairly recently developed geophysical tool. MRS surveying entails transmitting alternating current into a large loop on the earth's surface. The frequency of the current depends on the amplitude of the earth's magnetic field in the study area and will thus be equal to the resonance frequency of hydrogen nuclei ($^1H^+$) - nuclear magnetic resonance (NMR) in the study area (this will vary from area to area). The magnetic field generated by the current flowing in the loop will propagate into the subsurface. When this magnetic field encounters groundwater the hydrogen nuclei in the water is excited and these oscillating hydrogen nuclei produces a magnetic field that is measured and then interpreted in terms of the water content (porosity) versus depth. Note that the MRS method is sensitive to the free-water content of the subsurface; clay-bound and micropore-bound water will not generate a signal (Roy and Lubczynski, 2000).

However, useful MRS data can only be acquired where the NMR signal to noise ration is large enough to extract the NMR signal from ambient noise (the generated signal is very small). Sources of noise include man-made electrical noise and natural noise e.g. lightning. South Africa is a fairly difficult area for MRS surveys, but reliable data can be acquired (Roy and Lubczynski, 2000).

This technique has not been applied to groundwater exploration in the TMG rocks. The capability of the MRS method to directly detect groundwater can potentially make it a powerful tool and the feasibility of applying the method to the TMG should be investigated. It should be noted that IRIS instruments (1999) suggests that MRS is a good complement to other geophysical methods: "It is particularly useful when resistivity data cannot clearly be related to the presence of water".

Electromagnetic method

The electromagnetic method entails measuring the magnitude (and/or direction) of the secondary electromagnetic field that results from alternating current induced into the subsurface by a primary electromagnetic field. The difference between the primary and secondary electromagnetic fields can be directly related to the electrical properties of the subsurface. (Note that electromagnetic surveying is not very effective in distinguishing between rocks with low and very low conductivities). The electrical properties of a rock vary with porosity, water saturation and the amount of dissolved solids in the water.

The electromagnetic method can be used to distinguish between the TMG quartzites with a very low conductivity and the argillaceous lithologies of the TMG, the Malmesbury and Bokkeveld Groups with higher conductivities. The water-saturated fractured quartzite of the TMG will be more conductive than dry quartzite. However, groundwater in the TMG is normally of very good quality and thus water-saturated rock still has fairly low conductivities. This generally reduces the usefulness of the electromagnetic method to distinguish between water-saturated and dry quartzite. Similarly the difference between the conductivity of fractured and fresh TMG quartzite might not be obvious.

It is important to note that the electromagnetic method is not always successful in the TMG rocks: several boreholes were drilled in the Ceres area, to upgrade the town's water supply. The drilling positions were located either on visible fracture zones or electromagnetic anomalies (for more information see Rosewarne, 2001). Borehole SRK7 was drilled on a visible fracture with no associated electromagnetic anomaly and SRK4 were drilled on an electromagnetic anomaly without a visible fracture zone. Both these boreholes were successful (Rosewarne, 2001). This is because the electromagnetic method is not very effective at distinguishing between low and very low conductivities.

Electrical (resistivity) method

The resistivity method uses direct current to determine the electrical properties (resistivity) of the subsurface. An artificially generated electrical current is introduced into the subsurface and the resulting potential difference is measured. This measured current and potential differences are then used to calculate the apparent resistivity of the subsurface. Resistivity is the inverse of conductivity and the resistivity of rocks is dependant on the same variants mentioned above. Resistivity surveying can entail both lateral profiling or depth sounding. Due to the complexity (fault zones are normally also associated with increased depth of weathering around the fault) associated with any hard rock terrain, a combination of profiling and sounding should be used to acquire both lateral and depth information. The multi-electrode resistivity method allows for acquiring both sounding and profiling data. This method also allows for the acquisition of induced potential (IP) data at the same time. IP data can be used to verify if resistivity decreases are caused by clay or water in the pore spaces. The feasibility

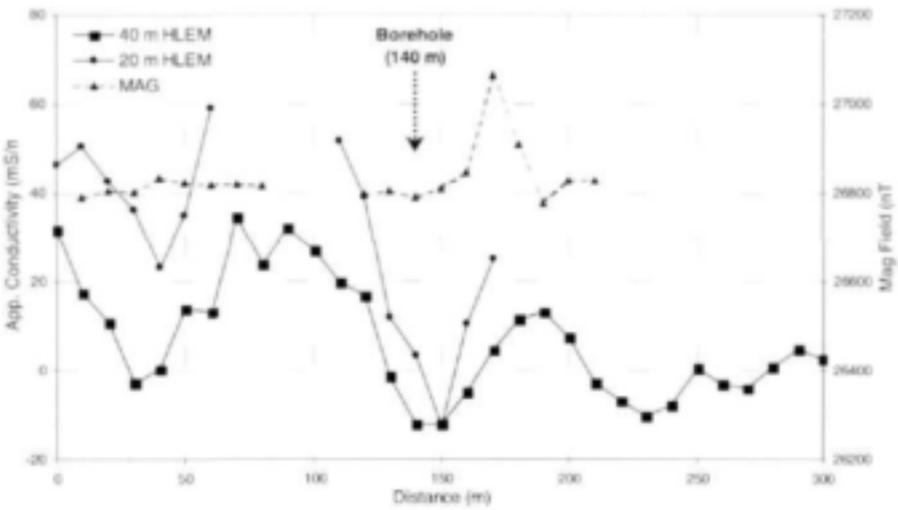


Figure 1
Geophysical data: Plettenberg Bay Traverse 3

of applying this method to groundwater exploration in the TMG rocks should be further investigated.

The TMG quartzites are electrically resistive and have a good contrast with the less resistive (more conductive) argillaceous lithologies of the TMG succession, the Malmesbury and Bokkeveld Groups. The granites of the Cape Granite Suite are more resistive than the TMG quartzites, but direct current resistivity methods are well suited to distinguish between resistive and very resistive strata. This is very important considering that the targets in the TMG rocks are linearly extensive fractures. According to Duvenhage and Meyer (1992) the fracturing of the TMG rocks has a notable influence on the resistivity character of the TMG rocks. The resistivity method can be used to distinguish between high resistivity fractured quartzite and the very high resistivity fresh quartzite. Note that groundwater may be associated with these fracture zones.

Case studies

Two short case studies from the experiences of the authors are described below. The electromagnetic method has been successfully applied to groundwater exploration in the TMG rocks for the past ten years. The electromagnetic data are acquired with the Geonics EM34-3, a frequency domain electromagnetic unit. The EM34-3 allows for different set-up configurations with associated pre-set frequency settings. The depth of investigation can thus be controlled by the operator. Electromagnetic data are normally acquired along traverses located using aerial photograph interpretation of the study area. The initial data are acquired using horizontal, co-planar coils with a separation of 40 m. This results in a (claimed) depth of investigation of about 60 m. The EM34-3 measures the apparent conductivity of the subsurface. The apparent conductivity of the TMG is low (between 0 and 15 mS/m), with negative anomalies targeted for drilling: the TMG quartzite weathers to sand and this dry sand normally has a very low conductivity. Anomalous zones in the subsurface are thus delineated and a second set of electromagnetic data is acquired over the anomaly using horizontal, co-planar coils with a separation of 20 m. The (claimed) associated depth of investigation is about 30 m. The targets for drilling are then located where both the data sets (20 m and 40 m separation) show a negative anomaly.

EM34-3 data were acquired at the Plettenberg Bay Airfield to locate a drilling position for a water supply borehole. A portion of the electromagnetic data acquired along Traverse 3 is shown in Fig. 1. The drilling position was located on the negative anomaly at 140 m. The borehole was drilled to a depth of 250 m with water-bearing fractures intersected at 67 and 126 m. The total airlift yield of this borehole was 6 ℓ/s. It is important to note that the maximum depth of investigation of the EM34-3 is 60 m, but by delineating the fracture zone, the deeper groundwater in the fracture zone could be targeted.

Historically magnetic data were also acquired along the traverses to correlate data and anomalies if possible. However, results obtained were very inconsistent. No magnetic anomaly is directly associated with the EM34-3 anomaly in Fig. 1. The positive magnetic anomaly occurring at about 170 m does not relate to fracture zones delineated by the EM34-3. Figure 2 shows the geophysical data acquired along the second traverse at the Plettenberg Bay Airfield. A possible drilling location would have been the anomaly at about 320 m on the profile. The magnetic anomaly occurs at about 290 m and there is no relationship between the magnetic anomaly and fracturing. It is very important to note that the magnetic anomalies are inconsistent: in the same study area, the magnetic anomalies are both negative and positive. The magnetic method cannot be used to delineate fracture zones in the TMG rocks, unless the fracture zones are intruded by dolerite dykes.

It is important to note that the geology of the study area must always be considered when using geophysical surveying to locate drilling positions. The electromagnetic data acquired along Traverse 7

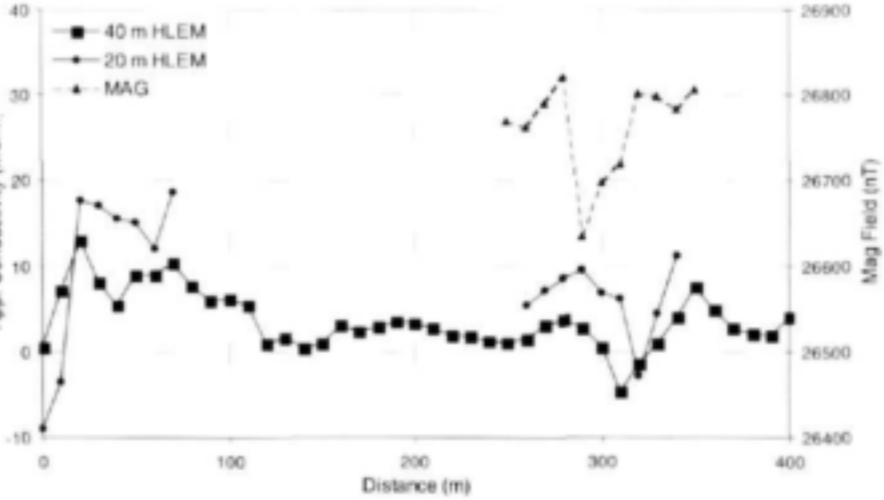


Figure 2
Geophysical data: Plettenberg Bay Traverse 2

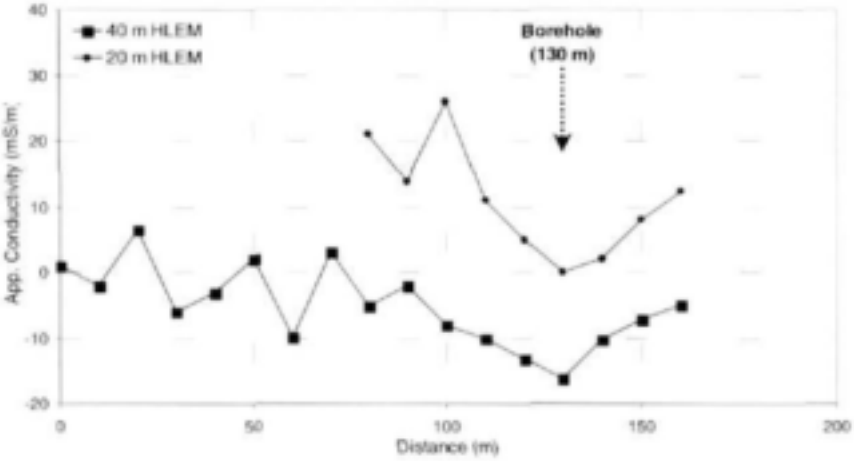


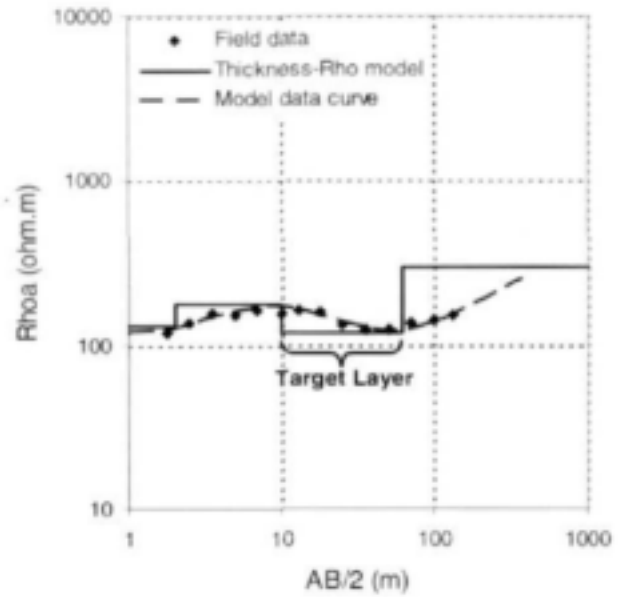
Figure 3
Electromagnetic data: Albertinia

in Albertinia shows a negative anomaly at about 130 m on the traverse (Fig. 3).

However, the borehole was drilled to a depth of 120 m with no water bearing fractures intersected. A vertical carbonaceous shale horizon was intersected in the borehole. This carbonaceous shale horizon also has a low apparent conductivity and caused the negative anomaly on the electromagnetic data, instead of the expected fractured TMG quartzite.

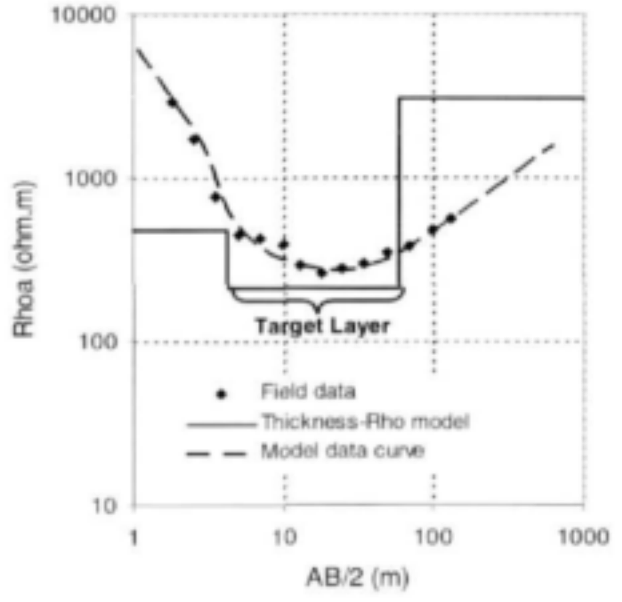
The resistivity method was successfully used to locate water supply boreholes in the TMG in the Botriver area (see Weaver, 2000 for more detailed information and maps). The area is underlain by quartzites of the TMG and shales and sandstones of the Bokkeveld Group. The TMG and Bokkeveld Groups are separated by a northeast-southwest trending reverse scissor fault. Shales of the Bokkeveld Group occur to the southeast of the fault and have been downthrown. The fault passes through the northwestern part of Botriver and is visible on the surface in places. The purpose of the geophysical survey was to locate the fault in the subsurface and then investigate the TMG rocks just northwest of the fault. The fractured TMG quartzite was identified as the prime target for water supply boreholes because the quartzite is a hard rock that is not very susceptible to weathering. The fractures will thus stay open. The shales of the Bokkeveld Group on the other hand, weather to clay (fracture zones are preferential weathering channels). Also, the shales of the Bokkeveld Group tend to yield poor quality groundwater as opposed to the good water quality associated with TMG Aquifers. The resistivity method was selected because of its reliability in distinguishing between lithologies with high and very high resistivities. The sounding technique was used instead of the profiling technique because information on depth of weathering was considered more important than delineating the fault on the surface.

Sounding data were acquired at several locations on both sides of the fault and a cross-section of three soundings will be discussed (see Fig. 2 of Weaver in this publication). The three soundings VES4, VES1 and VES2 were located in a line perpendicular to the fault (in a direction southeast-northwest). VES4 (Fig. 4) was located southeast of the fault line on the shale of the Bokkeveld Group. The low resistivity of the target layer (120 ohm.m) is indicative of the weathered shale of the Bokkeveld Group.



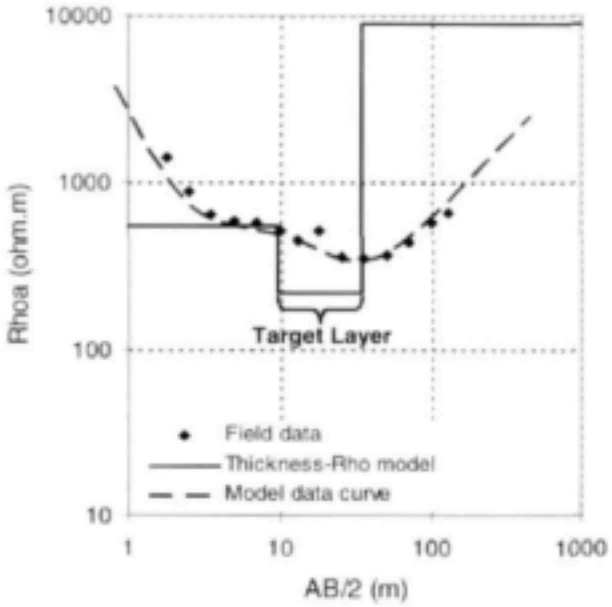
n	Thickness (m)	Resistivity (ohm.m)	Depth (m)
1	2.0	130	2.0
2	8.0	180	10.0
3	**52.0**	**120**	**62.0**
4		300	

Figure 4
Botriver: VES4



n	Thickness (m)	Resistivity (ohm.m)	Depth (m)
1	0.9	5500	0.9
2	3.3	480	4.2
3	**55.0**	**210**	**59.2**
4		3000	

Figure 5
Botriver: VES1



n	Thickness (m)	Resistivity (ohm.m)	Depth (m)
1	0.6	5500	0.6
2	8.8	550	9.4
3	**25.0**	**220**	**34.4**
4		9000	

Figure 6
Botriver: VES2

The thickness of the target layer (52 m) was considerable, but this sounding location was rejected as a drilling position because of the low resistivity. This is an indication of either poor water quality associated with the shale or high clay content as can be expected from the weathering of the shales of the Bokkeveld Group.

Sounding data for VES1 (Fig. 5) were acquired just northwest of the fault on the TMG. The interpreted sounding data show a considerable depth of weathering (60 m) as well as a higher resistivity (210 ohm.m) for the target layer, as was expected for the fractured TMG rocks. This location was selected as one of the priority drilling positions because of the depth of weathering and the higher resistivity. A successful borehole was subsequently drilled. The drilling log of the borehole showed 32 m of weathered TMG quartzite underlain by fractured TMG quartzite to a depth of 79 m. The total airlift yield of the borehole was 7.5 ℓ/s with a sustainable yield of 2.5 ℓ/s.

Sounding VES2 (Fig. 6) was acquired northwest of VES1 on the TMG. This sounding was located further away from the fault. The depth of weathering for the target layer (~35 m) is considerably less with a slight increase in resistivity (220 ohm.m). The depth of weathering was expected to decrease further away from the fault because the depth of weathering in the TMG rocks is directly related to the fracturing caused by the faulting. The frequency of fracturing will decrease further away from the fault. The resistivity is still low enough to suggest that the frequency of fracturing is still sufficient to ensure that water-bearing fractures will be intersected. This site was recommended as an additional drilling site, only to be drilled if sufficient groundwater was not obtained from other boreholes.

The difference in resistivity between the shale of the Bokkeveld Group and the TMG quartzite was used to delineate the fault position in the subsurface. The target sounding, VES1, and its relation to VES2, was used to define the positions of subsequent soundings. These were located just northwest of the fault. The sounding locations that showed the deepest weathering with a resistivity between 200 and 250 ohm.m were selected for subsequent drilling.

Conclusions and research needs

The geophysical techniques applied to groundwater exploration in South Africa include the seismic reflection and refraction, gravity, magnetic, electromagnetic and electrical resistivity methods. Most of these techniques have been applied to groundwater exploration in the TMG rocks, either through direct studies of the TMG or through indirect studies of the overlying material. The electrokinetic and magnetic resonance sounding techniques are new developments in the groundwater field and can potentially directly detect the presence of groundwater. These methods have not used in the TMG rocks, but the feasibility of applying it to groundwater exploration of the TMG Aquifer should be investigated.

The prominent geophysicists (and major users of geophysics) in South Africa agree that insufficient geophysics has been done on the TMG rocks. The setting and physical characteristics of the TMG are not ideal for geophysical study. However, geophysics is a cost-effective way of minimising the risk of randomly drilling boreholes and several geophysical techniques can be used for groundwater studies in the TMG rocks. The most successful of the conventional geophysical techniques is the resistivity method. Multi-electrode resistivity is the latest development in resistivity surveying and pseudo section resistivity data can be rapidly acquired along a section. This method should be applied to groundwater exploration in the TMG. The electromagnetic method has been used successfully in the TMG rocks and electromagnetic methods aimed at deeper exploration should be further investigated.

The electrokinetic and magnetic resonance sounding techniques are specifically aimed at groundwater exploration. Both these methods rely on the presence of water in the subsurface to generate a signal. These methods have been applied to hard rock aquifers in South Africa, but not the TMG Aquifer. The feasibility of applying these techniques to groundwater exploration in the TMG Aquifer should be investigated.

Acknowledgments

The general information about the applicability of certain geophysical methods to the TMG rocks was supplied by Johan de Beer of the CSIR. The electromagnetic data and related information were supplied by Jeff Jolly of GCS. The resistivity data from Botriver was supplied by John Weaver of the CSIR.

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The Application of Isotopes and Hydrochemistry as Exploration and Management Tools

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Abstract

The rationale behind the use of environmental isotopes and hydrochemistry as tools in hydrology is reviewed, with pointers to their potential in the study of Table Mountain Group (TMG) Aquifers. Case studies which apply these isotopes and trace elements to problems such as dating aquifer water, recharge determination, aquifer palaeotemperatures, mixing of water types and altitude of recharge are discussed.

Introduction

Oxygen and hydrogen isotope ratios have been an integral part of tracer studies in hydrology since the early 1960s. Along with carbon and nitrogen stable isotopes and the radioactive isotopes ^{14}C and tritium, they are sometimes collectively termed "environmental isotopes". The chemical constituents of groundwater are a reflection of the chemical composition of the rainwater from which it is derived, the recharge conditions and the processes occurring below ground. Analysis of the water chemistry therefore provides some insight in these processes. Dissolved gases (dissolved oxygen, CFC, nitrogen, argon, helium) are increasingly being used to identify some processes in the water with varying success. All of these together can be classified as environmental tracers and need to be distinguished form "artificial tracers" which are man-made tracers introduced in water for investigational purposes. Man-made constituents introduced unintentionally (commonly labeled as "pollution") are often also used for this purpose.

Rationale

Oxygen and hydrogen

Oxygen and hydrogen are the major elements present in water and as such they are the most conservative of all tracers. The oxygen and hydrogen isotope composition of rain water, which recharges aquifers, varies in a semi-predictable way and this provides the basis for O- and H-isotope hydrology (e.g. Clark and Fritz, 1997). In the case of both oxygen and hydrogen, the heavier isotope (^{18}O and D) is much less abundant than the light isotope (^{16}O and H) to the extent that it is convenient to report isotope ratios relative to a reference sample of seawater. Data are reported in δ notation, relative to SMOW (Standard Mean Oceanic Water), where $\delta = (R_{sample}/R_{SMOW} - 1)*1000$, and $R = {}^{18}O/{}^{16}O$ or D/H. The δ value, in per mil units, is a measure of enrichment in the heavy isotope (^{18}O or D). Thus a sample with a lower $^{18}O/^{16}O$ ratio than seawater has a negative δ value whereas a sample with a higher $^{18}O/^{16}O$ ratio than seawater has a positive δ value.

Tritium

Tritium is the radioactive heavy isotope of hydrogen (^3H) which has a half life of 12.4 years. The concentration of tritium in water is usually expressed as tritium units (1 TU = a T/H ratio of 10^{-18}). Tritium, is produced in the stratosphere by cosmic ray interaction with nitrogen. The tritium becomes incorporated into rain and the natural level of tritium in rain ranges from 3 to 10 TU. Once water is isolated from the atmosphere, the tritium decays. The detection limit for tritium is about 0.2 TU which would limit the maximum dateable "age" to 55 years. Hydrogen bomb tests between 1952 and 1963 introduced large amounts of tritium into the atmosphere, but this has now decayed to much lower levels. Southern hemisphere bomb tritium levels were much lower (60 TU, IAEA, 1992) than in the northern hemisphere, and the tritium content here has now reverted to its pre-bomb value. The main application of tritium is to identify recharge from the period when the tritium content in rain was above normal, i.e. 1960-1980. In due course it will again be used to date water by the radioactive decay of tritium.

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Carbon

Carbon has two stable (^{12}C and ^{13}C) and one radioactive isotope (^{14}C) of which ^{12}C is by far the most abundant (98.9%). Stable isotope data for carbon are normally expressed in δ notation (see above) relative to a marine carbonate reference (PDB). Hence marine carbonates have δ^{13}C values close to zero. Most organic carbon has highly negative δ^{13}C values (commonly -20 to -28‰). In groundwater it is possible to determine the δ^{13}C value of dissolved species (e.g. HCO_3^-) or exsolved gas bubbles (e.g. CO_2, CH_4) found in the water. A knowledge of the δ^{13}C value of groundwater is important in the interpretation of ^{14}C data because the δ^{13}C value indicates the amount of incorporation of carbon from ^{14}C-free carbonate minerals

In the upper atmosphere, ^{14}C is produced by the interaction of ^{14}N with cosmic rays. The ^{14}C concentration in the atmosphere has remained reasonably constant in the past. The explosion of nuclear devices and operation of nuclear reactors since 1945 has increased the atmospheric ^{14}C activity significantly. Atmospheric ^{14}C becomes incorporated into plants and, when these decay, enters seepage water during percolation of moisture through soil. Once the water is isolated from the near surface (e.g. in an aquifer), the ^{14}C can no longer be replenished and decays with a half-life of 5730 years. Any dissolution of carbon-bearing material (e.g. from carbonate rocks) will also decrease the ^{14}C/^{12}C ratio in the water. This process can be recognised if the ^{14}C content correlates with the δ^{13}C value or alkalinity. A measure of the ^{14}C activity of groundwater can therefore provide an approximate average "age" for the water back to about 40 000 years (depending on the level of accuracy of the method measuring the ^{14}C activity). The concentration of ^{14}C in groundwater is expressed in pmC (per cent modern carbon) and values close to 100 pmC would be consistent with recently recharged water. Proper evaluation of the chemistry of the water and its ^{13}C content is necessary in order to judge the extent of 'dead' carbon contribution to the ^{14}C content of groundwater (e.g. Clark and Fritz, 1997; Plummer and Sprinkle, 2001).

CFCs

CFCs are very stable gases with wide application. They have been produced since the 1950 and the atmospheric levels (at the 10^{-10} level) have steadily increased since then. As very stable gases they have permeated all atmospheres, including that in soils, and are also dissolved in groundwater. The CFC levels in groundwater, and the ratios of the three useful ones (CFC-11, CFC-12 and CFC-113) are being used to identify recharge events, date water in some circumstances and localise pollution events (Plummer and Busenberg ,1999; Talma et al., 2000).

Major ion chemistry

Groundwater and stream water associated with the TMG are renowned for its low level of all chemical constituents. The early work of Bond (1946) has shown that this water has the lowest TDS values of all water in the country; since confirmed by more recent surveys (Simonic, 2001). The levels of Na and Cl in water are primarily determined by the distance from the sea, since marine water is the major source. The absence of carbonates in the TMG has the consequence that alkalinity, Ca and Mg levels are primarily determined by weathering reactions of the felspathic minerals in the TMG (Cave et al., 2001). Since these reactions are quite slow, the water remains unsaturated with respect to carbonate and the pH is usually below the saturation level of pH 7.

Whereas there must be many thousands chemical analyses of groundwater from the TMG in various data bases and the properties must be known to many responsible to turning the water into a form usable for public water supplies, only a few studies have addressed the chemical composition as exploration and management tools. The main application is to use the Na and Cl content as indicator of sea water input, either via sea spray or as sea water intrusion (e.g. Weaver, 1998; Weaver et al., 1999). Other applications are to use the contrast between TMG and other water for source identification (Kirchner, 1994). More detailed surveys of the chemical composition of groundwater in relation to the geology of the aquifer are presently underway (Umvoto in prep, Kotze in prep) and will identify specific features of TMG groundwater chemistry. Smart and Tredoux (this volume) have summarised the main hydrochemical characteristics of groundwater in the TMG.

O- and H-isotopes in precipitation

In this section we review the factors influencing the H- and O-isotope composition of rain water in general and consider the likely variability of water in the area of outcrop of the TMG. Craig (1961) showed that there was a remarkable correlation between δD and δ^{18}O in precipitation waters world-wide with a best-fit line corresponding to $\delta D = 8\delta^{18}O + 10$. This line is known as the global meteoric water line The term 'meteoric water' is used to distinguish 'meteorological' such as rain, snow and hail water from connate and juvenile water. Although most precipitation world-wide lies close to the global meteoric water line, different areas have their own distinctive local meteoric water lines. Variations in the equation for the meteoric water line at a specific locality are a function of climate, geographic location and source region of evaporation to form clouds (e.g. Rozanski et al., 1993).

There are five major factors (Dansgaard, 1964) which influence the isotope composition of precipitation in a given region. These are temperature, altitude, the amount of precipitation, continentality and

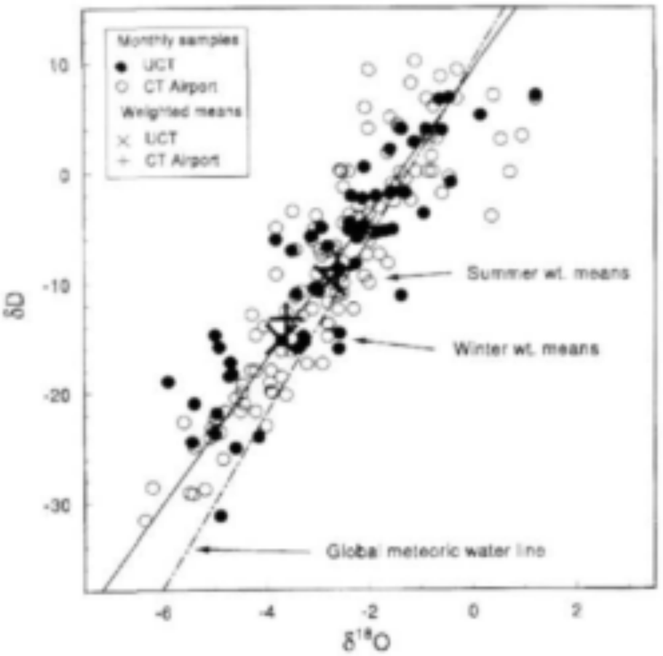


Figure 1

Plot of δD vs. $\delta^{18}O$ for monthly samples from Cape Town International Airport (IAEA, 1997) collected from 1962-1982 and UCT (Harris unpublished data) collected from June 1995 - June 2000. The solid line is the line of best fit through the data (δD = 6.59 $\delta^{18}O$ + 9.34; calculated using the RMA method, Rock, 1988). Also shown is the global meteoric water line (Craig, 1961) and the weighted mean values for summer rain (October-March) and winter rain (April to September) from both stations.

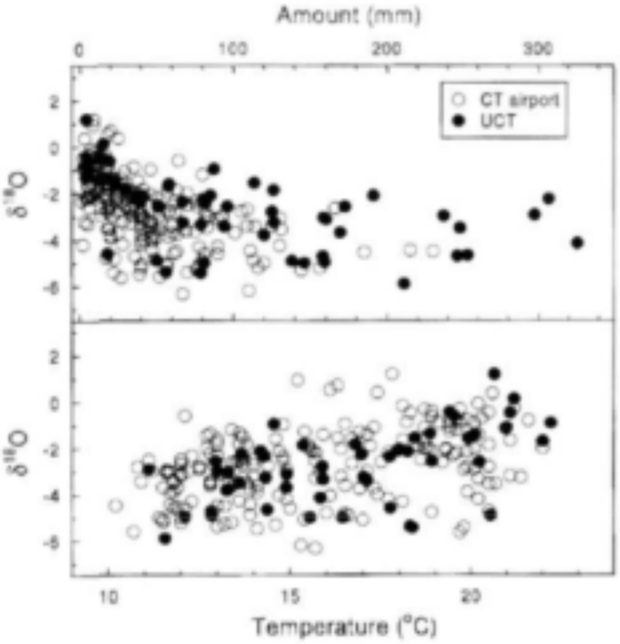


Figure 2

Plot of $\delta^{18}O$ vs. average monthly temperature and amount of rain for Cape Town International Airport and UCT (type and sources of data as for Fig. 1).

source region. Isotope data for precipitation on a monthly basis have been collated and summarised by the International Atomic Energy Agency (IAEA) (e.g. Rozanski et al., 1993) as part of an ongoing world-wide project. Southern African stations for which analyses have been reported between the 1960s and 1980s were those at Cape Town, Pretoria, Windhoek and Harare. Data relevant for the TMG are those from Cape Town International Airport (1962 to 1974) and at the University of Cape Town (UCT) since 1995. Selected stations were and are sampled for shorter periods to satisfy the demands of specific projects. It can be expected that the introduction of a cumulative rainfall sampler by which a pooled annual sample can be obtained with minimum attendance (Weaver et al., 1999) will expand this database in the future.

The isotope composition of rain in the Western Cape, has been discussed by Diamond and Harris (1997) and by Harris et al (1999). Diamond and Harris (1997) calculated the line of best fit through the rain data from the Western Cape to have the equation δD = 6.2$\delta^{18}O$ + 10.6 which represents the best approximation to a Western Cape meteoric water line. Two large data sets are available, for UCT (1995 to present; Harris, unpublished data) and Cape Town International Airport (complete data for 1962-1974; IAEA 1997). The O- and H-isotope measurements are for pooled monthly samples and are plotted on Fig. 1. The equation of the line of best fit is δD = 6.59$\delta^{18}O$ + 9.34 and this represents a local meteoric water line. It should be noted that no kind of weighting has been applied to the determination of the equation of the meteoric water line in Fig. 1, or that of Diamond and Harris (1997). The isotope composition of water which recharges groundwater is likely to be most closely approximated by the average weighted annual δD and $\delta^{18}O$ values. For Cape Town Airport, these δD and $\delta^{18}O$ values for the years 1962-1968 and 1974 (the only years in which the data are complete) are -12.7 and -3.31‰ respectively. For UCT the average 12 month weighted mean δD and $\delta^{18}O$ values from June 1995 to May 2000 are -11.4 and -3.42‰ respectively. The variation of monthly rain $\delta^{18}O$ value with the amount of rain and average temperature are shown in Fig. 2. It can be seen that where there are small amounts of rain, the $\delta^{18}O$ values tend to be higher. This amount effect is much stronger in the UCT data than that of CT airport. The correlation between $\delta^{18}O$ value and temperature is poor, nevertheless there is a general tendency for the months with the colder average temperature to have lower $\delta^{18}O$ values. Seasonal differences for UCT and CT airport are also shown on Fig. 1.

The δD and $\delta^{18}O$ values of rainfall decrease as altitude increases (Dansgaard, 1964), and variation in altitude is probably the most important factor influencing the isotope composition of recharge to TMG Aquifers. Midgley and Scott (1994) reported an altitude effect on $\delta^{18}O$ of -0.32‰ per 100 m for a single mid-winter month in the Jonkershoek Mountains, about 70 km east of Cape Town. Harris et al. (1999) observed a decrease in $\delta^{18}O$ value of 0.5‰ per 100 m for springs on the slopes of Table Mountain. Altitude effects must be used with caution because they are highly site-specific (e.g. Mazor, 1991; Clark and Fritz, 1997). In the Agter-Witzenberg valley Weaver et al. (1999) could not observe an altitude effect during two years rainfall sampling because the valley and its recharge area (80 m higher) were all located in the rain shadow of a higher mountain range in the west.

The final cause of variation in isotope composition of rain is geographical. This is due both to a rain out effect where the isotope ratio of clouds is depleted as the fraction of moisture remaining gets smaller and to the source of moisture. In the western parts of the TMG outcrop it can be assumed that rainfall comes from clouds arriving from the west coast. The Klein Karoo and areas further east receive rain from both the east (Indian Ocean) and the west (Atlantic Ocean). These influences have yet to be investigated in more detail.

The effect of evaporation

The most effective means of changing the O- and H-isotope composition of a body of water is by evaporation. The vapour pressure of water molecules containing any of the heavy isotopes is slightly lower than that of common water and as a consequence $\delta^{18}O$ and δD progressively increase as in the remaining water as evaporation proceeds. The actual evaporation process can be approximated using a Rayleigh-batch model (e.g. Merlivat and Jouzel, 1979) incorporating the mean humidity of the atmosphere. In arid regions, small amounts of evaporation (5-10%) are sufficient to have a noticeable effect on the isotope ratios of open water bodies. In the areas where TMG crops out, the effect is likely to be smaller. Evaporation enrichment of a water body can be indicated by utilising a plot of δD vs. $\delta^{18}O$. Evaporation produces enrichment gradients of 4 to 6 which are less steep than typical meteoric water lines (gradient 8). Evaporation of standing bodies of water and evapotranspiration from soil at the region of recharge will clearly have an effect on isotope composition of aquifer water.

Applications of isotopes and hydrochemistry in the TMG

Examples are presented where various isotope effects are applied to study aspects of the hydrology of the TMG groundwater.

Altitude effect

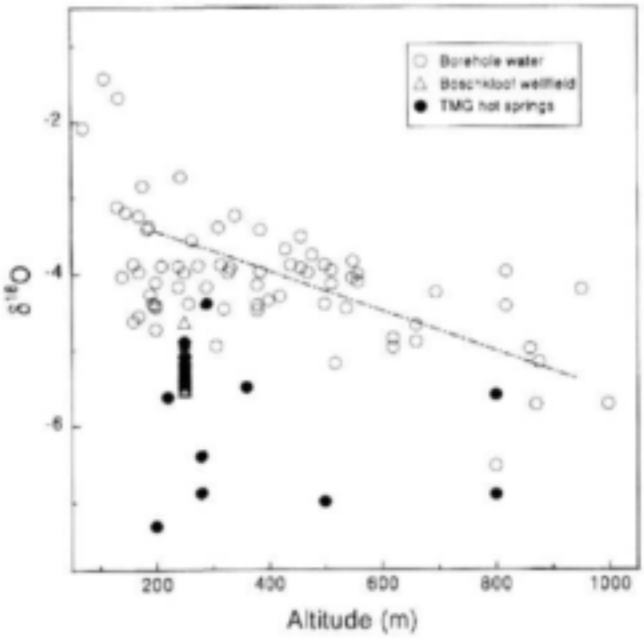


Figure 3

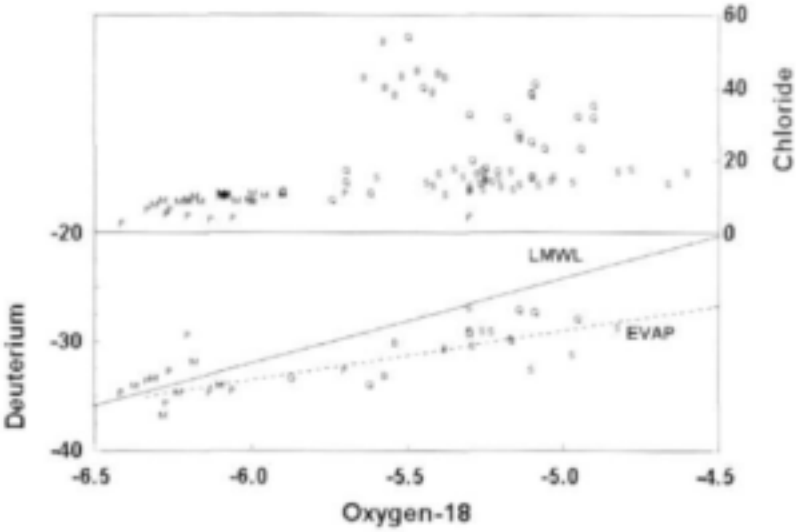
Plot of $\delta^{18}O$ vs. altitude above sea level (metres) for borehole water in the Citrusdal region of the Western Cape (CAGE samples; UMVOTO, unpublished report 2000), including samples from the Boschkloof wellfield. Also plotted are TMG hot springs (data from Diamond and Harris, 2000). The dashed line corresponds to a 'typical' decrease in $\delta^{18}O$ of 0.26‰ per 100 m increase in altitude observed in rain (see text).

The CAGE project (Hartnady and Hay, 2001) produced a large number of oxygen and hydrogen isotope analyses of borehole water associated with the TMG around Citrusdal in the Western Cape (Umvoto, unpublished report, 2000). The $\delta^{18}O$ values of borehole water generally decrease with increasing altitude of occurrence (Fig. 3), but without a strong correlation. Water from the Boschkloof well field has $\delta^{18}O$ (and δD) values which are more negative than expected for its altitude. This is best explained if the Boschkloof water is recharged at higher altitude than typical groundwater in the region and indicates more distant recharge in the nearby mountains.

Hot springs in South Africa are not associated with recent volcanism and their high temperatures (up to 64°C) must therefore be related to the deep circulation of water. The isotope composition of these springs is reviewed by Harris and Diamond (2001). One of the main conclusions is that the thermal springs have systematically lower δD and $\delta^{18}O$ values than expected for ambient meteoric water at the same location (Fig. 3). Caution should be emphasised in the interpretation of these data because most of the springs are found further inland than the Citrusdal area and the continental effect must be taken into account. Nevertheless, one interpretation is that that the springs were recharged at higher altitude than typical cold springs (see Harris and Diamond, 2001).

Figure 4

Relations between $\delta^{18}O$, δD and chloride in the Agter-Witzenberg area (Cave et al., this volume). Precipitation (P), stream water (S), groundwater from the mountain (M), from quartzites (Q) and Bokkeveld shales (B) in the valley are identified. Recharge in the mountains is indicated by the chloride increase between P and M. Evaporation of surface water shows up as isotope and chloride enrichment from P and M towards S. Direct recharge from streams is evident by the isotope similarity and chloride enrichment from S to Q. Mixing of mountain and valley water, and additional chloride solution, is indicated by the relation between B and both M and Q.



Use of evaporation effects

Evaporation enrichment of both deuterium and ^{18}O can be distinguished from local rainfall variations by its departure from the Meteoric Water Line along an Evaporation Line having a slope of 4 to 5. In the Agter-Witzenberg valley the difference between rainfall, direct recharge (same $\delta^{18}O$ and δD, higher Cl than in rain), stream water (higher Cl, $^{18}O/D$ enrichment along the Evaporation Line), the recharge of these two water types and their mixing in boreholes is quite visible (Fig. 4). Even though the isotopic differences are small, they are well enough separated to be useful indicators of different water types. This feature is also useful to trace recharge/leakage from open dams during summer.

Water-rock interaction

Oxygen is the major element present in rocks and, in theory, changes in $\delta^{18}O$ value of water can result from isotope exchange of oxygen between the water and the rocks through which they passed. This is commonly observed in geothermal waters of volcanic regions (e.g. Sheppard, 1986) where the $\delta^{18}O$ value of the water increases as a result of the process. In the case of the TMG hot springs, water/rock interaction is unlikely to take place above about 70°C where mineral-water fractionations are such that any change in $\delta^{18}O$ value would have been to *lower* not higher values with exchanged waters plotting to the left of the meteoric water line on Fig. 1. This is not observed in the TMG hot springs (Harris and Diamond, 2001) and in any case, oxygen isotope exchange at such low temperatures is likely to have been sufficiently slow that water-rock interaction has no effect on isotope ratios of the water.

Carbon is a trace element in groundwater and is, therefore, more susceptible to water/rock interaction. Carbon dioxide is produced in soils by root respiration and decay of plant material. Dissolved in water it becomes the main weathering agent of aquifer rock because of its acidic nature. Where carbonates are available in an aquifer they will rapidly react to raise the pH of the water and increase the alkalinity by the reaction:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$$

Weathering reactions of silicates of various types are slower reactions, of which the following is an example:

$$CaAl_2(SiO_4)_2 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + Al_2O_3 + 2SiO_2$$

Both types of reactions tend to increase the pH, dissolved cation and alkalinity levels and reduce the free CO_2 in the water as the reactions progress. Carbonate weathering, however, introduces additional carbon in the water with a different $\delta^{13}C$ value (usually 0‰) and will tend to increase the ^{13}C content of the dissolved carbon in the water (e.g. Clark and Fritz 1997).

The TMG rocks usually do not contain any carbonates and the silicate weathering reactions therefore dominate the hydrochemical evolution in the groundwater. The ^{13}C content of groundwater therefore remains close to that of the soil produced CO_2; usually around B22 to B18‰ (Talma et al., 1984). This simplifies the use of ^{14}C to calculate water ages since no, or little, provision has to be made for dilution of the original ^{14}C content of water by the addition of non-^{14}C containing carbonates (Weaver et al., 1999).

Palaeotemperatures

Different climatic and flow patterns in the past have the potential of producing different properties in water. The practical use of such studies would be to have some predictive quality as to how hydrological systems are likely to behave during future climatic changes. In fractured rocks where water flow is less predictable and mixing of different water types occurs, such studies are fraught with difficulty.

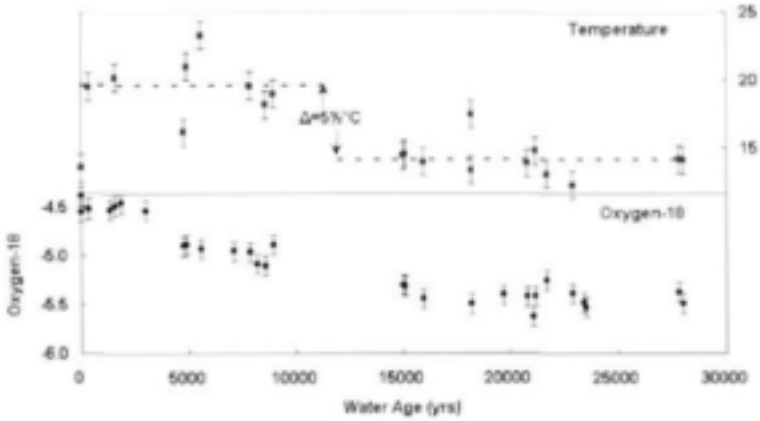


Figure 5

Plot of recharge temperatures calculated from N_2/Ar ratio and $\delta^{18}O$ vs. ^{14}C age for in artesian water of the Uitenhage aquifer (after Heaton et al., 1986).

The Uitenhage Springs near Port Elizabeth are at the head of an artesian aquifer in the TMG. The artesian part of the aquifer is bounded by Uitenhage Group and Bokkeveld sediments on the north and south, and overlain by an aquiclude of Uitenhage sediments having low permeability. The spring is fed from a substantial TMG outcrop in the east and water flows, in a flow restricted manner, towards the sea (Talma et al., 1984). The well-known Amanzi Springs down-dip and various boreholes drilled along a length of 30 km towards the sea, deliver low salinity water that is quite different from that of the overlying sediments. The ^{14}C ages (suitably corrected) indicate progressively greater ages up to 28 000 years. The $\delta^{18}O$ value of the water is 0.6‰ lower for water with ages greater than 15 000 years compared to the present (last 3 000 years) (Fig. 5). These older (Pleistocene) waters showed recharge temperatures (determined from dissolved nitrogen and argon) 5.5°C lower than present (Heaton et al., 1986). Isotope depletion for recharge during the Pleistocene is a common feature in many aquifers worldwide and the palaeotemperatures derived from this aquifer are similar to those found in other mid-latitude areas (Stute and Talma., 1998). This feature can be explained by a longer pathway for atmospheric moisture during colder periods. One can therefore expect similar isotope effects to exist elsewhere in the TMG area. The palaeotemperature effect is however smaller than most altitude effects and was only evident in the Uitenhage artesian water because of its exceptional flow situation.

Dating of groundwater

Groundwater can only be considered to have a 'date', or more correctly an age, when it can be considered to be an artifact that represents a specific recharge event. This might be true in primary aquifers when water is sampled from discrete depths but will, in general, not be the case in fractured rock aquifers such as the TMG. In the Uitenhage artesian situation described above the flow conditions were such that boreholes down gradient of the springs represent segments of the recharge history of the spring water and could be described as single dates.

Recharge determination

The presence of young water is an indication that recharge is occurring at that locality. In fractured rocks this is complicated by the irregular occurrence of water and the difficulty to estimate the water quantities involved. If one considers the aquifer as a phreatic aquifer with surface recharge, and discharge at a lower point, then any of the dating tools (^{14}C, tritium and CFC) can provide a measure of the mean residence time of water (MRT) in the aquifer; expressed as the ratio between aquifer volume and annual recharge amount. A striking example is the study of the Kamanassie mountains near Oudtshoorn (Kotze et al., 2000). In this area groundwater MRT was calculated to be in the order of 1 500 years using the relation (e.g. Verhagen et al., 1991, Gieske, 1995):

$$T=8270*(A_0/A - 1)$$

where A_0 and A are the initial and the measured ^{14}C content of the water. There were ample checks with tritium and CFCs to test the validity of the ages. Using assumed porosity and aquifer sizes enabled a recharge rate to be calculated as annual replacement volumes. The validity of these assumptions will eventually determine the trust that can be placed in the final result. In general it would seem that the accuracy of the dating is not the most critical parameter in this calculation.

Using the chloride content of groundwater in relation to that of rainwater has become an apparently easy and probably fairly trustworthy, method of recharge determination. It requires the chloride content of water in the recharge area aquifer, or at least in the water immediately below the root zone, as well as the long-term mean chloride content of precipitation (Edmunds et al., 1990, Bredenkamp et al., 1995). Being a mass balance approach there are certain assumptions that have to be satisfied i.e. no additional surface Cl input, no soil or aquifer Cl sources, no lateral water flow, etc. (Edmunds et al., 1990). These conditions seem to be satisfied in many TMG Aquifers. The large variation of rainfall amounts in the rugged TMG outcrops and the paucity of rainwater chemistry data are uncertainties that will have to be overcome in this area before this method becomes more widely used. Weaver et al. (1999) have used the chloride technique to estimate recharge amounting to 50% of the mean annual rainfall in the Skurweberg (Fig. 4) where steeply dipping TMG rock provide good opportunities for ample recharge (Cave et al., 2001). Preliminary observations at sites along the southern Cape coast suggest that recharge in excess of 20% may be more generally valid (Weaver and Talma, in preparation).

Mixing of water types

Groundwater collected from a spring or borehole in most fractured rock aquifers represents a mixture of a wide range of recharge events. The tracers used for dating (^{14}C, tritium and CFCs) have different input functions and half-lifes and this will be reflected in the sample mixture. In the Agter-Witzenberg valley it could clearly be shown that some boreholes deliver mixtures of a young (CFC, tritium and bomb-^{14}C containing) water and an older deep-flowing water (Cave et al., 2001, Talma et al., 2000). In this case the separation between young and old water was possible since the contrast between two water types was quite clear (Fig. 6). The features of these mixtures were confirmed by seasonal variations of chemistry and ^{14}C during which chemical and isotope levels indicated mixing ratio variations.

Hydrograph separation

Midgley and Scott (1994) measured the δ^{18}O values of streams from catchments in the Jonkershoek valley. They found that over periods of a few days the isotope values of the run-off do not resemble that of individual rainfall events. Within that time range they estimated that less than 5% of the rain ends up in the streams. This is a general feature emerging when isotopes and chemistry are used to elucidate the analysis of hydrographs in rainfall-runoff studies in other parts of the world (Generaux and Hooper, 1998).

Chemical characteristics of TMG water

The main characteristic of TMG water was formulated by Bond (1946) as the low TDS and high amount of free CO_2. This is also known for the TMG contribution to river water quality (Kirchner, 1994) and is clearly recognisable on the national groundwater map (Simonic, 2001). This feature also maintains the pH at low values and necessitates lime addition to make the water suitable for public use. As described above, it is likely due to the absence of carbonate in the TMG, the low reactivity of the aquifer material and the low plant abundance in most of the TMG outcrops. Smart and Tredoux (2001) have summarised the main chemical characteristics of TMG water.

Two projects at the extreme ends of the TMG outcrops (CAGE in the north-west, Hartnady and Hay, this volume, and Little Karroo in the east, Kotze et al., 2000) are presently analyzing large sets of hydrochemical data from controlled geological localities. Differences between the subdivisions of the TMG are apparent in early versions of the data analysis.

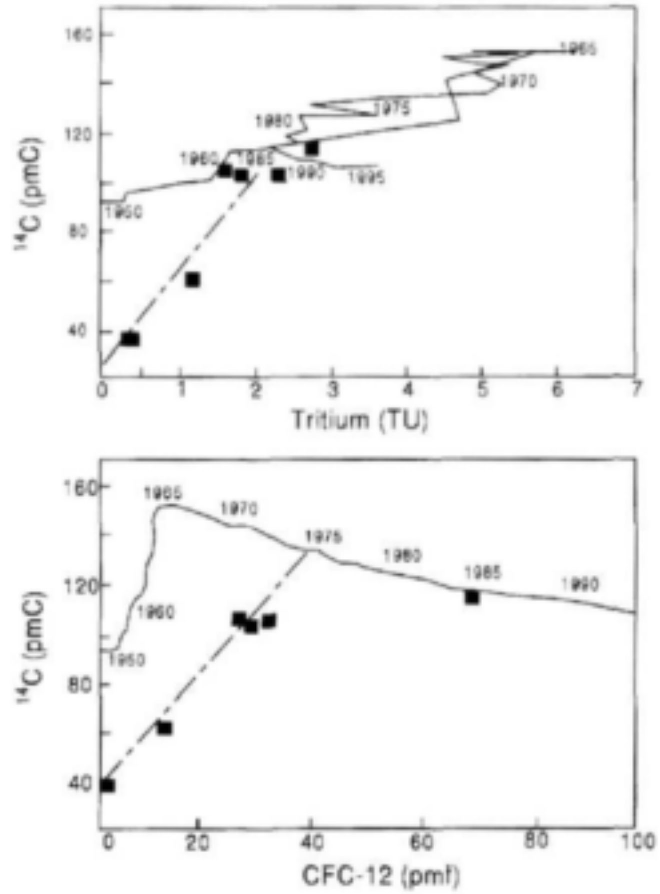


Figure 6

Relations between ^{14}C, tritium and CFC-12 in the Agter-Witzenberg groundwater (Talma et al., 2000). The dashed line indicates the end-members that are the expected relations in the case of piston-flow, i.e. single recharge events. Mixing between two water types is indicated by points between these end-member lines. CFC-12 resolves the younger water better than tritium can. The ^{14}C content of the old end-member indicates a residence time of 9 000 years.

Conclusions and research needs

Recent studies utilising isotope and hydrochemical approaches have certainly yielded new information that is of use to the groundwater explorer. The (so far) limited ^{14}C, CFC and tritium measurements have shown that the TMG can deliver good boreholes with water of surprising great age. This in turn implies that there must be reservoirs of significant size supplying these boreholes. The stable isotope data suggest that recharge is frequently at much higher elevation than where the water is being exploited. If these observations were to hold for the entire TMG, then there must be vast quantities of water that can be usefully exploited once they are properly explored (Weaver and Talma, 2000).

The increased pressure on water resources in the TMG area will inevitably imply that more information will be required in future. There is a need for basic information of the isotope and hydrochemical characteristics of rainfall at various localities in the area. Regular rainfall monitoring is required. The standard method of the IAEA-GNIP programme (IAEA, 1992) consists of daily collection of precipitation samples, and pooling them into monthly composites for isotope analysis. This should be done in some of the more common meteorological stations, but more important in the likely catchments which will help in understanding the extent of the continental and altitude effects.

The great altitude variations in the TMG area imply that much interaction between surface and ground water will occur. Studies similar to that of Cave et al (this volume) in the Agter-Witzenberg Valley should be undertaken in other areas in order to establish whether the flow patterns and inferred great storage capacity in the TMG are found elsewhere. The large area survey of CAGE (Hartnady and Hay, 2001) has shown that similar long-residence time aquifers exist as do they in Agter-Witzenberg and the Little Karroo. These should now be followed up with local studies on the distance scale of 2-10 km to acquire the type of detail that can yield useful water turnover information.

The first attempts to use isotopes in rainfall-runoff studies (Midgley and Scott, 1994) need to be followed up with more detailed work. This will indicate the retention times of water in catchments and are likely to add useful information to the question of how much water is stored in the TMG and what the range of residence times is likely to be.

Acknowledgements

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Interpretation and Applicability of Pumping-tests in Table Mountain Group Aquifers

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Abstract

In general, conventional step-drawdown and constant discharge aquifer-tests are widely used in TMG fractured-rocks aquifers to determine the 'safe yield' of potential production boreholes. Hydraulic properties of the aquifer are often incorrectly determined using conventional analytical methods for analysing flow in porous aquifers, but this information is rarely 'tested' or used for further quantitative analysis (i.e. numerical flow modeling). Very little research has been directed towards improving the testing or interpretative techniques aimed at quantifying the hydraulic characteristics of this fractured-rock aquifer – due mainly to the lack of a plausible conceptual model that adequately describes its geometry and groundwater flow system.*

Introduction

The term aquifer- or pumping-test is used interchangeably by many geohydrologists. Strictly speaking, however, a pumping-test refers to a more rudimentary form of testing, where the objective is to obtain information on the performance and efficiency of the production borehole itself. The results are usually reported in terms of yield, observed drawdown and/or specific capacity, and provide information on the productive capacity of the borehole, efficiency of the screens and for the design of the pump equipment (i.e. pump type and capacity, depth of intake etc.).

On the other hand, although capable of supplying the above information, the hydraulic- or aquifer-test is more a rigorous testing technique aimed at providing information on the water-bearing formation rather than the individual borehole being tested. It involves the use of more sophisticated testing techniques and specialised monitoring boreholes or piezometers. Proper aquifer-testing and data interpretation can yield information on the hydraulic character of the aquifer (transmissivity, storativity etc.), aquitard (leakage factor, hydraulic resistance etc.) and boundary conditions, screen efficiency, optimum pumping rates and the 'safe-yield'* of the borehole. Intuitive analysis of aquifer test data can be used to determine unknown geohydrological information (i.e. depth of major water-bearing fractures) and the effectiveness of borehole rehabilitation procedures.

Various methods of testing are available including slug-injection or -withdrawal tests, multi-rate or step-drawdown and constant discharge tests, including the more sophisticated packer-tests (dual-packer and cross-packer tests etc.). Any combination of the above testing methods may be used depending upon the problem being assessed, including multi-borehole or 'wellfield' tests.

The interpretation of aquifer test data using conventional analytical techniques requires the selection and fitting of a suitable theoretical aquifer model to the observed response of the water levels, using graphical or computer-aided curve-matching techniques. From a historic perspective these techniques originated from the work of Theis (1935). For a detailed description of the more conventional procedures for aquifer-testing and methods of data analysis the reader is referred to Kruseman and de Ridder (1994).

Kruseman and de Ridder (1994) stated that *'the analysis and evaluation of pumping test data is as much an art as a science'*. It is a science because it is based upon theoretical models that the geohydrologist must understand and on thorough field investigations, whilst it is an art in the sense that the intuition and interpretational skills of the practitioner are imperative in obtaining meaningful results, i.e. in the selection of an appropriate theoretical model where different types of aquifers often exhibit similar drawdown behaviour.

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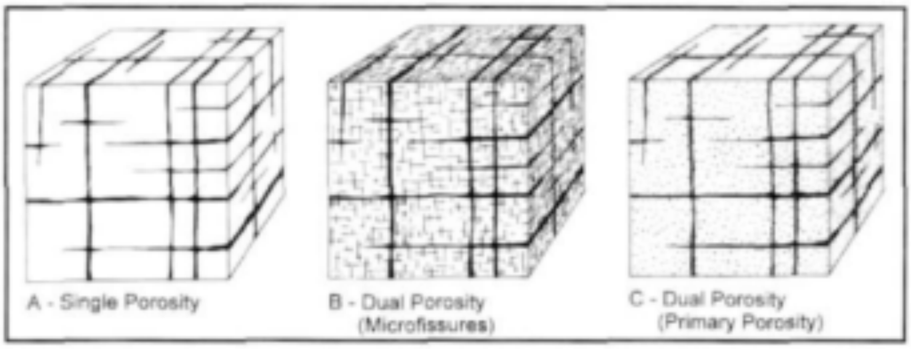
* *For purposes of this paper, safe-yield is simply defined as the maximum rate at which a borehole can be continuously pumped without lowering the water level in the borehole below a prescribed limit (i.e. the postion of the main water-bearing fracture)*



A - Single Porosity

B - Dual Porosity (Microfissures)

C - Dual Porosity (Primary Porosity)

Figure 1
Porosity Systems in Fractured-Rock Aquifers (Kruseman and De Ridder, 1994)

Conceptual framework

From a geohydrological point of view, the Table Mountain Group (TMG) rocks represent a multi-porous medium that essentially consist of two major components, namely: (i) fractures and (ii) inter-fracture 'blocks' or rock matrix. In general, the fractures serve as the more permeable conduits for the rapid movement of groundwater, whilst the matrix blocks form the main storage 'reservoir' which may itself be either permeable or impermeable. In reality, however, the rock mass probably contains many fractures of different scales.

A hardrock aquifer that only consists of discrete, permeable fractures that dissect the rock mass into inter-fracture 'blocks' with little or no fracture permeability is referred as a purely fractured-rock aquifer or single-porosity system (Fig. 1A). Kotze (2000) postulated that the aquifers in the Peninsula Formation of the Little Karoo area are of this type. However, where the inter-fracture blocks are microfractured (Fig. 1B) or have a primary porosity (Fig. 1C), the system is referred to as a porous fractured-rock aquifer or a dual-porosity system. This type of aquifer is characterised by at least two hydraulic subsystems, each having a different scale of inhomogeneity – referred to as the scale effect. Kotze (2000) states that aquifers in the Nardouw Formation of the Little Karoo area exhibit such a dual-porosity response.

TMG rocks are generally considered to form dual-porosity, fractured-rock aquifer systems, where it is difficult to simultaneously quantify the groundwater flow within the fractures and the rock matrix, as well as the hydraulic interaction between these two subsystems.

On the field-scale, one or two approaches may therefore be followed when dealing with fluid movements in such fractured rocks, namely: (a) continuum or (b) discontinuum (discrete) methods.

The continuum approach assumes that the fractured mass is hydraulically equivalent to a porous medium. The obvious advantage of treating fractured rocks as a continuum is that Darcy's Law can be easily applied. If, however, the conditions for a continuum do not exist, the flow must be described in relation to individual fractures or fracture sets. The question of when can a fractured medium be treated within the continuum approach is still a subject of continued research.

If the conditions for a continuum do not exist, the fracture orientation, density, degree of interconnectivity, aperture opening, and smoothness of fractures will need to be quantified in order to characterise the flow of groundwater in such aquifer systems. Secondly, if the apertures are large, the flow may be turbulent rather than laminar, and Darcy's law will also no longer apply. Thirdly, the hydraulic conductivity of the aquifer will vary with changes in the three-dimensional stress-field and the fluid pressure (Domenco and Schwartz, 1990).

If one wishes to apply continuum-based models to regional flow problems, the data employed in such an analysis should be derived from a testing programme that is conducted at a similar scale to that of the regional model. Virtually all the important parameters such as aquifer permeability, storativity and dispersivity are significantly smaller on the laboratory scale than on the field-scale (Domenco and Schwartz, 1990). Whether application of the continuum or discontinuum approach is valid will to a large extent depend upon the scale of the problem, i.e. local or regional flow domination. The information being gathered from relatively localised, short-duration pumping-tests will only be relevant to the local scale problem and the time span over which the test was conducted. In this regard it is important to consider what is an appropriate Representative Elementary Volume (REV) for the TMG aquifer systems. Bear (1972) defined this limit as '*a volume of sufficient size such that there are no longer any significant statistical variations in the value of a particular hydraulic property with the increasing size of the element*'. The practical approach is to test the rock properties over the largest feasible rock volume, although such an approach certainly does not guarantee success. Certain theorists question whether or not a REV actually exists in fractured rocks. They believe that as the scale of testing increases, the scale of heterogeneity expands along with it, i.e. it is fractal. In other words, every portion of rock will contain a few heterogeneities that are not representative of the fracturing found over the rest of the volume. If this is the case then the continuum approach will be of little value for the analysis of groundwater flow in fractured rocks, and flow will have to be described through the individual fractures or fracture sets.

Hydraulic properties and flow in fractures

A striking feature of such fractured-rock aquifers is the spatial variability of their hydraulic properties. A parameter such as the hydraulic conductivity determined by classical field methods normally varies by several orders of magnitude within the same rock unit and often within short distances.

The response of a fractured rock aquifer to pumping is to a large extent dependant upon the degree unto which fractures are interconnected, i.e. if the fractures in an aquifer are well connected then fracture-dominated flow will continue for longer periods prior to the onset of matrix-dominated flow than in the case where the fractures in the aquifer are poorly connected. Hydraulic "boundary" effects are commonly apparent in the drawdown-curves from aquifers where the fractures are not well connected due to the limited spatial extent of the water-bearing fracture(s).

Percolation theory deals with the concept of fracture connectivity (Domenco and Schwartz, 1990). The percolation threshold is defined as the density of fractures that intersect sufficiently to promote fluid flow. Key questions and difficulties remain in identifying the percolation thresholds and obtaining field data on actual 3-dimensional fracture densities.

Quantification of the hydraulic conductivity and storativity of the fractures and the rock matrix are essential for assessing groundwater flow within these aquifer systems, especially when modelling mass and energy transport.

Hydraulic conductivity/Transmissivity

The hydraulic conductivities of fractured-rock aquifers varies considerably and are dependent upon the following fracture properties (Van Tonder and Xu, 1999):

- aperture (spacing between fracture walls),
- frequency or spacing (density),
- length, orientation (random or uniform),
- wall roughness (asperities, including the skin factor),
- presence of filling material,
- fracture connectivity,
- channelling (preferred pathways), and
- porosity and permeability of the rock matrix.

Flow through a smooth-walled, planar fracture (Q_f) is described by the *Cubic Law*, which states that for a given pressure gradient, flow through a fracture is proportional to the cube root of the fracture's aperture.

$$Q_f = K_f \, b \, i \qquad \text{(Eq. 1)}$$

where:

$$K_f = \frac{\rho g \, b^2}{\mu \, 12} \qquad \text{(Eq. 2)}$$

where:

K_f = hydraulic conductivity
b = aperture of fracture
μ = dynamic viscosity
ρ = fluid density
g = gravitational acceleration
i = hydraulic gradient.

It thus follows that aperture width is the most important factor controlling the discrete flow of fluids within interconnected fractures. Maini and Hocking (1977) stated that groundwater flow through a 100 m thick, primary aquifer with a hydraulic conductivity of 0.0086 m/d could also occur through a fracture with an aperture width of only 0.2 mm in a purely fractured-rock aquifer. In general, the hydraulic conductivity of fractured-rock aquifers increase with increasing fracture density, average fracture length, interconnectivity and fracture aperture.

Typically, the transmissivity of an aquifer is derived from the analysis of aquifer-test data rather than the actual hydraulic conductivity and therefore it is useful to derive an equation that relates the hydraulic conductivity (K) to transmissivity (T) in a porous media (Van Tonder and Xu, 1999):

$$T = \rho g b^3 / 12\mu \qquad \text{(Eq. 3)}$$

Fractured-rock aquifers exhibit strong anisotropy mainly imparted by the occurrence of uniformly orientated, parallel sets of fractures and thus flow lines cannot be assumed to be orthogonal to the equipotentials. In general, the degree of anisotropy decreases as the number of fracture sets, fracture density and interconnectivity increases.

Porosity/Storativity

The porosity of a fractured rock mass is extremely difficult to quantify and can be subdivided into two basic components, namely: (i) the fracture and (ii) matrix porosity. Aquifer- and tracer-tests are the only field-based methods currently available for estimating fracture porosity and effective porosity.

The storativity of the highly permeable fractures are usually very low in the order of 10^{-4} to 10^{-7} (Van Tonder and Xu, 1999), whilst that of the matrix is much higher (i.e. 0.005 – 0.05). This implies that the radius of influence of hydraulic-tests can be very large and of an irregular shape, depending upon the geometry, orientation and interconnectivity of the fracture system(s).

The storativity of a pumped fracture is complex and can vary both in time and space as pumping progresses from (i) a confined 'storage coefficient' at the piezometric-level above the fracture at some distance from the abstraction point to (ii) an unconfined 'specific yield' at the level of the dewatered fracture in the production borehole.

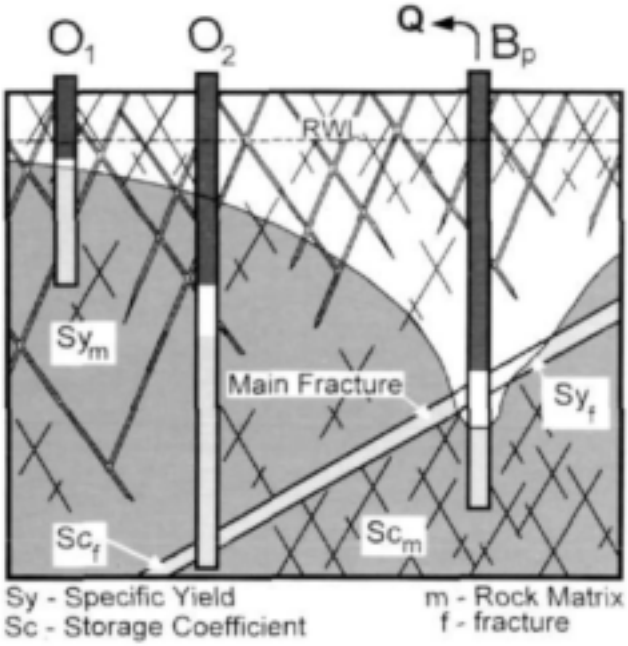


Figure 2

Variable storativity conditions in the vicinity of a production borehole in a fractured-rock aquifer

The various hydraulic conditions that may develop whilst pumping from a fractured-rock aquifer are schematically portrayed in Fig. 2, where a production borehole (B_p) taps a single water-bearing fissure situated in a micro-fractured aquifer matrix. The fissure is confined and commonly has a low storage coefficient ($Sc_f \sim 10^{-6}$) and a high transmissivity. Observation piezometer (O_2) monitors the response of the piezometric level in the fissure during pumping. The matrix is generally unconfined due to fractures opening to the top of the aquifer and therefore it has a high specific yield ($Sy_m \sim 10^{-3}$), although its transmissivity is very low. Observation borehole (O_1) is situated in the matrix and monitors the response of the phreatic- or water-table during abstraction. Deeper-seated micro-fractures associated with the fissure have a low storage coefficient ($Sc_m \sim 10^{-7}$). During the aquifer-test the fissure may become temporally dewatered in the vicinity of the production borehole, which results in the fissure becoming locally unconfined. At this point the storage coefficient of the fracture 'changes' to that of a specific yield (Sy_f). If the fracture is not infilled with secondary minerals, the specific yield of the fracture will be equal to 1 (although the volume is very small) because it can be considered as a void filled with water.

The storage coefficient (S_c) of a fractured-rock aquifer can, if it behaves in a similar manner to that of a confined, porous aquifer, be described as follows (Bear and Verruijt, in Van Tonder and Xu, 1999):

$$S_c = \rho g D(\alpha + n\beta) \qquad \text{(Eq. 4)}$$

On the other hand, the specific yield (Sy) of the fractures is a function of normal stress and can be defined as (Bear and Verruijt, in Van Tonder and Xu, 1999):

$$S_y = \rho g(1/K_n + b\beta) \qquad \text{(Eq. 5)}$$

In this case, the aquifer storativity (S) is the sum of the previous two contributions, namely:

$$S = \rho g[m/K_n + b/K + \beta(nD + b)] \qquad \text{(Eq. 6)}$$

where:

S_c = Storage coefficient (dimensionless)
S_y = Specific yield (dimensionless)
S = Storativity
ρ = Fluid density
g = Gravitational acceleration (ρg=9804 N/m^3)
D = Aquifer thickness
n = Porosity
α = Compressibility of the rock (typically ranging from 10^{-9} to 10^{-11} m^2/N)
β = Compressibility of fluid (β for water is 4.47×10^{-10} m^2/N at 10°C)
K_n = Elastic Bulk Modulus of fracture (pressure/length)
K = Elastic Bulk Modulus of matrix (pressure/length)
m = Number of fractures
b = Sum of fracture apertures.

An aquifers response to pumping is dominated by the elastic bulk modulus of the rock mass and it follows from Eq. 6, that by virtue of aquifers thickness and radius of influence, a scale effect will be observed (Van Tonder and Xu, 1999).

Pump-testing and hydraulic properties of TMG aquifer systems

A coherent conceptual model describing the flow dynamics of the TMG fractured-rock aquifer systems is a prerequisite to developing new or successfully applying existing methods of aquifer-test analysis to obtain accurate and useful information on their hydraulic properties. At present most groundwater practitioners use conventional aquifer-testing techniques and simplistic analytical methods to evaluate the field data, mainly aimed at providing estimates of the 'safe-yield' of the production borehole and information required for the design of the pump equipment (Weaver et al., 1990, Jolly, 1998). The hydraulic parameters calculated are not used in further quantitative analysis, as the reliability of the information is generally doubted.

A 4-stage step-drawdown test is commonly carried out upon a borehole before conducting a 48 h or 72 h constant-discharge and recovery test. The step-drawdown test is used mainly as a 'calibration' test to determine the optimum pumping rate for the ensuing constant discharge (CD) test. Most of the CD pumping tests in South Africa are conducted for

Table 1
Hydraulic Properties obtained from Aquifer-Tests conducted in the Boschkloof Wellfield, Citrusdal (after Hartnady and Hay, 2000)

Bore number	CD rate (ℓ/s)	Transmissivity (m^2/d)				Storativity	
		M-1	M-2	M-3	M-4	M-2	M-3
BK1	27.0	186	180	146	200	4.6E-03	1.2E-03
BK2	15.0	10	9	10	9	1.1E-05	7.0E-04
BK3	10.0	4	6	6	9	1.0E-04	1.0E-03
BK4	28.0	62	60	69	51	3.0E-03	1.0E-03
BK4	47.0	56	61	65	87	2.0E-03	1.2E-03
BK5	8.0	7	6	3	6	8.0E-04	5.0E-04

Note:
M-1 – AQUITEST Software.
M-2 – RPTSolv Software (Verwey, 1995).
M-3 – FC-Method (Drawdown).
M-4 – FC-Method (Recovery).

short durations of less than 48 h, often because of the large expenses associated with longer duration tests. In general, the information from the constant-discharge test is then evaluated using the Theis or Cooper-Jacob Method (Kruseman and De Ridder, 1994) for confined, porous aquifers, where deviations from the type-curve are noted and data extrapolation carried out to determine a 'safe' abstraction rate (Murray, 1996). The water level recovery information is also typically used to determine pumping schedules. Van Tonder and Xu (1998) have developed the Flow Characteristic (FC) Method to provide a first-order estimate of the long-term sustainable yield of a borehole, as well as the hydraulic parameters for both primary and secondary aquifers. The method attempts to ensure that the total abstraction from the aquifer does not exceed the sustainable yield of the aquifer by ensuring that the water level does not drop to the depth of the main water strike. The method is available on an EXCEL spreadsheet and is widely used by geohydrologists in South Africa.

Very little information has been published on the hydraulic properties of the TMG Aquifer systems, especially those derived from aquifer-tests. Typically, transmissivity values are presented in reports but are rarely used for further quantitative geohydrological assessment. The storativity values obtained from conventional analysis of aquifer-tests in TMG rocks are almost never published, as they are regarded to being even less reliable than the calculated transmissivity values.

Hartnady and Hay (2000), however, estimated the regional volumes of groundwater discharging from the TMG Aquifer system in the Citrusdal Valley using a regional aquifer transmissivity of between 100 to 150 m^2/d, obtained from aquifer-tests conducted in the Boschkloof Wellfield (Borehole BK-1 in Table 1) and elsewhere in the valley. They obtained a hydraulic conductivity of 1.4 to 2.5 m/d in the vicinity of the high-yielding (±100 ℓ/s) borehole BK1. Hartnady and Hay (2000) calculated a hydraulic conductivity of 0.5 to 1.0 m/d for the Nardouw aquifer matrix, using Eq. 2 and detailed fracture orientations obtained from down-hole flow-meter, borehole caliper, well imaging and gamma geophysical logging of the 'Boontjieskloof' borehole in the Citrusdal valley. They state that, based upon the results of the aquifer-tests, an *a priori* storativity value of 10^{-3} is reasonable for the deeper, confined portions of TMG Aquifers.

Kotze (2000) used the FC-Method to obtain transmissivity and storativity values from aquifer tests conducted in the Little Karoo area (Table 2). Kotze concluded that the transmissivity of the more highly fractured portions of the Peninsula Aquifer system (i.e. the faulted keystone blocks) varies between 150 to 200 m^2/d, whilst that of the micro-fractured matrix rock is in the order of 10 to 100 m^2/d (average 50 m^2/d).

Kotze states that groundwater flow in the Nardouw aquifer system appears to be dominated by matrix-flow and that the transmissivity of the fractured and more massive rockmass averages 50 and <1 m^2/d, respectively. She adds that the Nardouw rocks have on average a lower density and shorter length of fractures when compared to the Peninsula Formation.

Storativity estimates obtained by conventional analysis of aquifer test data shows a dependency upon the distance of the observation piezometer from the production borehole (Kotze, 2000), which is due to the use of inappropriate analysis techniques (i..e. Cooper-Jacob Method). Therefore, the storativity values obtained using the Cooper-Jacob method are all unrealistically low (Table 2), although reasonable estimates are provided by the FC-Method and are similar to those obtained by Hartnady and Hay (2000) (Table 1).

Table 2
Hydraulic properties of the TMG fractured-rock aquifers in the Little Karoo Area (after Kotze, 2000)

Bore number	CD pump rate (ℓ/s)	SWL (m.bgl)	FC-Method transmissivity (m²/d)		Storativity*	Geological formation
			Early time	Late time		
VR6	15.4^A	46.9	29 (17)	7	1.0×10^{-3} (1.6×10^{-12})	Peninsula
VR7	20.0^A 25.0^B 35.0^B	78.0 63.3 63.3	168 (228) 434 (229) 182 (191)	144 161 39	1.1×10^{-3} (2.7×10^{-7}) 2.2×10^{-3} 2.2×10^{-3}	Peninsula
VR11	8.3^B	125.5	60 (100)	49	1.1 x 10-3	Peninsula
DP28	20.2^A	101.0	265 (216)	10	2.2×10^{-3} (1.8×10^{-6})	Nardouw
DP15	-	90.0^B	66 (86)	43	2.1×10^{-3} (1.7×10^{-6})	Nardouw

Note:
( ) – Cooper-Jacob Method
* – Obtained from late time-drawdown data
SWL – Static-water level
A – Pump test conducted in 1997
B – Pump test conducted in 1990

Kotze (2000) SVF-Method Storativity = 5.5×10^{-3}
Murray (1996): Borehole VR11
Drawdown Late-T = 103 m²/d
Drawdown Early-T = 18 m²/d
Recovery T = 18 m²/d
$S_y = 2.0 \times 10^{-5}$ $S_M = 5.6 \times 10^{-4}$

It is interesting to note that the transmissivity estimates obtained from borehole VR7 vary with pumping rates and static-water levels (Table 2). In 1990, two constant-discharge tests were conducted on borehole VR7 at pump-rates of 25 and 35 ℓ/s under similar water level conditions. A third test was conducted in 1997 at a pumping rate of 20 ℓ/s, by which time the static-water level had declined to the level of the first of two major water-strikes (i.e. 8 ℓ/s at 76-81 m.bgl). The second major water-strike yielded an additional 7 ℓ/s at 129-140 m.bgl. The water level and specific drawdown (Sw/Q) curves from these tests are presented in Fig. 3. Local de-watering of the first water-bearing fracture occurred during all three of the tests. A similar aquifer response is noted in the 1990 test at 25 ℓ/s and the 1997 test at 20 ℓ/s, clearly shown in the Sw/Q curves, although the early T-value obtained from the 1990 test using the FC-Method is somewhat high (Table 2). The 1990 CD-test conducted at a pumping rate of 35 ℓ/s is in excess of the maximum yield of the borehole and hence the sharp decline in water level within the first 100 minutes. The inflection point and flattening of the drawdown curve after 100 minutes may indicate the presence of a significant water-bearing fracture at 101-103 m (the original drill-logs noted fracturing at 99 and 106 m, without an increase in the blow-yield of the borehole).

Step-drawdown tests are extremely useful and complementary procedures that should be included in most aquifer-testing programmes. They provide information on the yield potential of boreholes, the hydraulic efficiency of the screens and near-well aquifer zone or 'skin', effectiveness of borehole rehabilitation procedures and the presence of hydraulic (recharge boundaries) or physical discontinuities (i.e. water-bearing fractures). Kotze (2000) states that borehole efficiencies obtained from step-drawdown tests conducted in the Nardouw rocks of the Little Karoo area are low when compared to those tested in the Peninsula Formation, which she ascribes to the greater abundance of clay-rich layers in the Nardouw Formation and to the oxidising conditions of its groundwater, which leads to increased clogging of screen intakes by slime-forming bacteria.

Mulder (1995) and Jolly (1998) conducted step-drawdown tests on production borehole VR11 in the Vermaaks River Wellfield in 1991 and 1997, respectively. The 1997 test was carried out under lower water level conditions (static water level of 141.7 m.bgl as opposed to 125.5 m.bgl in 1991) and where the 2 ℓ/s yielding fracture at 139 m was de-watered. However, the hydraulic efficiency of the borehole was significantly lower in 1991 when compared to the 1997 test (SW/Q curves in Fig. 4A and B), despite the fact that the fracture at 139 m.bgl was still saturated. This is probably due to the gradual 'development' of the borehole over time after it was commissioned in 1993, whilst the 1991 test was conducted upon an undeveloped borehole directly after completion of the drilling (i.e. where the fractures were probably partially clogged by fine material left from the drilling process).

The 1991 test indicates the presence of the water-bearing fracture at 139 m.bgl, albeit not that apparent in Fig. 4A, by a sharp increase in the water level drawdown at this point. The presence of this fracture is more clearly visible in the drawdown curve of the constant-discharge test (Fig. 5).

The water level at the end of the CD test shows a sharp downward trend, following the localised de-watering of the 139 m fracture, and it is unfortunate that the test was not extended to confirm this trend. However, the step-drawdown tests would tend to indicate that, at this discharge rate, the water level may have 'stabilised' in the short-term above 148 m.bgl (Fig. 4A). The geological log indicates the presence of a fracture at this depth that 'may be water-bearing'.

This illustrates one of the values of a properly executed step-drawdown test wherein the full discharge capacity of the borehole has been tested (i.e. the pumping rate has been gradually increased to draw the water level down to the depth of the last major water-strike). In the case of borehole VR11, the water level was drawn down to the top of the major water-bearing (6 ℓ/s) fracture zone between 183 and 194 m (Fig. 4A). A deeper-seated fracture yielding 2 ℓ/s was intersected at 200 m.bgl.

Less (pers. comm.) used step-drawdown tests to ascertain the effectiveness of the Blended Chemical Heat Treatment (BCHT) and re-construction of production borehole DP10 in the Little Karoo Water Supply Scheme. The borehole was originally equipped with flame-slotted steel casing. The yield of the borehole began to decline over time due to clogging of the casing-slots and near-well fractures by slime-forming bacteria. Initially a 9 step-drawdown test was conducted on the original slotted-steel cased borehole (Fig. 6 – T1). The casing was then removed from the borehole and a second test (T2) carried out upon the open hole. The percentage open-area of the slotted-casing was found to be inadequate for the yield of the borehole and was further reduced by corrosion and clogging of the slots by slime-forming bacteria.

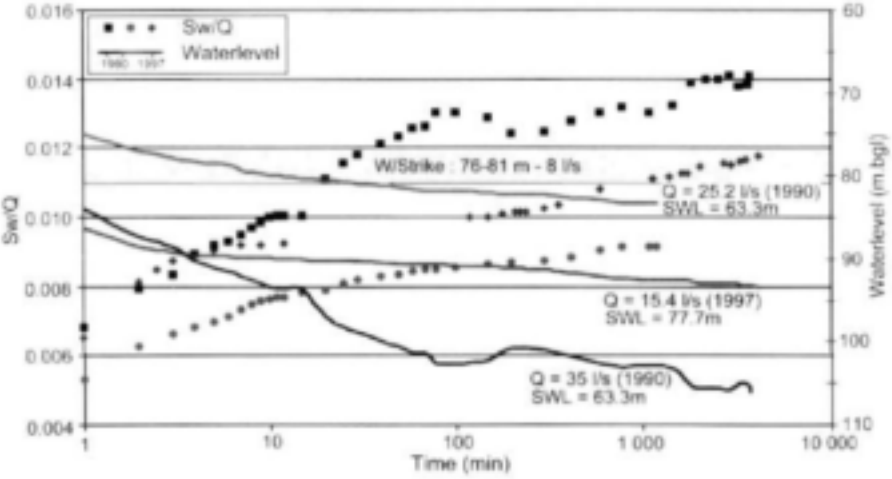


Figure 3

Borehole VR7 - Water level and SW/Q variations during CD-tests conducted in 1990 and 1997

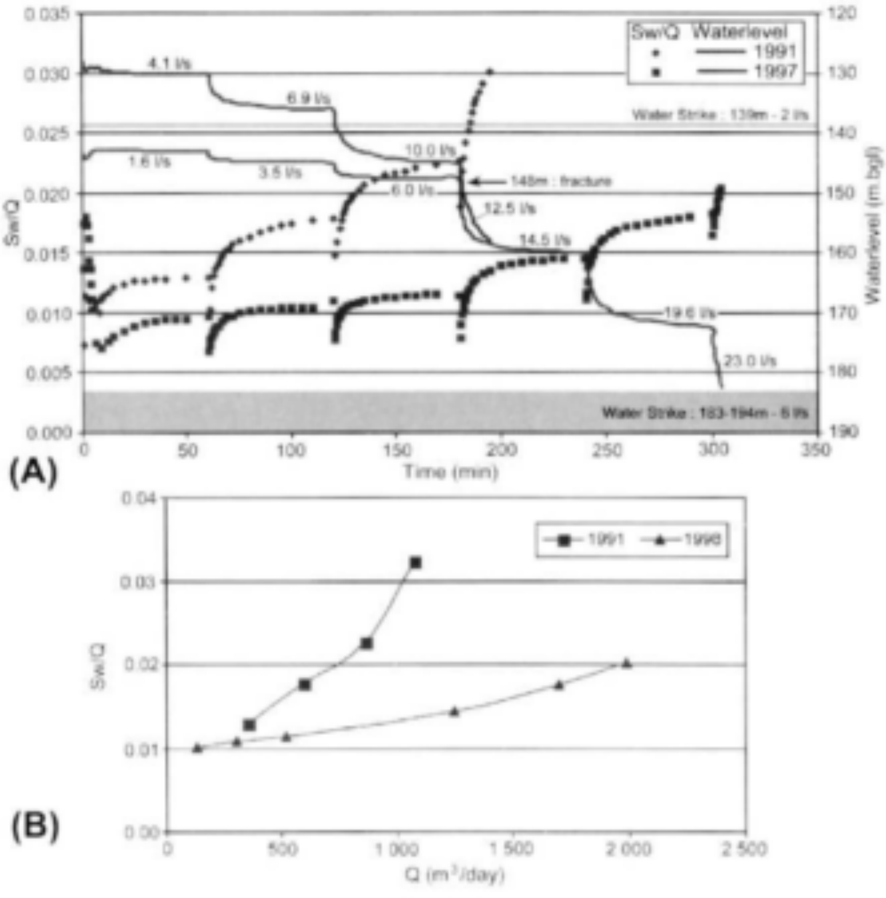


Figure 4

Borehole VR11 - Water level and SW/Q variations during Step-Drawdown Tests conducted in 1991 and 1997

The BCHT borehole rehabilitation method was then applied to the open hole in order to remove the bacterial-slime from the aquifer in the

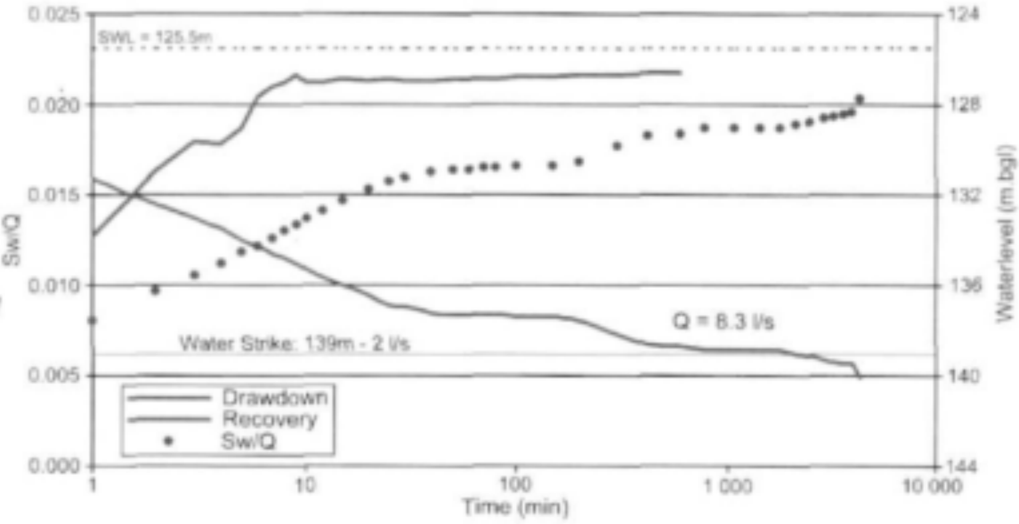


Figure 5
Borehole VR11 - Water level drawdown, recovery and SW/Q variations during a Constant Discharge Test conducted in 1991

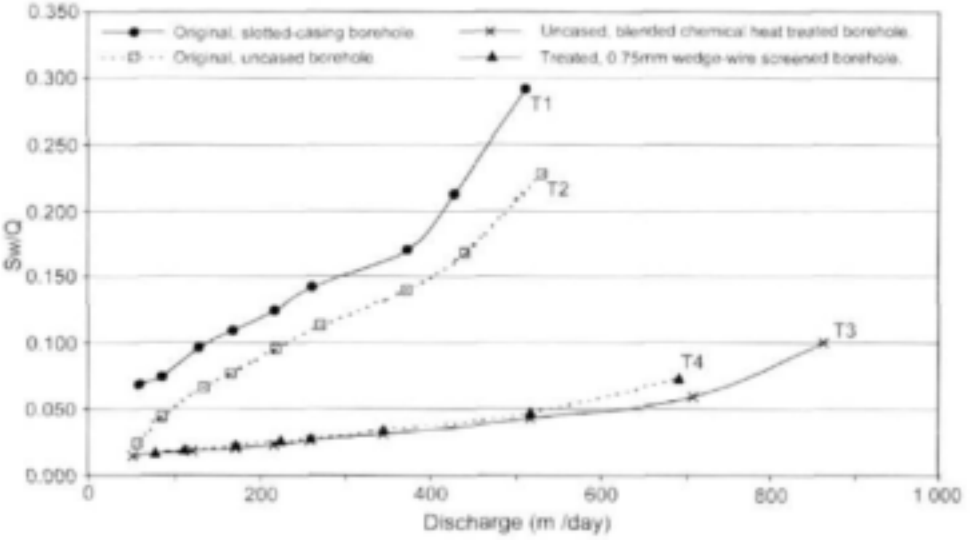


Figure 6
Specific drawdown curves obtained from step-drawdown tests conducted on borehole DP10, Little Karoo Water Supply Scheme

vicinity of the well, where after a third step-drawdown test (T3) was conducted. Stainless-steel wedge-wire, 0.75 mm slot-width screens and solid casing were then installed into the hole and a fourth test (T4) carried out (Fig. 6).

In this case, the 'inflection-points' on curves T1 and T2 at a discharge of 375 m^3/d (Fig. 6) indicates that the pumping rate is higher than the rate of groundwater inflow into the hole due to restrictions caused by clogged, poorly slotted steel casing (T1) and clogged near-well fractures (T2). In the case of curves T3, the 'inflection point' at 700 m^3/d is a reflection of the true maximum yield of the borehole (i.e. related to the transmissivity of the water-bearing fractures).

The step-drawdown tests were used to assess the effectiveness of the rehabilitation process, and they clearly showed that removal of the inefficient flame-slotted steel casing and the BCHT procedure improved the 'efficiency' of borehole DP10 by about 5% and 25%, respectively.

The majority of aquifer-tests conducted in the TMG Aquifers are aimed at obtaining a first-order estimate of the sustainable yield of a production borehole, as well as the design of the pump equipment and abstraction schedule. Various evaluation methods are used by geohydrologists with varied degrees of success. In the following case study, the 'safe-yield' estimates derived from the analyses of aquifer-tests conducted upon production boreholes in Vermaaks River Aquifer Unit of the Little Karoo Rural Water Supply Scheme (LKRWSS) are compared with the actual long-term performance of the wellfield.

Case Study

Little Karoo Rural Water Supply Scheme – borehole 'safe-yields' versus the sustainable yield of the aquifer

The Vermaaks River Groundwater Unit (VRGU) forms part of Little Karoo Rural Water Supply Scheme (LKRWSS) and some 36% of the annual 1.1 x 10^6 m^3

of groundwater abstracted is obtained from the Vermaaks River Wellfield (Jolly, 1998). A number of aquifer-tests have been conducted on the production boreholes in this wellfield over the past 10 years and evaluated in terms of their 'safe-yield' by various geohydrologists. Since being commissioned in 1993, the performance of the Vermaaks River wellfield has been monitored and therefore it provides an ideal opportunity to assess the aquifer-test evaluation techniques used to determine the long-term sustainable yield of the wellfield.

Table 3
Vermaaks River Wellfield – Recommended pumping rates of production boreholes

Borehole number	Recommended pumping rates (ℓ/s)					
	Feb 1993[A]	Nov 1993[A]	Feb 1995[A]	1995[B]	1998[C]	2000[D]
VR6	12 (20)	8 (15)	8 (10)	3.0	-	2.5
VR7	30 (40)	20 (30)	20 (30)	5.0	11 (25)	10
VR8	15 (25)	10 (20)	10 (20)	5.0	-	3
VR11	15 (25)	8 (15)	8 (15)	7.0	6 (10)	3
TOTAL	72 (110)	46 (80)	46 (75)	20.0	17 (35)	18.5

NOTE:
A Mulder (1995)
B Kotze (1995)
C Jolly (1998)
D Kotze (2000)

- *Mulder's February 1993 recommendations are based upon the evaluation of step-drawdown and constant-discharge aquifer-tests conducted in 1990-91.*
- Mulder's November 1993 and 1995 recommendations are based upon the evaluation of the 1990 aquifer-test data and monitoring of groundwater-levels and abstraction.
- Kotze's (1995) recommendations are based upon step-drawdown and constant discharge tests conducted in 1990, as well as the monitoring of groundwater-levels and abstraction.
- Jolly's recommendations are based upon step-drawdown and constant discharge tests conducted in 1997, as well as the monitoring of groundwater-levels and abstraction.
- Kotze's (2000) recommendations are based upon step-drawdown and constant discharge tests conducted in 1990 and 1997, as well as the monitoring of groundwater-levels and abstraction.

The VRGU covers an area of approximately 10.85 km² (Fig. 7) and receives a mean annual precipitation (MAP) of 494 mm. The boundaries of the groundwater unit are assumed to be similar to that of the Vermaaks River catchment, except that it's northwestern boundary is formed by the Cedarberg Shale. The Vermaaks River Wellfield consists of four production boreholes, namely: VR6, VR7, VR8 and VR11, which tap a fractured quartzite aquifer in the Peninsula Formation.

In February 1993, after evaluating the step-drawdown and 72 h constant discharge tests conducted upon the production boreholes in 1990-91, Mulder (1995) estimated the 24 h production potential of the wellfield at 72 ℓ/s – with a peak supply potential of 110 ℓ/s (Table 3). Costly, high-yielding pumps were installed in the production boreholes to meet this expected yield. In November 1993, after only eight months of production, Mulder re-evaluated the pump-test data in conjunction with the abstraction and water level monitoring data and down-scaled the long-term production potential of the wellfield to 40 ℓ/s (peak 80 ℓ/s). This indicates Mulder overestimated the production potential of the wellfield by at least 36% when only using aquifer-test information. In 1995, Kotze (1995) again re-adjusted the supply potential of the wellfield downwards to 20 ℓ/s due to continual declines in water levels in the wellfield, representing a 72% downscaling of Mulder's (1995) original yield estimates.

Jolly (1998) conducted further step-drawdown on boreholes VR6, VR7, VR8 and VR11, as well as 72 h constant-discharge tests on boreholes VR6 and VR7. He recommended that only boreholes VR7 and VR11 should be continuously pumped at a rate of 11 and 6 ℓ/s, respectively, as boreholes VR6, VR7, and VR8 are interconnected with one another. Jolly adds that this combined yield of 17 ℓ/s is a conservative estimate based upon the current water demand only. He also stated that boreholes VR7 and VR11 are capable of yielding up to 25 and 10 ℓ/s, respectively, on a continual basis, which could add an additional 18 ℓ/s to the supply – but added that accurate estimates of the volumes of rainfall recharge and a water-balance calculation were required in order to obtain the long-term sustainable yield of the Vermaaks River aquifer unit. Kotze (2000) conducted such recharge and water-balance studies using 74 months of hydrological monitoring data, as well as a re-evaluation of the 1990 and 1997 aquifer-test data. Kotze estimated that the long-term supply potential of the wellfield is in the order of 8.5 ℓ/s (Table 3), which is similar to that of Jolly (1998).

The gross overestimation of the long-term supply potential of the Vermaaks River wellfield when relying solely upon conventional methods of aquifer-test analysis serves to highlight a problem that is currently being experienced by many groundwater practitioners working in the TMG fractured-rock aquifers and has led some to question the value of such tests.

Table 4
Comparison of sustainable yield estimates obtained from the analysis of aquifer-test and long-term water level and abstraction monitoring in the LKRWSS (after Kotze, 2000).

Bore number (pump rate ℓ/s)	Sustainable yield estimates for production boreholes										
	Aquifer-test analysis								Analysis of long-term monitoring data		
	FC-Method[A]						Theis Method[B] (ℓ/s)				
	1997				1990						
	Yield $_A$ (ℓ/s)	D_A	Yield $_B$ (ℓ/s)	D_B	Yield $_B$ (ℓ/s)	D_B	1990	1997	Equal volume method[C] (ℓ/s)	Recom-mended[D] (ℓ/s)	Maxi-mum[D] (ℓ/s)
VR6 (15.4)	7.4	170	1.4	32	-	-	-	2.4	2.7	2.5	3.5
VR7 (20)	20.0	40	11.2	16	-	-	-	8.9	6.3	10.0	15.0
VR7 (25)	-	-	-	-	10.0	16	8.4	-			
VR7 (35)					4.2	16	5.9	-			
VR8	-	-	-	-	-	-	-	-	2.0	3.0	5.0
VR11 (8.3)	7.1	49	4.1	16	4.1	16	4.0	4.0	2.3	3.0	4.0
Total	34.5		16.7		-		-	15.3	13.3	18.5	27.5
m³/d	2981		1443		-		-	1322	1153	1598	2376

Notes:

A - Flow Characteristic Method (Van Tonder and Xu, 1999), which included consideration of hydrogeological boundaries (advanced solution).

B - Theis Method using the Cooper-Jacob Approximation (Van Tonder and Xu, 1999).

C - Saturated Volume Fluctuation Method (Bredenkamp et al, 1995), using rainfall, abstraction and water level monitoring data for theperiod April 1993 to March 1999 (74 months).

D - Visual interpretation by experienced hydrogeologist of rainfall, abstraction and water level monitoring data for the period April 1993 to March 1999 (74 months).

D_A - Available Drawdown (m) = Rest-Water level – Depth to 1st Major Water-Strike

D_B - Available Drawdown (m) = Rest-Water level – Maximum Drawdown During CD-Test or inflection in drawdown curve.

Table 5
Volumes of groundwater abstracted and water level declines over the period April 1993 to April 1999 (after Kotze, 2000)

Borehole number	Cumulative abstraction (m³)	Change in water level (m)*
VR6	648 151	-15.0
VR7	1 246 235	-20.0
VR8	428 419	-21.5
VR11	482 077	-28.5
TOTAL	2 804 882	-

NOTE:
* - negative values indicate a drop in water level over the period April 1993 to April 1999.

Table 6
Estimated mean, maximum and minimum rainfall recharge to the Vermaaks River Groundwater Unit

Recharge	Units			Recharge rate (% of MAP)
	m³/a	m³/d	ℓ/s	
Mean	206 072	565	6.5	3.8
Maximum	259 675	711	8.2	4.8
Minimum	133 787	367	4.2	2.5

Kotze (2000) re-interpreted the 1990 and 1997 aquifer-test data using the standard Theis method and the 'Flow Characteristic' or FC-Method (Van Tonder and Xu, 1999) and the results are presented in Table 4. The FC-Method is currently being widely used to obtain 'safe-yield' estimates for boreholes tapping fractured-rock aquifers in South Africa. A major problem in applying the method is that the 'safe-yield' obtained is strongly influenced by the 'available-drawdown' input into the programme. The authors suggest that the depth between the static-water level and the main water-yielding fracture be used as the available-drawdown. This may led to an overestimation of the sustainable yield of boreholes situated in TMG Aquifers where discrete, high-yielding, deep-seated fractures are common. The FC-Method provides a combined yield estimate

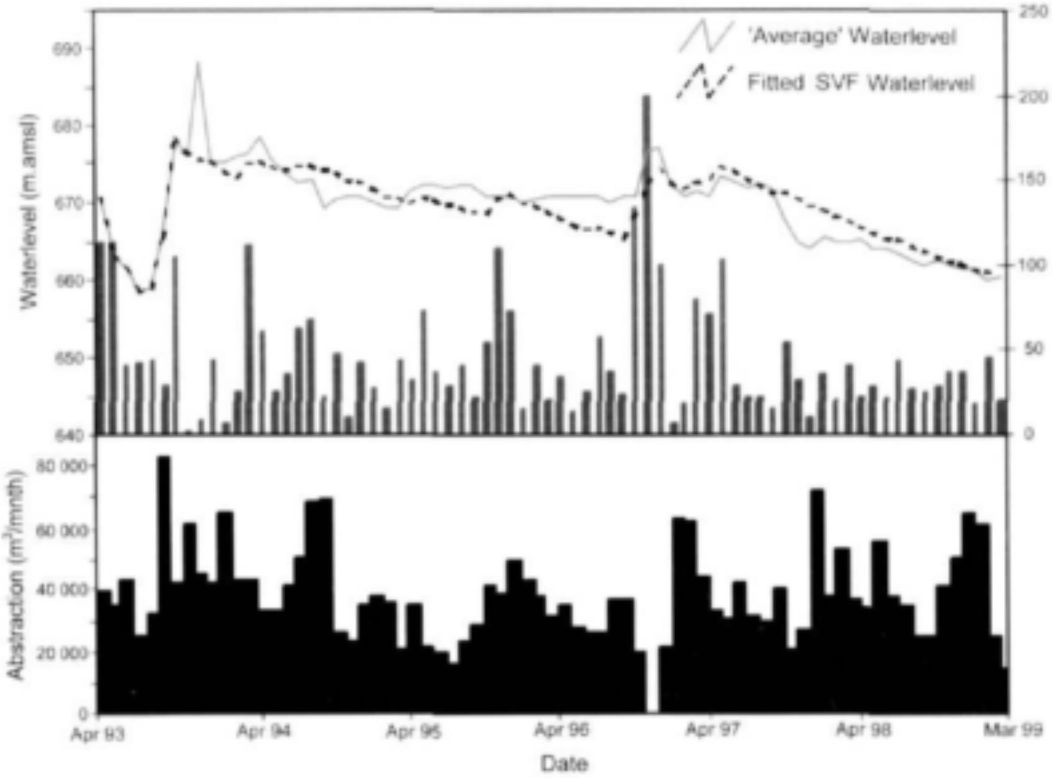


Figure 7

Vermaaks River Wellfield - abstraction, rainfall and water level fluctuations over the period April 1993 to March 1999

of 34.5 ℓ/s for three, namely VR6, VR7 and VR11, of the four production boreholes in the wellfield using this method of determining the available drawdown. The combined sustainable yield of these boreholes drops to 16.7 ℓ/s if the available-drawdown is arbitrarily taken as the difference between the static-water level and the maximum water level drawdown attained at the end of the constant-discharge test, which is similar to the Kotze's (2000) long-term recommended yield of 18.5 ℓ/s for the four production boreholes (Table 4).

In this case, the Theis Method provides a more realistic estimate of the combined sustainable yield (15.3 ℓ/s) of the three production boreholes. Murray (1996) estimated the 'safe-yield' of borehole VR11 at 7.2, 6.9 and 5.6 ℓ/s using the so-called 'Late-T', 'Drawdown-Boundary' and 'Distance-to-Boundary' methods, respectively, assuming an available drawdown of the 183 m. These results are similar to that obtained using the FC-Method where the available drawdown is taken as the saturated thickness above the first major water-strike.

Three constant-discharge tests were conducted on borehole VR7 at varying pumping rates (i.e. 20, 25 and 35 ℓ/s) (Table 4). The FC-Method's 'safe yield' estimates for two of the tests are similar (i.e. 11.2 and 10.0 ℓ/s), whilst the third is 'anomalously' low at 4.2 ℓ/s. This is due to the relatively large drawdown experienced during the 35 ℓ/s CD test in relation to the main water-strike (Fig. 5).

An average of 1 252 m³/d (14.5 ℓ/s) of groundwater was abstracted from the VRGU over the period April 1993 to March 1999. Kotze (2000) estimated that the sustainable yield of the wellfield is in the order of 1598 m³/d (Table 4), based upon the analysis of abstraction, water level and rainfall records - although this abstraction (up to March 1999) led to a substantial decline in the spring flow (Table 5) and water levels (Fig. 7, Table 5), which may suggest that the sustainable yield of the wellfield in even less than Kotze's estimate. The Vermaaks Spring was estimated to be flowing at 860 m³/d or 10 ℓ/s prior to the commencement of pumping. In March 1999, the spring flow was measured at 259 m³/d or 3.0 ℓ/s (Kotze, 2000). The regional water levels in the Vermaaks River aquifer unit have declined by approximately 2m, the area of decline being restricted to within a 1km radius of the production boreholes (Jolly, 1998). Below average rainfall conditions were experienced over this 74-month period (i.e. 2932 and 1890 mm was measured at the Wildebeesvlakte and Dysselsdorp Purification Works' rain gauges). Kotze calculated an annual recharge from rainfall of 452 600 m³ or 1 240 m³/d, assuming a 14% rate of recharge and using the Wildebeesvlakte precipitation data, which is equivalent to the average daily rate of abstraction from the wellfield.

Kotze (2000) used a number of methods to determine the rate of recharge from rainfall and obtained estimates that varied between 13 and 19% of

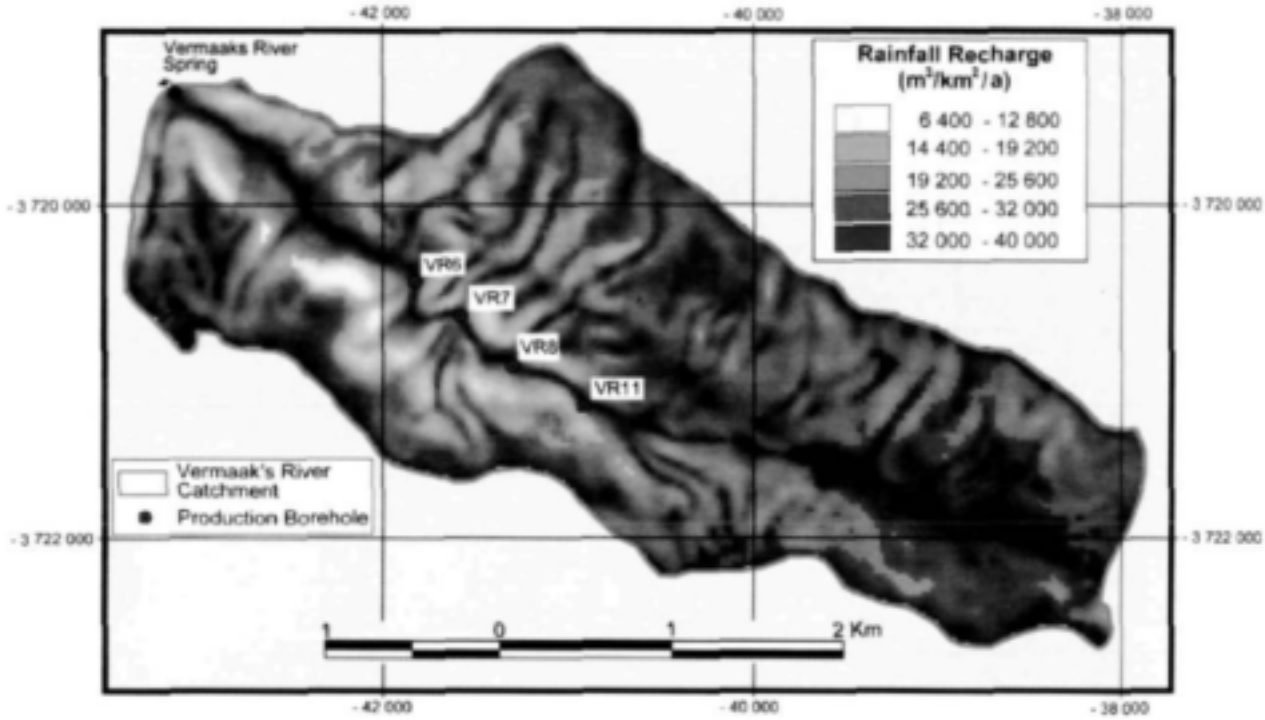


Figure 8

Production Boreholes and Rainfall Recharge to the Vermaaks River Catchment, Klein Karoo Water Supply Scheme

the MAP, i.e. 14.4% for the Cumulative Rainfall Departure or CRD method using a cut-off rainfall of 10mm/month and 16.4% for the Saturated Volume Fluctuation or SVF Method. Similarly Kotze determined a 5% rate of recharge for the adjoining Nardouw Formation aquifer system.

A GIS raster-based approach was adopted to estimate the annual volumes of recharge to the Vermaaks River Groundwater Unit (Fig. 8). The annual volumes of rainfall recharge to this unit were determined using a 25 x 25 m cell-size raster grid of mean annual precipitation and its statistical coefficient of variation (Schulze, 1997), as well as terrain slope (Table 6). It is likely that the present wellfield will intercept the majority of this recharge, given the size and geometry of the catchment, and placement of the production boreholes along faults in the narrow valley floor. These estimates are considered to be conservative and are substantially lower than Kotze's (2000) value of 452 600 m³/a, partly due to the fact that she used a smaller catchment area (6.5 km²) and a higher rate of recharge rate (14%). The annual rainfall recharge is thus estimated to vary between 250 000 (7.9 ℓ/s) and 450 000 m³ (14.3 ℓ/s) – the upper limit of which is accepted as the sustainable yield of the aquifer unit under normal rainfall conditions (i.e. limit at which no long-term 'mining' of the aquifer occurs).

If the estimates of the 'safe yield' of the wellfield obtained from the analysis of aquifer-test data (Tables 3 and 4) are compared to the results obtained from other methods that make use of the long-term hydrogeological and climatological monitoring information in the Vermaaks River Aquifer Unit (Table 4 and 6), it is apparent that the former tend to overestimate the actual exploitation potential of the aquifer system. This is especially true of the earlier wellfield 'safe-yield' estimates obtained from the conventional analysis of aquifer-test information alone, which resulted in an overestimation of about 400%. Recent more practical methods of analysing aquifer-tests in fractured-rock aquifers (Van Tonder and Xu, 1998; Murray 1996) tend to produce more realistic estimates of the sustainable yield of a borehole (25%). The testing of individual boreholes within a wellfield or aquifer unit does not take into account the interference effects of other production boreholes and thus simply summing the 'safe-yield' estimates obtained from such analyses will obviously result in an overestimation of the supply potential.

Conclusion and future research needs

Fractures strongly influence the movement of fluid through a rock formation. Conventional well-flow equations, developed primarily for homogeneous aquifers, therefore do not adequately describe flow in fractured rocks. In recent years, many theoretical fracture-flow models have been developed. These models are often complex due to the complex mechanisms of fluid flow in fractured rocks. The choice of the correct theoretical model is a crucial step in the correct interpretation of aquifer-tests. If the model chosen is incorrect, then the hydraulic parameters calculated will also not be correct. A troublesome fact is that some models, developed for different aquifer systems, respond similarly to a given pumping regime.

In general, conventional step-drawdown and constant discharge aquifer-tests are widely used in TMG Aquifers to determine the 'safe yield' of potential production boreholes. Hydraulic properties of the aquifer are often incorrectly determined using conventional analytical methods for analysing flow in porous aquifers, but this information is rarely 'tested' or used for further quantitative analysis (i.e. numerical flow modeling). Very little research has been directed towards improving the testing or interpretative techniques aimed at quantifying the hydraulic characteristics of this fractured-rock aquifer – due mainly to the lack of a plausible conceptual model that adequately describes its geometry and groundwater flow system.

Recently a number of practical methods of aquifer-test analysis have been developed locally and are aimed at estimating the 'safe yield' of a borehole. These techniques are widely used by groundwater practitioners and, if applied correctly, can produce reasonable results. However, subjective judgment is required and therefore the results obtained are ultimately dependant upon the skills of the interpreter. There is also an abundance of 'user-friendly' software packages available for the interpretation of aquifer-test data that operate in a 'black-box' fashion and where the results are simply accepted as being correct. This may lead geohydrologists to not fully evaluate the available geohydrological information and/or to the 'loss' of many of the skills of aquifer-test interpretation.

Due to the above problems it is often commented that '*conventional aquifer tests in TMG Aquifers are of little practical value, when compared to the costs incurred*', even when the aim is to simply assess the 'safe yield' of a borehole. The role of the aquifer-test must however be viewed in its proper perspective, where it is just one of the many 'tools' available to the geohydrologist to gain information on the physical characteristics of the aquifer system and the borehole itself. The limitations of the aquifer-testing procedures and analysis techniques adopted needs to be fully understood. The individual test results themselves only represent localised sources of information within the greater aquifer unit. It is therefore imperative that the results obtained from such tests be integrated into or collaborated using other methods that take into account the spatial and temporal variability of the aquifer system (i.e. interference of production boreholes, boundary conditions, aquifer recharge etc.). This is normally carried out using numerical flow models or, if sufficient information is not available, via some form of simplistic water-balance study.

In order to improve the aquifer-testing and analysis techniques and thereby the understanding of the flow dynamics of the TMG aquifer systems, the following research is required:

- Formulation of a more coherent conceptual understanding of the TMG aquifer systems on both the local and regional scale, i.e. aquifer geometry, flow dynamics (vertical versus horizontal flow, shallow versus deep groundwater circulation), hydro-chemistry, definition of hydro-stratigraphic units and their geohydrological characteristics etc.
- Collation and evaluation of existing aquifer-test information from selected geological units and at various geographic locations (i.e. according to pre-defined structural domains, stratigraphic units etc.) within the TMG outcrop area, as well as an assessment of the techniques currently available for data analysis. Characterization of the hydraulic properties of TMG aquifer systems.
- Quantification of regional flow systems using this information in numerical models, especially in areas where historical groundwater abstraction and hydrological monitoring data are available.
- Use of innovative and specialised aquifer-testing procedures (i.e. dual- or cross-packer techniques) and observation piezometers to isolate and test specific water-bearing fracture-zones. Other tools such as down-the-hole geophysical logging techniques (i.e. flow measurements) will aid in defining the important water-bearing fractures. These techniques will also be of use in assessing deep-seated aquifers in the TMG rocks.

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Identification of Targets for Drilling in Table Mountain Group Aquifers

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Abstract

The Table Mountain Group (TMG) comprises a >2 000 m thick sequence of sedimentary rocks ranging from orthoquartzite to arkose, conglomerate and shale. It comprises eight formations and outcrops over an area extending from Vanrhynsdorp to Cape Hangklip to Port Elizabeth.

The Peninsula Formation appears to be the best target for drilling, while the Graafwater, Pakhuis and Cedarberg Formations are aquitards at best.

Targets for drilling in the TMG range from regional scale fault systems or hydrotects to bedding plane openings.

Drilling depths of up to 250 m or more are warranted in suitable areas.

A sound understanding of the structural geology of an area is a prerequisite for successful borehole siting, as is air photo interpretation. Geophysical techniques are often of limited use in this respect.

Introduction

The TMG comprises rocks ranging from orthoquartzites to quartzose shales. This thick succession of sediments was deposited on the continental margin, the "Cape Trough". Subsequent to deposition they were subjected to low-grade metamorphism, essentially only lithification due to compaction, which has resulted in there being no primary porosity. Also because of the low grade of metamorphism, the minerals are stable and secondary porosity created by chemical weathering, such as found in granites, is not encountered. Thus, groundwater is found in secondary openings created during fracturing, faulting and folding. Consequently, to locate successful boreholes in the TMG, one has to site a borehole which will encounter an open fracture and of course which is filled with water.

There are other minor occurences of groundwater which are briefly mentioned. Weathering of the TMG produces a coarse grained sand. This is seldom more than a few metres thick and rarely over 10 m. When this is thick, areally extensive and the local geomorphology is suitable, it can produce sustainable boreholes. An example is Botrivier, where the sand is up 28 m thick and yields ranges from 0.5 to 2 ℓ/s.

The second occurrence is where thick piles of weathered and transported TMG material occur. Although not strictly TMG, they are mentioned because the existence of these aquifers is directly related to TMG geomorphology. These are the alluvial fans and river channel deposits. The Hex River Valley has both types of aquifers and high yields are obtained from boreholes in these deposits. Locally these can be very important aquifers.

Target formations

At the broadest level of target identification, and where the choice is available, there is the difference in groundwater potential between the various formations of the TMG to consider. The Graafwater Formation and Pakhuis/Cedarberg Formation are classified as aquitards at best and so the choice comes down to the Piekenierskloof Formation, Peninsula Formation and Nardouw Subgroup.

Piekenierskloof Formation

In the western outcrop area of the N-S limb of the Cape Fold Belt, the choice of drilling targets is between the Piekenierskloof and Peninsula Formations (PF). The former wedges out just south of Porterville and also changes from a rudaceous lithology in the north to more arenaceous in the south.

Umvoto-SRK (1998, 2000) class the Piekenierskloof Formation as an aquifer and, from yield distribution data presented, there is little difference in potential between this formation and the PF. However, this is based on existing farmers' boreholes. The PF is >1 000 m thick compared to ~100 m for the Piekenierskloof Formation and the former would be the preferable target for large-scale groundwater abstraction.

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In a water supply project for Lamberts Bay, Maclear (1998) sited two of the three wellfield production boreholes on the contact between a dolerite dyke and conglomeratic sandstone of the Piekenierskloof Formation at Wadrif. Sustainable yields (7 – 12 ℓ/s) of fresh to moderately saline groundwater were achieved with testing, indicating this type of drilling target to be favourable in TMG Aquifers. However, they are of fairly localised occurrence.

Peninsula formation

This thick pile of orthoquartzite is a prime target for drilling, although the thickness varies. For example at Table Mountain, it is 575 m thick, whereas in the Hottentots Holland Mountains, 50 km to the east, it is 1 200 m thick. As this is an orthoquartzite with virtually no argillaceous zones, fractures are open to great depths. Access for drill-rigs is usually quite difficult and is often via the Cedarberg Formation band and then into smaller kloofs leading off at right angles giving access to the upper zone of the PF. These kloofs are often fracture controlled and thus are drilling sites.

In the CAGE area (Umvoto-SRK) the confined Peninsula Aquifer is seen as the best target for increased groundwater exploitation, with many tens of metres of drawdown available above the confining Cedarberg Formation.

In the Citrusdal area Umvoto (*op. cit.*) recognised large-scale structural features in the PF, termed hydrotects, which largely control groundwater movement. These mainly trend NW-SE and are deep-seated features. They are interconnected with a shallower intensively fractured zone which is present over most of the area. The main aquifer in this area is the Peninsula Aquifer.

Nardouw formation

On visual appearance this formation has the promise of producing high-yielding boreholes. The quartzite weathers to produce a rough topography, colloquially often termed "Skurweberg" (translated as Rough Mountain), with weirdly-shaped bare rocks, many gullys and cracks exposed in the bare rock surfaces. However, drilling results are usually quite disappointing and, whereas water is usually obtained, yields are often low.

If given the opportunity, boreholes should rather be located in the underlying PF or the Lower Bokkeveld. For example, borehole siting for a farmer in the Citrusdal Valley some 13 km north of Citrusdal resulted in six low yielding boreholes in the Nardouw or in the Cedarberg (dry). Three additional boreholes were sited on prominent fractures in the Nardouw, again with indifferent yields. A fourth borehole was sited on the only access point into the PF at a point which appeared on the orthophoto to be a minor fracture. The borehole was high-yielding with an air-lift over 25 ℓ/s (Weaver, pers. comm.).

At St Francis-on-Sea, the main aquifer is the Nardouw Subgroup, which consists of thinly bedded sandstones dipping at ~ 45°,while the PF is more massively bedded. Even though the Nardouw Subgroup is covered by up to 40 m of superficial deposits and boreholes were sited randomly, a high success rate was obtained. Out of 15 boreholes drilled, only one was a failure and the rest gave yields of 2 to 15 ℓ/s. The main target feature here is bedding plane openings.

In the Hex River Valley a similar situation exists. The Nardouw Subgroup of the Hex River Mountains is dipping at ~45° to the south-east and bedding plane openings are again the main groundwater bearing features.

The Ceres municipal wellfield (50 ℓ/s) was developed on NW-SE trending fractures in the Nardouw Subgroup. This is a dominant trend of major faults and fractures in the Cape Fold Belt between Ceres and Vredendal.

Comparison between the Peninsula and Nardouw Aquifers

In the Klein Karoo area, significant differences in hydrogeologic characteristics occur between the Nardouw and Peninsula Aquifers in the absence of permeable aquizones, which may connect the two.

The Peninsula Aquifer usually outcrops at higher altitudes and is separated from the Nardouw by the Cedarberg Formation. These are the so-called TMG window areas. They receive more rainfall and snow and therefore more direct recharge. Groundwater flow paths and residence times are shorter, providing low EC/TDS groundwater. On the contrary, the Nardouw Aquifer receives less direct recharge and groundwater travelling via cross-cutting fractures from the Peninsula Aquifer has longer travel-times and therefore higher EC/TDS.

The Peninsula Aquifer has a lower shale content and is much more fractured than the Nardouw and the flow system is therefore more dynamic, i.e. more active flow circulation and recharge and less blocking of permeabilities from the products of shale weathering. The highest yielding boreholes (10 ℓ/s to > 20 ℓ/s) with the best quality groundwater are found in the Peninsula Aquifer of TMG window Areas on WNW, N-S, NNE and E-W trending fractures.

Lower Bokkeveld Formation

In many areas, this group of three shale and three quartzite units is quite heavily exploited with high yields being obtained from individual boreholes. Successful boreholes are sited so that 50-100 m of shale is drilled and then a quartzite band intersected.

In the Agter-Witzenberg Valley there are over 100 boreholes in this unit. The Nardouw is accessible but is not drilled because, although "water is usually intersected, yields are low and not worth the effort" (quote by a local farmer). During the Agter-Witzenberg project (Weaver et al., 1997;

Cave et al., 2001) one borehole was drilled into the Gamka Formation quartzite band. The airlift yield was about 25 ℓ/s and is currently being used by the farmer to irrigate 15 ha. About 1 km to the north-west is a borehole in the Hex River Formation, which is pumped continuously at ~18 ℓ/s for 8 months/annum. In the Ceres district (Rosewarne, 2001)) these quartzite bands are extensively exploited.

Access for a drilling rig is easy because the shales produce good quality soils which are extensively planted, especially to orchards and vineyards. This is a double benefit because the water is close to the point of consumption.

Another drilling target is the contact zone of the bottom shale band, the Gydo Formation, with the underlying Nardouw Subgroup quartzites. The differing properties of the shale and quartzite results in fracturing at the contact. During the Agter-Witzenberg project, a borehole was drilled specifically to obtain groundwater from this zone and had an air-lift yield of ~7 ℓ/s. At a farm development site some 31 km west of Touwsrivier on the Ceres road, four boreholes sited on an anticline of Nardouw quartzite plunging under the shales produced yields ranging from 3 to 6 ℓ/s (Weaver, pers. comm.).

Target features

Joubert (1970) was probably the first person to publish a paper identifying the TMG as an important regional aquifer. In terms of targets for drilling, he wrote, "Successful siting of boreholes in the Table Mountain sandstone depends on the recognition of a favourable fracture system which acts as both porosity reservoir and local high permeability zone.... In particular, is one fracture set of very constant orientation, striking east-west and dipping near-vertical to the south."

Specific target features within the various formations include the following:

- Major regional fault systems extending over tens of kilometres, termed Hydrotects by Umvoto (*op. cit.*). These are formed by major crustal deformation and drilling depths of 250 m or more are required to obtain optimum results.
- More localised fractures/faults associated with folding and other local stress fields.
- Bedding planes. These are important in the more thinly bedded Nardouw subgroup, particularly in the Hex River Valley and at St Francis-on-Sea (Rosewarne, 2001).

In regional flow systems such as at Citrusdal and the Kamanassie Mountains, groundwater recharge, movement and occurrence is related to a complex system comprising all of the above features.

Although the TMG has favourable groundwater potential, both quantitatively and qualitatively, some adverse features include:

- Hydraulic conductivity inhibiting material such as breccia, mylonite and iron and manganese oxides can render fractures less effective as groundwater conduits.
- Much of the TMG outcrop area is mountainous and inaccessible for direct groundwater exploitation.

Borehole siting methods

Air-photo and satellite image interpretation is an essential pre-requisite to identify target features. Having identified the various fractures one has to determine which are the more likely to be open and conversely which are likely to be closed. For a particular area determine/obtain the local stress field and choose to drill the fractures which parallel the tension direction and not the compression. If folding is present, then the axis of anticlines and synclines are drilling targets.

Quartzite horizons below shale are often good prospects. Detailed field mapping to determine the angle of dip and surface contact outcrop is needed so that 50 to 100 m of shale is drilled before intersecting the quartzite. Joubert (*op. cit.*) considered that magnetometer surveys were of particular use in picking up ferruginised breccia zones.

Geophysical methods have some limited application in the TMG and this is discussed in greater detail in this volume (Fraser and Quinton, 2001). Electromagnetic (EM) traverses may be useful to delineate fractures. The theory of magnetometer geophysics indicate that this method has no application in the TMG. Resistivity soundings (Schlumberger array) can be useful especially if used to eliminate very high resistivity response sites as being likely to be solid rock. However one must always take into account when evaluating the data that the very low salinity TMG groundwater will also have a high resistivity.

Conclusions

The following conclusions can be drawn from this case study:

- The Piekenierskloof, Peninsula and Nardouw formations are all classed as aquifers but the Peninsula Formation appears to be the most favourable for high yielding boreholes.
- The Graafwater, Pakhuis and Cedarberg Formations are all aquitards at best.
- Target features range from regional scale hydrotects extending over tens of kilometres to bedding planes. Drilling depths of 250 m or more are required to obtain optimum yields from the former features.
- A sound understanding of the structural geology of an area is required for successful borehole sitting, allied to air-photograph interpretation. Geophysics is of limited use.

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Fracture System and Attribute Studies in Table Mountain Group Groundwater Target Generation

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Abstract

The Table Mountain Group (TMG) hosts extensive stratabound aquifers with little or no primary porosity. Consequently the application of fractured-rock hydraulic concepts, developed mainly in the context of petroleum reservoirs and nuclear waste disposal, is important for TMG groundwater resource-targeting purposes. The permeability of the thickest hydrostratigraphic unit (Peninsula Aquifer) is controlled primarily by hydrotects, *large-scale structural features (major fault zones and master joints) that transect the discontinuous bedding plane fractures. The overlying Pakhuis-Cedarberg Meso-aquitard is an effective confining unit separating the Peninsula from the overlying Nardouw aquifers. Bedding-plane discontinuities along thin shale and mudstone layers are prevalent in the Nardouw, so that smaller-scale fracture sets tend to be limited within the thicker fractured quartzites of the Skurweberg Subaquifer, and permeability across bedding structures is reduced relative to permeability in the plane of bedding. The Peninsula versus Nardouw contrasts require varied approaches to field data collection and well-field targeting in different parts of the TMG. In future, 3D groundwater flow models based on fractured-rock methodology will also play a role in TMG target generation.*

Introduction

After a field trip that included visiting the first high-yielding artesian borehole[1] purposefully targeted at the deeper groundwater in the Peninsula Aquifer, the eminent Israeli hydrogeologist, Prof. Arie S. Issar, advised DWAF in July 1995 as follows:

> "It can be foreseen that the drilling of deep wells, of a diameter big enough to enable the pumpage of large quantities of water is going to play an important role in the future development of the water resources of the [R]epublic of South Africa. As this requires special investments in equipment and know how, it can be justified only if it involves a rather large number of wells" (Issar, 1995, p. 5).

More specifically with reference to the Western Cape Province, he also noted (*op. cit.*, p. 33):

> "... [T]here are many observations which speak for the conclusion that ... the TM[G] is a regional aquifer extending to big depths, in which the water is flowing along the deep fracture and fault systems.
>
> "As this semi-arid region is in the need of water, and most probably the solution sought will be in the direction of building a new dam, it is suggested to consider the possibility of launching a regional hydrogeological research project for this region ... The hydrogeological survey will be followed by a few deep exploration-exploitation wells along major fault lines, the results of which will be incorporated in a regional hydrological physical-mathematical model. ...".

Hydrotect concept

During hydrocensus surveys, structural interpretation, and borehole siting undertaken for private land owners and the municipality of Citrusdal (Umvoto, 1995), the "Boschkloof Fault" was identified as part of a wider system of NW/SE-striking 'first-order "megafault" structures' (*op. cit.*, p. 6-7). To emphasise the link between structural geology and groundwater flow, the term "hydrotect" was defined as "a distinct planar or linear tectonic feature - such as a fracture, a fault, a line of intersection between planar structures, or a fold closure - which is characterised by a ... permeability that is greater by orders of magnitude relative to the surrounding country-rock matrix" (*op. cit.*, p. 7).

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[1] The "TK-E1" well with a starting diameter of 12 "was drilled to a depth of 250 m at Tharakamma in the upper Olifants River area, about 40 km south of Citrusdal. It has an artesian flow of ~5 *ℓ*/s. The water has a temperature of 23.7°C.

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A wider review of the groundwater resources in the Olifants/Doring catchment (Umvoto, 1997, p. 10-14) considered that "an understanding of structural controls on groundwater movement is fundamental to appreciating the groundwater potential of the area". It concluded that:

"(1) The groundwater in the TMG Aquifers circulates freely to great depths in the upper crust of the Cape Fold Belt.

"(2) It can be tapped to surface in large volumes from depths at which conventional hydrogeological theory declares the hydraulic conductivity of fractured rock to be reduced due to lithostatic (i.e., rock overburden) pressure by 3-4 orders of magnitude, from ca. 10^{-5} m/s to 10^{-8}-10^{-9} m/s ...".

Geological factors related to "either or both of the contemporary ("neotectonic") crustal stress regime and the modern geothermal gradient" were cited as the probable reasons for suppression of the usual pressure effect on permeability, and it was noted that "[n]either of these aspects of Western Cape geology is well studied and thoroughly understood" (*op. cit.*, p. 12). Presently, it is still true that almost no pertinent data on crustal stress or geothermal gradient exists which would guide future hydrogeological exploration and sophisticated flow-modelling in the TMG terrains.

Some further elaboration of the original hydrotect definition is now appropriate. In hydrocarbon exploration within tectonically deformed, fractured-rock reservoirs, it is commonly observed that the fine-grained, friction-generated "gouge" along the principal displacement surface is an effective "fault seal" (Antonelli and Aydin, 1994; Main et al., 2000), i.e. an aquitard feature that is quite impermeable to fluid migration across the fault zone. Instead, the main pathways of relatively high permeability are the marginal "process zones" on either side of the main fault-plane. Initial propagation or later re-activation of the main fracture plane produces diffuse, fault-parallel volumes of subsidiary structural damage (micro-faulting and intense jointing), especially where the fault surface undergoes bends or "jogs". In the majority of cases, these potential flow-paths around even the largest fault zones become sealed by crack closure when the driving stresses are relaxed or re-orientated, and/or clogged by mineral re-precipitation during hydrothermal activity.

Successful target generation for the siting and drilling of deep boreholes, whether in the Peninsula Aquifer or the aquifers of the Nardouw Subgroup, is fundamentally dependent upon the accurate definition and field mapping of regional hydrotects traversing the TMG terrain. In our opinion, the *hydrotect* concept remains a valid exploration hypothesis applicable throughout the Western Cape, having particular reference to structural features providing possible "preferred flow paths" for deep circulation at all scales - local, catchment, or WMA.

Exploration in fractured sedimentary rock

Natural fracture systems fall into a range of geometrical types between two end-member systems, with important consequences for fluid flow and transport, which are presently not fully understood (Odling et al., 1999). In 'stratabound' systems, fractures are confined to single layers, their size distribution is limited and spacing tends to be regular. In 'non-stratabound' systems, fractures are laterally persistent, size ranges are broad, often power-law (Bour and Davy, 1997), and spacing-clustered. On the regional scale larger than that of individual well-field or waste-disposal sites, connectivity within the aquifer is enhanced by fracture sets at high angles, having broad length distributions (Balberg et al., 1991; Berkowitz et al., 2000).

Fracture-system geometries, and fluid-flow characteristics, are controlled by the mechanical nature of the rock mass (Aarseth et al., 1997). Until recently, studies into flow and contaminant transport largely concentrated on localised volumes within fractured crystalline rocks, motivated by the potential for hazardous waste disposal in such lithologies (Herbert et al., 1992; Clauser, 1992; Wittwer et al., 1994). These non-stratabound rocks are commonly isotropic in their mechanical properties and their fracture systems are often assumed to be isotropic. The host rocks are largely assumed to be impermeable and commonly only flow and transport within the fracture system is considered.

In sedimentary or low-grade metasedimentary rocks, the nature of layering has a major influence on the fracture-flow geometry. Un- or semi-consolidated sedimentary rocks have significant porosity and permeability, so that both the rock matrix and the fractures control flow and contaminant transport. Recent numerical studies (Odling and Roden, 1997) have shown that fractures in permeable rocks, even where unconnected, can have significant effects, especially on contaminant transport.

TMG Aquifers

The TMG (Table 1) is dominated by metasedimentary quartzites, which in the absence of well calibrated physical measurements are assumed to have little or no primary porosity at great depth below the near-surface weathered and fractured zone. Groundwater recharge and deep subsurface flow is controlled by secondary fracturing that has developed along the primary sedimentary bedding and also along fault and multiple joint systems at various angles to the bedding.

Within the TMG hydrostratigraphy the Piekenierskloof Aquifer has limited geographic distribution in the far north-western part of the basin, and is generally poorly exposed within coastal plain outliers surrounded by younger sediments. The Pakhuis-Cedarberg Meso-aquitard constitutes an important confining layer between the two main aquifers (Table 1).

Table 1
Proposed Coincident Hydrostratigraphical Units of the TMG (Hex River Mountains to Cederberg area)

Superunits	Units	Subunits
	Gydo Mega-aquitard	
Table Mountain Superaquifer	Nardouw Aquifer	Rietvlei Subaquifer Verlorenvalley Mini-aquitard Skurweberg Subaquifer Goudini Meso-aquitard
	Pakhuis-Cedarberg Meso-aquitard	
	Peninsula Aquifer	(no subunits)
	Graafwater Meso-aquitard	
	Piekenierskloof Aquifer	(subunits not yet identified)
	Saldanian Aquiclude	

Peninsula Aquifer

Where bedding does not impose a strong mechanical control, non-stratabound fracture systems develop in which fractures are less regularly spaced and length distributions are broad, usually following a power law. The nature of the fracture connectivity, and thus fluid flow, in these systems varies with the exponent of the power law, and may be dominated by either small or large fractures (Bour and Davy, 1997; Odling, 1997a,b).

The Peninsula Aquifer presents an interesting case in the spectrum of sedimentary fracture networks. Although well bedded, these rocks are compositionally quite monotonous, and the bedding planes tend to be rough and discontinuous, particularly where large-scale trough cross-bedding prevails. Joint systems within the Peninsula quartzites generally cut continuously across bedding, and tend to be less regular in length and spacing characteristics. Because they are rarely infilled by shaly partings, the bedding plane fractures within the Peninsula aquifer tend to remain open and permeable.

Nardouw Aquifer

Formations of the Nardouw Subgroup (Table 1) are generally well-bedded rocks with mechanical discontinuities at bedding planes, e.g. shale partings. Characteristically, they develop strata-bound fracture systems where the fractures are restricted to single beds with regular spacing and have a limited length distribution. In these systems, flow can be largely confined to individual beds, and thus permeability perpendicular to bedding is low.

The Goudini Formation, in particular, has a transitional contact with the underlying Cedarberg shales, contains frequent mudstone-siltstone interbeds of a generally ferruginous character, and is therefore generally disregarded as a aquifer target (Table 1). Within the upper Nardouw, the narrow (~15 m), carbonaceous shale-bearing Verlorenvalley Member is found, at least locally, to be an effective aquitard between the Skurweberg and Rietvlei subaquifers. In general, only the Skurweberg Subaquifer has sufficient overall thickness and massive thick-bedded zones to support large-scale groundwater abstraction.

Structural data collection for target generation

In the CAGE study, the size-frequency distribution of TMG-hosted fractures, mapped using the same methods at different scales, i.e. 1:100 000 (Landsat imagery) and 1:30 000 (SPOT) imagery), were analysed and compared. While the TMG fractures at these scales broadly follow power-law distributions, the controlling parameters of power law length distribution exponent a, the fractal dimension D and the fracture density (Berkowitz et al., 2000) are not yet fully elaborated for the TMG. There are deviations at the large-fracture tail of the distribution (i.e., individual fracture lengths of order ~10 km) that could have significant implications for large-scale fracture connectivity between recharge and discharge provinces. Furthermore, the full Landsat and SPOT data sets have not yet been separately grouped and geostatistically analysed for the different TMG Aquifers.

In the past, studies of the mass hydraulic properties of fractured rock have largely concentrated on the scale of tens of metres, where outcrop and tunnel observations and well-test data are relatively easy to obtain. However, in recent years it has become increasingly recognised that the scaling properties of fracture systems over a much wider size range are important (Heffer and Bevan, 1990; Yielding et al., 1992; Odling, 1997b).

After a general target zone has been selected on the basis of a regional understanding of the flow regime, recharge patterns, etc., detailed structural information is required from satellite and aerial photograph interpretation, as well as from direct field observation and measurement at the outcrop scale, before candidate borehole target sites can be prioritised. Practical matters such as drilling budget constraints that would limit the depth to be drilled, the required yield, and licensing constraints, inter alia, would also determine the data to be collected. Thereafter tectonic factors that impact on permeability and fracture connectivity over a range of scales need to be established.

The contribution of fractures (faults and joints) to the permeability of fractured, sandstone aquifers depends on:

- the nature of the fractures themselves, i.e. aperture, roughness, presence/absence of mineralisation or fault gouge, preferred flow channels; and
- the nature of the fracture system as a whole, i.e. orientation and length distributions, geometry, connectivity (Odling, 1997a).

The observable factors that impact on the above were implicitly defined by Gates (1997) in a permeability-related index for fractured bedrock formations - the hydro-potential (HP) value – that depends on six fracture characteristics:

- rock quality designation (RQD);
- joint number (Jn);
- joint roughness (Jr);
- joint hydraulic conductivity (Jk);
- joint aperture factor (Jaf;) and
- joint water factor (Jw).

The first two characteristics, RQD and Jn, describe the structure of the rock mass. The final characteristic - Jw - simply indicates the presence of water within the rock mass. The remaining three characteristics - Jr, Jk and Jaf - form a quotient that describes the "fluid flow resistance of the rock mass".

The "joint hydraulic conductivity" (Jk) factor relates to the presence or absence of joint mineralisation. In the HP scheme, the highest score is assigned on the criterion "90% joints open, clean, excellent flow", and an average hydraulic conductivity equal to 0.5 m/s is postulated for this condition (Gates, 1997, Table 5). Partially developed mineral fillings can prop fractures open and solution of carbonate cement in the country rock (or silica in the case of the TMG "prseudo-karst") can lead to high permeability channels within fracture planes and along fracture intersections (Daccord, 1987; Dreybrodt, 1989). On the other hand, mineral filling and development of fault gouge can seal fractures against flow (e.g. Antonellini and Aydin, 1994; Main et al., 2000).

Aperture size (involved in the Jaf factor) and shape are extremely important factors affecting the flow characteristics of a fracture, as the volumetric flow rate through smooth-walled fractures is a function of the aperture-size cubed. Aperture sizes measured on surface outcrop exposures will provide an estimate of the maximum width of fracture apertures in the subsurface bedrock. With increased depth below surface, the increasing lithostatic pressure normal to a joint plane results in reduced apertures. Normal pressure results in an increase in the contact area and flow channelisation (Tsang and Tsang, 1989). Joints can, however, remain open to flow at depths of several kilometres (Krans et al., 1979; Leary, 1991; Huenges et al., 1997).

On the outcrop scale, the semi-quantitative HP method of rock-mass classification around hydrogeological target sites forces the novice investigator to look closely at the rock mass near the proposed well sites. (An experienced structural geologist with hydrogeological insight might perform an intuitive HP calculation at the outcrop.) However, if HP-values are overtly measured and then combined with correlation curves relating known yields to HP at particular sites, they potentially provide a useful tool to predict target well yields in comparable terrain conditions.

In the TMG terrains both the bedding stratification and the fault and fracture structures may dip at variable angles between the ground surface. In many instances, the accurate extrapolation of structural data in the vertical dimension to depths >200 m is not a trivial problem, requiring the use of stereographic constructions and balanced geological cross-sections at a relatively large scale.

Groundwater flow modelling in TMG exploration

In the CAGE project a reconnaissance application of fracture-descriptive techniques was used to investigate large-scale flow in an exceptionally thick and extensive fractured sedimentary aquifer. At present, emphasis is laid on the gathering of essential field data on a very large scale, required for construction of a generalised, EPM-type, regional hydrogeological model. These investigations aim to consider the role of both fractures and matrix in storing and transporting fluid.

Numerical modeling has been in the past a powerful tool for evaluating the impact of fractures on groundwater flow and contaminant transport around problematic waste-disposal or other kinds of development site. Rarely, if ever has it been used as a groundwater-resources exploration tool. Discrete fracture-flow models that explicitly include fractures and their properties are currently important theoretical research tools (Long and Billaux, 1987; Herbert et al., 1992; Odling and Webman, 1991; Odling and Roden, 1997), and have the potential to become even more important as practical tools in the development and management of fractured-rock aquifer schemes.

At scales larger than that of the borehole or local well-field, however, a discrete fracture model is impractical and an equivalent porous medium (EPM) approach (Neuman, 1987; Hestir and Long, 1990) is required for quantitative understanding of the hydrogeological boundary and recharge-discharge conditions. The scale at which EPM approaches become valid depends on the fracture system geometry (stratabound or non-stratabound). These models are, however, only valid for flow, and much larger volumes must be considered for transport properties.

In future, more detailed numerical models, that explicitly include fracture patterns and properties, should be used to develop down- and up-scaling techniques so that the influence of fractures on fluid transport can be properly represented in large-domain or aquifer-scale models. Such models will be useful in establishing preferred targets for well field development where the natural head distribution in the aquifer favours the potential for large-scale abstraction.

Conclusion

Groundwater flow is strongly influenced by subsurface heterogeneities, among which fractures represent a major factor. Fractures are common throughout the upper earth's crust, and it is increasingly recognised that they play a significant role in many aquifers, even where fractures were not previously thought important. Variable fracture density, extent, and connectivity combine with differing matrix porosity and bedding characteristics to increase aquifer heterogeneity and the uncertainty in predicting aquifer properties.

Thus in any hydrogeological study in the TMG be it for borehole siting or other reasons, it is necessary to obtain a certain level of insight into and understanding of the fracture systems at a variety of scales in the proposed study area and for the different TMG Aquifers before any field based study is designed or embarked upon.

One of the outstanding tasks of quantitative TMG hydrogeology is to develop groundwater flow model systems that are physically representative of those in stratabound fractured rock aquifers, using as input the characterisation of the different types of fracture and bedding patterns in the real-world aquifers as a guide.

Within the TMG Aquifer system, scale and degree of connectivity need to be considered both in the target selection, depth to be drilled, pump test design as well as the management strategy of the aquifer.

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Part 5:

Resource Evaluation and Management

Recharge of Table Mountain Group Aquifer Systems

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Abstract

No comprehensive investigation of recharge of Table Mountain Group (TMG) aquifer systems has been undertaken. This has resulted in little quantified information being available with which to assess the sustainable rate at which groundwater can be abstracted. Historically, the rate of recharge was expressed as a percentage of mean annual precipitation, but the basis for such rates is not known. Recent attempts to quantify recharge using a variety of methods indicate recharge rates may be higher than previously considered. Recharge ranges from about 5% MAP in drier areas to in excess of 20% MAP in higher lying areas that receive an annual rainfall of greater than 600 mm/a. Rates of 35% MAP can be considered in those areas that receive more than 1 000 mm of rainfall each year. These rates are supported by analysis of baseflow from mountainous TMG catchments. A proper research programme, however, is required to quantify recharge of TMG aquifer systems under a range of conditions. Such a programme needs to be supported by long-term monitoring of groundwater levels, abstraction and springflow.

Introduction

It is somewhat surprising that no comprehensive investigation of recharge of TMG aquifer systems has yet been undertaken. Recharge is generally considered the most important factor governing the volume of groundwater that can be abstracted sustainably from an aquifer system over the long term. Absence of quantified information on recharge of TMG aquifer systems, therefore, is regarded as a major limitation to our current understanding of how these systems function and their exploitation potential.

This paper identifies key factors that control recharge of TMG aquifer systems and methods that can be used for the quantification thereof. The result of an informal survey of expert opinion is presented while the results from five case studies that attempted to quantify recharge are also documented. An assessment of current knowledge of recharge of TMG aquifer systems is presented and a number of research priorities identified.

Factors governing recharge

Lerner et al. (1990) defined recharge as 'the downward flow of water reaching the water table (or piezometric surface), forming an addition to the groundwater reservoir'. The recharge process includes most elements of the hydrological system. Inter-related factors that govern the frequency and extent of recharge of TMG aquifer systems include:

- rainfall (depth, duration, intensity);
- snowmelt;
- topography and altitude;
- lithology;
- depth and type of soil cover;
- vegetation type and density;
- fracture density, orientation and geometry;
- antecedent moisture conditions;
- depth to groundwater;
- regional groundwater flow patterns; and
- existing groundwater abstraction.

It is well recognised recharge is driven by single or multiple events and not annual averages. This is particularly true in arid and semi-arid environments. Recharge estimation is thus prone to the fallacy of averaging. This needs to be taken into account when trying to quantify recharge and manage groundwater resources.

Because of a lack of knowledge about recharge processes and the difficulty of modeling such complex processes, the quantification is often expressed as a percentage of mean annual precipitation (% MAP). Such an approach is useful in that it allows comparison with mean annual run-off (MAR) and mean annual evaporation (MAE).

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Recharge quantification methods

Using monitored groundwater level data, it is relatively simple to show recharge occurs throughout the TMG Aquifer system. Quantification thereof, however, is difficult. No single comprehensive estimation technique has been identified which can model recharge without yielding suspect results. This is true for most fractured aquifer systems. The availability of a number of different independent techniques, however, does furnish the opportunity to compare results and develop an integrated approach (Parsons, 1994; Van Tonder and Xu, 2000). Bredenkamp et al. (1995) propose an average of estimates of recharge, obtained using a range of methods, be used to quantify recharge in a particular area.

Historically, most practitioners have had to rely on an estimate of the percentage of rainfall that recharges TMG aquifer systems. Often the basis of the percentage used was not known. It is possible estimates were based on Enslin (1970) who stated recharge of fractured rock aquifers in South Africa ranged between 3.5 and 8% MAP.

More recently, a number of hydrogeological studies have been undertaken where workers attempted to estimate recharge using a variety of methods (Maclear, 1996; Rosewarne and Kotze, 1996; Weaver et al., 1999; Hartnady and Hay, 2000; Kotze, 2000; Kotze et al., 2000). Methods used include:

- the cumulative rainfall departure (CRD) method;
- the saturated volume fluctuation (SVF) method;
- the chloride mass balance (CMB) method;
- the C-14 method;
- the baseflow method (which provides an estimate of minimum recharge);
- catchment mass balance models; and
- groundwater flow models.

These methods are described in detail by Kirchner et al. (1991), Gickse (1992), Bredenkamp et al. (1995) and Van Tonder and Xu (2000). Each method has advantages and disadvantages. However, lack of suitable data is often a prime reason why recharge is not quantified.

It is beyond the scope of this paper to assess the most applicable methods for quantifying recharge. Further, the method used is generally governed by available data. However, it is proposed that, as a general rule, those methods based on direct measurement of groundwater levels, springflow and river flow should be preferred. Those methods where groundwater is calculated as a residual should be avoided as the quantification of evapotranspiration remains problematic. Small errors in the quantification of evapotranspiration and run-off in water balance models, for example, can have significant impact on the resultant quantification of recharge (Parsons, 1994; Bredenkamp et al., 1995). Direct measurement of levels and flows allows for a degree of verification and validation.

Bredenkamp et al. (1995) proposed, that for large time intervals, recharge conforms to simple relationships. To be able to establish these relationships, good long-term monitored data sets are required. This includes monitoring of groundwater levels, abstraction, springflow and rainfall. Lack of monitored data is identified as a key limitation in the quantification of recharge of TMG aquifer systems.

Expert opinion

Van Tonder and Xu (2000) included expert opinion as a legitimate method of quantifying recharge estimation. As a result, an informal telephone survey was undertaken to determine what practitioners estimated recharge of TMG Aquifers to be (Table 1). Participants were first asked what key factors controlled recharge of TMG Aquifers. Because rainfall was almost invariably identified as one of the key factors, participants were then asked to provide an estimate of recharge (expressed as %MAP) for three categories of rainfall. Results of the survey indicate recharge can be assumed to equate to about 5% MAP in drier areas and about 11% MAP in those areas that experience annual rainfalls between 300 and 600 mm/a. In higher rainfall areas, and particularly in the higher lying mountainous areas where the fractured rock is not covered by soil and snow melt may play an important role, it was estimated recharge exceeds 20% MAP.

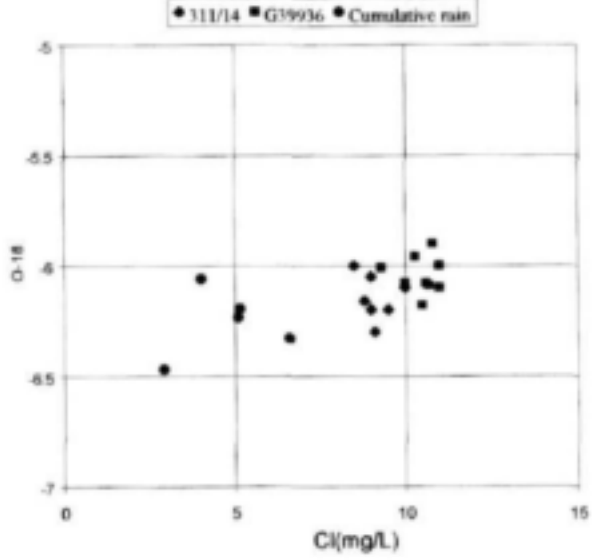
Case studies

Preamble

In the absence of a comprehensive study of recharge of TMG aquifer systems, results from a series of recent case studies in which attempts were made to quantify recharge of TMG Aquifers are briefly summarised below. These case studies made use of a wide range of methods. Readers are referred to the original work for more detail and explanation of the techniques used.

Table 1
Result of the survey of estimates of recharge of TMG aquifer systems

Parameter	Rainfall (mm/a)		
	0 – 300	300 – 600	600+
Harmonic mean (%MAP)	4.9	11.2	20.6
Average (%MAP)	7.1	12.9	22.4
Respondents (n)	8	9	11
Minimum (%MAP)	2	6	12
Maximum (%MAP)	15	25	43



(Weaver et al., 1999)

Figure 1

Data used at Agter-Witzenberg to estimate recharge

Agter-Witzenberg research project

Recharge estimation was an issue addressed by Weaver et al. (1999) and Weaver and Talma (2000) during their research of the Agter-Witzenberg area. They used hydrochemical and isotope time-series data to gain insight into recharge of TMG Aquifers and evaluate the hydrogeological resources of the area. The Agter-Witzenberg Valley is a synclinal structural feature where mountains comprise TMG quartzite and sandstone and the central part of the valley comprises shale of the Bokkeveld Group which conformably overlie the TMG. The valley sides dip inward at 30° or more. No major faulting has occurred, but fracturing due to the folding is present. A transect of boreholes was drilled from the top of the access pass toward the center of the valley which allowed groundwater to be sampled at various levels in the aquifer. The transect also allowed groundwater to be sampled at various distances from the recharge area. Recharge occurs in the Witzenberg and Skurweberg mountains which attain heights in excess of 1 800 masl. Mean annual rainfall in the valley amounts to 890 mm/a, most of which falls in the winter months between May and October. Significantly higher rainfall is expected in the mountainous areas. However, no real difference was observed by Weaver et al. (1999) in rainfall collectors in the valley and that in the mountain pass.

Chloride and $\delta^{18}O$ measured in five cumulative rain samplers was compared to groundwater from a borehole in the mountain recharge zone (Fig. 1). Using the chloride mass balance method, potential recharge was estimated to be in the order of 45% MAP. Figure 1 indicates the concentration of chloride in rain is 4.3 mg/ℓ while that in groundwater ranged between 9.4 and 10.6 mg/ℓ. The slight shift of $\delta^{18}O$ from rain to groundwater is probably the result of evaporation.

CAGE project

Recharge to TMG Aquifers was estimated by Hartnady and Hay (2000) as part of the Cape Artesian Groundwater Exploration (CAGE) project carried out on behalf of DWAF. Using a GIS-based approach, recharge in the E10 catchment containing the upper reaches of the Olifants River was estimated using the following balance:

$$I = P - (E + R)$$

where:

I = recharge or infiltration
P = precipitation
E = evaporation
R = surface water run-off

Using a series of data sets and corrections, each component was determined and recorded as a spatial data set. A high resolution (30 x 30 m) digital terrain model of the study area formed the basis of the recharge model. MAP was found to vary between 162 and 1 410 mm/a across the catchment. Actual MAE losses were modelled at a lower resolution (500 x 500 m). Losses varied between 36% and 99% of MAP. The surface water run-off model was based on Midgeley et al. (1994), but included local slope analysis from which the MAR spatial coverage was generated. Mean annual infiltration was then modeled by subtracting MAE and MAR from the MAP.

It was found infiltration ranged between zero and 57% MAP. Low estimates of infiltration were obtained in low lying areas which experience low rainfall and have a relatively thick soil cover. Higher estimates were found in the mountainous parts of the study area comprising rocks of the Peninsula Formation. In these areas rainfall exceeds 600 mm/a and the fractured rocks are exposed. Infiltration in excess of 50% MAP was restricted to the highest parts of the catchment and covered a small area. Modeled infiltration generally fell within the range of between 30 and 40% MAP.

It is interesting to note areas indicated by Hartnady and Hay (2000) to have a high infiltration rates are adjacent to the Agter-Witzenberg valley where Weaver et al. (1999) obtained estimates of recharge in excess of commonly accepted limits.

Hermanus area

Rosewarne and Kotze (1996) estimated recharge of TMG Aquifers in the Hermanus area as part of their assessment of the hydrogeological potential of the area. Using carbon-14 dating techniques they were able to determine groundwater had a mean annual storage time of less than 1 000 years which suggested an active recharge system. Using the CRD method described by Bredenkamp et al. (1995), they attempted to quantify recharge. However, lack of long-term groundwater level data restricted application of the technique. The Dörhöfer method (Dörhöfer and Volker, 1981) was then applied. The method takes into account vegetation type, soil type, evapotranspiration and entails overlying a series of graphs depicting the characteristics of the catchment.

Most of the catchment is underlain by fynbos, but slopes range from slight to very steep. Recharge for the three catchments studied was found to range between 20 and 24% of 635 mm/a MAP (Rosewarne and Kotze, 1996). Average recharge was hence set at 22% MAP. However, as the study area excluded most of the mountainous areas in which higher recharge rates are expected, it was considered that the determined rate was conservative.

Klein Karoo management model

Kotze (2000) and Kotze et al. (2000) investigated recharge of TMG Aquifers as part of research into developing a conceptual management model for groundwater exploration in TMG Aquifers. As a first step she used a simple water balance calculation to estimate the groundwater exploitation potential of the Kammanassie Mountains. Using a range of methods and estimates of storage based on C-14 data, recharge for the entire area was set at 5% MAP. Most of the catchment comprises Nardouw Formation and receives a MAP of about 320 mm/a.

When only considering the Peninsula Formation, which covers less than 15% of the catchment, recharge was set at about 14% MAP. A number of methods were used to determine recharge of the Peninsula Formation (Table 2).

Table 2
Methods used to estimate recharge of the Peninsula Formation

Method	Recharge (%MAP)
Cl mass balance	11.1
SVF (equal volume)	19.7
SVF (fit)	16.4
CRD	14.4
Baseflow	12.5
Earth model	23.9

In addressing recharge, Kotze (2000) recognised recharge to the Peninsula and Nardouw Formations occurs at different rates. Further, in the absence of permeable fractures cross-cutting it, the Cedarberg Formation acts as an aquitard which influences the recharge process. She also found that only the shallow aquifer system was considered by the calculation methods, but deep circulation could play an important role in the regional aquifer system.

Isotope data showed most local recharge occurred in the high lying mountainous areas, which largely comprise rocks of the more competent Peninsula Formation. Through a series of interconnected local and regional scale fractures, groundwater flows toward lower lying or discharge areas.

Uitenhage Artesian Basin

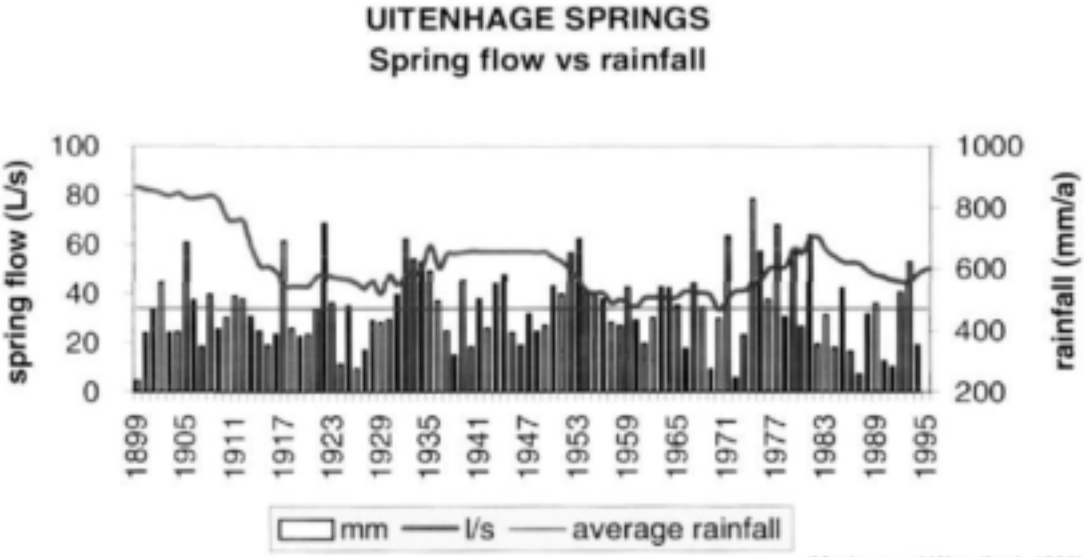
The Uitenhage Artesian Basin (UAB) has been studied in some detail by, amongst others, Parsons (1983), Venables (1985), Bush (1986) and Maclear (1996) and is described in this volume by Maclear (2001). The UAB covers an area of 3 700 km^2 and comprises quartzites and sandstones of the TMG overlain by confining sediments of the Uitenhage and Algoa Groups. The TMG Aquifer system is recharged by rainfall in the Groot Winterhoek Mountains whereafter groundwater flows south-eastwards towards the sea. As a result of widespread drilling in the early 1900s, the artesian aquifer system changed from a free-flowing artesian system to a sub-artesian system. In response to declining groundwater levels, the area was declared a Subterranean Government Water Control Area (SWCA) in 1957.

Earliest recorded flow at the Uitenhage Springs was 82 ℓ/s (Reynders, 1987). Groundwater development and mismanagement of the UAB in the early 1900s resulted in flow decreasing to about 35 ℓ/s by 1915. Declaration of a SWCA and grouting of leaking boreholes resulted in a reversal of declining springflow (Fig. 2). Flow increased to 63 ℓ/s in 1982 before the impact of a prolonged drought during the early 1980s further impacted flow (Maclear, 1996). Long term monitoring of the flowrate of the springs and piezometric levels in boreholes in the immediate vicinity allowed recharge patterns to be quantified. However, a clear relationship between springflow and rainfall was masked by the effects of drilling, abstraction, management and drought (Maclear and Woodford, 1995).

Using springflow data and an estimate of the catchment area of the Uitenhage Springs, Kok (1992) estimated recharge to be in the order of 10% MAP. Based on an analysis of rain and groundwater at the Uitenhage Springs, Maclear (1996) used the chloride mass balance method to estimate recharge to the TMG Aquifer system in the Groot Winterhoek Mountains at 25% MAP. Similar calculations elsewhere in the catchment indicated recharge may be as high as 55% MAP. However, recognising the limitations of his data set, Maclear (1996) proposed an estimate of recharge of 25% MAP to be reasonable.

Discussion

Based on work undertaken to date, it would appear most recharge of TMG aquifer systems occurs in mountainous areas were rainfall is highest, snowfall occurs and fractured rocks are directly exposed



(Maclear and Woodford, 1995)

Figure 2
Rainfall and springflow measured at the Uitenhage Springs

to rainfall. Preferential flow in fractures is a key mechanism in the recharge process. Groundwater movement toward discharge zones occurs through a series of local or regional interconnected fractures or fracture systems. Flow either takes place through the upper more localised aquifer systems or by means of deep circulation.

Estimates of recharge of TMG aquifer systems presented in this paper are generally higher than considered previously and it appears earlier estimates may have been conservative. As early as 1970, Joubert (1970) suggested infiltration into the TMG could be as high as 60% MAP, but this order of estimation was more an exception than the rule. If it is accepted that baseflow is an indication of minimum recharge in a catchment, recharge in the upper reaches of the Olifants River has to be greater than 20% MAP (Parsons, 2000). Proposals that recharge in mountainous areas is greater than 30% MAP thus have merit.

Current understanding of recharge of TMG Aquifers is limited. A number of issues require further attention before recharge can be quantified with a higher degree of certainty. These include:

- Development of sound conceptual models of TMG Aquifers, including difference in the various TMG Aquifer type areas eg. Western TMG Aquifers, Central portion aquifers, Little Karoo TMG Aquifers and Eastern Cape TMG Aquifers.
- Consideration of differences in recharge to aquifers of the Peninsula and Nardouw Formations.
- The relationship between shallow, local aquifer systems and deeper regional aquifer systems.
- The effect of different rainfall patterns on recharge.

Further, a common understanding of recharge and recharge processes has to be developed. The terms recharge, potential recharge, effective recharge, infiltration and percolation have all been used to describe water that infiltrates the ground. However, not all of this water enters the groundwater system or is available for later abstraction. Evapotranspiration losses and discharge from mountain springs, for example, have to be accounted for before estimating additions to the groundwater reservoir. It is quite possible the wide range of estimates of recharge to TMG Aquifers relates more to differences in definitions rather than actual recharge variation.

Proper quantification of recharge of TMG Aquifers systems is urgently required and is identified as a research priority. This information is a cornerstone to determining the exploitation potential of these aquifer systems and implementing proper aquifer management. Appropriate long-term monitoring of groundwater levels, abstraction, springflow and rainfall will be particularly important in this regard. However, any research programme implemented must include an integrated recharge quantification approach to allow a degree of comparison between results obtained.

Until such time that more reliable estimates of recharge are available, it is proposed the results of the recharge survey be used as a guide for estimating recharge of TMG aquifer systems (Table 1). In areas which receive rainfall in excess of 1 000 mm/a, recharge rates in excess of 35% MAP can be considered.

Conclusions

No comprehensive investigation of recharge of TMG aquifer systems has been undertaken. Recent attempts to quantify recharge indicate recharge rates may be higher than previously considered. Recharge ranges from about 5% MAP in drier areas to in excess of 20% MAP in higher lying areas that receive an annual rainfall of greater than 600 mm/a. Rates of 35% MAP can be considered in those areas that receive more than 1 000 mm of rainfall each year. A proper research programme, however, is required to quantify recharge of TMG aquifer systems under a range of conditions. Such a programme needs to be supported by long-term monitoring of groundwater levels, abstraction and springflow.

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Towards "Map-Centric" Simulation Modelling of Table Mountain Group Recharge

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Abstract

Quantification of recharge or infiltration into the Table Mountain Group (TMG) Aquifers is a pivotal part of any conjunctive surface and groundwater resource evaluation and development. Recharge calculations are sensitive to spatial and temporal averaging of rainfall distribution, EVT variations with respect to altitude, and the temperature range and mean during the recharge period. The high mountains where TMG Aquifer rocks are exposed and capture the greater proportion of MAP, including a substantial snowfall component in some winter seasons, are under-represented in public domain data. A GIS-based recharge model for the Peninsula Aquifer was assembled based upon an empirical regression curve of MAP versus altitude for 13 rainfall stations, all located within and immediately surrounding the CAGE Project area. This model, shows variation between a maximum of 1 410 mm and minimum of 162 mm, but is likely to under-estimate the high-altitude MAP. ***Actual*** *evapotranspiration was estimated using the simplified formula developed in the context of Mediterranean climatic areas. Mean annual evaporation (MAE) is based primarily on the areal distribution of MAP but uses actual* ***local*** *maximum monthly temperature data from throughout the area for the high rainfall months (May-August). This interim approach is regarded as reasonably conservative, but could under-estimate E in some parts. It is justified in that the recharge period in the Western Cape occurs predominantly during the months May-August when measured pan evaporation is lowest. For the estimation of mean annual runoff (MAR) distribution "run-off efficiency" (MAR/MAP ratio) statistics were reviewed for different sub-catchments within the area, and a factor related to local slope in the DEM was incorporated in the GIS model. No explicit GIS-based pedological, geological, vegetation, or flow-accumulation information was integrated such that it would form a predictive basis for stream-flow gauging. The calculations of recharge and mass balance for the Peninsula aquifers of the TMG is estimated to be in a range of 7-44%, with a spatial average of ~23%. It should in future be possible to calibrate the infiltration values obtained in this study using the chloride balance approach.*

Introduction

There are three basic elements in a hydrogeologic simulation model, viz.:

- equations governing the surface hydrological and subsurface percolation processes;
- maps that define the study area; and
- numerical database tables that characterise the area and the model parameters.

In conventional programming procedure, these elements are usually processed separately and brought together at runtime. Each time the study area is changed or additional data are obtained, modifications on a model map will not automatically update its related databases and programs. Efforts of data collection and preparation are therefore often repeated in the construction of a new model. Such unnecessary repetition can be avoided if all elements in a simulation model are integrated and if standard map bases can be built for extensive regions. Therefore the modern approach to water resource modelling has progressively developed in successive phases, described by Ye et al. (1996) as:

- 'function-centric' where numerical models are 'self-contained and supported by their own data sets';
- 'data-centric', where models are supported by some general, usually relational database management systems (DBMS); and
- 'map-centric' where models would be 'supported by or written in a geographical information system' (GIS), based also on the concepts of object-oriented programming (OOP).

During the CAGE (Citrusdal Artesian Groundwater Exploration) project (Hartnady et al., 2000), a map-based hydrologic flow simulation model, with integration of all three elements, was initiated in a move

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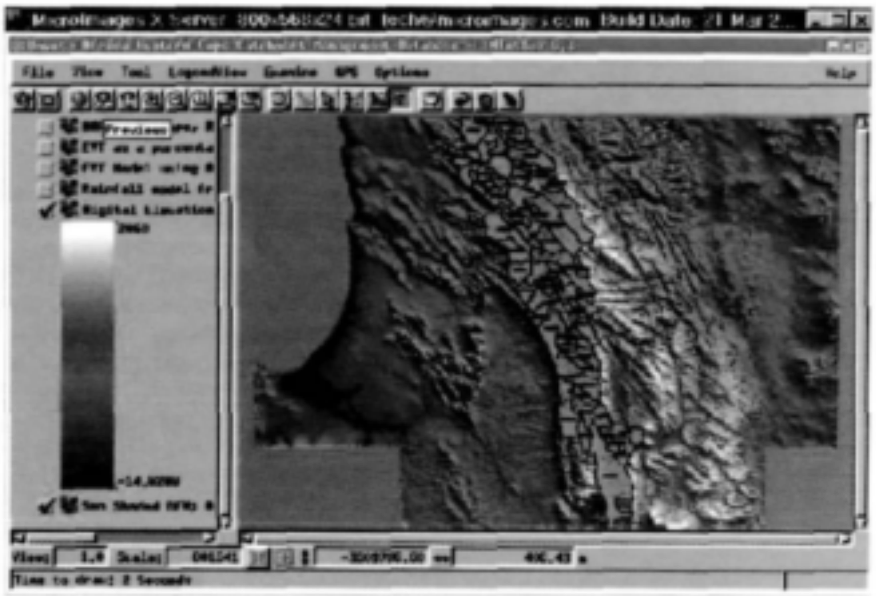

Figure 1

Sunshaded digital elevation model DEM; 30 x 30 m cells) of the CAGE project area with E10 (upper Olifants River) catchment area (red overlay) partitioned at sub-quaternary basin level

towards the goal of a fully 'map-centric' modelling approach. In principle, an integrated simulation of stream hydrologic and aquifer hydraulic processes requires two map-based flow simulation models, one for surface flow and one for groundwater flow, which are then connected through data tables to simulate the interactions between surface and subsurface water flows (Ye et al., 1996). Quantification of recharge or infiltration into the TMG aquifers is the pivotal part of the CAGE surface-flow modelling described below. In areas of high topography and strong orographic control on precipitation, as moist air carried by frontal systems from the South Atlantic is forced to rise over the western mountains of the Cape Fold Belt, spatial variability of recharge is a key aspect.

Infiltration/recharge modelling in the CAGE study area

GIS and elevation model

TNTmips™ from MicroImages, Inc.was selected as the host GIS environment for the surface hydrologic model because it provides the "geospatial" DBMS and analytical toolkits as well as OOP capabilities. Compatibility with similar systems based on Arcview, for example, is also available in TNTmips through interchange-ability of "shape" (.SHP) file formats.

The first requirement of the CAGE Project was a fairly high-resolution digital elevation model (DEM), constructed for this special purpose on a 30 x 30 m cell grid from contour shape files provided by the Trigonometrical Survey office. The area covered extended from latitude 32°S to 33.25°S, and from longitude 18°E to 20°E, centred about the E10 (upper Olifants River) catchment (Fig. 1). A shaded-relief image of the DEM is the graphic basis for all GIS maps presented here (Figs. 1-4).

Rainfall model

A high-resolution (30 x 30 m) model of mean annual precipitation (MAP) was assembled (Fig. 2A), based upon an empirical regression curve of MAP versus altitude for 13 rainfall stations, all located within and immediately surrounding the project area. The available public-domain data set (Midgley et al., 1994) is deficient in relation to altitude coverage, because most South African Weather Bureau (SAWB) rainfall gauges are located in low-lying valley areas with towns and/or farming populations. The high mountains where TMG Aquifer rocks are exposed and capture the greater proportion of MAP, including a substantial snowfall component in some winter seasons, are grossly under-represented.

Nevertheless, the current model, showing variation between a maximum of 1410 mm and minimum of 162 mm (Fig. 2A), closely resembles the more regional, lower-resolution GIS model of Schulze et al. (1997), and is likely to err on the conservative side (i.e. under-estimate the high-altitude MAP). There is, however, obviously room for further MAP model improvement through future incorporation of directionality ("rain shadow") effects, seasonality (monthly to daily time-step) influences, and ultimately space-time storm parameters (strength, duration, advective-convective character) based upon remote sensing of rainfall by radar and satellite imagery (Pegram and Clothier, 1999).

Evapotranspiration model

Recharge or infiltration (I) into any aquifer is most simply defined as:

$$I = P - (E + R)$$

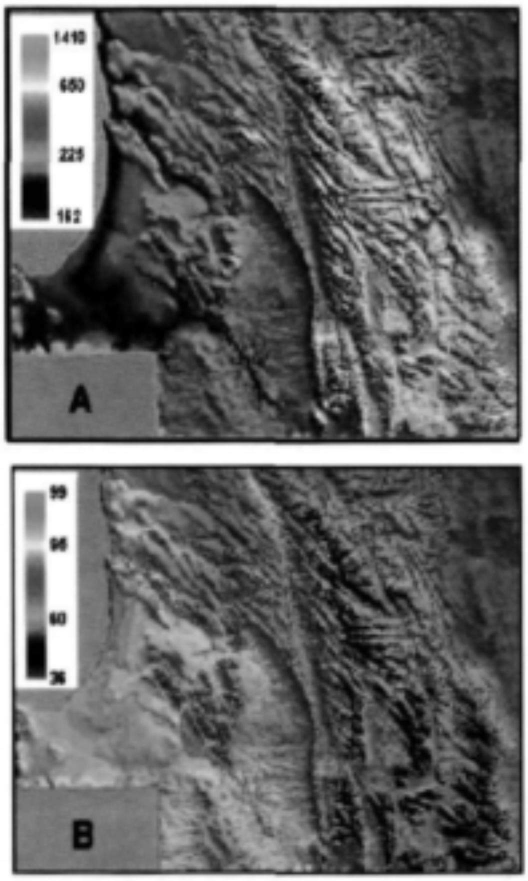

Figure 2

- A. *Mean annual precipitation (MAP) model, expressed as mm/yr*
- B. *Mean annual evapotranspiration (MAE) model, expressed as a percentage of MAP*

where:

E symbolises actual (not just potential) *evapotranspiration*,
R is surface-water *runoff*; and
P is *precipitation*, all expressed as a water depth (e.g. mm).

Potential evapotranspiration is usually estimated by a modified Penman-Monteith (P-M) equation, in which the key physical variables include surface air temperature, solar radiance, and soil moisture. However, for the areal estimation of I over the CAGE area (Fig. 2B), it is *actual*, not potential evapotranspiration, that is required. In the absence of empirically-based estimates for missing P-M variables, the simplified formula developed in the context of Mediterranean climatic areas by Turc (1954) is used instead.

The Turc equation links actual evapotranspiration E to precipitation P

$$E = P / [0.9 + (P^2/L)]^{0.5}$$

where L is a "heliothermic factor" involving temperature and solar radiance. In this application L was assigned only a non-linear dependence on average annual temperature, T, i.e.

$$L = 586 - 10T + 0.025T^3$$

as modified for dry areas by Santoro in 1970 (A. Amantia, pers. comm., 1999).

The CAGE project model for E (Fig. 2B), in which mean annual evaporation (MAE) is represented as a percentage of MAP on a coarser (500 x 500 m cell) grid, is based primarily on the areal distribution of P (Fig. 2A). It uses the local maximum monthly temperature data (cf. Schulze et al., 1997) from the area for the high rainfall months (May-August) as an estimator of T in the modified Turc formulae.

This interim approach is regarded as reasonably conservative, but may perhaps be criticised for under-estimating E in some parts. It is however justified in that the recharge period in the Western Cape occurs predominantly during the months May-August. A preliminary recharge estimate for all areas underlain by TMG and on which more than 200 mm of rain per annum fell was undertaken at an early stage in the CAGE project (Hay et al., 1998). Variable recharge rates for different topographic and rainfall domains were established in this study, which took into consideration the distinction between the wet, cold, winter-recharge phase and the dry, summer-abstraction/discharge phase in the hydrological cycle. Monthly average rainfall and evaporation pan records were used in the context of an isohyet distribution for MAP. The latter is primarily controlled by the winter rainfall pattern.

Application of a standard atmospheric lapse rate, controlled by observed temperature-altitude statistics from stations within the area, would represent a possible direction of model refinement. Other variables related to the P-M equations, which may have a topographic (or geological) dependence, could also be incorporated at some future stage.

Runoff model

For the estimation of mean annual runoff (MAR) distribution (Fig. 3), "run-off efficiency" (MAR/MAP ratio) statistics were reviewed for different sub-catchments within the area (cf. Midgley et al., 1994), and a factor related to local slope in the DEM was incorporated into a statistical analysis. Slope determines the horizontal component of gravity that drives water and all other materials downward. The topographic curvature or Laplacian $(\delta^2 z/\delta x^2 + \delta^2 z/\delta y^2)$, a scalar measure expressing divergence and convergence of water or material flow, could also be used in future as a possible physical proxy for soil saturation in hill slope hydrology, to further refine the provisional GIS-based "raw" MAR model (Fig. 3).

The current runoff model is herein described as "raw" because there has as yet been no attempt to incorporate explicit, GIS-based, pedological, geologi-

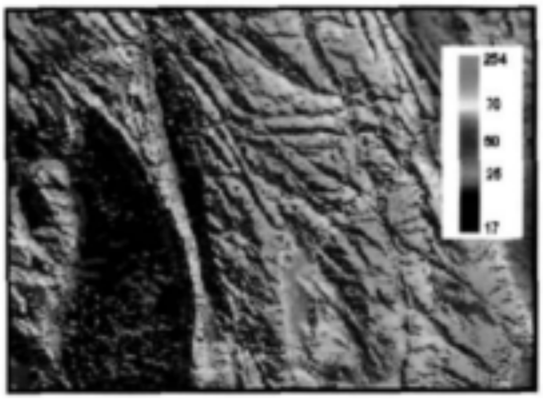

Figure 3
Mean annual runoff (MAR) model, expressed as mm/yr

Figure 4
Mean annual infiltration (MAI) model, expressed as a percentage of MAP

cal, or vegetational information into the output function for each cell, or to accumulate the indvidual cell outputs into a hydrological flow model, such that it would form a predictive basis for stream-flow gauging. The TNTmips software includes flow-accumulation modules in its geospatial analysis toolkit.

Recharge model

The final model of mean annual infiltration (MAI) is derived by simple subtraction of MAE (in mm) and MAR (Fig. 3) from MAP (Fig. 2A). It is expressed in map form, superimposed upon the sun-shaded DEM, as a percentage of MAP (Fig. 4), because various empirical models of groundwater recharge relate it directly to rainfall via a "coefficient of recharge" (Bredenkamp et al., 1995). The recharge is shown to vary from zero (purple and deep blue tones) to a possible maximum of 57% (far-red tones). The maximum values apply only to extremely restricted areas in the highest parts of the terrain. In all diagrams in this set (Figs. 2-4) the rainbow colour scale is non-linearly stretched, so that over most of the terrain above 1500 m (pale areas in Fig. 1), the modelled annual infiltration is generally in the range of 30-40% of MAP, with a spatially weighted average of ~23%.

In such high mountain areas, there is little or no empirical data on recharge, against which to test the infiltration model. However, in the Agter-Witzenberg area at the extreme southern end of the E10 catchment (Fig. 1), an analysis based on oxygen isotopes and chloride balance between rainwater and groundwaters suggested that recharge in the TMG aquifer may locally be as high as 50% (Weaver et al., 1999). In those particular parts of the current GIS model (not shown in Fig. 4, which is a closer view centred on the Citrusdal valley portion of the upper Olifants, cf. Fig. 2B), the maximum modelled infiltration ranges up to ~44%, and lies generally in the 38-42% range along the high axis of the Hansiesberg-Skurweberg mountain range. The infiltration model therefore appears reasonably consistent with the only other available piece of scientific information relevant to the TMG recharge problem in the high lying primary recharge domain.

As in the case of the MAR model, the current MAI model is "raw" in the sense that obvious controls related to soil-moisture, vertical hydraulic conductivity of the vadose zone, and the exact geography of recharge-discharge boundaries within the various TMG Aquifers, remain to be more explicity quantified within the GIS. As a first approximation in the CAGE area, modelled recharge into the TMG Aquifers is accumulated only over generally high-lying areas underlain by the Peninsula Formation. Other, generally lower-lying, TMG areas underlain by Pickenierskloof and Nardouw units are excluded from consideration on the grounds that they mostly form part of the discharge zone feeding shallow primary aquifers and baseflow in streams. Thus there is no spatial averaging implicit in these recharge models.

Conclusions

Recharge calculations are sensitive to spatial and temporal averaging of rainfall distribution, EVT variations with respect to altitude, and the temperature range and mean during the recharge period. It is therefore inappropriate to estimate a generalised recharge for the TMG superaquifer system as a whole. Given the differences between areas of rock exposure, the altitudes at which the different aquifers crop out, and the regional patterns of flow, calculations of recharge and mass balance for the Nardouw aquifers are best estimated quite separately from those for the Peninsula Aquifer.

The GIS-based theoretical models presented in this study (Figs. 2-4) have yet to be calibrated by experimental data at particular sites. For this purpose, the best and cheapest method is the chloride balance approach. In the course of the CAGE project hydrocensus and sampling (November 1998-April 1999), Cl concentrations were obtained from numerous ground- and surface waters over most of the area, but there was no opportunity to extend the database to the analysis of rainwater samples. By obtaining such data at carefully selected calibration sites in the model area, it should in future be possible to correctly scale the infiltration values obtained in the present study.

If the TMG recharge modelling and calibration problem is considered on a regional scale, estimations based on monthly data are probably adequate. However, as the study area decreases and the required level of accuracy and precision increases, daily precipitation and flow data related to particular recharge events, obtained within well defined boundary conditions, would become more critical.

At this future level of refinement it would be preferable that recharge and mass balance estimates are based on a number of different approaches and using a variety of data sets. The question of acceptable error is seldom addressed in recharge estimation, and where different approaches yield different answers, some form of stochastic or probabilistic analysis will also be necessary.

Acknowledgements

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Sustainable Use of Table Mountain Group Aquifers and Problems Related to Scheme Failure

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Abstract

Sustainable use of Table Mountain Group (TMG) Aquifers is dependent on appropriate assessment of recharge, aquifer storativity and transmissivity. Boreholes have been shown to have "blow yields" far in excess of proven sustainable yields. Some shallow TMG boreholes have been pumped at rates in excess of 30 ℓ/s, but these rates are not sustainable. In the inland area between Worcester and Port Elizabeth, the sustainable yields of most TMG boreholes ranges between 2 - 3 ℓ/s (continuous pumping). Many schemes have failed because the abstraction has exceeded recharge, resulting in water levels declining to the depth of the pump. Not only is recharge low, but it is also sporadic. As a result aquifer storage must be utilised before the next recharge event tops up the aquifer. The author suggests that the storativity in the TMG is lower than traditionally expected, resulting in continual decline in water levels in the pumping period between recharge events. This decline in water levels must be carefully managed to make certain that water levels do not drop below the top water strikes in the hole - should this happen, the risk of microbial induced biofouling causing clogging of the pump, the screens and the aquifer is dramatically increased. The ultimate cause of borehole or wellfield failure in the TMG Aquifers is however, the poor management of the resource.

Introduction

The unscientific testing and evaluation of boreholes drilled in TMG Aquifers has often created a false impression of the aquifer's long term sustainable potential. In many cases "blow yields" measured at the end of drilling have been taken to represent borehole yields. There is no doubt that blow yields from most shallow TMG boreholes exceed sustainable yield. Even the normal scientific assessment of the borehole's potential via step and 72 hour constant rate tests can grossly over-estimate sustainable yield, if assessments do not take into account issues like existing boundaries and matrix transmissivity/storativity. Boreholes, especially in the dryer areas, are capable of yielding far more than recharge to the area.

Abstraction rates in the production boreholes of the Klein Karoo Rural Water Supply Scheme (KKRWSS) have been reset a number of times as the scheme managers wrestle with the conflict of high yields and low recharge. Examples of the borehole blow yields and different recommended abstraction rates are provided in Table 1 (Mulder, 1995; Jolly, 1998).

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Sustainability

Setting of sustainable abstraction rates depends on the definition and conditions linked to sustainability. In South Africa, sustainable abstraction is presumed to take place when environmental impacts are limited and/or when long-term lowering of water levels does not occur.

Table 1
Comparison between blow yield and recommended abstraction rate

Borehole	Blow yield (ℓ/s)	Recommended abstraction rate (ℓ/s)		
		1992	1993	1998
DP10	7	14.3	4.5	-
VR7	15	19.7	-	11
VR8	13	9.8		8
DL17	15	15	3.5	3
KG1	15	15	-	3
DP25	20	9.8	-	7

In cases where lowering of water levels does not effect the environment (i.e. if water levels are deep and no springs or rivers exist), the necessity for no "long-term" lowering of water levels is debatable. Similarly, what degree of short-term water level decline is allowed before sporadic recharge causes a recovery in water levels is also contentious. A far greater decline in water level will be allowed if the management of the scheme is relying on a 1:50 rainfall event to recovery water levels to initial levels, compared to reliance on 1:5 year rainfall events.

Failure

Detail on failure of boreholes or wellfields in the TMG is limited. Most large-scale abstractions of groundwater for domestic use are relatively well managed, although municipalities are notorious for increase abstraction rates to above recommended rates when demand increases. Although detailed figures are not available, the abstraction of TMG water for irrigation uses is far higher than for domestic consumption. In the Breede River basin (Jolly, 2000) the majority of groundwater abstracted is from TMG rocks which are adjacent to Bokkeveld Group rocks - abstraction for domestic and municipal use is estimated at 1.6 Mm^3/a, while irrigation use is approximately 90 Mm^3/a. Unfortunately, the rate of failure for irrigation supply boreholes is unknown, but rates are expected to be greater than for municipal boreholes. This is because relatively few irrigation boreholes are adequately tested or managed.

Causes of failure

Failure of boreholes or groundwater supply schemes occurs when:

- the boreholes either deliver less water than that for which the system has been designed;
- water levels drop to such a degree that pumping becomes uneconomic; or
- the water quality changes and the water becomes unusable.

Reduction in borehole yield can either be as a result of dewatering of the aquifer, deterioration in the pump or clogging of the borehole. Decline in water level is either as a result of over-abstraction effecting the aquifer or clogging of the hole which reduces inflow and increases drawdown in the borehole.

Over-abstraction

Over-abstraction is considered to be the case when abstraction results in water levels continuously declining. This takes place when the abstraction rate is greater than the rate that water can flow into the borehole, either as a result of low aquifer transmissivity or low aquifer storativity. In the Vermaaks River Valley (KKRWSS), water levels are dropping slowly, even though boreholes have been shown to have high yields and aquifer transmissivity is moderately high, but variable between 24 and 274 m^2/d (Jolly, 1998). Storage in this aquifer cannot sustain the volume of water being abstracted. The storativity of TMG Aquifers is low - figure quoted previously included 5×10^{-3} (Rosewarne, 1984); 2×10^{-3} to 1×10^{-2} (Mulder, 1995). These storativity values were derived from aquifer tests undertaken on high yielding boreholes and represent the fractured zone directly adjacent to the production hole being tested. The values are not representative of the greater aquifer, distant to the production hole. It is likely that the storativity of the aquifer away from the fractured area, which the borehole has penetrated, will be lower than that of the fractured area. As a result, the storativity values commonly quoted are probably overestimates of the storativity of an aquifer exploited by a number of boreholes in a wellfield.

Where low aquifer transmissivity occurs (coupled with a high storativity), there will be no decline in regional water levels in the aquifer, but boreholes will be pumped with large drawdowns. This is not normally the case in TMG Aquifers, where the transmissivity of production boreholes is high (Table 2) and drawdowns during pumping are low.

Table 2
Specific capacities and pumping drawdowns for different wellfields

Wellfield	Specific capacity (ℓ/s-m)	Pumping rate (ℓ/s)	Average drawdown (m)
Vermaaks river	1.0	7	7
Calitzdorp	0.4	3	7
Caledon Hot Spring	1.2	10	8
Steytlerville	0.8	3	3.8
Plettenberg Bay	0.6	5	8
Albertinia	0.1	3	30

The highest specific capacities were calculated in the range 1.8 - 2 ℓ/s·m. Within wellfields specific capacities vary from 0.1 and 2 ℓ/s·m, although boreholes with low specific capacities are generally not used.

Iron clogging

In a number of circumstances (Klein Karoo Scheme, Albertinia, Waboomskraal) iron clogging (chemically induced biofouling) has greatly decreased the specific capacity of a borehole, to the degree that pumping water levels drop to pump level and the borehole is said to have "dried up". At Calitzdorp, borehole DL17 (KKRWSS) had a decrease in specific capacity from 1.2 and 0.1 ℓ/s·m in under 18 months - during this time the drawdown during pumping increased from 6 to 62 m, while rest water levels only decreased by 8 m. The process of iron clogging of holes is poorly understood by most wellfield managers, especially

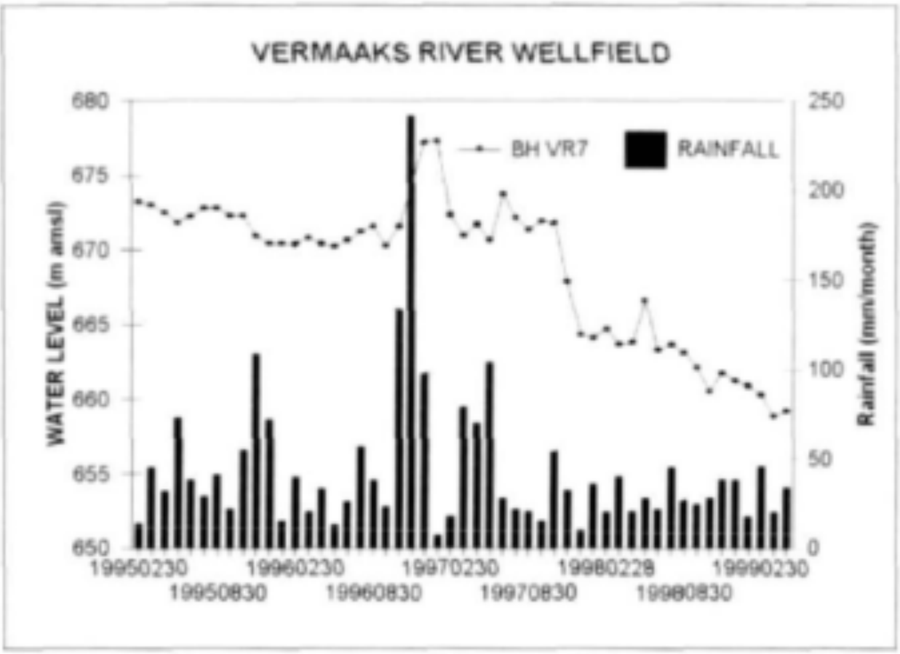

Figure 1
Recharge associated with a flood event in the Vermaaks River Valley

in the agricultural industry. As a result, failure of holes due to iron clogging is not always recognised, while no changes are introduced to limit clogging. It is, however, clear that boreholes with elevated iron levels do clog if overpumped - in this case overpumping being the lowering of the water level below the top fracture, thus allowing the water to cascade down the inside of the hole to the pump. This cascading oxygenates the water, allowing chemical precipitation to take place, and providing nutrients for rapid biofouling to take place.

Quality problems

Borehole failure is seldom related to chemical changes to the quality, although there have been some isolated cases where quality has deteriorated to such a degree that the water becomes unsuitable for use. Borehole DP28 (Dysselsdorp, KKRWSS) had a dramatic change in quality where pH dropped to 2, iron levels increased from 0.3 to 8 mg/ℓ and electrical conductivity rose from 30 to 90 mS/m. This deterioration was thought to be related to the activity of sulphate reducing bacteria in the borehole. Although increased iron concentrations as a result of biofouling do take place, the problem is seldom severe enough for a borehole to be abandoned.

Lowering of water levels during abstraction can induce poor quality water to flow into the area. In the upper reaches of the Hex River Valley, abstraction from the TMG Aquifer can result in inflow of saline water from the adjacent Bokkeveld aquifer. In some cases this deterioration can be severe enough to result in the borehole being temporarily taken out of use. Usually winter recharge results in an improvement in quality in affected areas.

TMG Aquifer response to abstraction

Data available from the monitoring of water level response to abstraction are limited to a few larger schemes. Where monitoring data exists, the normal water level trend is that of a slow but steady decline in water level, interrupted by comparatively dramatic rises in water level after recharge events. An exceptionally high recharge event is shown in Fig. 1, where a 1:75 year rainfall flood impacted on the water levels in the Vermaaks River wellfield near De Rust.

Decreasing risk

The more information that exists about a borehole and the aquifer it exploits, the lower the chance of the abstraction failing. Especially important is data related to the assessment of recharge to the aquifer. In the inland areas of the TMG (Worcester to Steytlerville) rainfall is low and the author believes that shallow TMG boreholes can seldom yield more than 3 ℓ/s (constant pumping), even though these boreholes may be able to yield far more during a short duration aquifer test. Boreholes drilled in Plettenberg Bay were tested at 8 ℓ/s with a stabilised drawdown of 6 m after 72 h. However, water levels in this aquifer dropped by 40m over a 16 month period after the borehole was over-abstracted by pumping at 8 ℓ/s almost continuously during peak demand periods (Easter and Christmas holidays). The abstraction rate was far above recharge rates, while the storativity in the aquifer was lower than estimated. Although higher yielding boreholes do exist in the TMG than those mentioned above, they invariably occur in areas of greater recharge (Hex River mountains and Agter-Witzenberg valley).

Aquifer storativity for the TMG is generally assumed to be approximately 1%. This storativity figure needs to be researched and refined, since storativity, in an environment of sporadic recharge, is, together with recharge and transmissivity, the factors that controls whether a scheme will fail or not.

In environments where iron related clogging can reduce a borehole's abstraction potential, the design of production holes needs to be re-thought. Boreholes must be constructed to cut off upper water strikes, so that water entering a borehole flows upwards to the pump which must be located above the fracture zone. Water must not cascade down a borehole to the pump set adjacent to deeper, stronger fractures. This necessitates the installation of PVC casing, which must be grouted into place, in a manner that seals off the upper shallow water strikes.

Conclusions

The failure of TMG Aquifers is predominantly hearsay, since limited data exists. Anecdotal evidence of boreholes having "dried up", is seldom backed up by any data related to abstraction, water levels or recharge. This lack of data is the root of the problem, since correct monitoring and aquifer management did not take place. Correct aquifer management is essential if scheme failure is to be checked before it takes place, thus improving the reliability of TMG Aquifers.

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Groundwater Dependent Ecosystems in the Fynbos Biome, and Their Vulnerability to Groundwater Abstraction

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Abstract

The fynbos is a unique and ecologically important vegetation type, but little is known of the hydrological functioning of the groundwater dependent communities within this biome. There is no published documentation of groundwater dependency by ecosystems in the TMG. Two WRC funded projects are underway to assess examples of aquatic (Saayman, pers. comm.) and terrestrial (Smart, pers. comm.) ecosystem dependency in the TMG, as well as a more generic project looking at groundwater dependent terrestrial ecosystems nationwide.

Groundwater dependent communities in the TMG are thought to be:

- *the smaller seeps, springs and wetlands in the mountains;*
- *the larger bottomland wetlands, mostly in river valleys, where the relative contributions of surface and groundwater are unknown; and*
- *the long and extensive riparian habitats and stream ecosystems that are dependent, to some extent and from various channel sections, on groundwater discharge during the summer droughts.*

Other TMG groundwater dependent ecosystems are those in cave and other underground systems, and coastal discharge zones where freshwater is thought to create lower salinity conditions. Both of these situations are largely undescribed.

There is a pressing need for further research in these areas so that decisions regarding ecological effects of groundwater abstraction can be taken with greater confidence.

Introduction

Information on groundwater dependence is scant, but there are general ecological principles and some basic conceptual models which can be applied to help direct research to the most important issues. Some preliminary work on groundwater dependence indicates that there are ecosystems that are groundwater dependent, and thus vulnerable to groundwater abstraction. The ecosystems can be grouped into two basic types: (a) those that are dependent on groundwater discharge and (b) those that depend on access to the groundwater in the aquifer. The first group includes springs, wetlands, rivers with groundwater derived flow (especially baseflow) and cave ecosystems. The second includes terrestrial ecosystems where there is no direct evidence of dependence. Both may provide essential habitat for fauna that are therefore also groundwater dependent.

This paper, therefore, draws much from logical inference of what is known generally about ecosystems, about fynbos ecosystems (particularly the plants), and the aquifers. We have made use of the background information compiled for the comprehensive determination of the reserve for groundwater (Braune et al., 1999) as well as the reviews of groundwater vegetation-interactions compiled by Le Maitre et al. (1999) and Hatton and Evans (1998).

Relationships between plant growth forms and root systems

In general, plants will utilise groundwater wherever their roots can access it. Many tree and shrubs species are deep rooted (5-10 m) and some are capable of reaching water tables at depths of 10-20 m and more (Stone and Kalisz, 1991; Jackson et al., 1996, Table 2); a number of fynbos shrub species e.g. Proteaceae) are likely to be among them. However, the ability to root deeply does not necessarily imply a dependence on groundwater. Kruger (1979) notes that the distribution of *Protea nitida* (waboom) communities on talus or colluvial slopes suggests that it

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may be exploiting lateral drainage in summer. *Dodonea viscosa* (sand olive) is a widespread, deep-rooted shrub which is noted by Moffet and Deacon (1977 in Boucher and Moll, 1981) as occurring in a renosterveld community on the contact between Cango Limestone and Table Mountain Group (TMG) Aquifer.

Phreatophytes are water-loving plants whose roots are in contact with the capillary fringe above the water table (phreatic surface) or sometimes free water itself. These plants are apparently particularly sensitive to manipulation of the water table such as a sudden lowering or raising, particularly when the layers above the capillary fringe have a low moisture content. The best local examples are species found along watercourses in semi-arid to arid areas (e.g. *Acacia erioloba, A. karoo*). Some of the fynbos species characteristic of alluvial deposits may have similarly deep roots. Succulents and short-lived plants are typically shallow rooted (<0.5 m) and very unlikely to be dependent on groundwater (Nobel, 1991).

Determining the importance

When groundwater dependent ecosystems are identified there must be some way of determining priorities for conservation and protection. The criteria used in the prioritisation need to take into consideration both the benefits of protection and the opportunities that are lost if the groundwater is not abstracted. Hatton and Evans (1998) suggest considering the (a) uniqueness (e.g. biodiversity, cultural, aesthetic and socio-economic value) and (b) the expected or likely vulnerability (sensitivity) to change (Table 3). Although ecosystems entirely or highly dependent on groundwater occupy only very limited areas (Hatton and Evans, 1998), they are often ecologically and socio-economically significant. Riparian zones are important areas for biodiversity, offering refuges and habitat for a variety of organisms (Milton, 1990; Naiman et al., 1993; Morrison et al., 1994). A good South African example is the Sabie-Sand River system in the Kruger National Park where the riparian ecosystems play key roles in maintaining the biodiversity and functioning of the adjoining terrestrial ecosystems (Davies et al., 1993; Jewitt et al., 1998). Similar studies are lacking in the TMG but it is likely that stream corridors could fulfil the same function.

Hatton and Evans (1998) suggest defining or assessing groundwater dependence using the annual water budget but we argue, for the reasons set out above, that seasonal (and inter-annual) variations in the budget also need to be considered. This can be illustrated using a hypothetical but not unlikely river baseflow dependent ecosystem. The total dry season flow may only be a small percentage (say 5%) of the total annual flow but it may be critical, and most or all of that flow may come from groundwater discharge. Changes in groundwater availability will, therefore, alter the affected ecosystems, but the nature of the responses is essentially unknown. The changes in ecosystem structure or functioning may be directly and linearly or non-linearly proportional to the changes in water availability, or may take the form of abrupt changes as critical thresholds are exceeded. The responses may also be similar to those described for state and transition models where ecosystems persist in a particular state or condition and then abruptly switch to a new condition (Westoby et al., 1989). Once the switch has occurred a high degree of intervention may be needed to return the system to its previous state.

Application to TMG

In the TMG, most groundwater-vegetation interactions will occur in groundwater discharge areas. There probably are three main kinds of groundwater discharge pathways:

- Springs and seeps in localised groundwater systems; where shallow, water-bearing fractures in the sandstones intersect the surface; storage is likely to be limited and flow rates fast; many of these may be in the form of seasonal, perched water tables.
- The contact between the sandstones and the relatively impermeable shales (e.g. Nardouw-Cedarberg contact); these are likely to be higher yielding, with greater storage volume in the fractures and faults and deep flow systems; in some cases they may occur where there are narrow inclusions in the sandstones (current WRC funded study by Smart et al. addresses this scenario in the Kammanasie reserve.
- The faulted contact between the sandstones and the basement rocks (Malmesbury, Cape granite), where the systems are likely to be similar to the previous class in terms of storage and flows; discharge areas can also be found along major fault lines in these contact zones.

The latter two kinds of TMG groundwater systems have the greatest potential for exploitation (Weaver and Talma, in press). The vulnerability of the ecosystems dependent on groundwater is likely to be highest in the localised systems but, given the potentially high flux rates and thus the ability to vary water levels very rapidly, any of these systems could be vulnerable to exploitation of the groundwater.

Fynbos ecosystems and groundwater

The vegetation of the TMG group is commonly known as fynbos because of the characteristic small-leaved and finely-branched shrubs and reeds. It is internationally recognised as a hotspot for plant biodiversity with some 8 580 plant species occurring in an area of about 90 000 km^2 (Cowling et al., 1992). About 68% of these species are endemic (found nowhere else) and there are six plant families which are endemic to the fynbos. One of the largest is the Bruniaceae which has many species that are characteristic of wetlands and seeps.

Fynbos shows large changes in species composition over altitudinal and rainfall gradients and between similar habitats on different mountains and mountain ranges, especially in the south-western mountains. This is important for conservation because the net result is that there are many species with restricted distribution ranges.

A number of syntheses and overviews of fynbos ecosystems and ecology have been written during the last three decades, for example Taylor (1978), Bigalke (1979), Kruger (1979), Boucher and Moll (1981) and Cowling (1992). The main emphasis of these syntheses has been on the flora and the ecology of the plants, especially the role of fire, soil nutrients, and the Mediterranean climate in the evolution and dynamics of these ecosystems. The emphasis also has been on the terrestrial (dryland) ecosystems and the ecology of springs, wetlands or aquatic systems, where there may be groundwater dependence, has been neglected. A detailed description of the aquatic communities of the Berg River is given by Harrison and Elsworth (1958) and of the Eerste River by King (1982) but the associated vegetation communities are only described very briefly.

Wetland vegetation

Detailed descriptions of the main wetland vegetation types found in the fynbos are given by Kruger (1979) and Boucher (1988) who recognise three main categories of mountain seep or wetland vegetation on the sandstones:

- shrub dominated communities often with members of the Bruniacaeae, Proteaceae and Asteraceae;
- those dominated by Ericaceae and Restionaceae; and
- those dominated by the Restionaceae which vary from tall (3 m) to short (0.25 m).

These communities are typically distinct from the adjacent dryland communities in both appearance and species composition. Similar vegetation types can be expected around springs and along watercourses and streamlines where the abiotic conditions are suitable. There are some plant species which appear to be restricted to these habitats (Kruger, 1979) but rarely to a single seep, spring or wetland although, given the high diversity in fynbos, it is risky to generalize too much. The structure and composition of this wetland vegetation appears to be related to water availability and quality, water flow rates and oxygenation (e.g. water logging) as well as other habitat factors (e.g. soils, geomorphology) but no detailed studies have been done of these relationships.

There is a large body of literature on the responses of fynbos to fire and the role of nutrient availability in fynbos structure and dynamics but comparatively little work has been done on plant transpiration and drought stress. The available data show the expected trends: deep-rooted shrubs (e.g. Proteaceae) experience little summer moisture stress; shallower-rooted shrubs are more variable but generally show greater moisture stress; whilst shallow-rooted growth forms, such as the restioids, show the greatest moisture stress (see reviews by Smith et al., 1992, Stock et al., 1992). The Proteaceae in particular show little sign of moisture stress and continue to transpire and photosynthesise at high rates even in apparently dry conditions (Van der Heyden and Lewis, 1989, Richardson and Kruger, 1990). The extent to which this water is drawn from the unsaturated rather than the saturated zones of the weathered profile is not known but, given the typically shallow TMG sandstone soils at some of the study sites, some at least must be drawn from the weathered and fractured underlying rocks.

The Proteaceae are known to be deep-rooted. Bredenkamp et al. (1995, Fig. 4.3.17) report that borehole water levels in the TMG of the Zachariashoek catchment, in the Wemmershoek mountains near Franschhoek, fluctuated from 2 to 8 m below the surface. These depths are easily within reach of the roots of Proteaceae and probably other plant species as well. These observations were only made in one catchment but they do suggest that even typical dryland species may be tapping into the saturated zone or, more accurately, the capillary fringe.

Animals

The vertebrate fauna of the Cape fynbos is poor in species compared with the fauna of the other biomes of South Africa. There are some mammal species, notably the otters, water mongoose and herbivorous vlei rats (e.g. *Otomys* species), whose preferred habit is in or near moist areas (Lloyd, 1988). None of these species are completely restricted to the fynbos on the TMG. The connection with groundwater would be indirect except for the herbivores which depend on the relatively palatable vegetation that grows in seeps and wetlands.

The same would apply to the birds (Brooke, 1988) with the possible exception of the Grass Owl which depends on the grassy vegetation found in certain wetland areas (Palmer, 1988). A number of reptile species occur or hunt in aquatic habitats, none are spring or wetland specialists or restricted to fynbos on TMG (Baard, 1988). There are a variety of amphibians, many of which are rare and have restricted distributions (Picker and Baard, 1988). A number of species require perennial water but the extent to which their populations or habitats depend on groundwater, as opposed to surface water, discharges is unknown. The same applies to the indigenous freshwater fish species (see Hamman, 1988).

Aquatic ecosystems

There have been some national overviews of South Africa's river ecosystems (e.g. Davies et al., 1993) and wetlands (e.g. Cowan, 1998 and Cowan and Van Riet, 1998) but little attention is paid to groundwater dependency. The one detailed study of the links between geomorphology, hydrology and the biota is of the Sabie-Sand River system in the Kruger National Park (Jewitt et al., 1998) but the environment and groundwater systems in the Cape TMG are very different. The most detailed review for the Cape region was compiled by King (1988). Both the terrestrial and aquatic invertebrates in fynbos generally are poorly known and there may be numerous endemic aquatic or otherwise water dependent species (King et al., 1988). Aquatic ecosystems in the Cape TMG are thought to be very sensitive to changes largely because of the low productivity, which results in slow development and extended life-cycles of the organisms involved. These features inhibit recovery and reduce the resilience of the aquatic ecosystems (King et al., 1988). In addition, many aquatic invertebrates in the headwater streams appear to be totally water dependent and woul not tolerate the seasonal or periodic drying up of the stream.

Observations that may indicate groundwater dependence

The CSIR has been involved in collecting information on the impacts of groundwater abstraction for a water rights dispute between adjacent landowners in the Hex River Valley (GCS, 2000). The drainage in question is a typical, steeply sloping TMG mountain stream, which has a rubble filled valley bottom and is lined with riparian shrubs. There is evidence that groundwater abstraction from five production boreholes in the valley has drained water from the alluvium and caused the stream to remain dry, for the first time, during the long summer of 1999/2000. Die-back was observed in the riparian vegetation by CSIR staff who carried out the streamflow measurements at the site. The circumstantial evidence suggests that the die-back was caused by the lowering of water levels in the alluvium during the abstraction of groundwater.

Conclusions

The fynbos is a unique and ecologically important vegetation type, but little is known of the hydrological functioning of the groundwater dependent communities within this biome. There is no published documentation of groundwater dependency by ecosystems in the TMG. Two WRC funded projects are underway to assess examples of aquatic (Saayman, pers. comm.) and terrestrial (Smart, pers. comm.) ecosystem dependency in the TMG, as well as a more generic project looking at groundwater dependent terrestrial ecosystems nationwide.

Groundwater dependent communities in the TMG are thought to be:

- the smaller seeps, springs and wetlands in the mountains;
- the larger bottomland wetlands, mostly in river valleys, where the relative contributions of surface and groundwater are unknown; and
- the long and extensive riparian habitats and stream ecosystems that are dependent, to some extent and from various channel sections, on groundwater discharge during the summer droughts.

Other TMG groundwater dependent ecosystems are those in cave and other underground systems, and coastal discharge zones where freshwater is thought to create lower salinity conditions. Both of these situations are largely undescribed.

The available information gives indications of the kinds of situations where fynbos ecosystems may be dependent on groundwater discharge. It also provides some *a priori*, qualitative estimates of the degree of dependence and vulnerability. But there is very little information which can be used to assess the groundwater requirements of dependent ecosystems for the reserve determination. For example:

- How much water is needed?
- How should that water be distributed in time and space?
- What is the minimum water requirement to prevent ecological degradation?
- What water quality parameters are vital for ecosystem functioning and what is their natural range?

Or when addressing the information needs of managers of these resources:

- How can one monitor responses to changes to minimise adverse impacts?
- What mitigatory measures can be taken?

These questions are made even more difficult to answer because of the delayed nature of the responses of the aquifers although this may not be applicable if the flow rates are as high as is being suggested (see Weaver and Talma, in press). The questions outlined above are key ones for the proposed research programme on the groundwater systems and exploitation potential of the TMG. They need to be developed and refined by both geohydrologists and ecologists.

The field of groundwater and vegetation interactions crosses traditional disciplinary boundaries and has typically been neglected worldwide, at least a far as explicit modelling of these links is concerned. The interactions also bridge the boundaries between the components of the Resource Directed Measures (e.g. rivers and wetlands) and therefore cannot be viewed independently. Finally, these interactions are mediated through root systems, probably the least understood parts of plants because they are underground and difficult to study. These linkages and interdependencies also need to be addressed in any research programme that emerges from the reviews of information of the aquifers of the TMG.

Priorities for research

There is an urgent need to be able to predict the ecological consequences of groundwater abstraction in the TMG. Existing knowledge prepares us very poorly for this challenge. The following are thought to be priority research areas in order to begin to meet this need.

- Identify and locate/map the dependent ecosystems or communities.
- Explain the functional relationship between these ecosystems and groundwater, including the degree of dependence, seasonal variations and quantitative aspects of the dependence.
- Prioritise the various dependent ecosystems in terms of suspected ecological importance and vulnerability.
- Better understand the flow paths, interconnections and residence times of groundwater, such that the zone of influence of abstraction proposals can be predicted. It is important to know where in the landscape abstraction may cause changes in baseflow or other discharge.
- How much of the baseflow in rivers is produced in the lower parts of catchments as opposed to the upper parts (where the groundwater discharge may be unaffected by abstractions).

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Groundwater Quality and Fitness for Use

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Abstract

Natural groundwater in the Table Mountain Group (TMG) has a high quality and it is eminently suitable for most purposes. The groundwater tends to be slightly acidic, soft to very soft and, therefore, corrosive. Ferrous iron is prevalent in the Nardouw Formation and to some extent also in the Peninsula Formation. The presence of Fe causes borehole clogging and related problems, particularly in association with sulphate. The Fe occurrence is only partially understood and research is needed for identifying the processes of its formation and for developing suitable prevention measures. The TMG Aquifers consist of inert quartzitic rocks, are highly vulnerable, and special protection strategies need to be designed.

Introduction

The TMG Aquifers generally yield groundwater of high quality, i.e. it has a very low salinity. Over most of the area, it is also characterised by the absence of calcium and magnesium. This is largely due to the inert quartzitic nature of the host rock, as well as the fact that these resistant rock formations mostly form topographic highs with elevated rainfall and flushing of salts via recharge. Figure 1 shows the extensive occurrence of the TMG rocks, spanning five Water Management Areas (WMAs) [*Area established as a management unit in terms of the Water Act (1998)*]. Figure 2 summarises the more important aspects of the groundwater quality according to each WMA. By referring to Figs. 1 and 2 a lithological and spatial comparison of TMG groundwater quality is possible.

Hydrochemical characteristics

Electrical conductivity

The electrical conductivity (EC) rarely exceeds 100 mS/m with a median value in the 20 to 50 mS/m range. This conforms to the recommended limit for human consumption of 70 mS/m and, with most of the ECs falling in the range from 10 to 100 mS/m, is well within the maximum acceptable limit of 300 mS/m for town supply. In general, the groundwater quality in the Peninsula Formation is similar to that of the Nardouw Formation as reflected in the EC. Elevated ECs are found in the more shale-rich lithologies, for example in the Piekenierskloof and Graafwater Formations occurring toward the coast in the Olifants-Doring WMA. Above average ECs also characterise groundwater in the Peninsula Formation in the Eastern Cape (Fish-Gamtoos WMA), which has higher shale contents than its lithological equivalent in the Western Cape (Meyer, pers. comm.). In the coastal areas, cyclic salts from marine origin slightly increase the EC of groundwater. Weaver et al. (1999) investigated this phenomenon in shallow aquifers in the Struisbaai area.

In the three available 1:500 000 map brochures covering the TMG (see Meyer, 1998, 1999 and 2000a), the groundwater chemistry in each of the three areas is briefly described with a number of typical analyses from the various formations with Stiff diagrams. In the case of the Cape Town map sheet 3317, it includes the analytical data for the Brandvlei hot spring that has an EC of only 7.8 mS/m. For this map sheet the groundwater EC generally varies from 7 to 70 mS/m (Meyer, 2000). In the case of both the Oudtshoorn map sheet 3320 (Meyer, 1999), and the Port Elizabeth map sheet 3324, the groundwater EC varies from 10 to 100 mS/m (Meyer, 1998). The significant effect of the interbedded shales in the Nardouw Subgroup on the EC is demonstrated by analytical data for the area near Port Elizabeth where ECs are in the order of 250 mS/m (Meyer, 1998).

Detailed investigations by Kotze (in press) near Oudtshoorn in the Gouritz water management area reveal a better water quality in the Peninsula than in the Nardouw Formation, which is ascribed to the influence of the higher feldspar content and more abundant shale horizons in the Nardouw Formation. However, it cannot be generally assumed that water quality in the Nardouw will be inferior. Instances have been noted where groundwater of similar quality occurs in the Nardouw and Peninsula Formations, for example where fresh surface wa-

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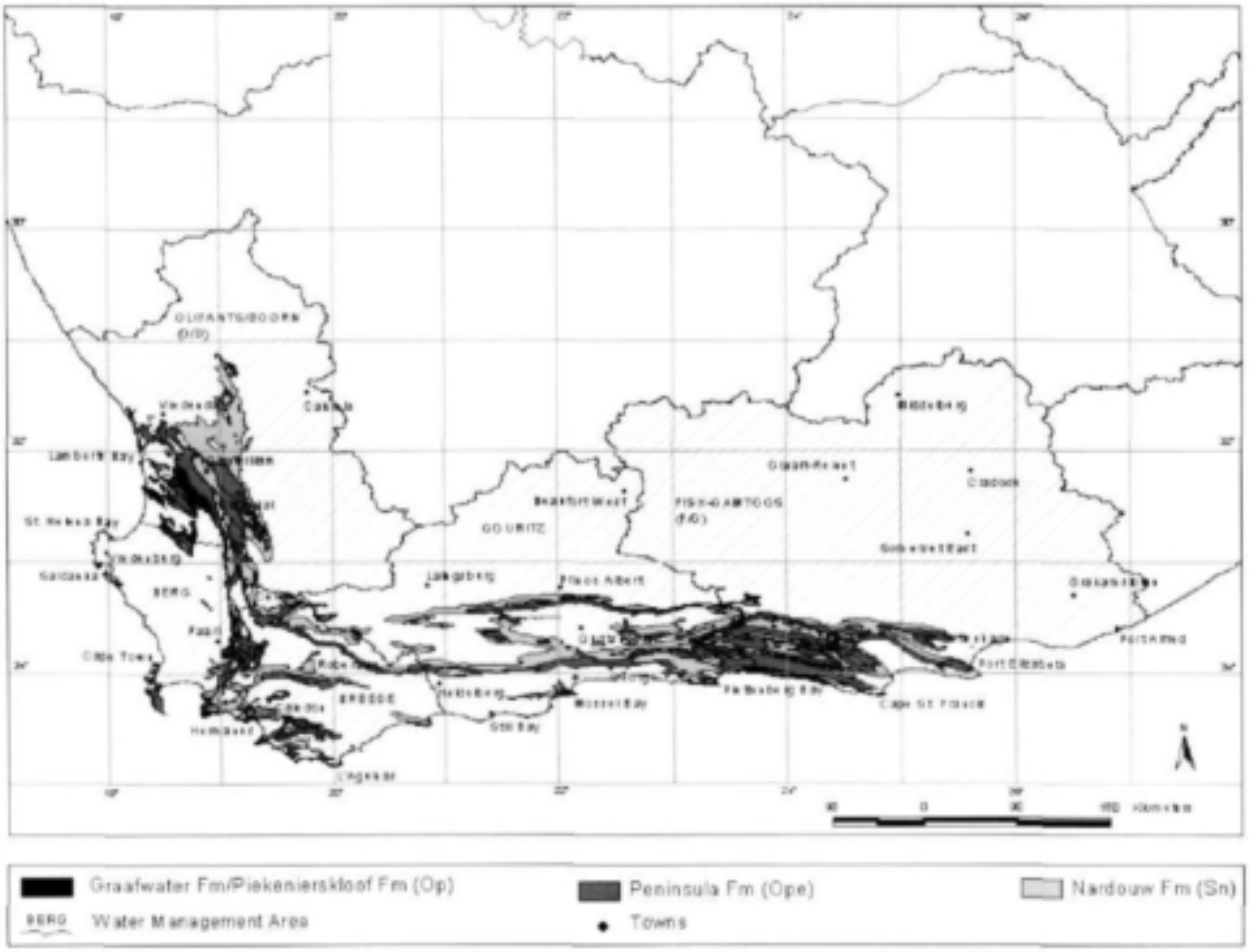

Figure 1
Table Mountain Group and water management areas

ters flow over and recharge the Nardouw along drainage channels as well as where faults displace the Cedarberg Formation, allowing upward leakage of better quality groundwater from the Peninsula Formation.

Major inorganic ions

Generally, sodium is the major cation and chloride the major anion in TMG groundwater. Hence, it is classified, as Na-Cl dominant. This is illustrated by the Piper classification of TMG groundwater (see Fig. 3), which shows groundwater is more often of a (Na) (Cl, (SO_4)) type rather than of a (Ca, (Mg)) (Cl, (SO_4)) type. The former is predominant, constituting more than 60% of analyses over most of the area. However, in the "western limb" and "syntaxis" areas, (Ca, Mg) (Cl, SO_4) water constitutes more than 40% of analysed samples (Vegter, 1995), and in the Groot Swartberg over 50% (Simonic, 2001). However, less than 20% of the TMG sample population is of a Ca-Mg-CO_3 water type (Simonic, 2001). In most rock types, the naturally acidic rainwater dissolves calcite from the host rock, which neutralises the carbonic acid. In the TMG, this process is excluded and the normal development of alkalinity and a buffering capacity by the carbonate system cannot take place. The poorly buffered pH can be seen in the wide pH range measured for all formations. The low alkalinity, low pH and high acidity lead to the widespread occurrence of corrosive waters. In thermal springs, the free CO_2 generally evolves into (calcium) alkalinity, i.e. it causes the points to plot further to the left in the Piper diagram.

In addition, Kotze (in press) noted that the macro-chemistry of groundwater associated with hot springs differs from that of boreholes drilled into the TMG. Hot spring water is more mineralised, and is considered to represent a mixture between TMG water from depth with groundwater in the overlying Bokkeveld shale during its upward flowpath. Shallow boreholes drilled on more localised structures in the Nardouw subgroup, and also those drilled near the Bokkeveld shale contact, are more mineralised.

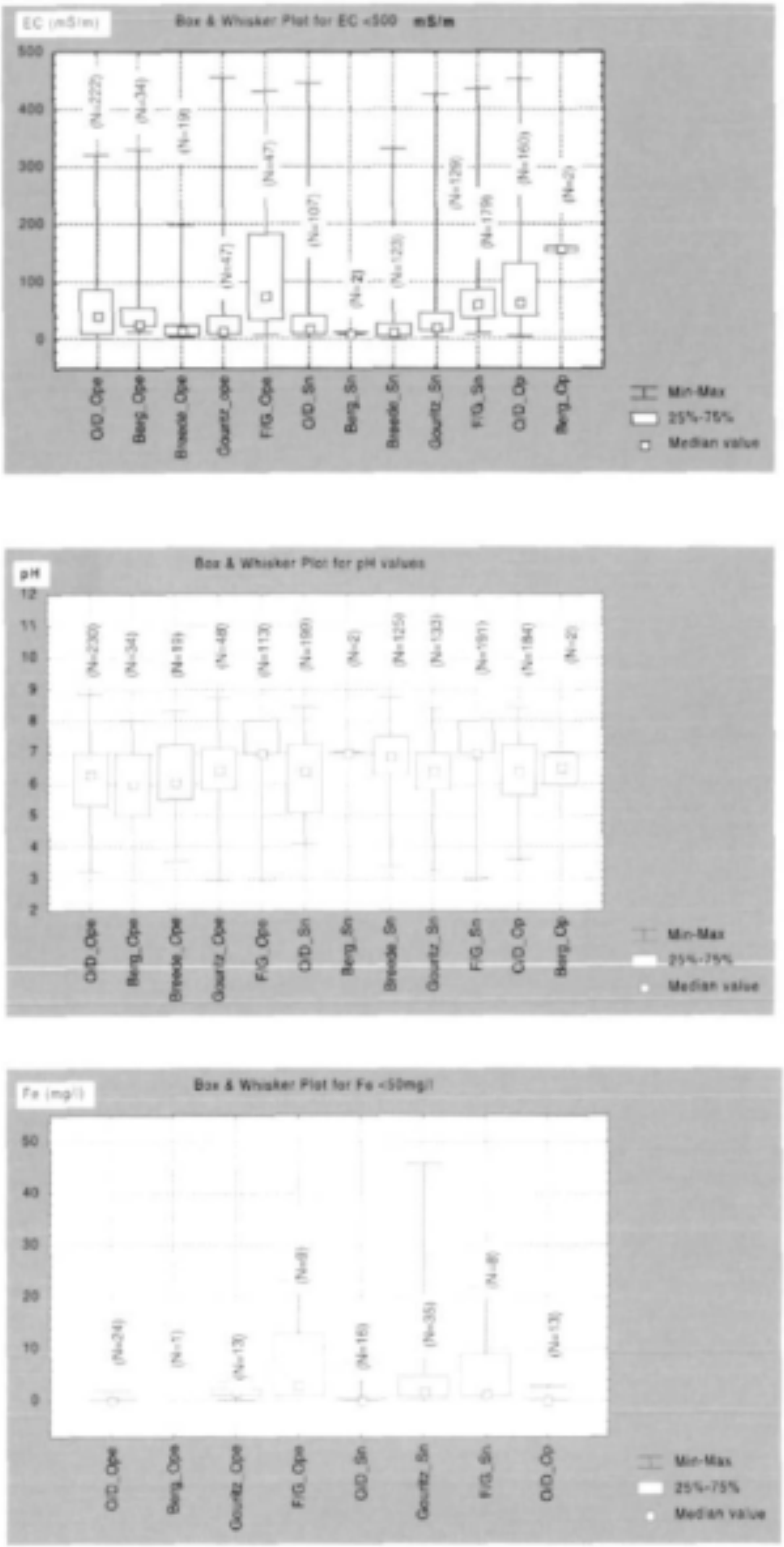

Figure 2

Summary of more important aspects of groundwater quality per water management area

Trace elements

For the Klein Karoo area, Kotze (in press) made the following deductions based on trace element data:

- In general, TMG groundwater does not contain significant concentrations of As, V, Cr, Mo, Pb, Hg or Cd. Therefore, any occurrence of significant concentrations of these metals will indicate contamination. The presence of Cd in one particular borehole was assumed to be due to impurities in the acid used for borehole remediation.
- Ba, Al, and Sr prove to be valuable tracers which are associated with the dissolution of silicate minerals (feldspars and clays, respectively).
- From the limited data set, Al contents for TMG aquifers are generally less than 0.5 mg/ℓ. The Al content for the Peninsula aquifer is generally the lowest (less than 0.02 mg/ℓ) and in-creases in less densely fractured areas. The Al concentration in groundwater is controlled by the dissolution of feldspar and the formation of Al ion complexes.
- Ba proved to be good tracer for distinguishing between Nardouw and Peninsula groundwater. The Ba content in the Peninsula aquifer is generally below 0.002 mg/ℓ, compared to the Nardouw aquifer where it exceeds 0.002 mg/ℓ, with the only exceptions being two boreholes drilled on shallow structures far from the recharge area. Ba is one of the trace elements present in shales. Therefore, the higher shale content of the Nardouw Subgroup, most likely gives rise to the higher Ba concentration in Nardouw groundwater.
- Sr seems to be the most informative trace element for TMG aquifers and commonly replaces Ca and K in feldspar minerals. Sr concentrations are the lowest in the Peninsula aquifer (< 0.003 mg/ℓ).
- Ni, Cu, Zn and Co are present in groundwater in contact with minerals containing these trace elements, in shales and quartz veins (Hälbich et al., 1995).

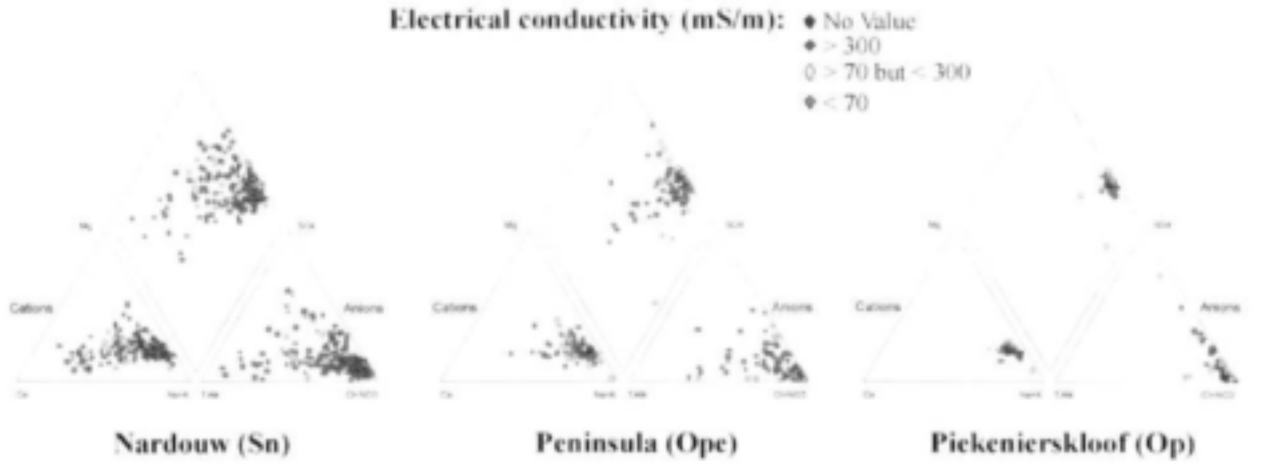

Figure 3

Piper diagrams for the Nardouw, Peninsula and Piekenierskloof formations

- Mn concentrations are generally low (< 0.1 mg/ℓ) and increase towards the Baviaanskloof Formation/Bokkeveld Group con-tact.
- Fe concentrations are generally low (< 0.1 mg/ℓ) and increase towards the Cedarberg Formation contact and in shallow boreholes drilled into weathered TMG rocks. Fe concentrations increase with a decrease in pH and dissolution of pyrite, leading to the formation of sulphates in an oxidising chemical environment;
- B (boron) seems to be an important indicator of flow paths through Enon, Bokkeveld Group or alluvial aquifers, which overlie the TMG.

Hydrochemical problems

Corrosivity

The softness of TMG groundwater together with its poor buffering capacity and acidic nature results in the water being corrosive. The pH is generally in the range of 5.5 to 7 (Fig. 2b). According to Simonic (in press), groundwater is classified as being soft and even very soft in parts of the Breë and Gouritz water management areas. In the Eastern Cape the groundwater is moderately soft (Simonic, 2001).

As TMG water is aggressive, care must be taken in the selection of materials such as well screens, casings, reticulation piping and reservoirs. Corrosion of conduits and reservoirs can have a significant financial impact and can affect the water quality to a point where it becomes unfit for household use (Mackintosh et al., 1998). The problem can be overcome by good design, for example using corrosion resistant materials such as PVC. In addition, suitable quality steel must be used for borehole pump components. At one borehole of the Klein Karoo Rural Water Supply Scheme, particularly corrosive water (pH 3.6) destroyed a new bronze submersible pump and impellers within 25 months. Treatment and stabilisation of the waters can reduce reticulation system corrosion (Mackintosh, 2001).

Iron and sulphate

In anaerobic conditions TMG groundwater contains ferrous iron (Fe^{2+}) of up to several milligrams per litre (Fig. 2). This is particularly prevalent in the Nardouw Formation in the Gouritz WMA and in both the Peninsula and Nardouw Formations in the Eastern Cape. The concentrations shown may underestimate the problem, as exact concentrations of Fe in the aquifers are generally unavailable, largely because of the instability of dissolved iron in the water samples.

The presence of iron gives the water a metallic astringent medicinal taste. The taste threshold is approximately 0.3 mg/ℓ and above 0.1 mg/ℓ it causes other aesthetic problems such as staining of laundry, walls and plumbing fixtures (Mackintosh, 1998). Once exposed to oxygen the Fe^{2+} oxidises to Fe^{3+} and precipitates as $Fe(OH)_3$ giving the water an undesirable reddish brown colour. A major problem with ferruginous groundwater is the tendency for iron bacteria to establish themselves together with slime forming bacteria, which then create a slimy reddish brown substance clogging pump inlets, well screens, and the reticulation systems. Measures that can be taken to manage this problem are discussed by Jolly et al. (2001).

At Arabella Country Estate the oxidation of sulphides caused the groundwater pH to decrease from 6.5 to 4.0, while sulphate increased from 7 to 70 mg/ℓ and the Fe concentration from 10 to 20 mg/ℓ (Parsons, pers. comm.). The sulphides originate from pyrites in the Bokkeveld Group, the Cedarberg Formation and secondary enrichment in a fault zone. It is noteworthy that the problem only emerged to its full extent after the second year of pumping. Similar conditions occurred at Dysselsdorp in the Klein Karoo Rural Water Supply scheme where the groundwater pH decreased to 2.8 at borehole DP 28 (GCS, 2000). The occurrence of the low pH and high iron levels has major ramifications for future treatment and usage of TMG groundwater.

Nitrate and phosphate

Inspection of the available data on the National Groundwater Database (NGDB) confirmed that the isolated occurrences of the nutrients nitrate and phosphate in groundwater from the TMG are directly related to pollution. Generally, the occurrence of phosphate in groundwater is limited due to the abundance of calcium, but in the TMG phosphate can attain measurable concentrations due to the paucity of calcium.

Pesticides

In a study carried out in the Hex River Valley, it was found that all the pesticides used in the cultivation of crops degrade rapidly enough not to be found in the groundwater (Weaver, 1993). In shallow groundwater signs of irrigation return flow was confirmed by the presence of slightly elevated levels of nitrate.

Saline or brackish water intrusion

The quartzitic TMG generally forms steep, rugged and relatively inaccessible terrain for drilling rigs and farming machinery. In addition, soils are poorly developed for agricultural purposes. The less resistant, overlying Bokkeveld Group shales on the other hand, form fertile, more easily worked soils on flatter terrain occupying intervening valleys, and are suitable for agricultural development. In instances where the groundwater quality in the Bokkeveld is more saline, irrigation boreholes are commonly developed in the adjoining TMG. The lowering of groundwater levels causes reversal of the flow direction, resulting in the intrusion of poorer quality water from the Bokkeveld shale water into the TMG. Examples where such intrusion have occurred are the Hex River Valley (SRK, 1997), Olifants-Doring WMA (Hartnady, pers. comm.), and at Dysselsdorp.

The coastal aquifers are particularly susceptible to seawater intrusion, and this has apparently occurred at Struisbaai (Weaver et al., 1999) and Vleesbaai (Meyer, pers. comm.). The earlier well field at Struisbaai was close enough to the shoreline to be affected by seawater intrusion, while the salinity in the new well field located further inland, can be ascribed to sea-spray originating from the southwest (Weaver et al., 1999).

Pollution

The TMG aquifer system largely occurs in rugged terrain, which often comprises protected mountain catchments and, until now, relatively little development has taken place in areas overlying these aquifers. As a result, pollution of this resource is likely to remain limited. The excellent water quality in this aquifer has to be protected and as a result, the Department of Water Affairs and Forestry has been particularly strict in this regard when evaluating applications concerning waste disposal sites, industrial effluent management, and land use rezonings.

Conclusions

The TMG underlies a significant part of the Western and Eastern Cape. Generally, the water quality is excellent with a very low salinity because of the inert nature of the rock, mountainous terrain, and locally high rainfall.

The TMG groundwater consists mainly of a low salinity Na-Cl type, and is very soft. It is generally acidic, poorly buffered due to the low calcium and bicarbonate, and, therefore, very corrosive.

The main problem associated with TMG groundwater, i.e. the presence of iron, sulphate and the associated iron bacteria, is only partially understood.

Although the TMG aquifers are very susceptible to pollution, those parts consisting of rugged, mountainous terrain are naturally protected, as free access of potential polluters is extremely limited. For those areas, which are more accessible, pollution presents a significant threat.

Recommendations

DWAF needs to take special precautions when issuing permits or when sanctioning development in areas underlain by the TMG. This is imperative due to the vulnerability of the TMG Aquifers to pollution, the sandy soil cover, the limited attenuation capacity, poor buffering capacity of the water, and the need to maintain the excellent water quality in these aquifers.

Research needs

The Nardouw Formation is postulated as the source of the iron in the groundwater. Confirmation is required to ascertain if this is actually the source. For this purpose it will be necessary to determine the mechanisms of Fe dissolution and the role of iron- and sulphur bacteria. The geographical and geological setting as well as other factors may play a decisive role in the release of the iron from the host rock.

The susceptibility of the TMG Aquifers to pollution needs the drafting of specific protections measures for use by DWAF in the decision making process.

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Treatment of Soft, Acidic and Ferruginous Groundwaters

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Abstract

The soft, acidic nature of Table Mountain Group (TMG) groundwaters results in aggressive and corrosive attack of fittings, conduits and reservoirs. Such attack can have significant financial impact, and can lead to deterioration in water quality to a point where water is unfit for household use. Furthermore, these groundwaters frequently contain problematic levels of dissolved iron and, to a lesser extent, dissolved manganese. Even low concentrations of these dissolved metals cause poor taste, poor appearance and the staining of laundry and walls. This paper provides a brief overview of water treatment requirements to address the abovementioned problems, and provides design considerations applicable to both conventional and small scale groundwater treatment plants.

Introduction

Significant areas of the southern and eastern fringes of South Africa are underlain by thick sandstone formations of the TMG. The importance of these deposits is that they contain sizeable aquifers of which many are tapped by local towns, villages and farmers. Groundwater abstracted from these aquifers is usually low in suspended solids and bacteriologically safe, hence the use of groundwater is often regarded as being preferable to the use of surface water. However, inherent chemical characteristics of these groundwaters can necessitate treatment.

Generally, TMG groundwaters are soft and acidic, typically with low conductivity (5-50 mS/m), low total alkalinity (0-20 mg/ℓ as $CaCO_3$), low calcium (0-20 mg/ℓ as $CaCO_3$) and low pH (4.0 - 6.0). These characteristics result in the water being corrosive (to metals) and aggressive (to cement concrete), attacking pipes, conduits and reservoirs. Such attack can have significant financial consequences, arising from:

- lost water;
- replacement and repair of supply pipes, conduits and reservoirs; and
- replacement and repair of household geysers and plumbing.

Furthermore, such attack can result in a decrease in water quality as a result of both:

- raised levels of dissolved metal corrosion byproducts, often in excess of standard drinking water requirements; and
- cross-contamination of piped water by groundwater.

In addition, the TMG groundwaters frequently contain problematic levels of naturally occurring dissolved iron (typically between 0.5 and 5.0 mg/ℓ), and to a lesser extent occurrence of manganese (0.1 to 1.0 mg/ℓ). The presence of even low levels of these dissolved metals cause *inter alia* poor taste, poor appearance and the staining of laundry and walls.

Groundwater quality of TMG Aquifers is relatively homogeneous although changes in the concentration of the various major chemical parameters may occur depending on location and depth of specific boreholes.

Treatment technologies and know-how to address the water quality problems associated with these aquifers are readily available for larger water supply systems and areas close to technical support centres. However, treatment technologies and know-how for small scale and/or remote rural application are not as readily available. This paper provides a brief overview of water treatment requirements for TMG groundwaters, and in particular provides design considerations applicable to smaller scale rural application.

Soft water aggression and corrosion

Saturation state with respect to calcium carbonate

In terrestrial waters, the carbonate system is the dominating weak acid-base system to the extent that other systems can be neglected. The carbonate sys-

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tem in water is comprised of the species molecularly dissolved carbon dioxide, $CO_{2(aq)}$, carbonic acid, H_2CO_3, and the ionic species bicarbonate HCO_3^-, and carbonate, CO_3^{2-}, and the water species, H^+ and OH. The relative concentrations of the dissolved species are governed by chemical equilibrium, and it is the interaction between these species that controls the pH of natural waters. Furthermore, consideration needs to be given to inter-phase equilibrium, i.e. water brought into contact with a gaseous phase (carbon dioxide in the air) or a solid phase (calcium carbonate).

For TMG type soft, acidic waters, the solubility of the mineral $CaCO_3$ is of importance. In this context it is necessary to obtain both a qualitative description of saturation (i.e. whether the water is saturated, undersaturated or supersaturated with respect to $CaCO_3$), and a quantitative description of the saturation state (i.e. the mass of $CaCO_3$ that will dissolve into or precipitate from the water). Use of non-quantitative methods such as the *Langelier Saturation Index* and the *Aggressiveness Index* should be actively discouraged, as their values are often misconstrued as being of quantitative significance. It is recommended that the Calcium Carbonate Precipitation Potential (CCPP) type approach is used.

The CCPP defines the mass of $CaCO_3$ to be precipitated from a water to attain saturation with respect to $CaCO_3$. For example, a water with a CCPP of 35 mg/ℓ as $CaCO_3$ will precipitate 35 mg/ℓ $CaCO_3$, to reach chemical equilibrium. In doing so, the pH, total alkalinity and calcium levels of the water will decrease, whilst the CCPP will decrease eventually to zero. Conversely, a water with a calcium carbonate dissolution potential (CCDP) of 10 mg/ℓ as $CaCO_3$ will dissolve 10 mg/ℓ $CaCO_3$ to reach chemical equilibrium. These parameters, CCPP or CCDP, both give a *quantitative* and *qualitative* description of the aggressiveness of a water. Determination of CCPP/CCDP is most easily determined using the computer software, STASOFT (Friend and Loewenthal, 1992). TMG groundwaters have very high CCDPs when first brought to surface (up to, say, 250 mg/ℓ as $CaCO_3$) as a result of the presence of unstable excess CO_2. CCDPs of a well aerated TMG water are typically 20 mg/ℓ as $CaCO_3$.

Aggressive attack and aggression mitigation

Soft, acidic waters attack cementitious material by leaching free lime, calcium aluminates and silicates out of the cement matrix. Where the chemical characteristics of the water are such that it is undersaturated with respect to calcium carbonate, progressive leaching of calcium minerals will occur, and may result in the eventual failure of the structure. Such attack is referred to as aggressive attack and the water is referred to as aggressive water. It should be noted that TMG derived groundwaters are generally highly aggressive to commonly used cement type materials (Mackintosh et al., 1998).

In order to prevent aggressive attack of distribution networks, it is important to alter the chemical characteristics of the water so that it is saturated with respect to $CaCO_3$ prior to distribution in the reticulation network. Under such conditions, initially the dissolution process continues with the more soluble free lime being leached from the outer surface of the cement paste. Dissolution of free lime results in pH increase, and saturation with respect to $CaCO_3$ at the cement surface. Concomitant precipitation of $CaCO_3$ takes place, sealing off the uncarbonated cement surface from the bulk water body, and thereby preventing further dissolution. To guard against the development of undersaturated conditions resulting from carbon dioxide generation by biological activity, a slight degree of supersaturation is desirable. To prevent aggressive attack by soft, acidic waters a CCPP of 1 to 4 mg/ℓ (as $CaCO_3$) is usually recommended (Loewenthal et al., 1986).

Corrosive attack

When water is conveyed, stored or heated, it will react with metal components in the water distribution system and with storage tanks, geysers and other plumbing components. In Southern Africa the most commonly utilised metal components are galvanised steel, epoxy lined steel and copper for pipes; glass lined or copper domestic hot water cylinders; galvanised steel storage tanks; and brass or galvanised steel fittings.

Galvanised steel components are mostly confined to the inland hard water areas, because galvanised steel is very vulnerable to soft water corrosive attack. Copper is commonly used in soft water areas, mostly along the coast. Corrosion of metals principally results from oxidation and reduction reactions at sites on the metal-water interface. Depending on the characteristics of the water and the metal, the reactions may give rise to continous dissolution of the metal into the water (corrosion), or precipitation of stable minerals onto the metal surface, thereby reducing the areas of active electro-chemical sites and the rates of reaction, even eventually stopping the corrosion completely (passivation).

Whilst the corrosion processes in water is complex, it is suffice to note that TMG derived groundwaters are generally highly corrosive to commonly used metals (for further detail relating to corrosion see Stumm and Morgan, 1996; AWWA, 1996, Mackintosh et al., 1999).

Corrosion mitigation

Control of corrosion in low pH, low alkalinity waters may take several forms including selection of materials resistant to corrosion and chemical addition. In brief, corrosion prevention and minimisation approaches include consideration of the following:

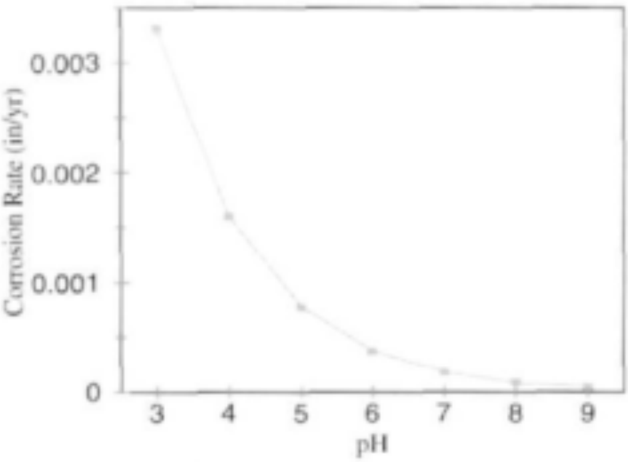

Figure 1
Influence of pH on the uniform corrosion of copper tubing (from AWWA, 1996)

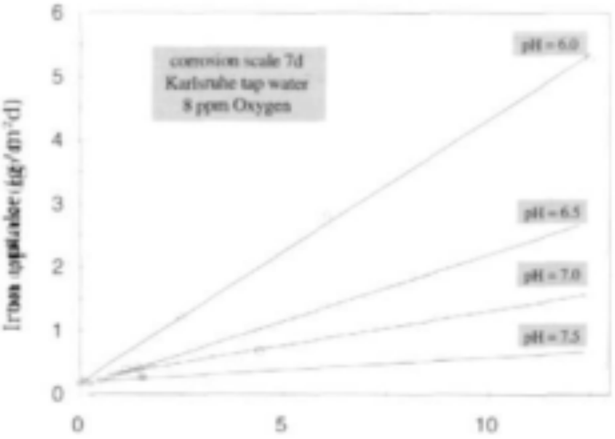

Figure 2
Influence of pH and CO2 concentration of synthetic water on the iron uptake rate in steel pipes with scale (from AWWA, 1996)

Materials selection

Lead pipe, lead solder, uncoated steel and galvanised pipe are not suitable for soft, acidic waters. Whilst iron and copper are subject to corrosive attack, water conditioning requirements to reduce corrosion to acceptable levels are reasonably readily achieved.

Phosphate

Poly- and/or ortho-phosphate addition with pH adjustment to neutral or slightly alkaline pH values has been found to be effective in reducing iron and galvanised pipe corrosion. However, human health impact concerns and concerns relating to the discharge of phosphates via waste-waters into receiving natural water bodies exist.

Silicate

Addition of silica with pH adjustment has been found to reduce corrosion in copper, steel and galvanised steel; but the effects are not significantly different from those of pH adjustment only.

Protective films and pH adjustment

If passivating protective films can be formed on plumbing materials, they may become protected from corrosion. In soft, acidic waters the solubility of these films is critical in reducing corrosion rates to acceptable levels. In many cases adjustment of pH and total alkalinity, short of calcium carbonate saturation, gives sufficient protection. For example, with copper, pH increase itself has been found to significantly reduce corrosion through the formation of a stable copper oxide scale (see Fig. 1).

Iron and steel corrosion can also be significantly reduced by pH and total alkalinity adjustment if the pH is initially very low (see Fig. 2).

Stabilisation

The predominant corrosion control measure utilised in most parts of the world is pH adjustment for calcium carbonate saturation control. Most major utilities practice this method of corrosion control because of the relative economy and proven effectiveness of protection.

Stabilisation of soft, acidic waters

The principal treatment component of measures to prevent corrosive and/or aggressive attack by TMG type soft, acidic waters is the chemical conditioning, or stabilisation, of the water. Complete stabilisation of water requires adjusting the chemical characteristics of the water such that:

- calcium and total alkalinity >50 mg/ℓ as $CaCO_3$
- $6.5 < pH < 9.5$
- CCPP of about 4 mg/ℓ as $CaCO_3$.

Stabilisation is usually achieved via the addition of lime ($Ca(OH)_2$), to increase calcium (Ca^{2+}) and total alkalinity levels, and the addition of carbon dioxide, (CO_2), to add carbonate species and adjust pH. Whilst such stabilisation methods are well documented and understood, control of the process requires well trained staff and reliable equipment - both seldom available in the many small towns and communities receiving such waters. At smaller works, it is often the practice that lime is added on its own; thereby creating a poorly buffered product water (no carbonates added) the pH of which will be unstable. (On occasion sodium carbonate, sodium bicarbonate or sodium hydroxide is used; however, this is generally very expensive and is not practically effective with soft water as no calcium is being added.) For the rural small volume user, lime mediated stabilisation is not practically feasible, and the costs of corrosion/aggression are usually significant (Mackintosh et al., 1998). An alternative approach is partial stabilisation using limestone.

Partial stabilisation of soft, acid waters with limestone

In the limestone contact process the existing natural driving force of the water (CCDP) is used to take up the necessary carbonate and calcium species by exposing the water to solid limestone ($CaCO_3$). Typically a water with CCDP of 25 mg/ℓ $CaCO_3$ will take up 25 mg/ℓ $CaCO_3$ if sufficient contact time is allowed to reach chemical stability; in doing so pH, total alkalinity and calcium levels of the water naturally increase to desirable levels. By definition this approach will never lead to a $CaCO_3$ supersaturated water, hence the term "partial stabilisation". Implementation of partial stabilisation with limestone by CSIR at numerous sites in South Africa has shown that correctly implemented partial stabilisation is effective in reducing the aggressive and corrosive characteristics of the water, making the water essentially non-aggressive to cement concrete, non-corrosive to copper and with a significantly reduced corrosiveness to iron. Stabilisation with limestone has also been shown to have significant advantages over the traditional use of lime and carbon dioxide. These include *inter alia*:

- A significant running cost saving of about 75% relative to lime stabilisation. Limestone is significantly cheaper than suitable quality white lime, approximately SAR 225/t vs. SAR 1200/t (year 2001 prices).
- No carbon dioxide is used.
- pH is controlled naturally at desirable levels as the water approaches chemical equilibrium.
- A well buffered product water.
- The process requires little or no operator skill.

Perceived disadvantages of the use of limestone relate to the required contact time (about ten minutes) and associated reactor size and capital costs. However, these perceived disadvantages have been shown to be negligible relative to the significant chemical and operational running costs savings, and the robust, simple nature of the limestone based process (Delport, 2001).

Stabilisation of groundwaters

Soft, acidic groundwaters usually have very low pHs resulting from very high *in situ* dissolved carbon dioxide content. When pumped to surface and exposed to the air, the difference in partial pressure between air and water creates a driving force for CO_2 expulsion. Whereas equilibrium between species in the aqueous phase is virtually instantaneous, when two or more phases are present (aqueous, solid and gas), the rate to equilibrium is usually relatively slow. When considering stabilisation of a soft groundwater it is critical to consider the effect of this unstable excess CO_2. Where contact with limestone is practised prior to expulsion of excess CO_2, care must be taken to ensure that excessive limestone uptake does not result from the temporarily high CCDP created by the unstable CO_2. Where excessive limestone uptake is allowed to occur, subsequent significant precipitation of $CaCO_3$ will take place when the unstable CO_2 is gradually expelled from the water.

An example of how to effectively stabilise a groundwater using limestone is the "Spraystab" system; which has been found to be very effective in stabilising, and removing dissolved iron from, groundwater (Mackintosh et al., 1998). The system, as shown in Fig. 3, is suitable for small-scale users (1 to 3 m^3/h).

The system consists of three main components with the following specific functions:

- *Aeration unit*, to strip excess carbon dioxide and dissolve some oxygen into the water to assist in the oxidation of iron and manganese.
- *Stabilisation unit*, to increase calcium, total alkalinity and pH of the water such that the CCDP is significantly reduced. Partial stabilisation is achieved via providing sufficient contact time with a suitable limestone aggregate. The associated increase in pH and total alkalinity promotes the oxidation of iron and manganese to their trivalent state, which is insoluble and precipitates to form floc.
- *Filtration unit*, to remove limestone fines and other insoluble matter such as iron and manganese floc. The filter is a dual media filter comprising both hydro-anthracite and filter sand. The filter bed is divided into two by a splitter to allow backwashing of half the filter area at a time, using the available low volume supply to the aeration unit.

Iron and manganese removal

Groundwater extracted from aquifers is usually low in suspended solids and bacteriologically safe, making a managed groundwater source usually aesthetically superior to surface water. However, TMG groundwater may contain dissolved iron and manganese at problematic concentrations. Whilst iron concentrations of up to several milligrams per litre can exist without discolouration or turbidity in the water when first brought to the surface, with time the iron will come out of solution giving the water an undesirable reddish-brown colour. Furthermore, the presence of both iron and manganese give water a taste described as metallic, astringent or medicinal. The taste threshold for iron and manganese is approximately 0.3 mg/ℓ and 0.15 mg/ℓ respectively.

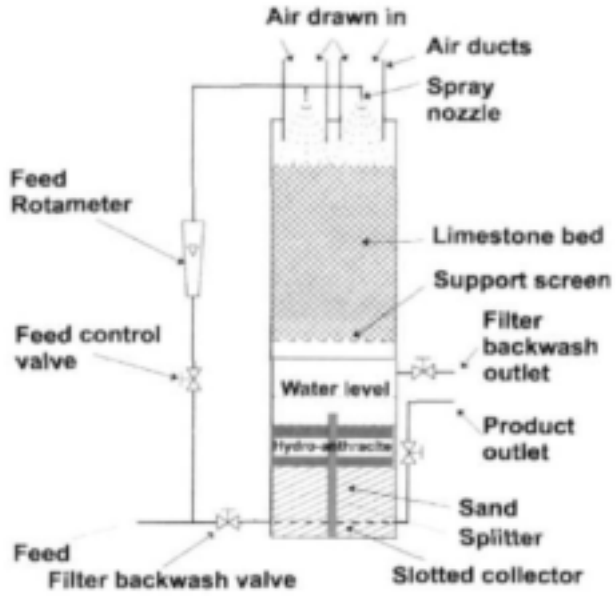

Figure 3

Configuration of Spraystab Unit

Iron and manganese may also cause other aesthetic problems such as staining of laundry, walls and plumbing fixtures at levels above 0.2 mg/ℓ and 0.1 mg/ℓ respectively. It is desirable to remove iron and manganese from water to values below 0.1 mg/ℓ and 0.05 mg/ℓ respectively.

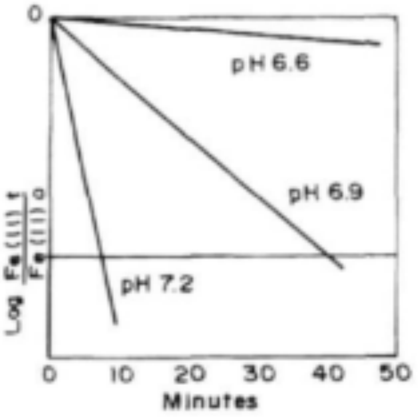

Figure 4

Oxidation of iron at various pH values (from Van Duuren, 1997)

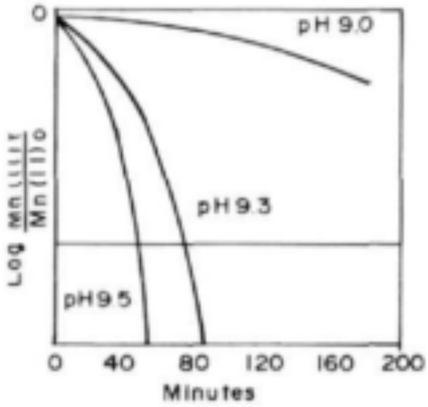

Figure 5

Oxidation of manganese at various pH values (from Van Duuren, 1997)

Water treatment requirements

Treatment requirements for the removal of both dissolved iron and manganese from water are well understood and documented. All methods will require the oxidation of the relatively soluble Fe(II) and Mn(II) to insoluble Fe(III) and Mn(III, IV). This is followed by conventional coagulation/flocculation, and sedimentation in a settling tank, followed by filtration.

Important considerations for the optimisation of iron removal include:

- The rate of oxidation of Fe(II) with oxygen is very pH dependant. In solutions with pH >5.5 a 100-fold increase in the rate of reaction occurs for a unit increase in pH.
- As shown in Fig. 4, Fe(II) requires a pH >7 in order to be oxidised at a reasonably rapid rate.
- Oxidation by aeration is a viable option for iron, and has the additional benefit that concomitant stripping of dissolved carbon dioxide will also occur, thereby raising the pH.
- The oxidation of Fe(II) is catalysed by the reaction product Fe(III). The associated significantly improved efficiency of oxygenation can be capitalised on by contacting the aerated water with Fe(III) in, for example, filter media.
- Ferrous carbonate, such as may be formed when iron rich water is contacted with limestone, is 50-100 times more filterable than the usual Fe (III) form of ferrous hydroxide (Olsen and Twardowski, 1975).
- Soft, acidic waters with low total alkalinity require dosing of an alkali to assist oxidation.

Important considerations for the optimisation of manganese removal include:

- The chemical behaviour of manganese is similar to that of iron; however, it is more difficult to remove manganese from water than iron.
- As shown in Fig. 5, the oxidation of Mn(II) to Mn(III) by aeration is a slow process unless the pH is raised above 9.5. Generally, a stronger oxidant than oxygen is required to remove manganese. Under dual precipitation conditions with iron, reasonable oxidation rates occur at a pH of 8.5.
- The presence of a coating of manganese dioxide on sand grains of a filter has an autocatalytic effect and increases the removal efficiency of manganese.

- The presence of dissolved calcium carbonate is beneficial to manganese removal, possibly due to the formation of manganese carbonate; and the rough surface of limestone has been shown to improve flocculation of manganese even though the manganese precipitate does not adhere to the limestone.
- Soft, acidic waters with low total alkalinity require dosing of an alkali to assist oxidation.

Conventional iron and manganese removal

Because of the slow reaction kinetics with molecular oxygen, chemical oxidants are often added at the beginning of the water treatment process to oxidise iron and manganese. Common oxidants which may be used are chlorine, potassium permanganate, ozone and chlorine dioxide. With the use of such chemical oxidants, oxidation is quite rapid at pH 7 and higher. Very soft waters with a low total alkalinity and low pH (pH 4 to 6) require pre-dosing with an alkali. Hence, conventionally iron and manganese removal from TMG type soft waters is achieved by dosing of lime (pH and alkalinity adjustment) followed by chemical oxidant, coagulation, floc formation and settling, followed by filtration. This necessitates a combined retention time of about two hours. However, this conventional approach is both impractical (chemical dosing and expert operator input requirements) and costly (high capital cost and high running costs) for small rural water treatment systems. (For further details of conventional large-scale iron and manganese removal, the reader is referred to Van Duuren, 1997.)

Small-scale iron and manganese removal

In rural communities in developing countries, processes requiring dosage of chemicals are to be avoided because of the cost of mechanical plant and chemicals, as well as the lack of technical back-up and frequent failure of poorly maintained water treatment plants. Under these conditions methods using natural processes such as aeration and multimedia-filtration should be encouraged. For the use of these simple processes to be effective, maximisation of the optimising factors noted above is crucial; in particular, additional benefit is provided for both removal of iron (Smith et al., 1993) and manganese (Hamidi and Smith, 1992) by including contact with limestone.

The aforementioned Spraystab unit (see Fig. 3), capitalises on these design considerations and has been shown to be effective for iron removal for small scale users (1 to 3 m^3/h) where iron is less than 3 mg/ℓ. This system can be upgraded to treat, say, 10 m^3/h and iron of up to 5 mg/ℓ. Importantly, the Spraystab system is able to achieve iron removal with a total retention time of about fifteen minutes; i.e. considerably less than the two hours of a conventional system. Larger plants can be designed to capitalise on the chemistry/engineering of this approach, and a number have been installed by CSIR in the Western Cape, South Africa. These plants have been shown to be effective in stabilisation, and iron and manganese removal. Such a plant would typically consist of an aeration tank, autocatalytic up-flow reactor/separator, dual media filtration (hydro-anthracite and sand), followed by a limestone contactor. For rural schemes, these iron/manganese removal systems have significant advantages over conventional processes including:

- Low operator skill and input requirements.
- No risk of oxidant and/or alkali overdosing.
- Significantly reduced capital and operating cost savings.
- pH is controlled naturally at desirable levels.
- No use of industrial type chemicals.
- No use of dosing pumps.

Finally, it is important to note that when the Fe or Mn ion is associated with natural organics present in the water, typically dissolved humic substances, oxidation will only be possible with use of powerful chemical oxidants.

Conclusions

TMG groundwaters are soft and acidic. Conduit and reservoir materials selection, and water conditioning are important in preventing the pernicious effects of aggressive and corrosive attack. Partial stabilisation will make the water essentially non-aggressive to cement concrete, non-corrosive to copper and with a significantly reduced corrosiveness to iron. Use of correctly designed limestone contact systems eliminates most of the complications of conventional stabilisation plants, and supervision and maintenance is minimal. Careful consideration must be given to unstable excess CO_2 when designing groundwater stabilisation systems.

TMG groundwaters may contain dissolved iron and manganese at problematic concentrations. The conventional approach to iron and manganese removal is usually not appropriate for groundwater schemes, being impractical and too costly. Methods using natural processes, such as aeration and multi-media-filtration, in combination with limestone contact, have been shown to be effective and have significant operational and cost advantages over conventional approaches. For these systems to operate successful, careful consideration must be given to design considerations.

Acknowledgement

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Occurrence and Management of Iron Related Borehole Clogging in Table Mountain Group Aquifers

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Abstract

The first part of this paper discusses theoretical conditions and circumstances influencing borehole clogging as a result of iron precipitation and allied biofouling processes, covering the chemical and biological processes involved, the monitoring of clogging and management measures to reduce clogging. The second part of the paper describes clogging in Table Mountain Group (TMG) Aquifers, its occurrence, effect on abstraction and remediation measures. The groundwater from some of the TMG Aquifers has elevated iron levels (>0.2 ℓ/s) contributing to borehole clogging. In some circumstances iron concentrations exceed 10mg/ℓ although there is no clear correlation between clogging and iron concentration. In advanced stages of clogging borehole yield decreases, although the most noticeable indication of clogging is a dramatic increase in drawdown during pumping with limited effect on yield. Correct management of abstraction can reduce clogging impacts. Boreholes need to be pumped at lower rates and for longer periods, compared to limited periods of abstraction with high abstraction rates and high water level drawdowns. High drawdowns invariably result in water levels dropping below upper water strikes, thus resulting in water cascading down the inside of a borehole. This cascading promotes aeration of the water, dramatically increasing the rate of biofouling. Design of production holes and the management of abstraction in TMG Aquifers, must take into account the added problems of clogging, if failure of abstraction schemes is to be avoided.

PART I: IRON RELATED CLOGGING

Introduction

Borehole clogging as a result of iron precipitation and biofouling has been studied for many years. The clogging process reduces the yields of production boreholes and is a problem experienced all over the world. It is a complex phenomenon that is caused by a variety of physical, chemical and biological factors (Howsam, 1990), functioning alone or in combination with each other (Mansuy et al., 1990). Clogging deposits can be attached to the borehole screen or can occur in the aquifer immediately surrounding the screen and treatment of the problem will differ accordingly. The clogging results in reduced groundwater flow to the boreholes, causing a decrease in borehole efficiencies, a decrease in specific capacity, lowering of the borehole yield and eventually, failure of the pump or the borehole. In addition, in mature biofilms under anaerobic conditions, corrosion of metals occurs as a result of microbial activities resulting in the total disintegration of borehole equipment.

There are differences in the depositional patterns under different environments. Generally, if clogging has affected all the boreholes in a well field, then the clogging is probably caused by geohydrochemical or geomicrobiological processes. If only some of the boreholes in a well field are clogged, the cause will more likely be accidental (Van Beek, 1984). The different depositional environments can result in different rates of clogging, hence the difference in clogging between PVC, iron or stainless steel screens. Deposition over PVC screens seems to be more even, while there tends to be more tuberculation on steel and stainless steel screens. As a result stainless steel wells plug faster than PVC screens - PVC screens have been found to plug on average 63% slower than stainless steel screens under the same conditions.

Clogging can be extremely rapid, reducing the borehole yields to below their recommended capacity within months of installing (Smith, 1982; Hackett, 1987; Cullimore, 1992). Boreholes can however be remediated, although effective remediation requires knowledge on the causes of clogging. The rehabilitation of boreholes is often made very difficult and

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ineffective when the problem is not successfully identified. It is therefore imperative that the type and cause of clogging be identified before rehabilitation is attempted.

Chemical clogging

Clogging of a chemical nature may result from the deposition of chemical precipitates that are often initiated by the presence of oxygen, pH shifts to the alkaline range, or increases in the redox potential. Chemical precipitation processes that can affect the aquifer, the well, the pump and pipework include :

- Iron oxyhydroxides precipitation
  Occurs when ferrous (Fe^{+2}) bearing anaerobic groundwater becomes oxygenated, causing a ferrous to ferric (Fe^{+3}) conversion and the precipitation of insoluble ferric oxyhydroxides.
- Electro-chemical corrosion of components made of iron and steel. Corrosion can lead to failure of pump components, screens and rising mains.

The degree of iron oxidation or reduction is strongly influenced by a number of physio-chemical factors such as:

- redox potential;
- pH;
- the presence of organic compounds;
- dissolved oxygen; and
- micro-organisms (which can affect Eh-pH conditions).

Oxidised forms of iron found in groundwater are typically insoluble precipitates of various morphology at moderate pH ranges.

Within the usual pH range of natural water (pH 5 to 9) and within an Eh range of 100 to 200 mV, a considerable Fe^{2+} concentration can be maintained in solution (Hem, 1970), although soluble ferric may occur at low pH values. However when oxidation takes place due to the introduction of oxygen or via bacterial activity, the precipitation of insoluble ferric products occurs. The Fe^{+2} form of iron is used in bacterial chemoautotrophic oxidation. When oxidation due to well conditions or bacterial activity occurs, precipitation of insoluble Fe(III) products occurs. As the system becomes more oxidised (higher Eh), the ferric ion (Fe^{3+}) or its mineral or polymeric salts (ie $Fe(OH)_3$) become prevalent. By definition of Glathe and Ottow (1972), strongly oxidising conditions occur at or above Eh +390 mV at pH 6.

Ferric iron is soluble at low pH values, but above pH 4.8 the solubility of ferric species is below 0.01 mg/ℓ. Only under highly reduced conditions, such as found in coal, for example, will iron occur as pyrite (FeS_2), which is insoluble.

Groundwater that is high in dissolved iron can be associated with the oxidation of reduced iron minerals. Aquifers that contain oxidised iron minerals and organic debris may provide an environment favorable for iron reduction and high concentrations of ferrous ion in solution (Hem, 1970). Iron reduction and oxidation in most environments can proceed without the intervention of microorganisms, particularly at near-neutral and alkaline pH values, but bacteria are frequently associated with oxidised iron complexes (Aristovskaya and Zavarzin, 1971).

Pumping frequently oxygenates iron-rich water flowing in from the aquifer and iron precipitation can result (Heidel, 1964). Boundary layers in redox-stratified environments such as pumping and recharge wells provide the setting for both chemical and microbiological oxidation of iron.

Insoluble iron compounds make up approximately 90% of the dry weight of iron biofouling deposits (Pedersen and Hallbeck, 1985) therefore necessitate an understanding of iron clogging processes when attempting to prevent subsurface clogging. The chemical and biological mechanisms by which iron may be transformed from the soluble to the insoluble state are not easily distinguishable. McCrae et al. (1975) explained the iron precipitation process as follows:

- Iron is dissolved from iron-containing formations under anaerobic/acidic conditions.
- The iron will remain in the soluble ferrous form until there is a rise in the pH or Eh of the water. An increase in Eh may be encountered because of increased oxygenation as the groundwater approaches a pumping borehole, initiating chemical iron precipitation at the aerobic/anaerobic interface. Some bacteria (like *Gallionella*) can obtain energy from the oxidation of ferrous to ferric iron and tend to grow at the aerobic/anaerobic interface.

Distinguishing between the pure chemical and a biological enhanced process of iron precipitation taking place in this region is very difficult.

The mineral content of the scale developed in a borehole dictates the kind of treatment required to remove the scale. The first minerals precipitated are of low crystallinity (amorphous) and thermodynamically unstable. However, with time the minerals recrystallise and become more stable - the process is called "scale aging". Old scale, because it is more stable, is more difficult to remove. The iron precipitation sequence is:

ferrihydrite → lepidocrocite → goethite.

Dissolving iron oxyhydroxides takes place either via proton assisted dissolution or ligand-promoted dissolution or reductive dissolution.

Biological clogging

Biological clogging is the most common form of clogging of water wells and is commonly referred to as biofouling. About 80% of all wells that are experiencing clogging, have a high level of biological activity (Mansuy et al., 1990). Although iron oxidation is always a chemical proses, bacterial induced iron precipitation is distinguished from chemical iron oxidation by far more rapid and severe clogging (Smith, 1982). Rates of biologically enhanced iron biofouling can be 100 000 greater than rates of chemical clogging. Even under conditions where bacterial levels are low, the bacterial activity increases clogging rates considerably compared to natural chemical clogging (Cullimore, pers. comm.).

Bacteria causing borehole clogging occur in complex biofilm communities. The biofilm can range in size and thickness depending on a number of factors which are usually site specific. The analysis and identification of these microbial communities is necessary in order to understand the underlying biological nature of the problem and to be able to design effective borehole maintenance and control procedures.

There are three major groups of bacteria which have been generally identified as contributing to clogging problems. These three groups have been identified as slime forming bacteria (SFB), iron related bacteria (IRB) and sulphate reducing bacteria (SRB). SFBs are the most common group of micro organisms found in aquifers. The majority of slime forming bacteria are also responsible for large deposits of chemical precipitates leading to the overall volume of biomass. The most frequently described bacterial degradation of borehole performance involves the phenomenon known in the groundwater industry as "iron bacteria". Iron bacteria are described as 'the most notorious microbiological pests in the borehole industry". Iron related bacteria consists of many genera and species of bacteria, with varying morphology and physiology. Attempts to predict the occurrence of iron bacteria and to rehabilitate the systems suffering from them often fails. This may be, in part, due to a lack of understanding by microbiologists of the complexity of the subsurface environment and by hydrogeologists of the nature of the micro-organisms involved (Tyrrel and Howsam, 1997). Typically, most iron related bacteria are also slime forming bacteria which are also capable of precipitating and accumulating chemical precipitates. A biofilm developed on a surface can be particularly hardy, having been found to exist in environments of extreme temperature, pressure and chemical condition. Within a biofilm anaerobic conditions can develop - even in a biofilm only a few millimetres thick (Howsam, 1990). The SRBs grow under the anaerobic conditions within the biofilm. SRBs are obligately anaerobic heterotrophic organisms which use organic matter to assist in the reduction of sulphate to sulfide (e.g. *Desulfovibrio* and *Desulfotomaculum*). The products of sulphate reduction are hydrogen sulfide and sulphuric acid - the sulphuric acid can lead to corrosion, while hydrogen sulfide creates problems with water treatment. There is often an association between pseudomonads and sulfate reducing bacteria involved in corrosive biofouling.

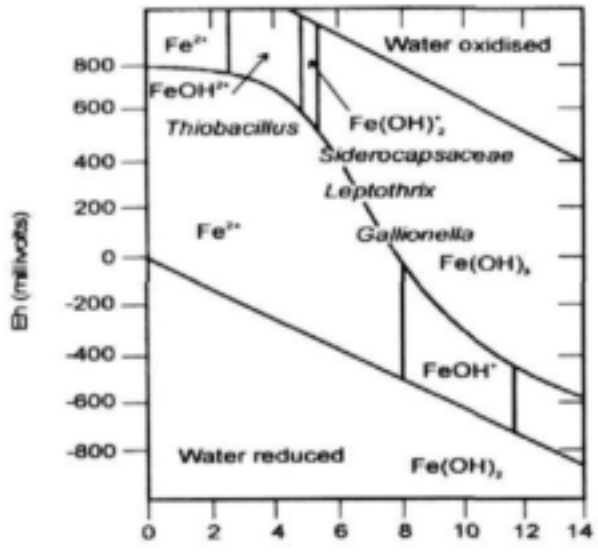

Figure 1

eh - pH diagram for iron species and iron bacteria

Through the years of scattered research, the various iron bacterial species have been linked to specific Eh-pH ranges for growth. Most of these environmental conditions occur in ground water and wells. Bacteria associated with iron cause its precipitation in the oxidised state by modifying the local redox conditions, either directly or indirectly - ferrous irons are oxidised to the ferric state and the ferric irons so produced form insoluble oxyhydroxides.

$$Fe^{+2} + H^{+} + \tfrac{1}{4}\,O_2 \rightarrow Fe^{+3} + \tfrac{1}{2}\,H_2O$$
$$Fe+^{3} + 2H_2O \rightarrow FeOOH + 3H^{+}$$

Most of these reactions are microbially catalysed under natural conditions. The role of microorganisms in iron reduction has only been studied extensively since 1985. Prior to 1985, most geochemists and microbiologists considered Fe^{+3} reduction to be an a biologic reaction initiated by "reducing conditions" (Chapelle, 1992). However, with the isolation and characterisation of Fe^{+3} - reducing microorganisms in the late 1980s, it became clear that this important component of the iron cycle is largely mediated by microbial processes.

Bacteria growth is enhance under conditions of high flow velocities - the higher velocities increase nutrient uptake and thus the rate of biofilm development. The design of the boreholes and the operation of the pumps should therefore be aimed at reducing flow velocities to the lowest possible levels.

Figure 1 shows the Eh-pH diagram for major iron species in relation to the occurrence of iron bacteria in the environment (after Hem and Cropper, 1959; Aristovskaya and Zavarzir, 1971). *Thiobacillus*

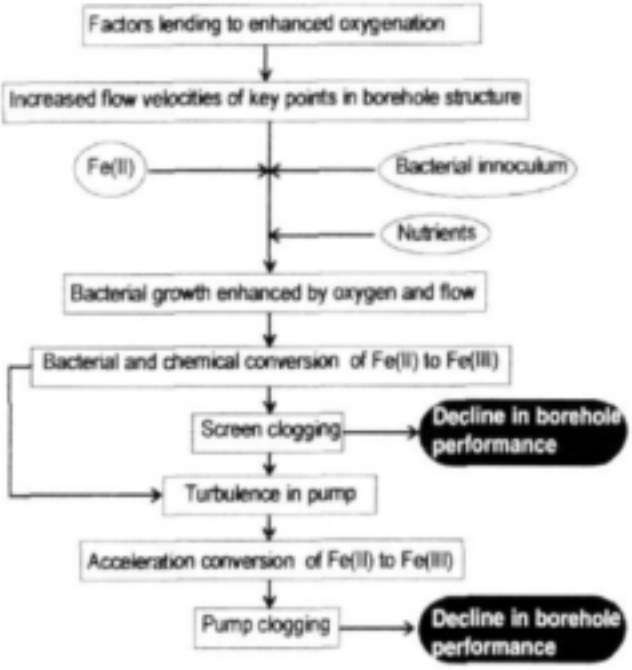

Figure 2

Simple iron biofouling process model

(*T. ferrooxidans*) is an acidophile that uses dissolved Fe^{2+} as an energy substrate and requires an acidic environment. *Siderocapsacae*, *Leptothrix* and *Gallionella* typically thrive at circum-neutral pH, most often at the Eh-pH boundary, which involves the formation of Fe^{+3} precipitates, as the result of their metabolic activities. *Gallionella* is associated with the lowest Eh of the bacteria indicated.

Microbial activity normally concentrates around the redox front - the position where water changes form being reductive (from approximately -50 mV) to oxidative (greater than 150 mV). Positive Eh values support aerobic microbial activity while negative Eh values encourage anaerobic biomass generation - under anaerobic conditions biomass generation is reduced there is a downward shift in pH, a greater potential for gas production i.e. hydrogen sulphide.

A pH of between 7.2 and 8.8 is optimal for the growth of most micro-organisms. At lower and higher pHs the microbial diversity and microbial growth becomes restricted. At pHs of less than 5.5 (as typically seen in the Klein Karoo) the process of biofouling becomes retarded while the only bacteria that grows with any vigour is *Thiobacillus*. The ideal pH for most bacteria is 8.3 - 8.7. At a pH of less than 4.5 microflaura are restricted, although microbial generated acidic leaching can occur (assisted by *Thiobacillus*) if oxygen and sulphates exist. At a pH less than 5.5 biofouling is retarded since the microorganisms are generally traumatised by the conditions.

The redox potential also provides an indication of current growth environments:

- Under highly oxidised conditions (>150 mV), the water being abstracted has passed through a redox front, the front being located away from the borehole, deeper in the aquifer.
- Redox values between -50 and +150 mV indicate a redox front in or directly adjacent to the borehole, with potentially serious impacts on the screens and the pump.
- 50 - 150 mV, pseudomonads are often dominant, especially if a source of organic carbon nutrient exists. Most of these pseudomonads will form a slime, often in the upper oxidised zone in a borehole, with SRBs found in the deeper, oxygen poor, reduced environment.
- The zone between -50 and + 50mV constitutes the redox front and is the biozone of greatest microbial activity.
- at redox values of between -50 and -200 mV oxygen is limited, and SRB corrosion is likely.

Tyrrel and Howsam (1990) demonstrated a simple process model, as shown in Fig. 2, which identifies those factors considered to govern the initiation and the rate of iron biofouling. Iron biofouling requires a groundwater with a 'significant' dissolved iron content, a microbial inoculum and concentration of nutrients sufficient to support an active biofilm. The assumption of Tyrrel and Howsam's (1990) model is that the nutrient supply and microbial inoculum is always present.

The clogging deposits consist of mainly iron hydroxides, microbial cells, ECPS and water and has a slimy/sludgy texture when relatively fresh (Tyrrel and Howsam, 1990). The characteristics of the biofilm change with age and when the deposit is quite old it tends to become harder, brittle and more compact. Oxygen is considered to be the key factor in iron biofouling as it is responsible for the growth of aerobic iron precipitating bacteria and the oxidation of soluble ferrous to insoluble ferric iron. Flow is required for biofilm development and it has been demonstrated that in certain circumstances, higher flow velocities will increase the rate of biofilm development (Pedersen, 1982; Caldwell, 1986). In addition, turbulence caused by higher flow velocities would enhance nutrient uptake (Cullimore, 1986) and also promote nucleation.

Enhanced biofouling is only one of a number of impacts resulting from biological activity. Micro biologically influenced corrosion (MIC) can affect the well screens, the pump and pipework. MIC is caused by various micro-organisms including bacteria, fungi and algae although a group of anaerobic micro-organisms called sulphate-reducing bacteria (SRB) have been cited as the most important cause of MIC (Cloete and Von Holy, 1991).

Monitoring and measuring biofouling

One of the greatest problems related to the clogging of boreholes is related to the monitoring of any clogging taking place. It appears inevitable that some form of biofouling will take place in most boreholes with high iron levels and where oxygen is introduced into the hole. However, groundwater chemistry alone will not necessarily reflect the risk or level of biofouling. Other factors which can be monitored to obtain an indication of where the clogging is taking place, and whether this clogging is chemical or biological in nature are discussed below.

Colour

A clean clear water sample does not necessarily indicate a lack of bacterial growth - if a sample is left to stand and then develops a cloudiness it is likely that some bacterial growth exists. Cloudy water (especially red/yellow or brown/black colouration) is likely as a result of bacterial growth. Use of laser particle sizing systems allows one to count the number of particles and to evaluate the size and shape of the particles in the water. This may allow some form of identification of the structure of the particles and a quantification of the amount of particulate matter.

Odour

Odours commonly related to micro-biological activity include rotten eggs, earthy/musty and fishy smells. The rotten egg smell is associated with anaerobic conditions, the generation of hydrogen sulphide and the potential for the corrosion of equipment utilised in the borehole.

Camera detection

The use of down-the-hole cameras provide direct evidence of the growth of bacteria and the clogging of well screens. Under most circumstances camera investigations are only appropriate in the latter phases of biofilm development and also serve limited purpose in identifying bacterial types or the aggressivity of the bacterial growths. Bacterial growth in a borehole are identified as large nuciod or platelike structures attached to the side of the casing and extending into the water column. A TV camera only allows identification of problems within the borehole, as a result, biofouling in the gravel pack or aquifer cannot be directly observed.

Specific capacity

As a boreholes begins to clog, water has difficulty entering into the borehole through the clogged aquifer and clogged screens, resulting in inefficient flow and a greater drawdown at constant pumping rates. It is however questionable whether monitoring of specific capacity can assist as an early warning monitoring activity, since most boreholes have excess production capacity, i.e. they are pumped at a sustainable rate much lower than the maximum yield potential of the borehole. As a result a high amount of deposition can take place before there is any impact on the efficiency of the borehole and hence the specific capacity. It is likely that a decrease in the specific capacity will take place once clogging is in an advanced stage. Difficulties related to monitoring bacterial growth (because of the attachment - detachment phenomena) necessitates alternative methods of monitoring the clogging of boreholes. If a decrease in specific capacity is noticed (usually a 15 - 20% decrease is used as a reaction level), it is likely that clogging is well advanced and rehabilitation will be necessary. Cases where boreholes are being pumped at a fraction of their capacity (as in the Klein Karoo) any loss in specific capacity probably indicates that advanced clogging has taken place. In monitoring specific capacity it is important that specific capacity is calculated for equivalent conditions, i.e. drawdown must be measured at exactly the same pumping rate and after exactly the same amount of time has elapsed since pumping started.

Bacterial activity

Majority of IRB bacteria are slime formers where the monitoring of bacterial levels can be exceptionally difficult because of the attachment - detachment phenomenon. Should sampling co-inside with the period of detachment it would appear that the bacterial growth is exceptionally high. This needs to be taken into account when monitoring takes place. Typical methods of assessing the level of bacterial activity include bacteria culture and BARTS tests (Biological Activity Reaction Tests).

Aquifer and borehole management

Under ideal conditions an expected life time of 15 to 30 years can be achieved for a properly constructed and developed borehole, with a minimum of maintenance. However, if the chemical composition of the groundwater is such that it causes corrosion, incrustations and clogging of the screen, casing, riser pipes and pumping equipment, then the borehole's lifespan can diminish dramatically. Experience (Gehrels and Alford, 1990) have shown that there is no one method which can be used as the described formula to effectively rehabilitate all clogged boreholes. Once the biomass is established, several treatments may be required to restore borehole yields to acceptable levels.

It is therefore very important to take into account the chemical composition and biological quality of the groundwater when a borehole is drilled for water supply. This will help with the setup of the borehole and equipment management plan. Where clogging takes place regular maintenance and rehabilitation becomes a crucial part of the management plan. The management plan for any borehole must include everything related to the specific borehole from the need, the siting, the drilling, the testing, the commissioning, the maintenance, the rehabilitation and the decommissioning. Issues that need to be considered include :

- employ good drilling practice all the time, especially cleaning of equipment to prevent cross contamination from effected boreholes;
- use appropriate construction material (steels screens are not appropriate);
- take care over screen/gravel pack design to ensure lowest inflow velocities and limited aeration;
- don't over-pump relative to borehole design and aquifer capacity (cascading of water resulting from water levels dropping below water strikes must be eliminated);
- don't allow pumping water levels to fall below top of screens;
- don't employ intermittent pumping, rather pump continuously.

Preventive monitoring and maintenance have been neglected in routine operation and management of boreholes. This resulted in problems of drop in pumped groundwater, borehole efficiency and water quality. Although borehole clogging is now a common, recognised problem, it is still not routinely monitored in boreholes. The problem is usually discovered only when the pump performances noticeable deteriorate. The occurrence of a severe microbial infestation within a borehole and in the aquifer immediately surrounding often goes unrecognised and undiagnosed. It has been recognised that there is a need to develop a management-response cycle which would be able to predict, monitor and evaluate the control strategies applied to such infested installations (Cullimore, 1990).

Well management must include monitoring, maintenance and rehabilitation. It must also be integral parts of an inseparable programme rather than separate functions;

- monitoring is required to show the need for active maintenance measures;
- maintenance (servicing of both the pump works and well structure) is needed to maintain well performance; and
- rehabilitation is required to repair damaged pump or well structures.

It is very important that a monitoring program should also include the monitoring of the water quality. An increase in suspended solids, for example, may be the first indication of the perforation of well screens as the borehole structure deteriorates. Maintenance of wells is frequently seen as well rehabilitation, but this is wrong. Maintenance consist of a program of routine actions taken to prevent borehole deterioration while rehabilitation is the action needed to repair a well that has failed.

The development of iron and manganese scales is mostly associated with the introduction of oxygen into the borehole either causing a chemical precipitation or an increase in biological activity which accentuates the chemical scale development. Most measures aimed at reducing scale build up are associated with reducing the inflow of oxygenated water into the borehole. A number of applications to achieve this aim are discussed below.

Correct screen emplacement

In a situation where screens are emplaced above the pump, water can enter the borehole and cascade through the screens to the pump. The pump should therefore be preferably be installed above the screen location. In a situation where multiple fractures occur in a borehole, especially where the upper fractures are comparatively low yielding, it would be better to seal off the upper fractures (thus reducing cascading and oxygenation of the water) and only screen the lower high yielding fractures. Screens and casing should only be installed where necessary in a borehole drilled into hard rock. The borehole below the depth at which the pump will be installed should be left open, thus increasing the flow efficiencies in the hole.

Abstraction management

Abstraction management should be undertaken in such a way so as to have the least drawdown and therefore the most efficient flow of water to the borehole. Boreholes should rather the pumped continuously at low rates than high pumping rates with a periodic pumping schedule. Intermittent pumping allows for the mixing of anaerobic iron containing waters and aerobic surface waters thus developing a redox front and promoting bacterial growth.

Introduction of anoxic block systems

Inert gasses can be introduced into a borehole to prevent oxygen from entering the well. By restricting the entry of oxygen the amount of aerobic activity taking place is reduced and plugging is also therefore reduced. Normally nitrogen is the inert gas. There is however a high cost associated with keeping a nitrogen anoxic block in a borehole and these blocks are normally utilised in vitally important production boreholes with severe plugging problems.

In situ chlorination

The South Australia Water Corporation (Forward, 1996) use in situ generation of chlorine by electrolysis of the groundwater being pumped, to control bacterially accentuated clogging. Chlorinator electrodes are placed in a section of the water supply line and energised during a daily one hour period of non pumping. The electrolysis produces 3-4 mg/ℓ free chlorine from the brack water (12 000 mg/ℓ chloride). The chlorinated water is allowed to backflush down the borehole providing effective daily sanitation of the pump, screens and adjacent aquifer. However, low chloride levels in groundwater will limit the application of this treatment method.

In situ iron precipitation

Biofouling tends to be worst in the reduction - oxidation fringe within a borehole, where oxygen rich waters enters the borehole. Under suitable conditions it may be possible to extend the position of the oxidation zone into the aquifer by the direct injection of aerated water to specially placed recharge boreholes. The oxygenated water injected mixes with the groundwater in the aquifer, activating bacteria which result in the precipitation of unwanted iron and manganese at a distance away from the borehole. This has the potential of reducing the iron levels in the groundwater reaching the borehole and therefore decreasing the potential for clogging in the production borehole. This technique has been patented under the name of the Vyredox method.

Monitoring

Any monitoring procedure has to rely upon evidence relating to the particles shearing from the biofilm during pumping, along with the releases of any inorganic of organic product which can be linked to the clogging. The types of bacteria found during the monitoring will indicate the probable form of the clogging. For example, very high populations of IRBs would indicate that a severe clogging is occurring with the bioaccumulation of iron and/or manganese. The presence of large populations of SRBs would indicate that the clogging is anaerobic, sulphate is present in significant concentration and that hydrogen sulphide is being produced which could stimulate electro-chemical corrosion.

Success of remediation treatment, such as disinfections, acids, wetting agents, application of heat, etc., applied to clogged boreholes can be based on an evaluation of the amount of particulate matter removed and the incumbency of different microbial groups. Subsequent monitoring of the boreholes on a routine basis (e.g. monthly) can then be used to determine the speed with which the biofouling is recurring within the well (Cullimore, 1990).

PART II : BOREHOLE CLOGGING IN TMG AQUIFERS

Occurrence in TMG

Clogging of boreholes is found throughout the area overlain by TMG rocks. Problems have been encountered in the following aquifer:

- St Francis Bay (Cohen and Wood, 2001)
- Steytlerville (Jolly and Welman, 1999)
- Plettenberg Bay (Jolly, 1998a)
- Waboomskraal, inland of George (Miller, 2000),
- Calitzdorp (Jolly, 1998b)
- Cape Agulhus (Toens and Associates,1991)
- Arabella, Kleinmond (Parsons and Associates, 2000).
- Clovelly Country Club, Cape Town (Maclear, 2000).

No known problems exist up the West Coast - this may only be because there are no "public" abstraction schemes, only private abstraction, thus no data is available. Alternatively, the TMG may be lithologically different (ie more arenaceous) along the West Coast. At this stage insufficient data exists for a meaningfull assessment.

Boreholes in the Nardouw Subgroup rocks do, however, have a greater clogging problem than the Peninsula Formation rocks. Further, Nardouw Subgroup rocks in close proximity to Bokkeveld Group shales appear to be the worst situation, probably as a result of inflow of poor quality water from the Bokkeveld during abstraction. Chemical analysis of the sediments formed in some of the boreholes in the Klein Karoo Rural Water Supply Scheme (KKRWSS), showed the precipitate to consist of Fe, C and O. Carbon is an important nutrient, which together with oxygen "feeds" the biofouling. The shales of the Bokkeveld Group and the more argillaceous units of the Nardouw Fm are sources of this carbon.

Iron concentrations in TMG waters

Iron concentrations in groundwater from TMG Aquifers are generally high (>0.2 mg/ℓ).The iron appears to be related to pyrite in the sediments - pyrite levels being higher in more argillaceous sediments. Pyrite develops when the sediments were formed. In reducing, anaerobic environments, iron and sulphur are abundant and pyrite develops, especially if organic rich conditions exist.

Iron concentrations in groundwater from the Peninsula Formation aquifers are lower (<0.1 mg/ℓ) than the Nardouw Subgroup groundwater (2 - 20

Table 1
Iron concentration in different groundwaters

Area	Geology	Av. Fe levels (mg/ℓ)
Hex Valley	Nardouw	0.2 - 4.8
Albertinia	Nardouw	6 - 11
Calitzdorp	Nardouw	1 - 3
Vermaaks River	Peninsula	<0.1
Steytlerville	Nardouw	2 - 3
Arabella Golf Course	Nardouw	20
Plettenberg Bay	Peninsula	0.3 - 2.4
Dysselsdorp	Nardouw	2 - 8
Rooiberg	Nardouw	0.2 - 1.5 (dissolved) 5-33 (total)

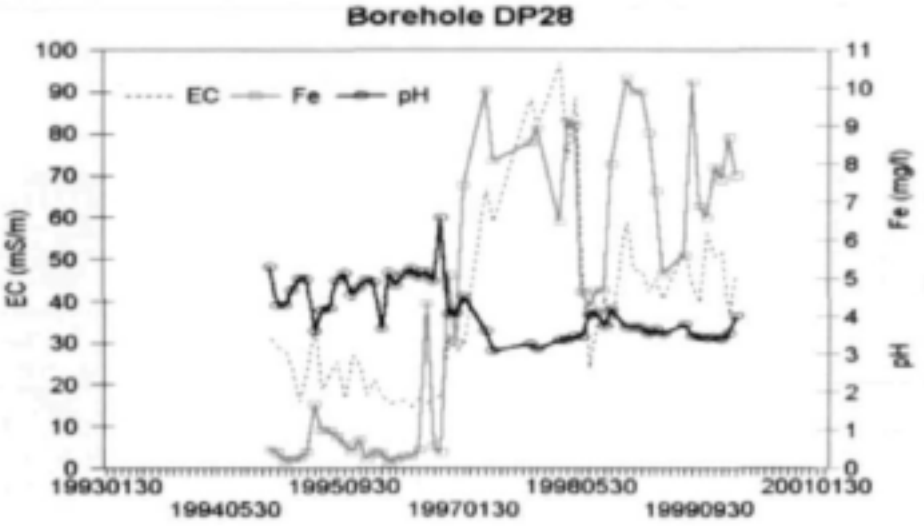

Figure 3
Variations in chemistry as a result of biofouling in borehole DP28 (KKRWSS)

mg/ℓ). Typical iron levels in different wellfields are listed in Table 1. The sampling technique greatly influences the iron levels measured - total iron concentrations are far greater than dissolved iron levels. In many of the iron problem boreholes the water is a characteristic orange - red colour, with very high total iron levels (> 20 mg/ℓ) - the worst case being a borehole at Albertinia with a total Fe concentration of 169 mg/ℓ.

Effects of biofouling

The onset of biofouling in a borehole is often first announced by a change in colour of the water abstracted, Colour changes to a characteristic orange - brown colour, often accompanied by a hydrogen sulphide odour. As clogging worsens, there is an increase in the pumping drawdown. If this is not monitored, it would not be possible to assess the advancement of clogging. The pumping drawdown in borehole DL17 at Calitzdorp (KKRWSS) increased from 13 - 62 m over 6 months, while the static water level remained constant. In advanced cases of clogging, inflow into the hole or to the pump is reduced and the borehole yield drops. This occurred at Steytlerville, during a period when the monitoring of water levels was not undertaken.

Changes in quality as a result of biofouling are unpredictable. Iron concentrations vary considerable, depending on the stage of biofilm development. High variability in Fe levels from monthly samples collected (2 - 8 mg/ℓ at DL17) is typical. Generally, the iron levels increase. A borehole at Albertinia (SDR hole) has a pH of 5.9 and an iron level of 11.5 mg/ℓ when drilled - after 2 years of use the pH had dropped to 3.3 and the Fe increased to 69 mg/ℓ! There appears to be no clear relationship between pH and quality, although some holes have shown a dramatic increase in electrical conductivity (EC) and Fe levels as the pH drops (see Fig. 3).

In holes with a low pH and where sulphate reducing bacteria exist, cathodic reactions take place resulting in the corrosion of pumps. In some cases only high quality stainless steel pumps last more than a few months.

Rehabilitation carried out and results

Rehabilitation of clogged boreholes or pumps is not common place. A few boreholes in the KKRWSS have been rehabilitated by the Department of Water Affairs and Forestry (DWAF) and by More Water, while boreholes at St Francis Bay and a number of private boreholes have been rehabilitated by Pumpcor. The DWAF/More Water treatment took place using the Blended Chemical Heat Treatment (BCHT) process, while Pumcor utilise a similar, but less sophisticated methodology without the application of heat. The acid utilised during the precipitate treatment is sulphamic acid, while swimming pool chlorine (calcium hydrochlorite) or sodium hypochlorite is used for sanitation of the bacteria.

The success of the treatment is variable and not well documented, however step tests undertaken after rehabilitation invariable show better efficiencies than before treatment.

Conclusions

High iron concentrations in groundwater in TMG rocks, especially in the Nardouw Subgroup rocks, together with oxygenation of the water as a result of over-abstraction, can cause biofouling of boreholes. The resultant decrease in borehole efficiency , increase in drawdown and decrease in yield, can result in a claim that boreholes have "dried up". An understanding of the causes of clogging are important if aquifer management in the TMG is to address clogging issues. Management and borehole design have to aim at minimising aeration in the borehole, thus reducing the risk of clogging.

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Part 6:

Case Studies

The Use of Geochemistry and Isotopes in Resource Evaluation: A Case Study From the Agter-Witzenberg Valley

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Abstract

Geochemistry and isotopes were used to trace groundwater recharge and flow patterns in the Table Mountain Group (TMG) and Bokkeveld Group (BVG) aquifers of the Agter-Witzenberg valley. There is evidence that mixing occurs between shallow groundwater and water that has travelled through deeper regions of the TMG Aquifer. Isotope data shows groundwater recharge both by rainfall in the mountain zone and by surface drainage systems in the valley. A conceptual flow model has been developed, based on which a method of aquifer management is advocated that exploits medium-seated groundwater flow in the TMG.

Introduction

Isotopic and hydrochemical information can provide a practical management tool for groundwater resources. Patterns in chemistry and isotope data are useful for fingerprinting water sources and for tracing flow and mixing processes in the subsurface.

Water chemistry and isotope data were collected from a network of rainfall collectors, streams and boreholes at a research site in the Agter-Witzenberg valley over a three-year period for use in evaluation of the groundwater resource. The valley was chosen as a test site for appraising the application of geochemical techniques in the fractured hard rock aquifers of the TMG, with emphasis on the estimation of recharge characteristics, flow patterns and ground-water residence times (Weaver et al., 1999). It was ideally suited for this purpose, being a closed synclinal basin with simple geology and a minimum of major faulting or cultural interference, which could complicate the interpretation of hydrochemical data (Pietersen et al., 1995).

Site description

The Agter-Witzenberg valley, near the town of Ceres in the Western Cape Province, South Africa, consists of a north-south trending basin, covering an area of approximately 245 km^2. It is surrounded by the Witzenberg and Skurweberg mountains of TMG sandstone, which form part of the Cederberg range of the Cape Fold Belt. The valley floor is covered by more easily-eroded shales of the BVG. Elevation varies from 1 884 m above sea level at Sneeugat peak to 880 m above sea level at the valley floor.

The area falls within a winter rainfall region with mean annual precipitation and evaporation in the order of 890 and 1 650 mm respectively. Surface drainage is diverted northwards and southwards by a topographic mound within the valley.

Metasediments of the Malmesbury Group form the bedrock in the study area (De Beer, 1989). These are overlain by the Peninsula, Pakhuis and Cedarberg Formations of the TMG, which are not exposed within the research site. The overlying Nardouw formation forms a 30 to 1 100 m westward thickening wedge of quartz arenites that outcrops as the mountain peaks. Younger mudrock, siltstone and sandstone units of the Ceres Subgroup of the BVG form the Agter-Witzenberg valley floor.

Groundwater utilisation

Both the Bokkeveld and Table Mountain Groups have the capacity to yield significant amounts of water, but the relative abundance of the groundwater resource is regionally variable. In the Agter-Witzenberg valley, the semi-unconfined aquifer is controlled by the lithology, stratigraphy, synclinal structure and fracturing of the geologic formations (Pietersen, 1994).

Deciduous fruit crops are produced in the valley and most of the groundwater abstracted is used for irrigation, particularly during the dry summer months. The majority of the irrigation boreholes are

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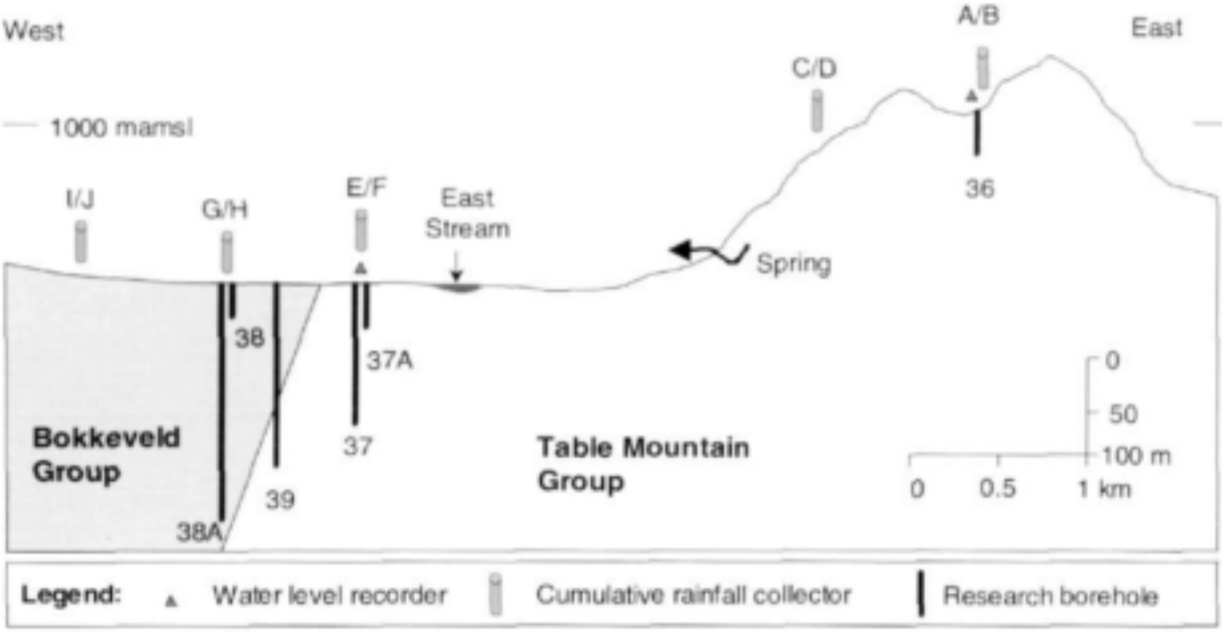

Figure 1

Position of rainfall, stream and groundwater sampling points in the Agter-Witzenberg valley

located within the BVG, but some water is also drawn from springs at the foot of the mountains. The total volume of groundwater used by the farmers is unknown, but the abstraction is sufficient to cause significant drawdown of the water table, causing many of the irrigation boreholes to dry up over the summer season. The application of the new Water Act should allow the quantification of groundwater use in future years.

Research methods

Rainfall and water level measurements were taken and water samples collected along a transect across the eastern side of the valley (Fig. 1). The monitoring network was designed to collect data on the groundwater levels and hydrochemical and isotope changes along a flow path from the recharge zone in the TMG sandstones to the discharge point in the BVG shales of the valley.

The Department of Water Affairs and Forestry installed automatic chart recorders at boreholes 36 and 37 to collect a continuous record of rainfall and groundwater levels at these two points. Rainwater was collected using five pairs of cumulative rainfall collectors (A-J). The collectors, designed by the CSIR to minimise evaporative losses, accumulate a sample of the rainwater, and therefore of the recharge water chemistry, for an entire year. They were erected in the valley in May 1995 and emptied in May 1996 after a water sample had been collected and the total volume of rainwater recorded.

Surface water samples were collected at three sampling stations on streams draining the valley to the north, south and east.

Six research boreholes were drilled for the project and constructed with uPVC casing and screens, which would not interfere with chemical measurements. Three boreholes were drilled in the TMG (36, 37 and 37A) and two in the BVG (38, 38A). Borehole 39 was drilled through the BVG/TMG contact at 124 m into the underlying Nardouw sandstones to a total depth of 171 m. The BVG units were then cased off and sealed with a bentonite plug. Boreholes 36 (21 m), 38 (17 m) and 37A (21 m) were drilled only to the first water strike. Two deep boreholes, 37 (109 m) and 38A (181 m) were left uncased. Water levels and groundwater samples were collected from these boreholes, where possible at two-month intervals. Because of seasonal fluctuations in the water table, borehole 38 was frequently dry. A natural spring at the base of the mountains was also included in the groundwater network. Details concerning sampling and analytical methods, analytical accuracy and data handling have been described elsewhere by Weaver et al. (1999).

Discussion of results

Water levels

Groundwater levels in the mountain recharge area (borehole 36) show little or no influence of the abstraction in the valley and fluctuate by only 2.2 m on a seasonal basis. Data from the continuous chart recorder at borehole 36 showed that the discharge slope of approximately 8×10^{-3} m/d is shallower than the recharge slope of 0.02 m/d. Peak water levels occur in August/September after the wet winter season and troughs in late summer (February/March).

The seasonal pattern is repeated for the groundwater levels in the valley, but with increasing amplitude for the boreholes closer to the farmers' abstraction points (Fig. 2). Water levels for boreholes 37 and 37A in the TMG oscillate by approximately 5 m on a seasonal basis. These boreholes sample the same semi-unconfined aquifer and the similarity in their water levels demonstrates the hydraulic continuity between the deeper and shallower regions of the aquifer at this point.

The most striking variations in water level occur in the boreholes drilled in the BVG rocks, which drop over 30 m in summer, and yet are almost fully recovered after the next winter season. These dramatic changes in water level are due to the proximity of the pumping boreholes on the farms to the west of the research area and higher transmissivities in the BVG compared with the TMG. Farmers in the valley have observed water level fluctuations of over 80 m per annum (R. Fell, farmer, pers. comm.).

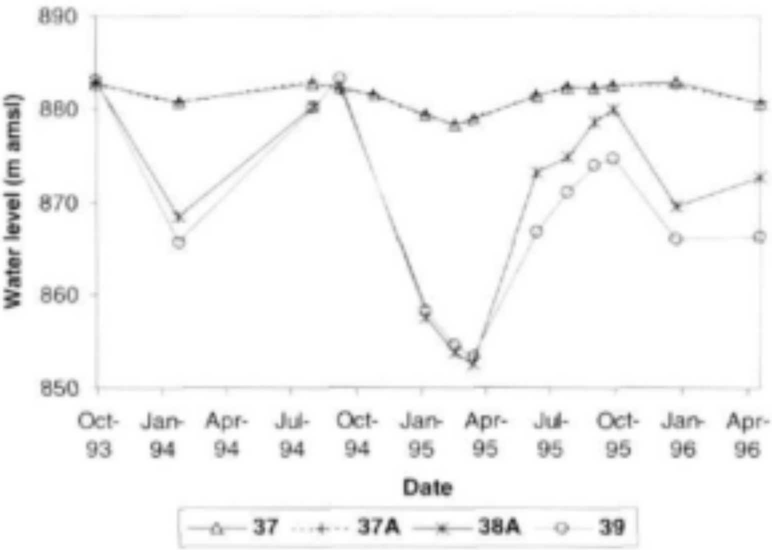

Figure 2

Groundwater level fluctuations in research boreholes

Geochemistry of groundwater

Major ion chemistry provides a useful tracer of groundwater flow and mixing processes in the Agter-Witzenberg Valley, partly because the contrasting lithologies of the TMG and BVG impart different chemical signatures to the groundwater.

Figure 3 shows the influence of mineralogy on solute compositions in the TMG and BVG. A general increase in Ca and Mg concentrations is observed along the direction of flow, but the change from boreholes 36 to 37 and 37A in the TMG is not accompanied by an equivalent increase in total alkalinity as seen in the BVG boreholes. This is because of the low carbonate mineral content in the TMG rocks. Instead, Ca and Mg are more likely to originate from the slower process of silicate mineral weathering. This is confirmed by the constancy of ^{13}C in the aquifer. Total alkalinity increases sharply once the groundwater enters the BVG rocks (boreholes 38 and 38A) where reactive carbonate minerals are present.

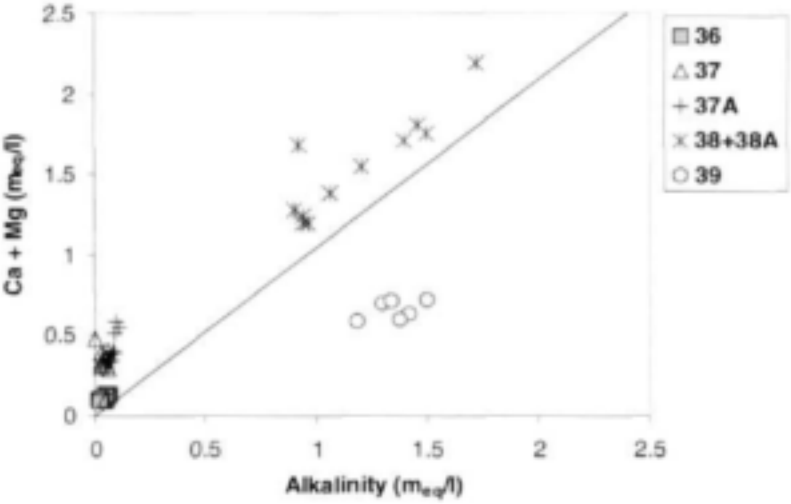

Figure 3

Ca + Mg vs. alkalinity for groundwater samples from the Agter-Witzenberg boreholes

A molar ratio of Na/Cl just less than one is typical of a marine signature, probably derived from rainfall recharge to the mountain groundwater. Soluble NaCl salts, particularly in the BVG shales, are added to the groundwater along the flow path, increasing the concentrations of Na^+ and Cl^-, but maintaining a 1:1 molar ratio between these ions. Silicate mineral weathering may add Na, but not Cl, to the groundwaters and so would tend to elevate the Na/Cl ratio. There is a slow increase in pH along the flow path in the TMG (boreholes 36, 37, 37A), which becomes much more rapid in the BVG (boreholes 38, 38A) (Fig. 4).

Data for borehole 39 are anomalous in Fig. 3 and Fig. 4, having a deficiency of Ca and Mg in comparison with alkalinity and excess Na over Cl, accompanied by an increase in pH. Ion exchange processes on the surfaces of clay minerals along the BVG/TMG contact zone could result in the increased Na and removal of Ca and Mg from solution. The Na/Cl ratio, therefore provides a useful tracer for the TMG/BVG contact zone in the Agter-Witzenberg Valley.

Sulphate is another tracer that is added to the groundwater as it moves from the recharge to the discharge zone. It accumulates by the dissolution of sulphate minerals such as gypsum or the oxidation of trace sulphide minerals along the flow path (Fig. 5).

Minimal SO_4^{2-} is present in the TMG boreholes (36, 37, 37A), probably due to a lack of sulphur-bearing minerals in the rock. Being an anion, SO_4^{2-} is unaffected by cation exchange and so SO_4^{2-} in borehole 39 follows the general evolution pattern of the other boreholes.

Isotopes in groundwater

Graphs of $\delta^{18}O$ vs. chloride are very useful in tracing the recharge pathways in the Agter-Witzenberg valley (Fig. 6). Borehole 36 and the spring at the foot of the mountain have low $\delta^{18}O$, similar to the rainwater, and low chloride. The groundwater in this region of the study area is directly recharged by rainfall. Groundwater in the valley has a higher $\delta^{18}O$, and the samples collected from 37 and 37A have the same isotope signature as the surface water streams. These boreholes are recharged by surface water that has undergone some evaporation before infiltration.

Boreholes 38 and 38A are at a greater distance from the stream and show a lower $\delta^{18}O$, with still further increase in chloride, due to the higher leachable chloride content of the BVG shales. The isotope data for boreholes 38, 38A and 39 suggests that some mixing of unevaporated groundwater from the TMG with surface water may have occurred.

Radioactive isotopes give further evidence for the flow patterns in the study area. Relative ages from tritium and ^{14}C isotope data show increasing age of the water from the TMG boreholes in the mountains to the BVG boreholes in the valley (Fig. 7). The presence of tritium indicates that at least a component of the groundwater is young i.e. post 1952. Absolute age dating with ^{14}C is simplified since no addition of "old carbon" (with $^{14}C = 0$) by dissolution of carbonate minerals occurs. Tritium data for two deep boreholes, 37 and 39, suggest some contribution of older water from the deeper part of the aquifer.

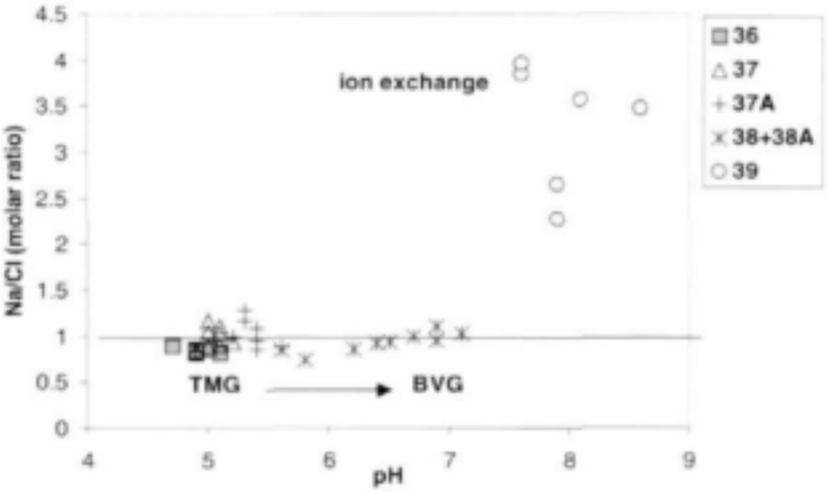

Figure 4

Na/Cl molar ratio vs pH for Agter-Witzenberg groundwater samples

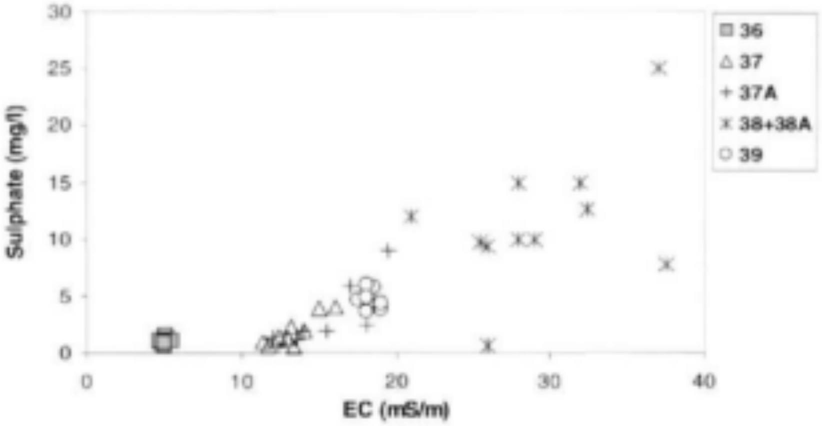

Figure 5

Sulphate concentrations vs. electrical conductivity in the Agter-Witzenberg groundwaters

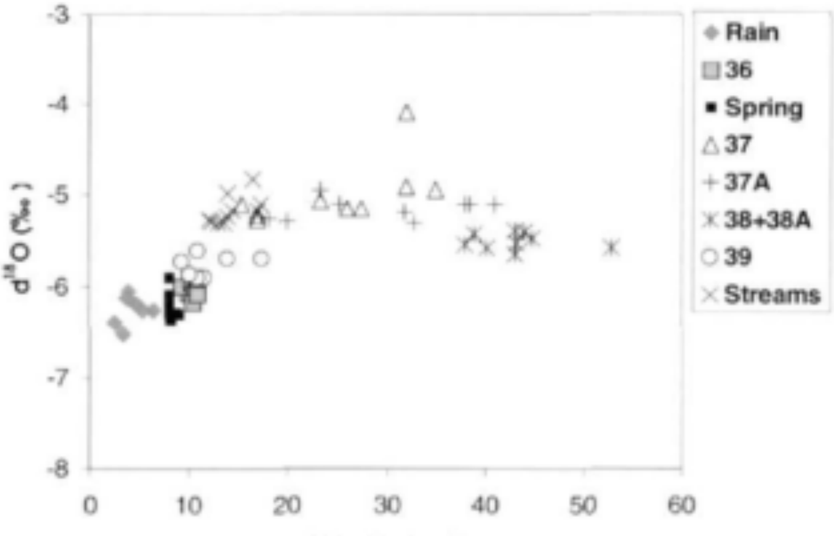

Figure 6

$\delta^{18}O$ vs. chloride for rainwater, surface water and groundwater samples from Agter-Witzenberg

Recent analyses of dissolved chlorofluorocarbons (Talma et al., 2000) have supported the concept that the boreholes all contain mixtures of young and old water and enabled the fraction of old water (> 8 000 years) to be established (Table 1).

Conceptual groundwater flow model

Water chemistry, isotopes and water level observations corroborate a seasonally-variable model of groundwater flow in the TMG Aquifer of the Agter-Witzenberg valley, which includes both mixing of different water types and hydraulic connectivity between the shallow groundwater and a deeper flow component (Fig. 8).

During winter most of the recharge takes place in the mountain zone. Rainfall infiltrates into the fractured TMG quartzites before evaporation takes place and recharges the aquifer, elevating the groundwater levels.

The spring and mountain borehole (36) share the $\delta^{18}O$ ratio signature of the rainwater. The aquifer fills up at this stage and excess groundwater seeps out as springs along the sides of the mountain. Recharge in the valley is minimal and surface runoff predominates.

In the summer months, there is little rainfall recharge and the natural water levels in the mountain area slowly decline. The abstraction of large volumes of water in the valley causes a dramatic drop in the piezometric surface. The steep hydraulic gradient from the mountain to the valley accelerates the movement of groundwater from the TMG across the contact zone into the BVG, resulting in mixing of groundwaters of different water chemistry. Older, deep groundwater is fed up the contact zone (which has a high hydraulic conductivity) and mixes with shallower water to produce the anomalous water composition found in borehole 39. The lowering of the water table also induces recharge of evaporated surface water from the perennial stream, giving the groundwater at borehole 37 the same isotope signature as the surface water streams.

Very rapid vertical mixing of groundwater occurs in the TMG quartzites in the valley. This is evident from the similarity of the chemical and isotope properties of the shallow (37A) and deep (37) TMG boreholes. Extensive ion exchange, such as in borehole 39, could be a useful geochemical marker for the BVG/TMG contact zone.

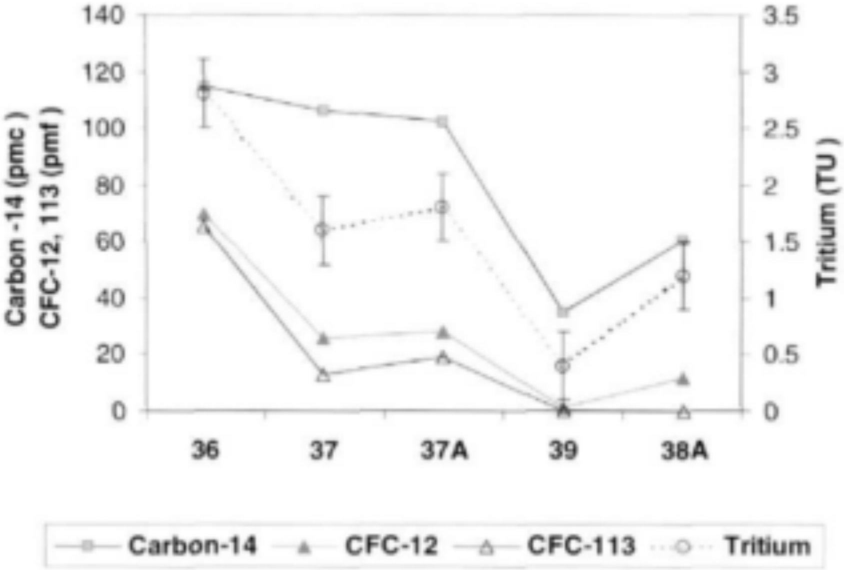

Figure 7

Radioactive isotopes and CFCs in groundwater samples collected from Agter-Witzenberg. These allow relative ages of waters to be determined.

Conclusions and implications for groundwater management

The groundwater research project in the Agter-Witzenberg valley has shown that geochemical and

Table 1

^{14}C, tritium and CFC data from the Agter-Witzenberg valley (Weaver and Talma, 1999). CFC data are expressed as fractions of the maximum likely values, in pmf (percent modern freon). Mixing calculations are described by Talma et al. (2000).

Bh	^{14}C pmc (±0.5)	Tritium TU (±0.3)	CFC-11 pmf	CFC-12 pmf	CFC-113 pmf	Old water fraction
36	111-115	2.8	17-37	22-38	25-49	0
37	102-106	1.6	18-22	23-32	11-16	40%
37A	100-104	1.8	18-22	26-29	14-24	38%
39	29-53	0.4	0-6	1-10	0	90%
38A	54-72	1.2	6-7	12-13	-	72%

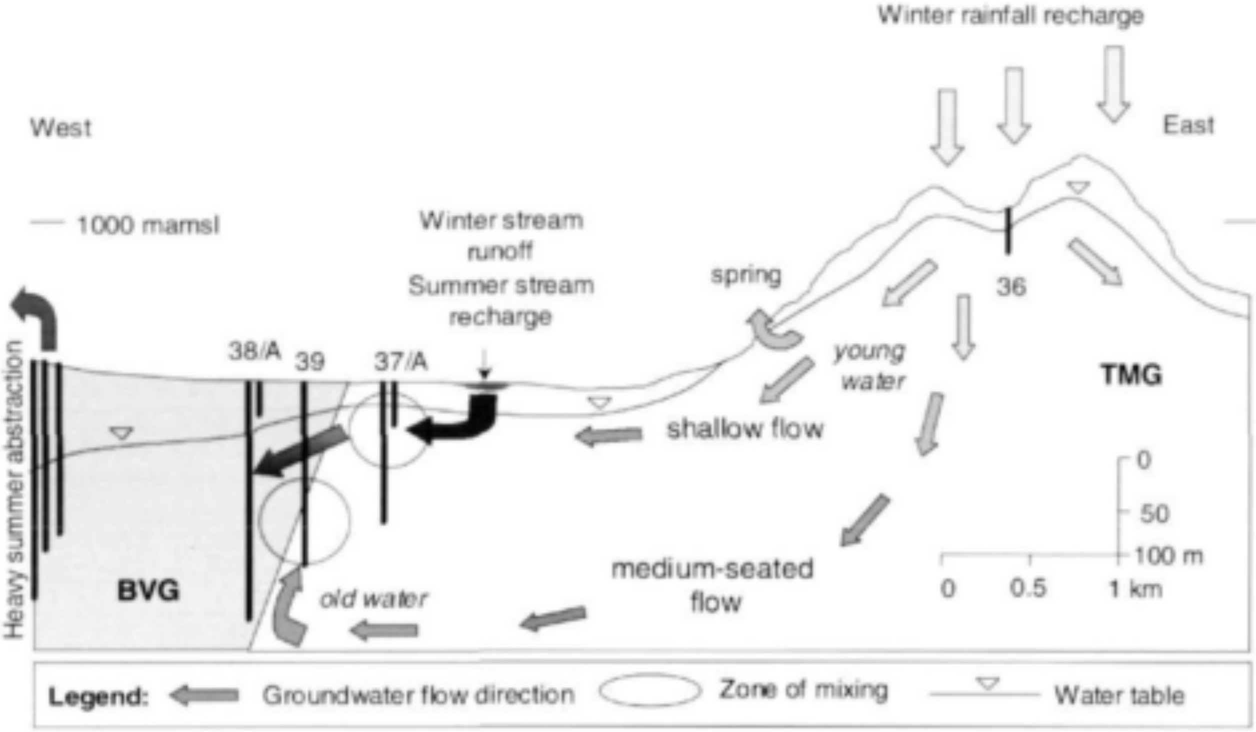

Figure 8

Conceptual model of groundwater flow and mixing patterns in the Agter-Witzenberg Valley

isotope tools may be applied with confidence for tracing flow patterns in TMG Aquifers. The TMG quartzites are recognised as one of the major aquifer systems in South Africa due to their large area, extensive fracturing and highly competent nature, which results in fractures remaining open at depth.

One of the obstacles to large-scale development of the TMG Aquifers is quantification of the available groundwater resource. There is abundant evidence of shallow groundwater in the TMG and high-yielding hot water springs are proof that deep-seated flow occurs (Weaver and Talma, 2000), but thus far, strong evidence for medium-seated flow has been lacking.

In this study it was found that the deep TMG borehole (39) exhibits a number of chemical and isotopic signatures which indicate that it intersects groundwater from deeper levels in the aquifer than the shallower TMG boreholes (37, 37A) or the BVG boreholes (38, 38A). Chloride and $\delta^{18}O$ show that the deep water is a mixture of unevaporated water from the mountain and the more evaporated recharge in the valley. Tritium and ^{14}C show that the deep TMG borehole taps much older water than its shallow mountain and valley water end-members. The interpretation is that a large portion of the recharge from the mountains circulates through the deeper regions of the aquifer before mixing with shallower recharge water from the valley. Both the chemistry and isotopes support the existence of this medium-seated flow.

Evidence that medium-seated groundwater flow does occur makes available water-resources that could not previously be relied on. This suggests that a successful method of aquifer management may be to "over-exploit" the aquifer in summer, tapping the medium-seated groundwater flow and lowering the water table up to many tens of, if not a hundred, metres. This will create storage space for the aquifer to fill up over the next winter rainfall season when there is excess recharge.

Such a method is already in practice by the Agter-Witzenberg farmers who draw the water table down many tens of metres by pumping groundwater for summer irrigation. Water levels then recover over the following winter recharge season. Mountain springs and the borehole at high elevation also appear to be largely unaffected by the heavy pumping.

Detailed monitoring of the long-term impact of heavy abstraction from TMG Aquifers is needed at a study site such as Agter-Witzenberg. A study of this nature could provide valuable information needed to quantify the impact of such practices on the groundwater resource and the aquifer itself. If a comprehensive, multi-disciplinary study can show that these management practices have a negligible impact on the groundwater resource, it is quite conceivable that dramatic lowering of the water table in TMG Aquifers, even by over one hundred metres or more, could be allowed.

Acknowledgements

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Development of Groundwater Resources for the Arabella Country Estate

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Abstract

A groundwater exploration programme was carried out to develop a sustainable water supply for Arabella Country Estate. This entailed aerial photograph interpretation, geological mapping, a resistivity survey and test pumping. Five boreholes were drilled into quartzites and sandstones of the Nardouw Subgroup aquifer north-west of a major fault. Following testing, the boreholes were brought into production in September 1998 and used to supply water for irrigating a new 18 hole golf course. Monitored groundwater levels are deeper than predicted while high Fe concentrations require Fe removal before reticulation. In spite of these limitations, sufficient groundwater resources exist to meet the demand of the Estate. However, this is dependent on the scientific management of the production boreholes, implementation of effective irrigation demand management and appropriate long-term monitoring of groundwater levels, Fe concentration and abstraction. Failure to do so will require the more expensive option of harnessing winter run-off be implemented.

Introduction

Arabella Country Estate is located about 100 km east of Cape Town and some 15 km east of the town of Kleinmond. Because of the proximity of the Estate to a major geological fault, groundwater was proposed as a source of water for the hotel, residential erven and 18 hole golf course. A groundwater exploration programme was initiated to establish a 1.2 Mℓ/d supply of water for the Estate. This entailed aerial photograph interpretation, geological mapping, a geophysical survey, drilling and test pumping. Once abstraction commenced in September 1998, some monitoring was implemented. This paper describes work carried out and the response of the aquifer to abstraction.

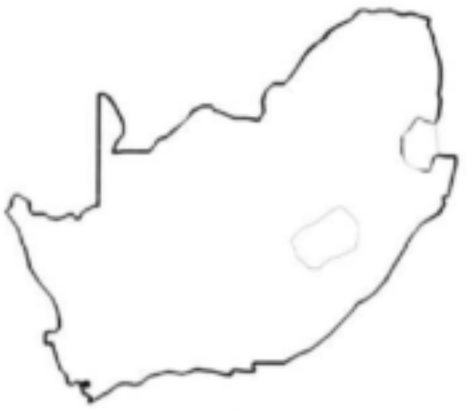

Figure 1
Locality map of Arabella Country Estate

Setting

Arabella Country Estate is located on a south-east facing slope adjacent to the Bot River lagoon. The Estate straddles the western fault of a typical horst and garben structure that resulted in development of the north-south trending Bot River Valley. The fault extends some 40 km north-eastwards and is the same structure targeted by Weaver (1989) when developing groundwater supplies for the town of Botriver.

The upthrown north-western part of the fault comprises quartzites and sandstones of the Nardouw Subgroup of the Table Mountain Group (TMG) while the downthrown south-eastern component comprises weathered shales of the Bokkeveld Group (De Beer, 2001). Prevailing geology resulted in rugged topography and relatively steep slopes north-west of the fault. Flatter slopes prevail south-east of the fault as a result of the shale being less resistant to weathering. Most of the Estate development has taken place on the lower lying part of the property underlain by shale.

The highly weathered nature and perceived poor water-bearing properties of the shale resulted in the quartzites and sandstones north-west of the fault being targeted for exploration. As the target area was upgradient of the development, development posed little threat to aquifer system.

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Exploration

Distinct geological differences on either side of the fault result in the position of the fault being readily determined from aerial photographs (topography) and field mapping (brown clayey soils as opposed to white sandy soils). Resistivity profiling (Wenner array) and vertical electrical soundings (Schlumberger array) were also carried out to aid optimal siting of initial exploration boreholes (Parsons, 1996). Because of distinct differences in the resitivity properties of quartzite and weathered shale, the geophysical survey allowed for the subsurface position of the fault and its dip to be accurately determined (Fig. 2).

Two exploration boreholes were drilled in March 1997 on the north-western side of the fault to validate results of the geophysical survey and assess the water-bearing potential of the fractured TMG rocks (Fig. 3). LL-BH1 and LL-BH2 were drilled to depths of 56 m and 82 m respectively and had blow yields of 3.7 ℓ/s and 11.0 ℓ/s (Table 1). Excessive well losses during pumping because of borehole construction prevented interpretation of both step-drawdown and constant yield tests (Parsons, 1997). However, the tests did confirm groundwater could be used as a source of water for the development. Though electrical conductivity (EC) was in the order of 20 mS/m the groundwater had a low pH and high Fe and Mn concentrations.

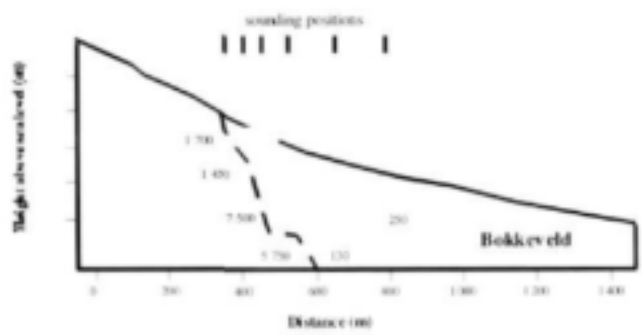

Figure 2
Interpreted results of the geophysical survey

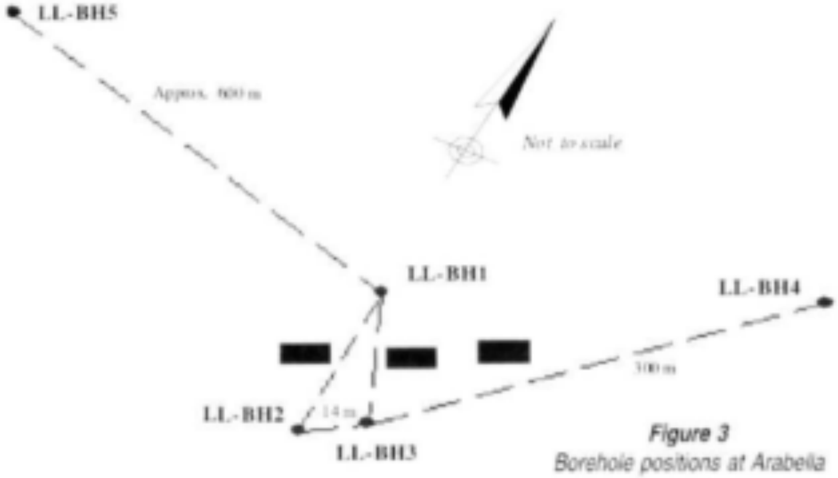

Figure 3
Borehole positions at Arabella Country Estate

Based on the results of exploration, two production boreholes were drilled adjacent to the fault in February 1998 (Parsons, 1998). LL-BH3 was drilled 14 m east of LL-BH2 as it was planned LL-BH2 would only be used as a standby (Fig. 3). LL-BH4 was drilled a further 300 m eastwards to reduce interference between the production boreholes. PVC screens were installed from about 20 m below surface to the bottom of the borehole. The 165 mm inner diameter screens had 2 mm slots with an estimated percentage opening of 12.5%. The annulus was backfilled with 10 mm crushed gravel. After performing step drawdown test on both boreholes, a 72 h constant rate test was performed on LL-BH3. The borehole was tested at a rate of 22.5 ℓ/s. This resulted in a maximum drawdown of 32.09 m in the pumped borehole and drawdowns of 15.28 m and 4.92 m in LL-BH1 and LL-BH4 respectively. Groundwater quality remained relatively constant throughout the test.

Recognising the difficulty of interpreting pumping test data from fractured rock environments, transmissivity (T) and storativity (S) were interpreted to be in the order of 80 m^2/d and 0.0002 respectively. Though S remained relatively constant (Table 1), T ranged between 58 m^2/d and 320 m^2/d. This range is typical for the given geohydrological regime. Using conventional interpretation techniques (Kruseman and De Ridder, 1994), recommended simultaneous abstraction rates of 14.5 ℓ/s and 16.0 ℓ/s were determined (Table 1). To avoid iron precipitation, it was recommended boreholes be pumped at a low rate with a short period being allowed for recovery. A pumping regime of 18 h/d for no longer than 60 days, therefore, was proposed. It was further recommended monitoring of abstraction and aquifer response be instituted as a means of validating the above estimates.

Abstraction

Formal abstraction from LL-BH3 started in September 1998 (Parsons, 1999). A continuous water level monitoring device was installed in LL-BH1 soon after abstraction commenced. In spite of a number of teething problems and difficulties in measuring groundwater levels in production boreholes, a relatively good record of groundwater levels (Fig. 4) and abstraction has been collected.

At present, almost all abstraction takes place between October and April and is used for irrigating the newly established 18 hole golf course. Peak demand occurs during the hot dry months of De-

Table 1
Data from the five boreholes drilled at Arabella Country Estate

Parameter	LL-BH1	LL-BH2	LL-BH3	LL-BH4	LL-BH5
Depth (m)	56	82	95	103	142
Blow-yield (ℓ/s)	3.7	11.0	+25	+25	10.0
Static water level (mbc)	0.30	art.	4.13	art.	?
EC (mS/m)	18	18	19	21	18
pH	5.7	6.1	6.5	6.0	6.3
Fe (mg/ℓ)	8.7	8.9	10.9	15.5	12.7
Constant discharge test rate (ℓ/s)	step	7.5	22.5	step	-
Recommended rate – individual (ℓ/s)	3.8	7.5	22.5	19.0	-
Recommended rate – simultaneous (ℓ/s)			14.5	16.0	-
T (m^2/d)	75	320	68	143	-
S	0.0005	0.0002	0.0003	0.0001	-
Status	observation	standby	production	production	production
Current rate (ℓ/s)	-	2.1	9.0	11.0	8.4
Current summer abstraction (m^3) (Oct – May)	-	2 000	68 000	125 000	57 000
Water level – winter high (mbc)	25	20	20	18	?
Water level – summer low (mbc)	55	47	47	45	75
EC (mS/m)	-	-	25	31	47
pH	-	-	6.3	5.9	7.1
Fe (mg/ℓ)	-	-	16	24	2.4

cember and January. As a result of very dry conditions experienced in December 1999 and poor water demand management on the Estate, a third production borehole (LL-BH5) was established (Fig. 3, Table 1). This borehole was immediately brought into production and has not been tested. The volume of groundwater abstracted from each production borehole is presented in Table 1.

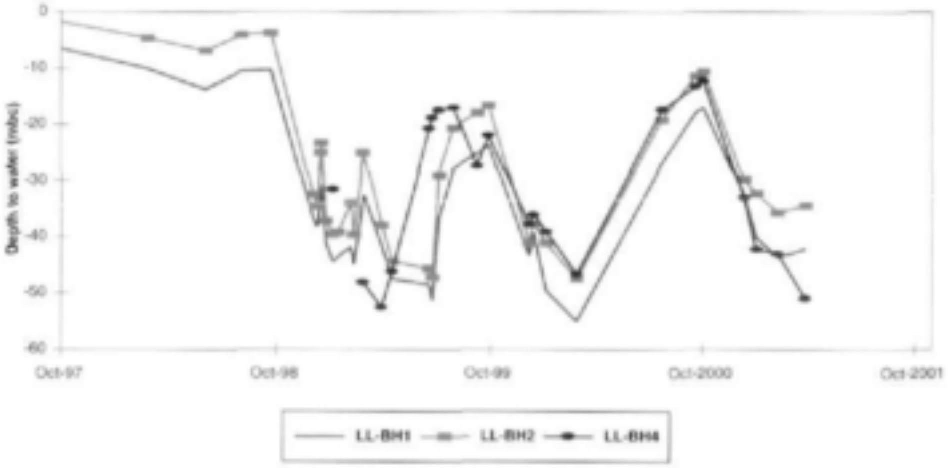

Figure 4
Monitored groundwater levels

Management and monitoring

The groundwater supply scheme has not been managed nor monitored, as it should be. Initially, monitoring was hampered by pump installation preventing groundwater levels being measured. Further, abstraction volumes and rates were only measured on an *ad hoc* basis. In spite of this, a relatively good record of the response of the aquifer to abstraction has been developed.

Drawdowns resulting from summer abstraction and recovery induced by recharge and switching off the pumps in winter are evident in Fig. 4. During summer, groundwater levels ranged between 45 m and 55 m below surface. In winter, water levels rise to about 20 m below surface, but not to pre-pumping artesian conditions. A later start to the irrigation season in late 2000 resulted in better recovery of groundwater levels than the previous year. As the level of recovery is governed by the duration of non-abstraction, development of a dam to catch winter run-off and the conjunctive use thereof has merit. Water in the dam is to be used for early season irrigation and thereby delay the start of groundwater abstraction by about a month. This conjunctive approach to water resource management on the Estate will allow better recovery during late winter and spring.

From the outset, very high Fe concentrations were recorded in all boreholes. A harmonic mean of al-

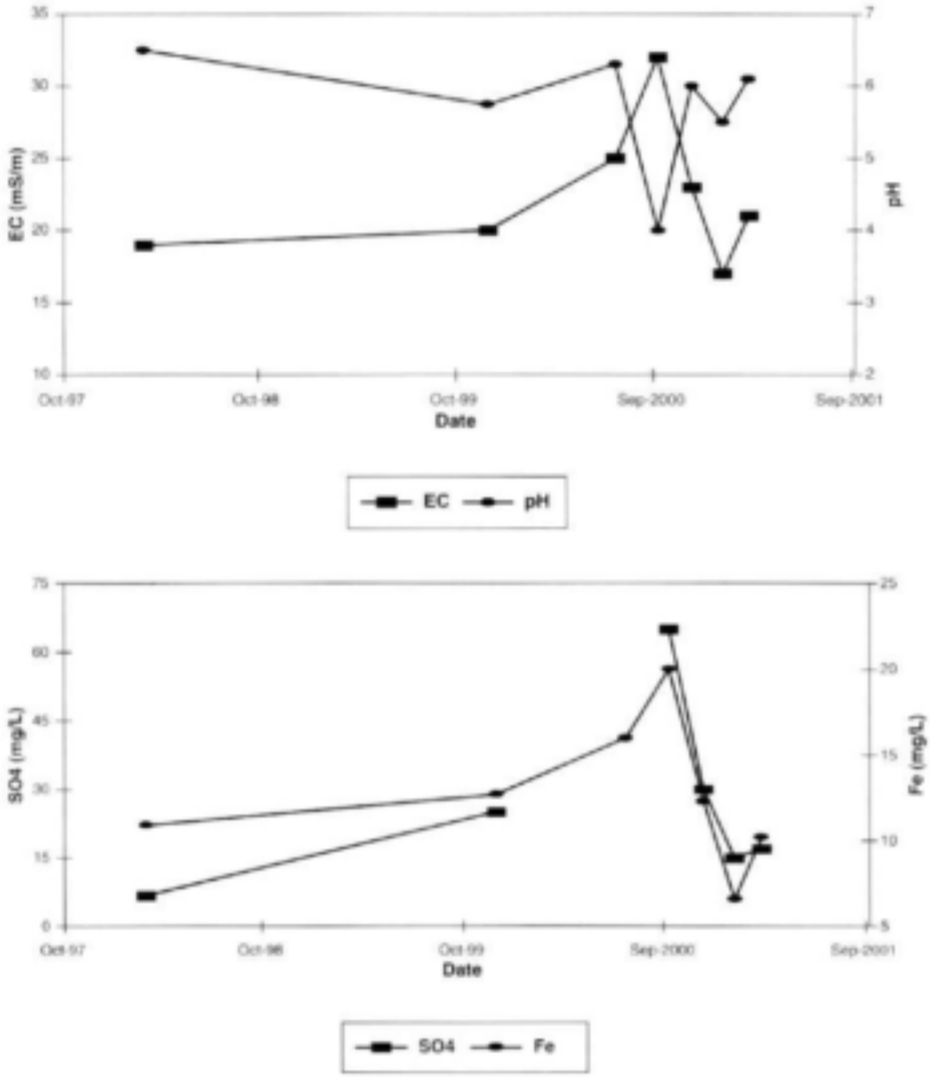

Figure 5
Groundwater chemistry monitored at LL-BH3

most 11 mg/ℓ was determined using concentrations from initial samples collected from each borehole. This, unfortunately, appears to be a characteristic of Nardouw Subgroup aquifers, particularly when juxtaposed to shale of either the Cedarberg Formation or Bokkeveld Group. Though abstracted groundwater passes through a Fe removal plant before reticulation, no effort has been made to manage the boreholes so Fe concentrations are kept as low as possible.

Once-off sampling during late winter 2000 indicated a dramatic increase in Fe concentrations. A drop in pH and rises in EC and SO4 levels accompanied this (Parsons, 2000). It was hence decided to investigate the state of the pump and investigate whether iron clogging was reducing borehole efficiency. On removing the pump from LL-BH3 after two years of abstraction, no evidence of corrosion or iron deposits were found (Parsons, 2000). Further, treatment of the borehole using sulfamic acid and flushing had no effect on borehole performance.

Follow-up monitoring during the summer of 2001 indicated a rapid decline in EC, Fe and SO_4 concentrations with pH remaining relatively constant (Fig. 5). Monitored data are insufficient to develop a comprehensive understanding of the patterns and mechanisms driving the water quality fluctuations. However, it appears oxidation of pyrite results in acid rock drainage (ARD).

Relatively high concentrations of pyrite and other sulphide minerals in shale horizons in the TMG and adjacent Bokkeveld Group coupled to secondary enrichment of pyrite in fault and breccia zones provide an adequate source of sulphide minerals. Introduction of oxygen into the subsurface by lowering the piezometric surface during the summer abstraction period and/or during abstraction trigger the oxidation process. However, a trend is apparent that Fe and SO_4 concentrations are highest after the winter recharge period (Fig. 5). Concentrations decline rapidly with summer abstraction, but then appear to start to increase as soon as abstraction is reduced.

It is also interesting that pH drops to 4 for a short period toward the end of winter and before increasing to an ambient level of about 6 (Fig. 5). This, together with other chemical trends, need to be monitored so a better understanding of the geochemistry of the system can be developed. It is nonetheless clear that high Fe concentrations could place a restriction on the use of groundwater from the Nardouw Subgroup aquifer system.

Discussion

At present, groundwater abstraction is governed by irrigation water demand for the golf course. No water demand management is practiced, resulting in excessive irrigation and unnecessary abstraction from the boreholes. During the early stages of abstraction, both LL-BH2 and LL-BH3 were pumped simultaneously. As the boreholes are only 14 m apart, this resulted in excessive drawdowns and inefficient pumping. Since LL-BH5 was established in December 1999, most pumping takes place from LL-BH4 and LL-BH5 with little abstraction from LL-BH3. To date, no effort has been made to manage the wellfield so abstraction is as widespread as possible and at the lowest rates possible.

Monitoring of abstraction has shown groundwater is capable of meeting current demand. However, high Fe concentrations and the lack of management and ongoing monitoring are of concern. It is proposed the rate of abstraction from each borehole be reduced to 6 ℓ/s and a continuous pumping regime during summer be implemented. Conjunctive use of surface water during the early part of the irrigation season should be encouraged to allow the aquifer system a longer rest period after winter recharge.

Regular monitoring and data interpretation is essential if the response of the aquifer to abstraction is to be understood. Because of rising Fe concentrations, monitoring must include monthly chemical sampling. As high Fe concentrations could seriously limit development of Nardouw Subgroup aquifers, a proper understanding of the source of Fe and the mechanisms controlling Fe concentrations is urgently required.

The developers of the Estate aim to develop a second 18 hole golf course. Implementation of a scientific groundwater management and monitoring plan coupled to effective water demand management (particularly related to irrigation of the golf course) is essential if the Department of Water Affairs and Forestry are to be able to favorably review future applications for water use.

Conclusions

Five boreholes were drilled into the Nardouw Subgroup aquifer to develop a source of water for Arabella Country Estate. Following testing, three production boreholes were brought into production and used to supply irrigation water for new 18 hole golf course. Monitored groundwater levels were deeper than predicted while high Fe concentrations require Fe removal before reticulation. In spite of these limitations, sufficient groundwater resources exist to meet the demand of the Estate. However, rising Fe concentrations as a result of ARD remains a matter of concern. Scientific management of the wellfield, implementation of effective irrigation demand management and appropriate long-term monitoring of groundwater levels, Fe concentration and abstraction is required to ensure the long term viability of the groundwater supply scheme and the viability of the golf estate itself.

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Hydrogeology of the Table Mountain Group. A Case Study at Botrivier

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Abstract

Low pH groundwater caused the casing of the single town water-supply borehole to corrode and collapse. A hydrogeophysical survey delineated potential drill sites in Table Mountain Group (TMG) adjacent to a downfaulted block of Bokkeveld shales. Five boreholes can be used for town water-supply, with a daily yield of 1 749 m³/d. High impact resistant UPVC casing was used to circumvent the corrosive nature of the groundwater. This paper describes the process of developing the water supply and describes the lessons learnt from this case study.

Introduction

In May 1988 the CSIR was approached by the Overberg District Council to give advice on a submersible pump specification. The village of Botrivier (Fig. 1) had an existing borehole which during summer peak demand supplied 5 ℓ/s (430 m^3/d). The installed pump regularly failed, needing replacement, usually at less than 6 months intervals. A visit to site showed the pH of groundwater from this borehole (BH4, Fig. 2) to be 4.2, i.e. highly corrosive to metals. However, the actual problem of pump failure was not that the phosphor bronze impeller pump could not tolerate this low pH, but that the steel casing had corroded and pebbles were falling into the borehole, being sucked into the impellers and breaking them. Evidence of this was the pile of sand and pebbles below the reservoir inlet pipe.

Over the following five years the CSIR carried out three phases of groundwater exploration which included re-drilling Bh4, testing one existing borehole which proved to be low-yielding and drilling and testing five new boreholes. The proven yield from these five boreholes is 1749 m^3/d, with recommended pumping rates varying from 1.8 to 8.0 ℓ/s for 24 h per day pumping. The various phases of hydrogeological investigation is described in Weaver (1989), Weaver et al. (1990), Weaver (1993a) and Weaver (1993b).

Geology of Botrivier

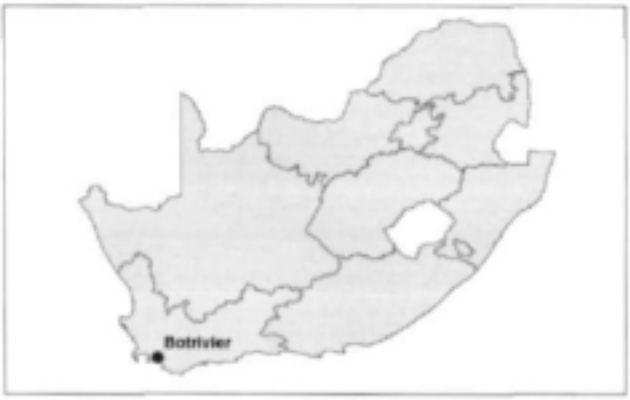

Figure 1
Locality map of Botrivier

Botrivier is underlain by quartzites and shales. The village is bisected by a NE-SW trending scissor-fault (Fig. 2) which at Botrivier has a 600 m downthrow to the east. This fault brings quartzites of the Skurweberg Formation, Nardouw Subgroup into contact with shales of the Gydo Formation (Ceres Subgroup, lower zone of the Bokkeveld Group). This fault also passes west of Arabella Country Estate (Parsons, 2001) and controls the headland at Kleinmond where throw is greatest. Towards the north the displacement reduces to a few metres and the fault veers to the East and links up with the east-west trending Greyton fault.

The fault and consequent distribution of the geological formations has had some control on social development at Botrivier. At the contact there are a number of springs, and all the older houses of the village lie downgradient of these springs, ie the households had the better agricultural soil derived from the shales, and also water for irrigation supplied by gravity. There is a large dam in the village (Fig. 2), which supplied water to the steam-engines of the South African Railways. This dam is sited so that it is on shales, thus is not leaky, which it would be if it were on the quartzites, and the western high-level waterline parallels and coincides with the fault trace.

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Figure 2
Botriver hydrogeophysics and water supply borehole positions

Previous work

Kent (1955) carried out a survey for the South African Railways to obtain possible sources of water for locomotive and domestic supply. The purpose was "A supply of about 3 000 gph is required for loco and domestic purposes as the existing supply from springs is inadequate." He located seven existing boreholes, five in the Bokkeveld which were brack to very brack, and two in the TMG with good quality water. He recommended drilling in the weathered TMG west of the fault, but warned, "it will be remembered that boreholes at Houwhoek gave considerable trouble because sand came into them with the water. It is believed that this sand comes from highly weathered layers in the T.M.S. sandstones. Few drillers in this country have any knowledge of the techniques of "developing" holes and installing screens so as to prevent ingress of sand. If a competent driller can be found - -". Forty years later with the development of drilling techniques and with the aid of competent drillers, successful boreholes have been completed.

The CSIR (Weaver, 1989) carried out a hydrocensus which located nine boreholes, five of which had been noted by Kent (1955). The four new boreholes were all in the TMG and between 500 m to 900 m west of the fault, i.e. they were away from the weathered material found close to the fault and were in the more solid rock which is easier to drill. One of these, BhCPA (Fig. 2) had been drilled to more than 250 m (250 m being the length of the depth-probe owned by the test-pumping contractor) for water-supply for road building. The borehole was test-pumped during our investigation. The water levels did not stabilise and aquifer dewatering occurred, thus the recommended yield was not considered sufficient for town water-supply. Two boreholes had been drilled on the farm south of Bh4, one to 162 m was dry the second to 100 m had 1.3 ℓ/s at 92 m and was used for house hold supply. The fourth borehole is 120 m south of Bh4 and is used for limited farm irrigation.

Hydrogeophysical survey

Due to a legal dispute regarding servitude to Bh4 it was decided to establish a wellfield within the municipal boundaries. Prior to fieldwork a conceptual model was developed. According to this conceptual model the target for drilling water-supply boreholes would be the zone in the TMG adjacent to the fault. In terms of geophysical response, closer to the fault the weathering/fracturing would be more intense thus a lower resistivity would be measured, and further from the fault a higher resistivity response would be measured in the less fractured zone. A geophysical survey, using d.c. electrical sounding methods (Schlumberger array) was carried out (Fig. 2). The results are described in some detail in Fraser and Stemmet (2001). The geophysical survey results confirmed the conceptual model. Seven sites were selected as being suitable for drilling. Boreholes were drilled at five sites.

Drilling

Prior to commencement of drilling operations extensive planning discussions were held with the driller, J.J. Myburg en Seuns. This was done to plan how to overcome the problems of low pH water which corrodes steel casing, and expected difficult drilling conditions of collapsing conditions close to the fault For the low pH water it was decided to use PVC casing, which at that stage was not widely used in the drilling industry. The expected drilling conditions were 10 m to 20 m of weathered loose material which would need casing. Below this zone would be fractured rock, which could be left as open-hole construction, not needing casing. The planned drilling method was to drill, using large diameter steel casing, through the overburden to competent rock. Upon intersecting a few metres of competent rock, to continue drilling with a smaller diameter to the expected water-strikes in the fractured rock. After the final drilling depth had been reached, to then key the PVC casing into the hard rock and recover the steel casing. Because drilling involves rough handling, ordinary PVC casing was regarded as being unsuitable. Thus special, high-impact resistant HDPE, which is used in the mining industry was obtained from Gauteng.

Two differing occurrences of water were obtained in the six boreholes. The first of these was water in the transported sands and residual weathered TMG. This sand/weathered TMG overburden was thicker than anticipated at 29 m to 32 m thick. The water-table is about 6m below surface, thus a substantial aquifer is developed in the this sand, with the advantage that downgradient is the barrier of shales downfaulted against the quartzite, thus reducing discharge. To access this water slotted casing was required. The second occurrence of water was in fractures within the TMG.

For two boreholes no fractures were intersected in the bedrock, so screened and gravel packed boreholes were constructed to exploit water in the sand/weathered TMG Aquifer. These produced production boreholes with recommended yields of 1.8 and 2.0 ℓ/s for 24 h pumping per day.

Three boreholes intersected fractures in the bedrock below the saturated overburden. For these boreholes the sand was cased off with solid casing. The idea being that the fractures would be hydraulically linked to the sands, thus such a borehole exploits a high hydraulic conductivity fracture linked to the high storage of the saturated sands. Test-pumping confirmed this as the late-stage portion of the constant discharge test-pumping curve showed a leaky aquifer response with the late-stage of the curve remaining flat (Fig. 3). These two boreholes have recommended yields of 2.5 and 8.0 ℓ/s, pumping 24 h per day. The third borehole was not tested as the airlift yield was only 0.5 ℓ/s.

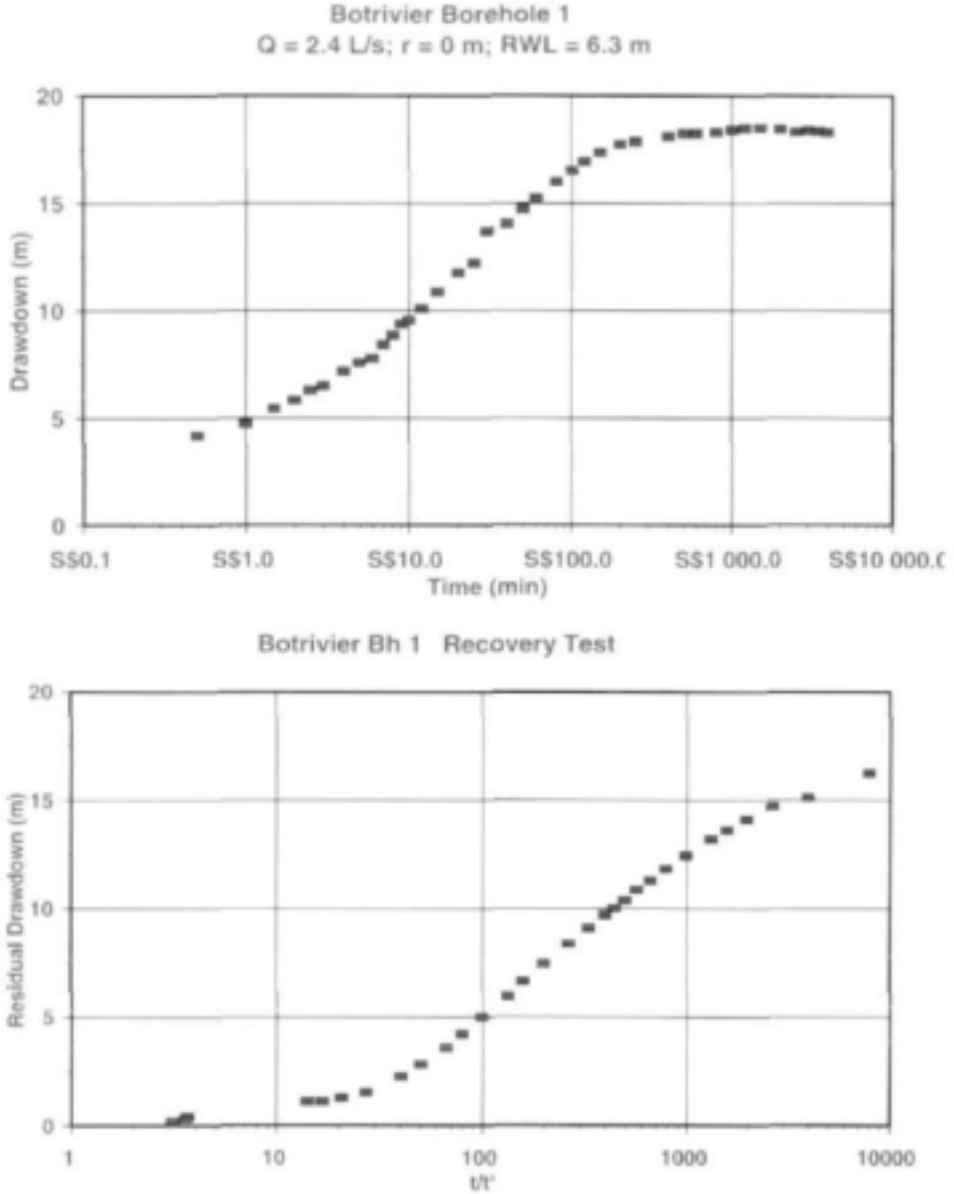

Figure 3
Botrivier: Bh1 constant discharge test (68 h) and recovery test curves

The sixth borehole was the replacement borehole for the collapsed Bh4. The first 1 m of drilling gave overburden, thereafter solid and fractured quartzite was intersected. The borehole was drilled to 61 m and had seven fracture zones, with a cumulative air-lift yield of 20 ℓ/s. The fractures were collapsing, thus slotted casing was installed opposite all the fractures. The HDPE casing was coarsely slotted, vertical cuts of 80 mm long, 0.8 mm slot size and 600 slots per metre of screen. Coarse gravel was poured into the annulus as a formation stabiliser to prevent a side-wall collapse from damaging the casing. The shape of the test-pumping curve was that of a semi-confined response with the late-stage of the curve rising at the same slope as early-stage and the recommended yield of this borehole is 6 ℓ/s pumping for 24 h per day.

The beneficial effect of the saturated sand overburden towards aquifer sustainability can be seen when comparing the ratio of airlift yield to recommended yield. Usually for a borehole in a fractured rock aquifer the airlift yield is substantially higher than the calculated sustainable yield. To illustrate this for the Botrivier boreholes, the drawdown after 24 h of pumping at the calculated sustainable yield is compared to the airlift yield. For the four boreholes close to the fault with a thick saturated overburden the ratio of air-lift yield to recommended yield is 3:1, 1.4:1, 1.4:1 and 0.8:1, whereas for Bh4, which is in fractured rock only, the ratio is 4:1. If Bh4 had also had the benefit of a thick saturated overburden the calculated sustainable yield would probably have been higher.

Water quality

The water quality from all the boreholes was typical of TMG Aquifer water, i.e. it has low salinity with

ECs ranging from 17 to 35 mS/m, low pH, virtually no alkalinity and some dissolved iron.

Low pH is a water quality problem, with the lower lying boreholes against the fault averaging 5.4 and the higher lying Bh4 being 4.6. Dissolved iron at about 0.2 mg/ℓ also is problematic. These problems could be solved by installing a Calcostab unit (MacIntosh, 2001), but to date funding has not been made available.

The original domestic waste disposal site was about 150 m to the north-east of borehole Bh6, which at 8 ℓ/s is the highest yielding of all the boreholes drilled. As a consequence the waste-site has been closed and a new waste-site developed downgradient of the water-supply boreholes and thus on the Bokkeveld shales. Bh6 was drilled in 1993 and has not yet been commissioned as the water-supply from the rest of the boreholes currently is satisfying the demand.

Overview

The Botrivier water supply project was successful because:

- A conceptual model was developed
- The hydrocensus and a literature review confirmed the conceptual model
- The geophysical survey tested and confirmed the conceptual model
- Drilling proved the model and obtained water
- Prior understanding of the potential drilling problems enabled actual problems to be anticipated and solved.

Conclusions

The development of groundwater for a water-supply for Botrivier has followed a routine path of drill-target identification, drilling and testing, evaluating results and recommending sustainable pumping yields.

There are two aspects making this project slightly different (or lessons learned). The first is development of the thick saturated overburden of sand and weathered TMG overlying the fractured quartzites. This provided leaky aquifer conditions and a large storage, which is accessible to the fractures. For future investigations of water-supply such a geological setting, if present, should be classed as a prime target for drilling, so as to obtain a sustainable yield.

The second aspect concerns daily and annual recharge to the wellfield. Upgradient of the various boreholes of the wellfield is a vast expanse of Nardouw Formation quartzites. The amount of water in storage, plus the annual rainfall recharge, makes this an aquifer that will be difficult to deplete. The future (year 2010) water demand for Botrivier Village was predicted to be about 1 200 m^3/d, which is a bit less than 0.5 million $m^3/year$. The wellfield is fed by the aquifer underlying the large area of mountain (Nardouw Formation) lying to the west of Botrivier. This mountain, over a distance of about 8 km, rises to about 300 m above the village. The volume of water in storage (at $S = 0.1\%$) is estimated to be about 10 million m^3, and the annual recharge (at 20%) about 6 million m^3. Thus, aquifer sustainability is not the limiting factor when developing the management scenario for the Botrivier wellfield. The controlling factor will be the hydraulic conductivity of the fractures and/or weathering, which enables water to move downgradient to the pumping borehole and wellfield. The Nardouw Formation quartzites are known to have low hydraulic conductivities (the T-value for Bh1 is approximately 5 m^2/d). Thus developing a pumping rate for a 24-hour pumping cycle which does not produce excessive drawdowns is probably the sum total of aquifer management that is needed. This can be likened to a spring which flows all-year – no-one is concerned with aquifer management – it manages itself. Such aspects have to be borne in mind when evaluating the test-pump data and developing a recommended yield.

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Case Study:
Ceres Municipality

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Abstract

By the early 1990s it had become clear that the existing Ceres Dam could not meet domestic requirements of the town and the local Koekemoer Irrigation Board. A new dam was therefore commissioned on the site of the existing dam. Water supply would be disrupted over the two-year construction period starting in 1995 and SRK Consulting were appointed to develop local groundwater resources to supply 100 ℓ/s for bridging purposes and also for subsequent summer peak demand. Five boreholes were developed in the Table Mountain Group (TMG) Aquifer with a supply potential of 48 ℓ/s and three in the Bokkeveld Aquifer with a supply potential of 50 ℓ/s. Surprisingly, the Bokkeveld Aquifer proved to be a more efficient and cost-effective source of groundwater than the TMG.

Introduction

In 1993, SRK Consulting were appointed by Ceres Municipality to upgrade the town's water supply systems to secure the projected long-term requirements. A major part of this work involved construction of a new water supply dam over a two-year period starting in late 1995. The existing dam supply would be disrupted during construction and local groundwater supplies were therefore required for bridging purposes during this period and for subsequent summer peak demand times. The initial requirement from groundwater was 100 ℓ/s (268 000 m^3/month).

Hydrogeology

Two aquifers occur in the Ceres area, namely sandstones of the TMG and shales and sandstones of the Bokkeveld Group.

TMG Aquifer

Due to the apparent advantages of developing the TMG Aquifer, i.e. higher yield potential, better water quality and little existing development, initial borehole siting was limited to the southern and western base of the Skurweberg and ten sites were pegged. Four sites selected by the Department of Water Affairs and Forestry (DWAF) were also reviewed (see Fig. 1). Two of the latter sites, G 33222 and 33224, were drilled by DWAF in 1992 and equipped with pumps by the municipality in 1994.

Borehole development was confined to the western area of Ceres for ease of incorporation with existing/proposed pipelines and reservoirs. Boreholes SRK 4, 6 and 7 were drilled on geophysical anomalies and visible fracture zones. SRK 5 and 10 were drilled in gaps between surveyed sites to test the hypothesis that boreholes could be sited almost anywhere because of the highly fractured nature of the TMG Aquifer (as at St Francis-on-Sea), in the syntaxis area of the Cape Fold Belt.

A feature of the borehole site survey was the variable responses obtained with the EM-34 magnetometer. At SRK 6 and 7 there was no anomaly recorded by the electromagnetic method used, although fracture zones were clearly visible in the field. A major anomaly was recorded at SRK 4 but, in this case, there was no visible fracture zone.

Drilling depth ranged from 120 to 200 m, all in very hard quartzitic sandstones of the Nardouw Subgroup beneath a shallow layer of sand and boulders. Low yielding fracture zones were encountered between about 18 to 60 m, with the main high yielding fractures being in the range 80 to 150 m. Blowout yields ranged from 3 ℓ/s (SRK 6 and 10) to 20 ℓ/s (SRK 5 and 7), while target production borehole yield was 10 ℓ/s. SRK 6 was continued down to 200 m despite its low yield and the hard, unfractured nature of the sandstone in the belief that additional groundwater strikes would be encountered, given the structural setting at Ceres, but this did not occur.

With seven boreholes so far drilled into the TMG Aquifer the success rate stands at 70%, which is very reasonable in terms of the yields obtained and in the broad context of groundwater occurrence in South Africa, but is somewhat below expectations given the favourable structural environment. The

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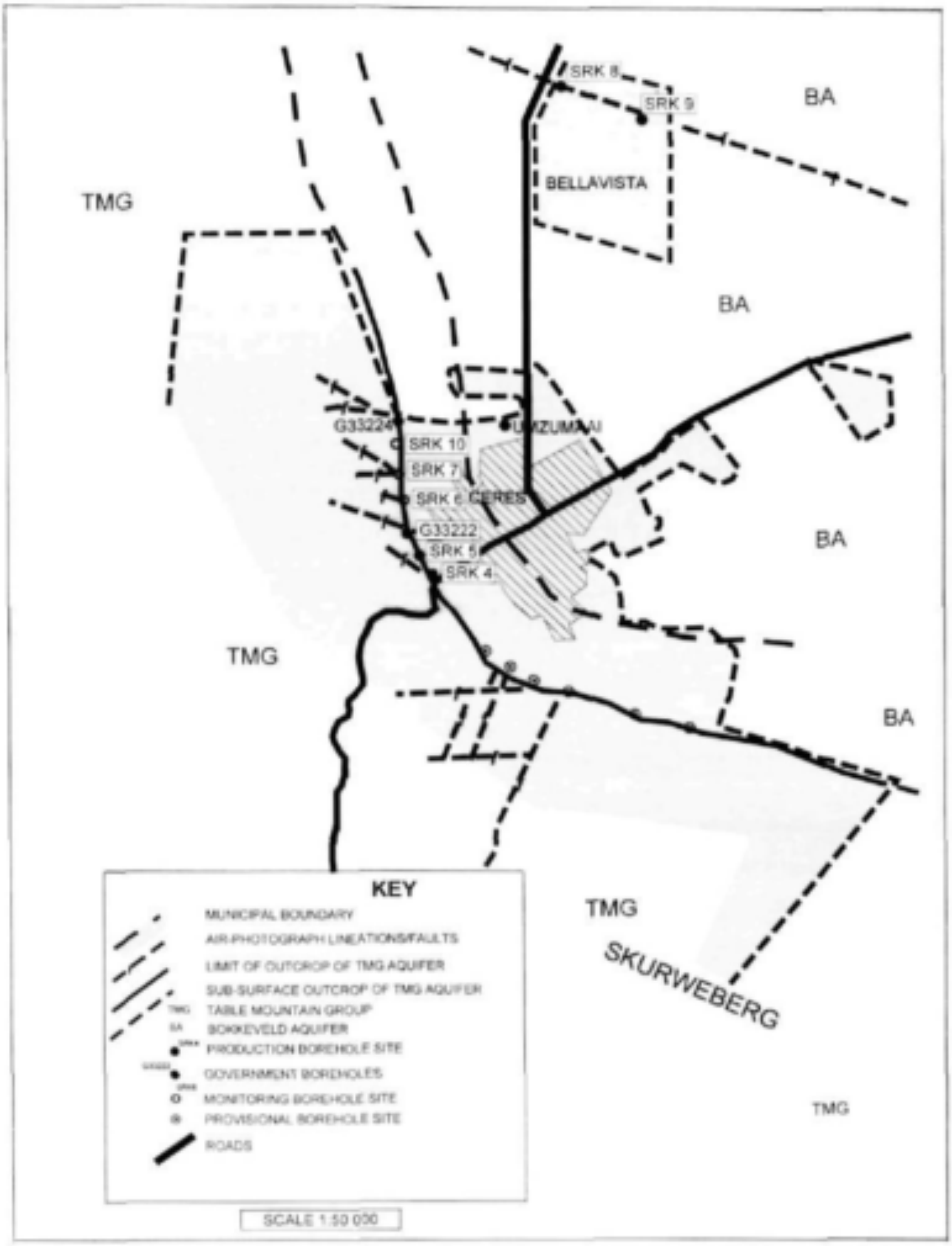

Figure 1

Ceres groundwater investigation: Locality plan

hypothesis that one can drill anywhere in the TMG Aquifer at Ceres is unresolved, with one success, SRK 5, and one failure, SRK 10.

Rest water levels are high, considering the depth to main water strikes, ranging between ~2 and 7 m below ground level (mbgl). This reflects the pressure head of groundwater from the recharge area of the Skurweberg to the west.

Discharge rates of up to 19 ℓ/s were achieved during the step tests (SRK 5) but such rates are typically not sustainable given the limited storage of fractured aquifers of this type. These aquifer types are characterised by low yield/drawdown ratios due to limited storage and fracture hydraulic conductivity, resulting in large drawdowns. Accordingly, discharge rates for the 72 h constant discharge tests were set at between 8.5 and 12.0 ℓ/s.

With the exception of G 33224, the time-drawdown plots from these tests all show a large and rapid initial drawdown which then levels-off at varying stages into the tests, indicating that equilibrium conditions have been reached (see Fig. 2). G 33224 shows a different response to pumping in that after the initial rapid drawdown, the time-drawdown plot

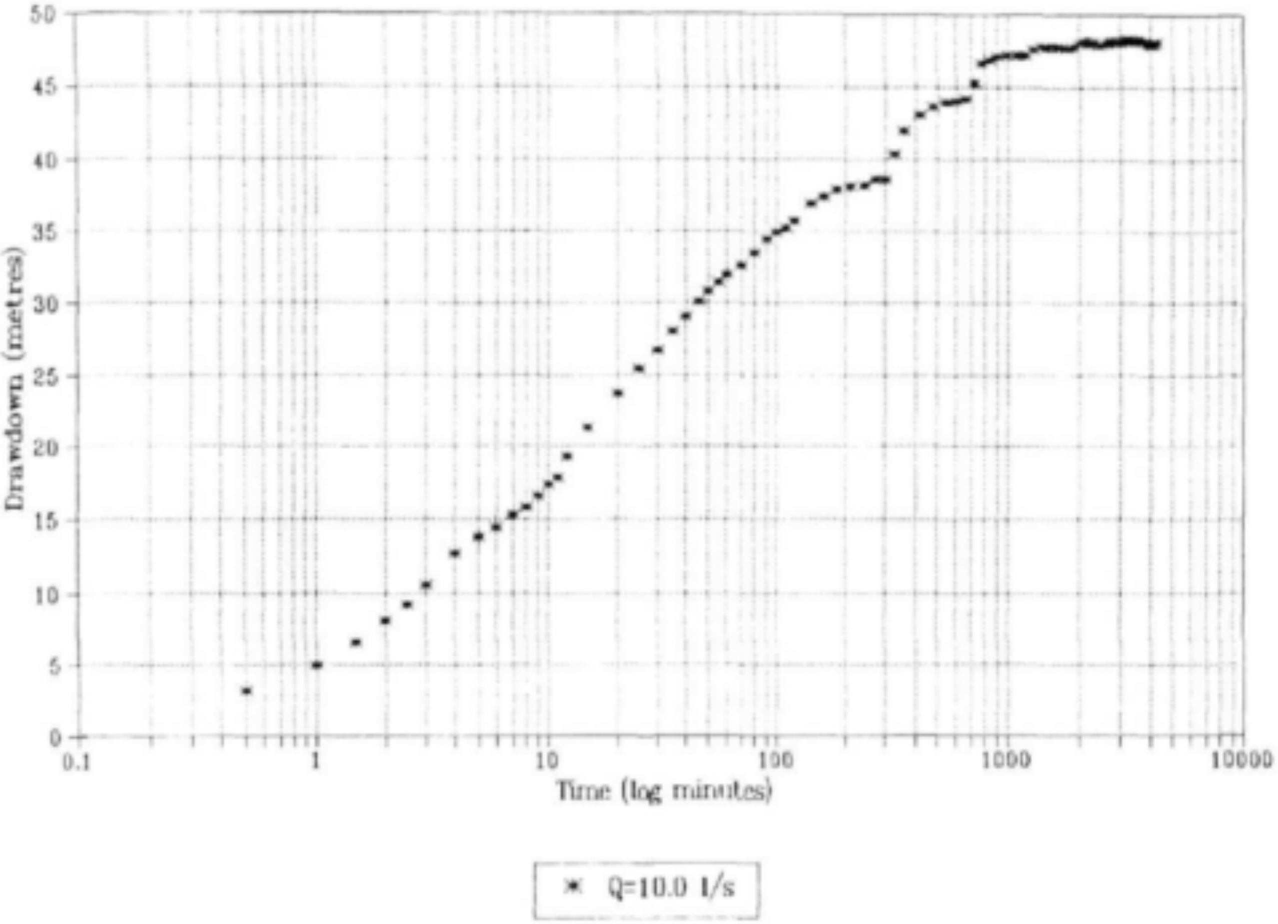

Figure 2

Borehole G33222 constant discharge test

shows a continuously steepening trend, indicating aquifer dewatering at this pumping rate.

Mutual interference of water levels occurs between SRK 4, 5 and G 33222 when they are pumped, resulting in additional drawdowns of up to 5 m in each borehole. This is not considered to be significant given the available drawdown in each borehole.

Bokkeveld Aquifer

Discussion on the Bokkeveld Aquifer is included for interest because of the contrasting results obtained.

At the request of the municipality, two additional boreholes, SRK 8 and 9, were sited at Bellavista Township, 5 km north of Ceres, in the Bokkeveld Aquifer. These were sited by means of an electromagnetic survey across a fault zone. There is also an existing municipal borehole within Ceres itself (Umzumaai) which is tapping the Bokkeveld Aquifer.

Rest water levels ranged from ~7 mbgl in SRK 8, in a topographically low area, to ~21 mbgl in the more elevated SRK9.

Discharge rates of up to 38 ℓ/s were obtained during the step-test on SRK 9, with a drawdown of only 9.5 m. However, the constant discharge tests showed that these rates are not sustainable, with SRK 8 & 9 and Umzumaai all showing steepening drawdown trends with time, indicating that water levels would eventually have reached pump intake at the discharge rates of 25.0, 30.6 and 20.0 ℓ/s, respectively.

SRK 8 is slightly affected by pumping of a private borehole, but there was no measurable interference between SRK 8 and 9.

Groundwater quality

Groundwater from the TMG Aquifer boreholes has an electrical conductivity (EC) of 2.8 to 3.5 mS/m, i.e. it contains virtually no dissolved salts and has a pH of around 4.8. It is therefore aggressive and will corrode any metals or concrete it comes into contact with. It also contains dissolved iron in sufficient concentration to cause aesthetic problems, such as taste and staining.

Groundwater from the Bokkeveld Aquifer is more variable in quality, with EC ranging from 20 m/Sm in the Umzumaai groundwater to 148 mS/m in SRK 8. This reflects the closer proximity of the Umzumaai borehole to the TMG Aquifer. All constituents analysed for are within SABS recommend limits for domestic water supplies, with the exception of Fe.

None of the boreholes showed any measurable trend to an increase in EC over the 72-h constant discharge tests. The only trend was a decrease in iron concentration in all boreholes, which still remained above risk-free levels.

Wellfield development

Based on their geographical location the boreholes have been grouped into two wellfields, the Western and Bellavista Wellfields. For each borehole a long-term and peak pumping rate have been determined, the former being a continuous, year-round rate and the latter for peak demand periods not exceeding one week's continuous pumping. Experience from other wellfields developed in TMG Aquifers containing groundwater with dissolved iron, e.g. St Francis-on-Sea, has shown that continuous pumping alleviates the problems caused by iron precipitation, such as discoloured water. Details of pumping schedules are given in Table 1.

It can be seen that the target groundwater supply of 100 ℓ/s has been met from the eight production boreholes and that there is an additional 18 ℓ/s available for short-term peak demand periods. Yield testing was carried out at the end of the dry summer months and so the water level responses to pumping, on which the above production yields have been selected, should represent a worst-case scenario.

The drilling and testing program has brought to light some interesting statistical comparisons between production boreholes developed in TMG and Bokkeveld Aquifers in the Ceres area, with practical significance for further wellfield development. These are summarised in Table 2.

Conclusions

The following conclusions can be drawn from this case study:

- There are two aquifers in the Ceres area, developed in the TMG and Bokkeveld Group, respectively.
- Seven boreholes have been drilled into the TMG Aquifer to the west of Ceres with a 70% success rate (blow-out yield >10 ℓ/s). The combined operational yield of these boreholes is 48 ℓ/s.
- Three boreholes have been drilled into the Bokkeveld Aquifer, with a combined operational yield of 50 ℓ/s.
- Somewhat surprisingly, boreholes in the Bokkeveld Aquifer yield twice as much as those in the TMG Aquifer and drilling depth and cost are about half that for a TMG borehole.
- The TMG groundwater has very low EC of 2.8 to 3.5 mS/m, a pH of <6 and is thus very aggressive. It also has a typically high iron content.
- Groundwater from the Bokkeveld Aquifer is more variable in quality, with EC ranging from 20 to 148 mS/m but also with a high iron content.

Table 1
Production borehole specifications

Western Wellfield	**Pumping rate (ℓ/s)**		**Pump depth (m)**
	Long-term	**Peak**	
SRK 4	10	12	119
SRK 5	12	12	110
SRK 7	10	10	110
G 33222	10	12	100
G 33224	6	7	98
UMZUMAAI	10	15	63
Sub-total	58	68	
Bellavista Wellfield			
SRK 8	20	25	55
SRK 9	20	25	65
Sub-total	40	50	
TOTAL	98	118	

Table 2
Comparison of aquifer development parameters

Parameter	**TMG Aquifer**	**Bokkeveld Aquifer**
Average borehole depth (m)	150	70
Average production yield (ℓ/s)	10	20
Average drilling cost *	95 000	50 000
Water quality	Buffering and iron removal required	Iron removal required

* Based on 1995 costs escalated at 15% p.a.

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The Geohydrology of the Ceres Waste Disposal Site

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Abstract

The Ceres waste disposal site is located on a viable groundwater resource. The site serves a population of 24 000 and was established in 1985 before current siting, design and operation requirements were specified. Geohydrological investigation and monitoring have shown the facility to already have had an impact on the underlying fractured aquifer system. Because of the disposal of large volumes of liquid waste by the fruit processing industry, it was not possible to define the extent and severity of contamination. The Department of Water Affairs and Forestry required the site be closed and rehabilitated, but this has been prevented by the lack of an alternative disposal facility. The geohydrological properties of Table Mountain Group (TMG) aquifer systems result in existing or potential sites on the TMG being unsuitable for development as waste disposal facilities. Because adjacent Bokkeveld Group aquifer systems are also often not suitable and other factors have to be considered in the selection process, appropriate engineering and management is required to reduce the impact of waste disposal sites on underlying aquifer systems. This should be coupled to demarcation of zones around the sites from which groundwater abstraction is prohibited.

Introduction

The town of Ceres, which has a population of some 24 000 people, is situated 100 km north-east of Cape Town. Ceres is the centre of the fruit farming industry in the area, with fruit juice production being a major component of the town's industrial activity.

The Department of Water Affairs and Forestry (DWAF) minimum requirements for waste disposal by landfill (DWAF, 1994) requires geohydrological investigations form part of the application for a permit to operate waste disposal facilities. A series of investigations were hence commissioned by the Ceres Municipality (Ninham Shand, 1993), culminating in the preparation of a site closure and rehabilitation plan after DWAF refused to issue a permit for the site and required the site to be closed (Hemingway Isaacs Coetzee, 1996). One of the main reasons for DWAF's decision was the disposal facility is situated on a major TMG aquifer system.

This paper describes the geohydrological setting of the waste disposal site and results of groundwater monitoring. It also examines the vulnerability of TMG Aquifers to anthropogenic activities and the feasibility of establishing waste disposal sites on TMG Aquifers.

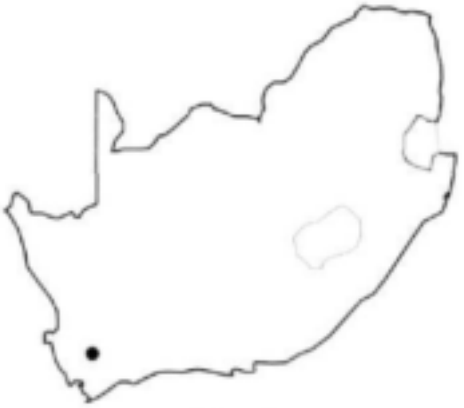

Figure 1
Locality map of Ceres

Background

Ceres is located at the base of the north-south trending Skurweberg Mountains. Mean annual rainfall amounts to 1 300 mm/a, of which 75% falls during the winter period between May and August.

It is somewhat ironic that at the time of the investigation of the waste site, the town's main water supply dam was undergoing major refurbishment. Because of safety reasons and the need to develop additional water supplies, the dam underwent a R100 000 000 upgrade. Though the town uses groundwater to an extent, the position of the waste

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site severely limits possible future expansion of the wellfield south-east of the town.

The waste disposal site is located 1.2 km south-east of the town, directly adjacent to the wastewater treatment works. The west-flowing Titus River is located 500 m north of the site. A small stream between the waste pile and the Skurweberg Mountains prevents run-off from the mountains entering the site.

Hydrogeological description

The waste disposal site is situated on light grey quartzitic sandstones of the Nardouw Subgroup of the TMG. The highly fractured rocks dip at 30° northwards. Previous geohydrological studies of the area showed the prevailing aquifer system to have a high geohydrological potential, principally because of the highly fractured nature of the aquifer system, a high recharge potential and good water quality (Meyer, 1984, 1987; Rosewarne, 1993).

Sustainable long-term yields in excess of 10 ℓ/s are commonly obtained while the aggressive groundwater has an EC of less than 20 mS/m, a pH of less than 5 and a NaCl character. In the vicinity of the waste site, groundwater flows in a northerly direction toward the Titus River.

Based on prevailing geohydrological characteristics, the aquifer was classified as a major aquifer system (Parsons, 1996) highly vulnerable to anthropogenic impacts.

Waste disposal

The waste disposal site was established in 1984 by the Ceres Municipality and is used to dispose of domestic waste and waste from the fruit processing industry. The waste site has not been engineered and no protective barriers have been installed. Because of high winter rainfall and large volume of liquid waste or effluent disposed of, the waste disposal facility is expected to produce large volumes of leachate. However, no mechanism is in place to measure the quantity nor quality of leachate generated.

Large volumes of liquid waste from the fruit processing industry are disposed in unlined ponds which surround the waste pile (Fig. 2). Typically the effluent sampled in the ponds has a relatively low EC (30 mS/m), a neutral pH, a COD value of 800 mg/ℓ and a CL concentration of about 90 mg/ℓ (Parsons, 1997). The chemical character is sufficiently different to easily distinguish between effluent, groundwater and surface water.

Monitoring

A surface and groundwater monitoring network was established at the waste site (Parsons, 1997). High yields of up to 10 ℓ/s were obtained in five monitoring boreholes drilled north of the waste pile (Fig. 2). Boreholes were drilled to a maximum depth of 30 m. Measurement of groundwater levels indicated the piezometric surface to be within 4.5 m of surface in winter and within 6.0 m in summer.

Figure 2
Position of boreholes at Ceres waste disposal site

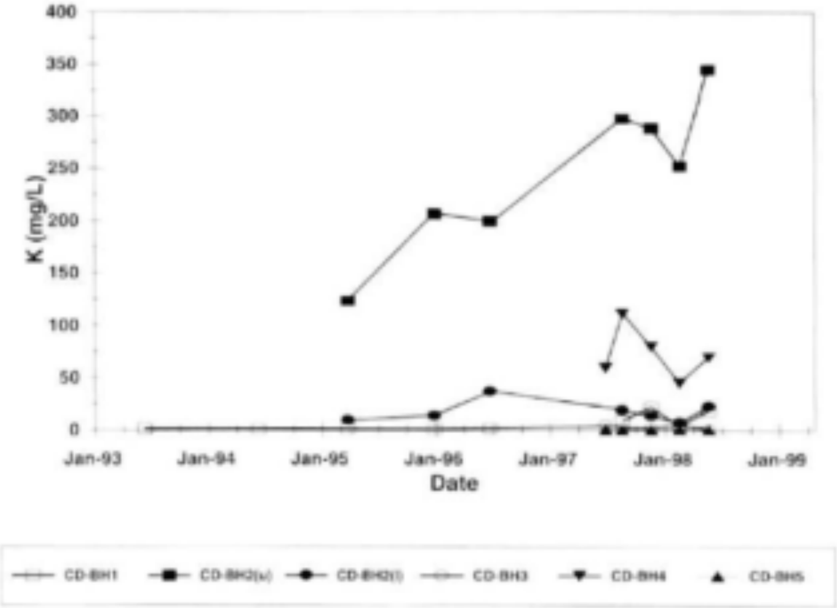

Figure 3
Results of monitoring at the Ceres waste disposal site

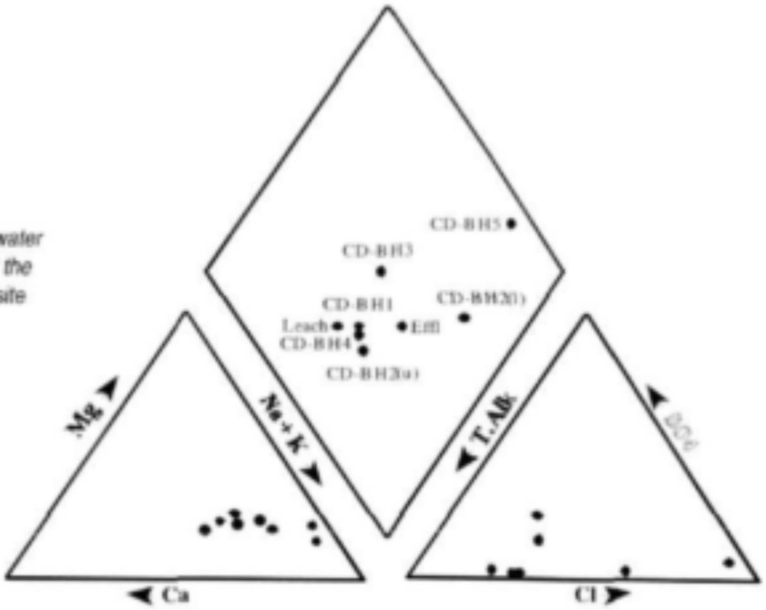

Figure 4
Piper diagram of groundwater and effluent sampled at the Ceres waste disposal site

Two piezometers were installed in CD-BH2 with CD-BH2(u) installed to a depth of 14 m and CD-BH2(l) installed to a depth of 26 m. All other monitoring boreholes have a typical open hole construction. It is interesting to note that groundwater quality stratification with depth was only observed in the piezometers. This indicates a high degree of mixing of leachate and groundwater takes place in the boreholes.

Monitoring data clearly indicates groundwater has been contaminated by the waste disposal site (Fig. 3). However, determination of the extent and severity of contamination is difficult because of the dilution effect of effluent from the ponds recharging the groundwater system. Contamination is readily detected in CD-BH2(u) and CD-BH4 as these two monitoring stations are least impacted by the effluent ponds (Fig. 2). CD-BH1 and CD-BH5 are closest to the ponds, and in terms of concentrations, yield groundwater similar to that of the effluent (Fig. 3). However, the chemical character displayed in the Piper diagram suggest CD-BH5 is typical of prevailing groundwater (NaCl type) while CD-BH1 has been influenced by recharging effluent and leachate (Fig. 4).

Discussion

The waste disposal site does not meet modern design and operation standards. It is, therefore, not surprising that the facility has already had an impact on the underlying aquifer system. Leachate generated by the waste pile and effluent disposed of by the fruit processing industry provide a large volume of a liquid chemical cocktail which rapidly reaches the highly fractured and transmissive aquifer system.

Under current legislation (DWAF, 1998), it is improbable that a waste site would ever have been established at the current site. Further, DWAF has instructed the Ceres Municipality to close and rehabilitate the site, but lack of an alternative facility prevents this from taking place in the short term.

Geohydrological characteristics of the site result in the site being unsuitable for waste disposal. This is true of most TMG Aquifer systems. Though prevailing geohydrological conditions allow for a degree of mixing and dilution of leachate, conditions also result in the aquifers being both important sources of water and vulnerable to contamination. The fractured nature of the rocks and shallow water table result in little attenuation taking place. Contaminants are also transported relatively quickly over long distances in the subsurface.

Alternative geologies on which to place waste disposal sites in the area is problematic. The Bokkeveld Group, which predominantly comprises of sandstones and shale, provides a better alternative. However, sandstones in the Group also have high geohydrological potential and have successfully been developed in the Ceres Valley as a reliable source of large quantities of groundwater. Potential sites have to target highly weathered shale and clay horizons which can prevent leachate from impacting viable water resources.

Unfortunately, geohydrological considerations are but one of a set of factors which govern the suitability of sites for development as waste disposal facilities. Public reaction, availability of cover material and transport distance are arguably as important. In those instances where sites have to be located on TMG Aquifer systems, appropriate engineering (with liners) and operation have to be used as a means of reducing the impact of waste disposal activities on underlying groundwater resources. This should be coupled with demarcation of zones around the waste pile in which groundwater abstraction is prohibited or restricted.

Conclusions

The Ceres waste disposal site is located on a viable groundwater resource. Geohydrological investigation and monitoring has shown the facility has already had an impact on the underlying groundwater system. Because of the disposal of large volumes of liquid waste by the fruit processing industry it has not been possible to define the extent and severity of contamination. DWAF requires that the site be closed and rehabilitated, but this has been prevented by lack of an alternative facility.

The geohydrological properties of TMG aquifer systems result in sites on the TMG being unsuitable for development as waste disposal facilities. Because adjacent Bokkeveld Group aquifer systems are also often not suitable and other factors also have to be considered, appropriate engineering and management is required to reduce the impact of these facilities on underlying aquifers.

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Boschkloof Groundwater Discovery

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Abstract

The Boschkloof Wellfield was developed for the Citrusdal Municipality between December 1997 and June 1998 following concern about the summer-season surface-water supply. Five boreholes (BK1-BK5) were drilled to depths ranging from 165 to 352 m. BK1 was a landmark event in the Olifants River area as a major water strike (air-lift yields of 100-120 ℓ/s) was encountered at 154 m depth, demonstrating the groundwater potential of the Peninsula Aquifer. Another major water strike (blow yields of 95-109 ℓ/s) was encountered in BK4 at 294 m. Experience during drilling of BK3 and BK4 was that groundwater yields increased dramatically below a "threshold depth" of ~200 m, possibly related to a stress-generated confining zone within the uniformly quartzitic rock type. BK1, BK4 and BK3 were jointly test-pumped for over 50 h at a combined rate close to 90 ℓ/s, and during the 2000 summer drought, BK1 and BK4 produced continuously for a few weeks at a combined rate of 60 ℓ/s. Isotope data from borehole water sampled during drilling and pump-testing shows a trend of constant ^{18}O, but D generally decreasing with depth. The distinctive isotopic lightness of the groundwater indicates recharge to this part of the aquifer from higher and/or colder and/or more interior inland settings. Most samples have $\delta^{18}O$ values <-5‰, and are isotopically similar to surface water samples from high-altitude Peninsula and Nardouw sites. ^{14}C results and elevated groundwater temperatures point to an influx of groundwater from a relatively deep flow path into the wells. The possible recharge area is ~40 km distant in a south-easterly direction along a major hydrotect, the Elandskloof-Boschkloof Fault Zone.

Introduction

In late 1997, the appearance of a strong El Niño effect in the eastern Pacific Ocean raised concerns about possible drought effects in Southern Africa, at a time when the Western Cape region had lately experienced a very dry winter season. Low rainfalls in the Olifants River valley had caused the Citrusdal authorities to anticipate that, for the first time in living memory, the river would cease to flow at the municipal pump station near the road bridge across the river (Fig. 1). Consequently, an application was made to access a special emergency fund created by the SA government for the mitigation of El Niño-related droughts, in order to provide a reserve groundwater supply to the town.

This application resulted in the urgent implementation of the earlier hydrogeological recommendations (Umvoto, 1995) around the target area on Boschkloof 466, approximately 5 km to the north-east of the town (Fig. 1). In January 1998 the first of the five planned Boschkloof wells encountered a major water strike at a depth of 154 m, when exceptional air-lift yields of 100-120 ℓ/s were achieved for ~30 min intervals of compressed-air blow by the drilling rig. After intersecting the water strike, this BK1 well had a constant artesian flow of about 7-10 ℓ/s (Hartnady, 1998). Attempts to deepen BK1 by further percussion drilling below 165 m were foiled by high water pressures in the in-flow zone, which could not be overcome even with air-compressor capacity boosted to ~50 bars.

The Boschkloof BK1 discovery was a landmark event in the Olifants River area, as it provided a practical demonstration of the unrealised groundwater potential in the thick fractured-rock aquifer of the Peninsula Formation (Fig. 2). Because of its location along the mountainous valley borders (Figs. 1 and 3), and consequent distance from both the town and the main areas of agricultural activity, where the valley floor is underlain by either young alluvial deposits and/or easily weathered Bokkeveld shale, the Peninsula Aquifer had been neglected as a possible groundwater source. The only previous borehole on the Boschkloof property (nicknamed the "Grass" well because of overgrown vegetation on the weak artesian flow) had been sited in the general target area, but was drilled into the nearby Cedarberg shale aquitard, and was abandoned at a depth of ~90 m due to nominal yield.

Between December 1997 and February 1998, five wells (BK1 through BK5) were drilled within an area measuring ~500 m (S or X-dimension) by 300 m (E or Y-dimension), and later pump-tested. Following

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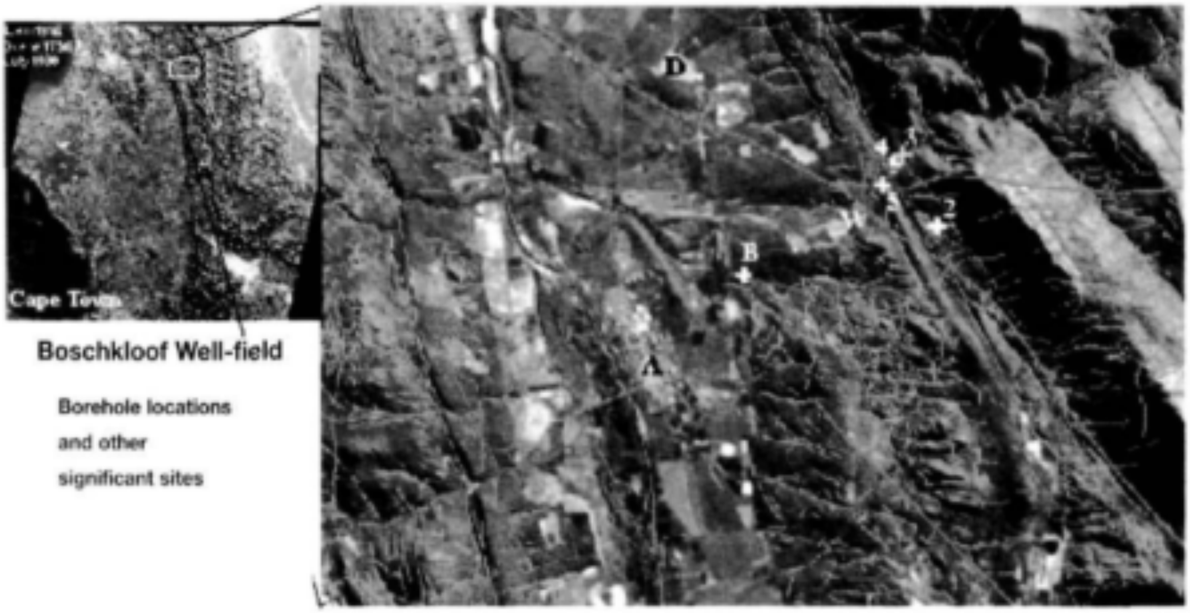
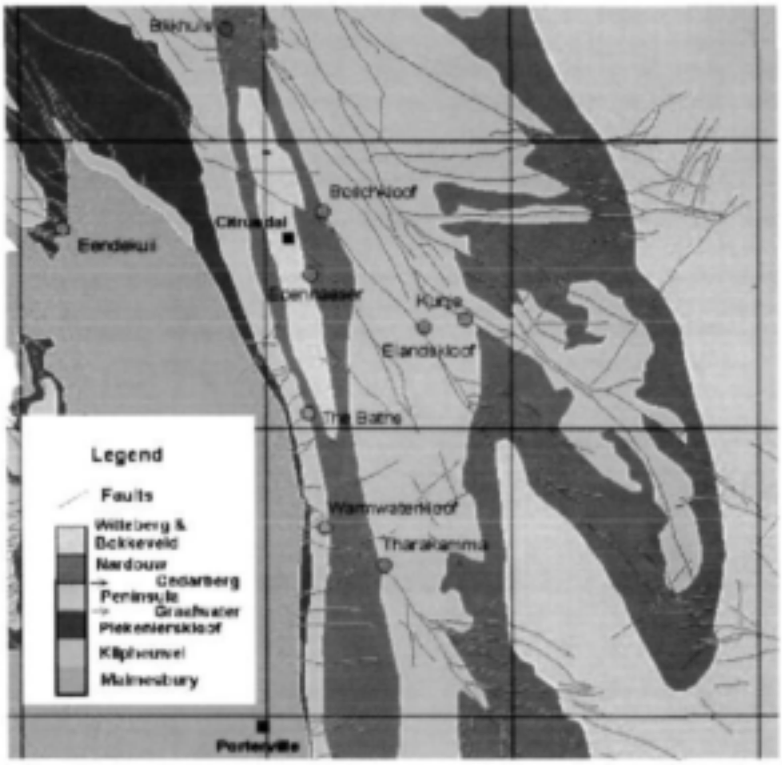


Figure 1
July 1998 Landsat imagery showing location of the Boschkloof well-field (numbered crosses) in relation to the town of Citrusdal (grey area marked A in). The wellfield accesses the Peninsula Aquiferwhere the Cedarberg Formation crosses the Boschkloof River. Also shown are:
(i) the location of an artesian borehole(B) in the Nardouw Aquifer,
(ii) a recently constructed large farm dam (D) supplied from a pipeline from a weir (W) on the Boschkloof River, not far downstream from the well-field,
(iii) superimposed major faults (red) and fracture traces (orange).

Figure 2
Simplified geological map of part of the CAGE project area, showing locations of Boschkloof and other key hydrocensus sites (green circles), also significant thermal springs (red circles)



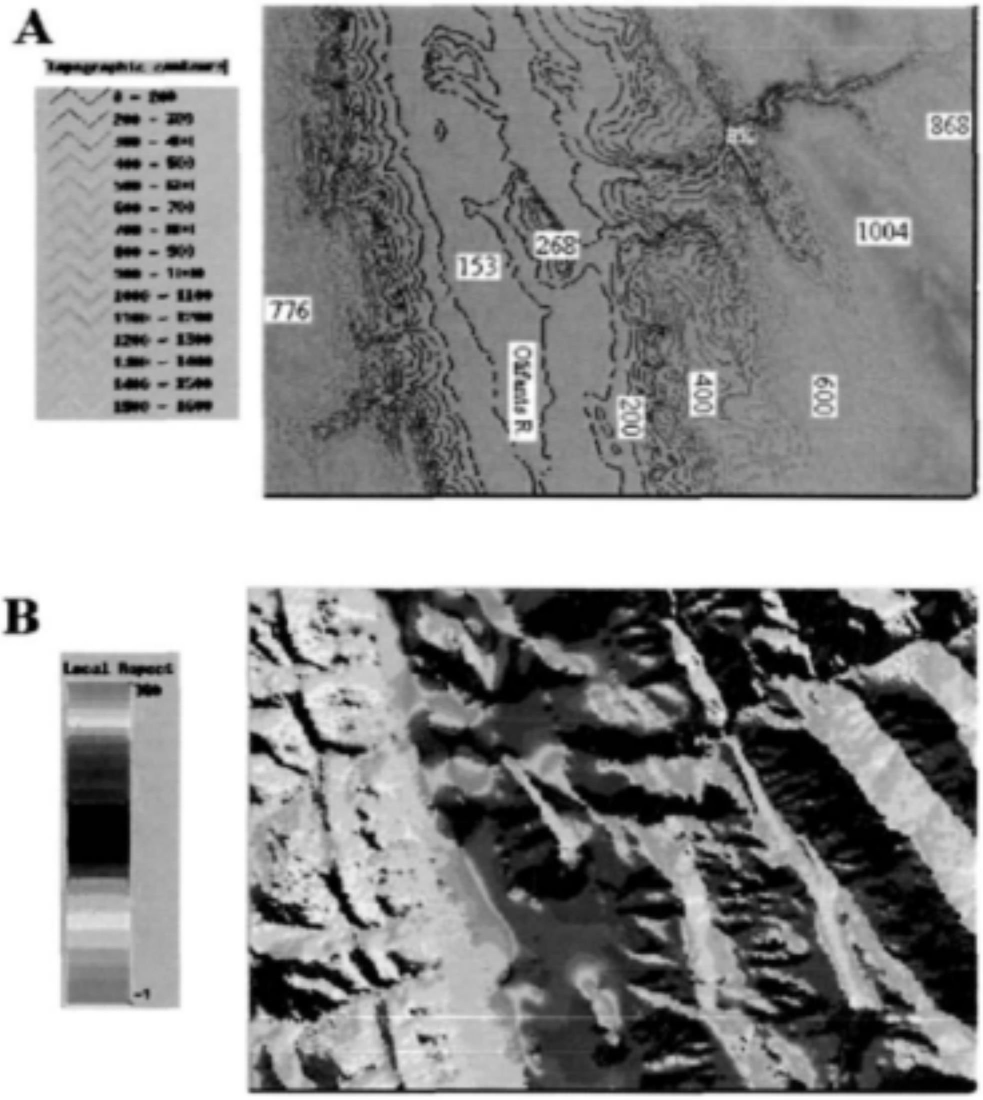


Figure 3
Citrusdal-Boschkloof terrain display, based on the DEM in the CAGE Project geographic information system (GIS), covering the same area as the main frame of Fig. 1: A. Topographic contours, colour-coded with selected elevations and spot heights; B. Local slope aspect, colour-coded red (N-facing), green (W-facing), blue (S-facing), and yellow(E-facing) with intervening hue gradients. The Olifants River separates theE-facing Olifantsberge slopes on the left from the Cederberg foothills on the right (mixed green, blue and red hues).

this development, a wide-ranging hydrogeological project, funded by the Department of Water Affairs and Forestry (DWAF) was undertaken with the E10 drainage basin (upper Olifants River) being the main focus (Hartnady and Hay, 2000). Oxygen and hydrogen isotope analyses were also undertaken on Boschkloof samples at the time of drilling and pump-testing, and these results are integrated with environmental isotopic analysis (including carbon) on samples gathered during the CAGE project hydrocensus (1998-1999 summer) as well as others in the Western Cape.

Geographical and geological setting

Aspects of the terrain physiography around Citrusdal and Boschkloof (Fig. 3) can be illustrated and selectively enhanced from a 30 × 30 m-resolution digital elevation model (DEM) constructed during the CAGE project. Together with the GIS-based and co-georeferenced satellite imagery, from both Landsat and SPOT sources, the DEM provides a powerful analytical tool for digital geospatial analysis over the wider area (Hartnady, 2001).

The well-field is at the mouth of an impressive canyon on the Boschkloof River, a right-bank tributary of the upper Olifants River in the E10 quaternary subcatchment, which cuts through the foothills of the Cederberg mountain range. Headwaters of this river drain the western slopes of the highest peak in this range, namely Sneeuberg (2026.8 m). The foothills through which the canyon is incised (Fig. 3A, upper right corner) include the peaks of Duiwelskop (1 471.6 m) to the north of the river, and Witberg (1 330.0 m) to the south.

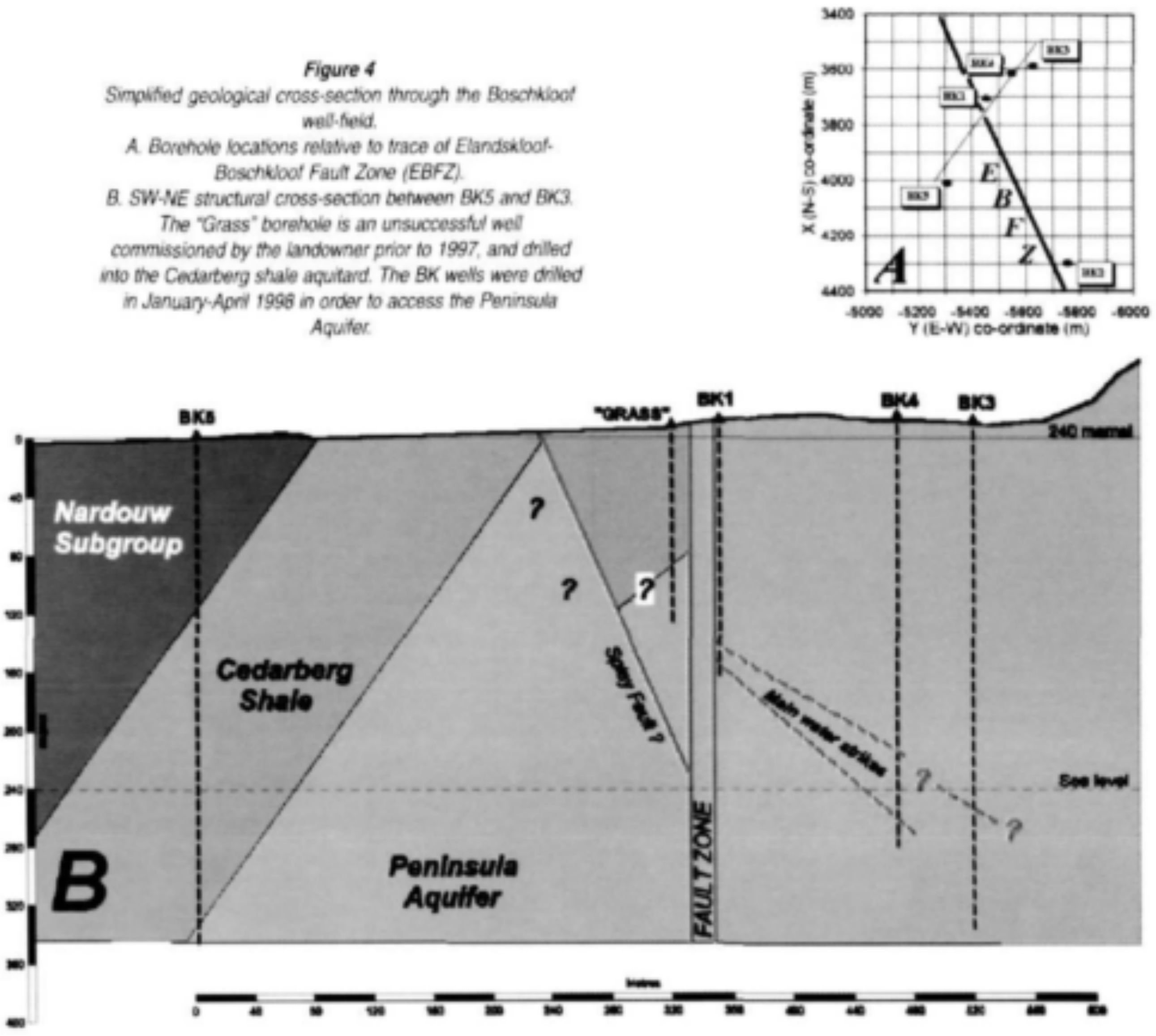
The NNW/SSE structural grain to the valley and mountain topography is controlled by the stratigraphic boundaries between the Peninsula Formation, Pakhuis and Cedarberg formations, and the Nardouw Subgroup (see De Beer, 2001; Fig. 3). Around Boschkloof NNW/SSE-and E-W striking major faults and fractures also dominate the structural geology (Fig. 4). A simplified geological cross

Figure 4

Simplified geological cross-section through the Boschkloof well-field.

A. Borehole locations relative to trace of Elandskloof-Boschkloof Fault Zone (EBFZ).

B. SW-NE structural cross-section between BK5 and BK3. The "Grass" borehole is an unsuccessful well commissioned by the landowner prior to 1997, and drilled into the Cedarberg shale aquitard. The BK wells were drilled in January-April 1998 in order to access the Peninsula Aquifer.



section showing the relationship between the boreholes is shown in Fig. 4B.

Drilling and geophysical logging

Drilling operations commenced on 12th December 1997 and were completed by 23rd February 1998. Summary details of the five boreholes drilled are contained in Table 1.

Down-hole geophysical logging of selected boreholes (BK1, BK2, BK4, and BK5) was undertaken before the boreholes were cased. This was considered necessary information for practical decisions that had to be taken on site in a severely limited time-frame with potential cost-saving implications, e.g. a decision to case to protect the pumps rather than to case the full length of the borehole, which did result in considerable savings. The down hole observations when the test-pumps had fallen down BK4, were critical to fishing this equipment so that borehole could be saved and the test continued.

Blow-yield and pump-testing results

Of the five wells drilled in the Boschkloof field (Fig. 4A), four were artesian at the completion of drilling operations. (The exception, well BK2, subsequently became weakly artesian). None yielded less than 10 ℓ/s in driller's blow-yield tests, except for well BK5 (8 ℓ/s).

The BK1 discovery strike at a depth of 154 m has already been mentioned. Well BK4, nearest to BK1 and drilled to a depth of 294 m, encountered a major water strike at a depth of 220 m, after which exceptional compressed-air blow yields in the range of 95-109 ℓ/s were achieved for 30 min to 1 h intervals. It is clearly connected at depth to the BK1 major strike (Fig. 4B), because the artesian flow at the BK1 well ceased at the time of this strike. The BK1 static

Table 1
Boschkloof drilling summary table

No.	Dates (days)	Coordinates X, Y, Elev. (m)	Final depth (m)	Brief geological log	Final blow yield (ℓ/s)	Temp (°C)	EC (mS/m)	pH
BK1	5/12/97 to 17/1/98 (21)	3701.875, -5455.737, 252.70	174	0-174 m qtz sstn, (96-102 m mic. qtzite) [Peninsula]	120	increase with depth 26.0 to 28.5	decrease with depth 60 to 40	6
BK2	19/1/98 to 5/2/98 (16)	4295.917, -5756.266, 270.44	314	0-314 m qtz sstn [Peninsula]	15	fluctuation 26.2 to 29.7; final = 26.8	fluctuation 11.1 to 77.3; final = 60	fluctuation 6.08 to 6.34
BK3	6/2/98 to 24/2/98 (15)	3585.423, -5628.356, 255.56	350	0-350 m qtz sstn, (44-61 m very soft silty sstn) [Peninsula]	15	fluctuation 25.6 to 30.1; final = 27	fluctuation 120 to 180 final = 120	decrease with depth 7.25 to 6.5
BK4	26/2/98 to 12/2/98 (15)	3613.339, -5547.380, 250.34	294	0-294 m qtz sstn [Peninsula]	95	fluctuation 24.1 to 27.5; final = 26	fluctuation 73 to 141; final = 90	6.5
BK5	14/2/98 to 23/2/98 (7)	4007.228, -5306.162, 240.86	348	0-105 m qtz sstn [Nardouw]; 105-336 m sandy qtz sltstn & shale [Cedarberg]; 336-348 m qtz sstn [Peninsula]	10	increase with depth 23 to 26	decrease with depth 240 to 110	6

water level then fell to 41 cm below the collar of the standpipe (0.36 m above ground level).

Boschkloof well BK3, like BK4 located along a transverse E/W striking lineament to the east of the main Boschkloof Fault structure, was drilled to a final depth of 350 m. The BK3 well is notable in that the blow yield did not rise above 5 ℓ/s until a depth of 199 m was exceeded, and the main increment to the blow yield (from 9 ℓ/s to the final 15 ℓ/s) was not attained until a depth of 255 m was exceeded.

Similarly, the blow yield in the exceptionally high-yielding well BK4 remained at only ~4.5 ℓ/s until a depth of 206 m was exceeded, whereupon it increased to ~100 ℓ/s at 294 m. This newly discovered phenomenon of dramatically increased groundwater yields below a critical "threshold depth" is of enormous practical importance in TMG hydrogeology, being crucial to future exploration and drilling strategy in the Citrusdal region and elsewhere in the Western Cape. It deserves the fullest possible further scientific investigation.

There is *no ostensible lithological change* associated with the ~200 m deep transition between low-yielding and high-yielding fractures with the uniformly quartzitic Peninsula aquifer at these Boschkloof sites (Fig. 4B). It is therefore strongly suspected that this transition - in which the upper 200 m thick, dry "skin" of the aquifer effectively confines the deeper geopressured parts - is controlled by the ambient stress regime.

A possible working hypothesis to explain this interesting and important phenomenon is the existence of a high horizontal compressive stress generated in the shallow bed-rock layer around the valley floor of the deeply incised Boschkloof stream by the adjacent steep mountainous topography, which is a well-known effect observed during stress investigations around many large dam sites in narrow valley settings.

This postulated superimposition of a near-surface "thrust-fault stress regime" upon the prevailing "wrench-fault regime", characteristic of the deeper crustal layers in the Western Cape region (Zoback, 1992), might explain the inhibition of groundwater flow from depth through the highly-stressed shallow zone. In the context of the Boschkloof well-field, however, this hypothesis must remain speculative until actual crustal stress measurements are obtained by systematic hydrofracturing or *in-situ* overcoring experiments.

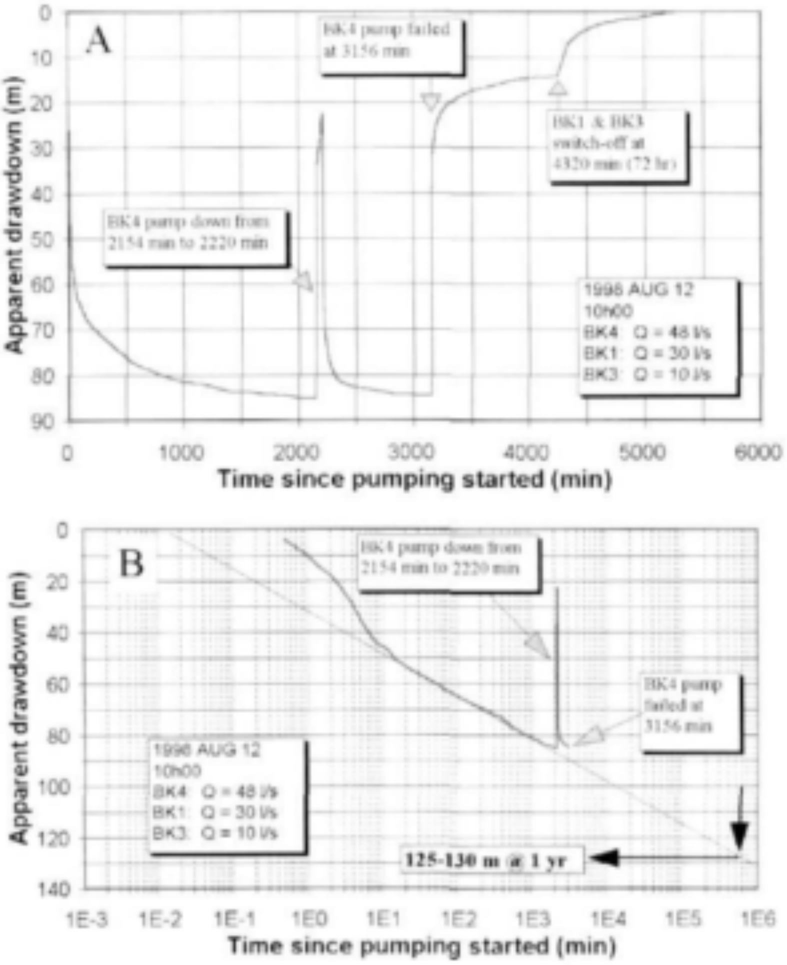


Figure 5A-D

Pump-testing results from BK4 and monitoring wells in the Boschkloof field

Figure 5A

72 h test involving simultaneous abstraction of 48 ℓ/s from BK4, 30 ℓ/s from BK1 and 10 ℓ/s from BK3

Figure 5B

Log plot of BK4 apparent draw down data from Fig. 5A above.

Pump-testing on the Boschkloof boreholes was undertaken during two separate operations. In April 1998 the boreholes were individually pumped in step-test and constant-discharge (CD) mode, while draw-downs in the pumped and non-pumped wells were monitored. In August 1998 a well-field test was conducted, during which three wells (BK1, BK3 and BK4) were pumped for 72 h at a combined CD of nearly 90 ℓ/s while water levels in all wells were monitored. The largest pumping rate was achieved in well BK4, which consequently showed the largest draw-downs (Fig. 5).

A sample of the well-field data for BK4 is given in Fig. 5A with interpreted results in Fig. 5B. The thin dashed line is fit to 20-2154 min CD data, from which a transmissivity T = 87 m^2/d is deduced. It is extrapolated forward to 5-month and 1-year predicted levels (~104 m and 125 m, respectively), and also backward to time at zero drawdown, from which storativity $S = 1.25 \times 10^{-4}$ is deduced.

The hydraulic property values obtained for the individual (April 1998) CD tests are contained in Table 2, and a sample 72 h test for well BK4 at 47 ℓ/s CD is illustrated in Fig. 5C. The range in estimated T is from 4 m^2/d in BK3, which is farthest away from the Elandskloof-Boschkloof fault zone, to 180 m^2/d for BK1, which is the original discovery well. The S range is from 1.1×10^{-5} for the low-yielding BK2 well to 4.6×10^{-3} for BK1. Results from different interpretative software (Aquitest, RPTSOLV, and the fracture-characteristic (FC) method) are reasonably consistent. The individual BK4 test (Fig. 5C) produced a drawdown of ~77 m after 4 320 min (72 h), theoretically extrapolating to ~80 m at 10 000 min (166.6 h), and only ~105 m at 1 million minutes (~694 d or 1.9 yr).

These predicted drawdowns after extended intervals still fall far short of the pump intake level at ~120 m, so that the ~50 ℓ/s CD could be regarded as a sustainable yield over a 1-2 year period of no recharge. For the April 1998 individual test data, a sustainable yield of ~34 ℓ/s has been estimated for the Boschkloof BK1 well on the basis of a ~40 m maximum drawdown (G van Tonder, 2001, in preparation).

During the 2000 summer season drought in the Western Cape, the Olifants River ceased to flow at the Citrusdal supply pump-station, and two newly equipped wells in the Boschkloof field were commissioned on an emergency basis as an alternative supply to the town. For a limited period between January and May, the BK1 and BK4 wells were pumped continuously at a combined rate of 60 ℓ/s, with occasional interruptions for system "teething troubles". Drawdowns over this period did not exceed 90 m, which was the approximate depth of pump installation.

Isotope hydrochemistry

Oxygen and hydrogen results

During the drilling of the Boschkloof borehole BK1, water samples were collected from progressively deeper levels. The data show a trend of constant $\delta^{18}O$, but δD generally decreasing with depth. The D-depth correlation is still tenuous, and is mostly

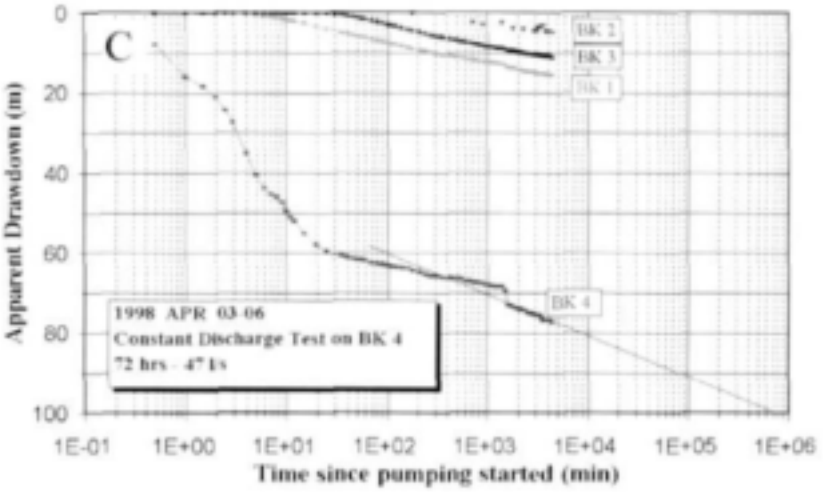


Figure 5C
Comparison with earlier results of 72 h constant discharge CD test on BK4 alone at abstraction rate of 47 ℓ/s. Drawdown histories of monitoring boreholes BK1, BK3 and BK2 are also shown.

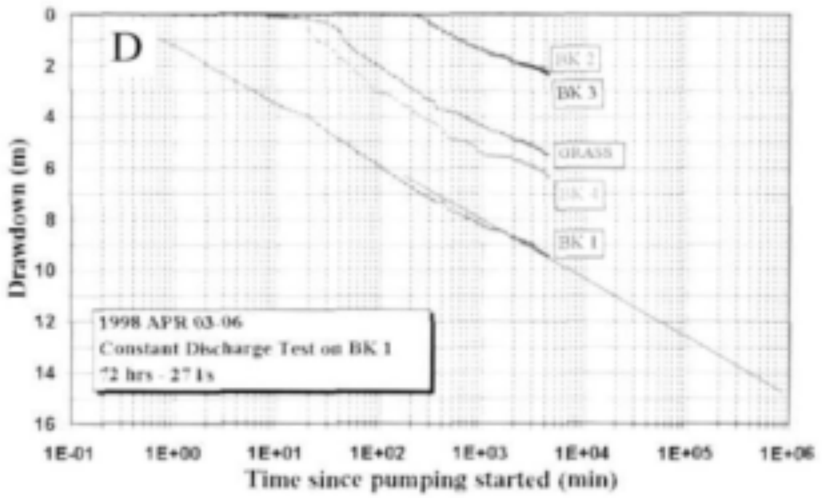


Figure 5D
Comparison with earlier results of 72 h constant discharge CD test on BK1 alone at abstraction rate of 27 ℓ/s. Drawdown histories of monitoring boreholes BK4, BK3 and BK2 are also shown.

Table 2
Estimated T and S values for Boschkloof wells

Borehole	CD rate (ℓ/s)	AQUITEST T (m^2/d)	RPTSOLV T (m^2/d)	RPTSOLV S	FC T (m^2/d)	FC recovery T (m^2/d)	FC S
BK1	27	186	180	4.6E-3	146	200	1.2E-3
BK2	15	10	9	1.1E-5	10	9	7.0E-4
BK3	10	4	5.5	1.0E-4	6	9	1.0E-3
BK4	28	62	60	3.0E-3	69	51	1.0E-3
BK4	47	56	61	2.0E-3	65	87	1.2E-3
BK5	8	6.5	6	8.0E-4	3	6	5.0E-4

a function of the deepest sample (169 m), but should still be regarded as significant in the geological context of increasing depth into the aquifer. The decreasing D values with depth probably reflect a lessening degree of interaction with near-surface or surface waters that would carry a heavier isotopic signature. The isotopic lightness of the deeper water is therefore indicative of recharge to this part of the TMG Aquifer in higher and/or colder and/or more interior inland settings.

Isotope data from borehole water sampled during drilling and pump-testing of five wells developed within TMG Aquifers in the Boschkloof area near Citrusdal (open blue squares), are distinctly lighter in δD and $\delta^{18}O$ than the main cluster of TMG borehole (B) and surface water (S, R) samples obtained in the wider CAGE area (Fig. 6). Most Boschkloof samples, dominated by those taken from the BK1 well during drilling to a depth of 169 m, have $\delta^{18}O$ values <-5‰, and are isotopically similar to surface water samples from high-altitude Peninsula and Nardouw sites.

Boschkloof (BK) groundwater samples (open blue circles in Fig. 7A) from borehole sites with collar elevations at ~250-270 m plot distinctly below the field

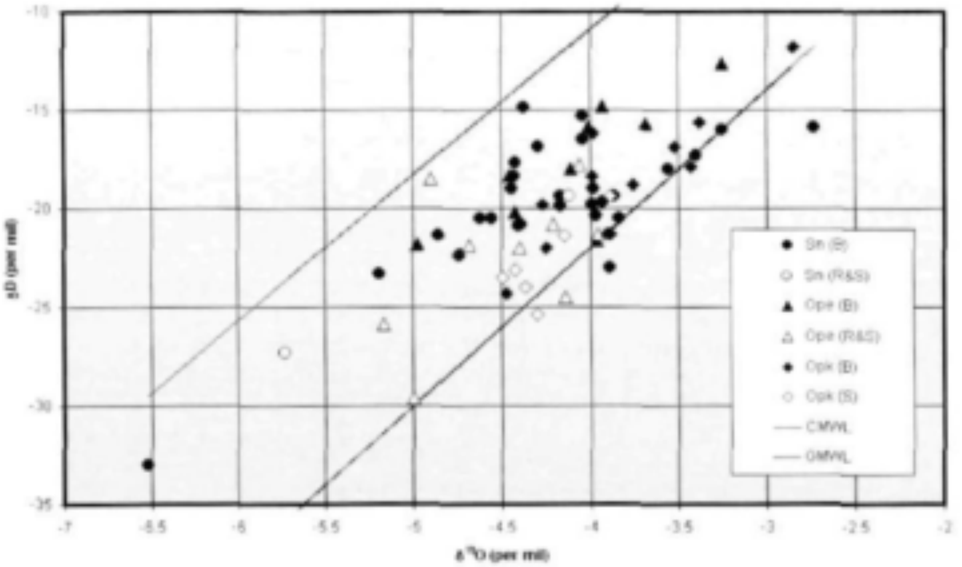


Figure 6
Boschkloof well-field data compared with TMG. Solid symbols represent borehole samples (B) from different TMG aquifer units (circles – Nardouw; triangles – Peninsula; diamonds – Piekenierskloof). Open blue squares are Boschkloof borehole samples, but other open symbols are TMG spring and river (surface water) samples. CMWL – Cape Mediterranean Meteoric Water Line. GMWL – Global Meteoric Water Line.

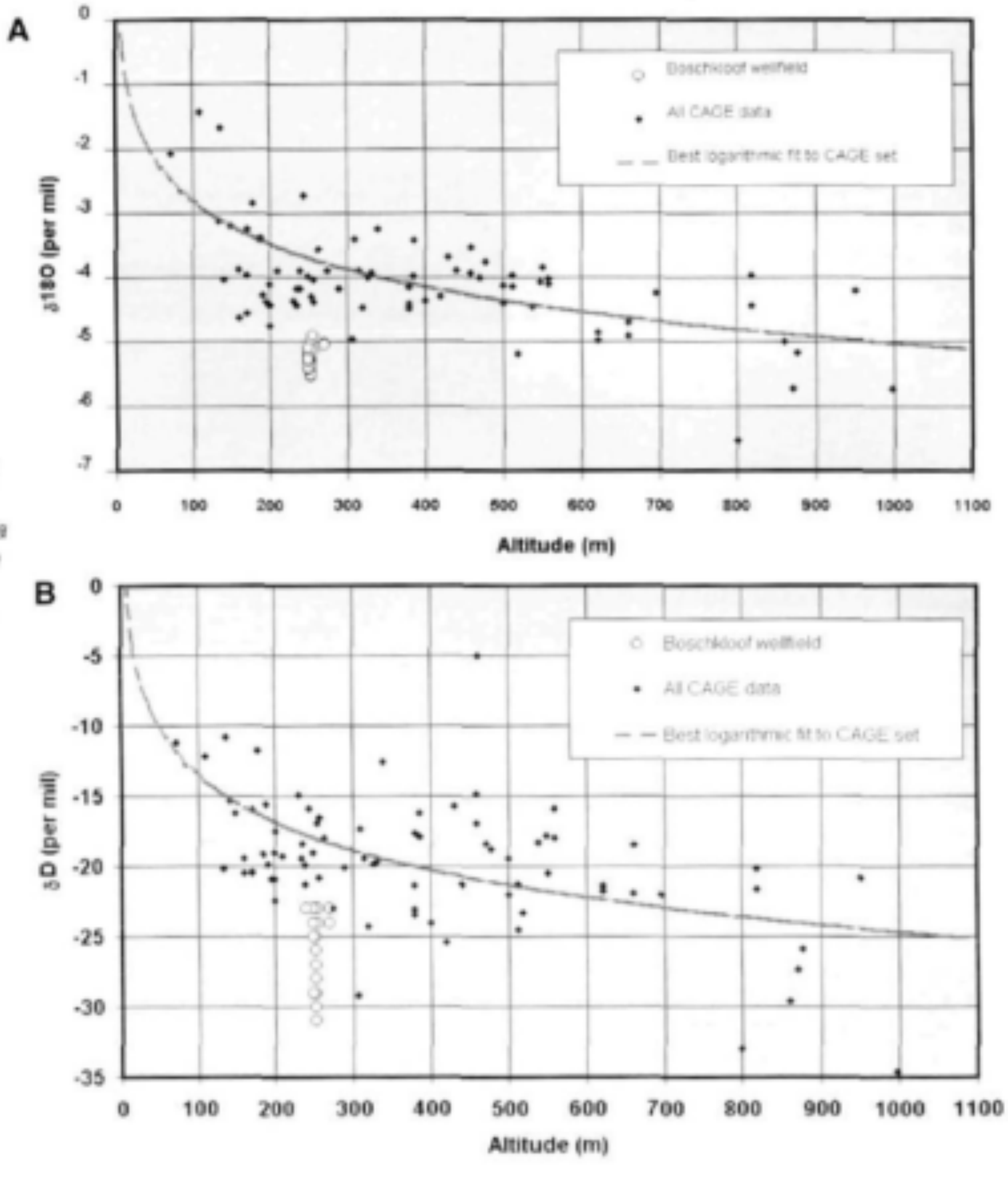


Figure 7
Isotopic compositions of Boschkloof samples compared to all CAGE data
A. δ18O compared to site elevation
B. δD compared to site elevation

Table 3
Carbon isotope results

Lab. No.	Site No.	Sample identification	Location lat. (N)	Long. (E)	Alt. (m)	$\delta^{13}C$ (‰)	^{14}C (pmc)
MV83Ci	-	The Baths	-	-	300	-20.0	70.7
UMV 1	3219CC 1042	Warmwaterkloof	-32.80307	19.05527	320	-18.31	75.5±1.9
UMV 2	BK 1	Boschkloof BK1	-32.64211	19.09210	250	-	79.3±2.0
UMV 3	BK 2	Boschkloof BK2	-32.64621	19.09314	265	-18.22	78.8±2.0
UMV 4	3219CA 3025	Eendekuil	-32.64550	18.78667	155	-19.48	74.7±1.9
UMV 5	3218DB 5108	Ebenhaeser	-32.63350	19.04372	220	-	88.6±2.0
UMV 6	3219CA 3082	Kunje	-32.67511	19.20886	720	-20.63	105.5±2.2
UMV 7	3219CC 1002	Tharakamma	-32.80609	19.10611	300	-	89.2±2.0

Notes:
$\delta^{13}C$ results for three UMV samples were lost due to split vials in the laboratory
Sample MV83Ci was collected ~1970-1 by Mazor and Verhagen (1983)

of all CAGE data, with scarcely any overlap. Tightly clustered about their $\delta^{18}O$ mean, the BK samples may be compared with CAGE samples from the >800 m elevation range, with reference to the best logarithmic fit to the full CAGE data set. In δD versus site elevation (Fig. 7B) BK samples again plot below the field of CAGE data, with only slight overlap, as some CAGE samples in the 300-600 m range have similar δD compositions. With reference to the CAGE best logarithmic fit curve, the BK samples generally compare with other CAGE samples in the >700 m elevation range, but there is a wide scatter about the fitted CAGE curve in the >800 m range.

Carbon isotope results

The radioactive environmental isotope ^{14}C, measured as percent modern carbon (pmc) relative to a standard, forms naturally in the upper atmosphere through the reaction of neutrons and nitrogen. As with tritium (^{3}H), its concentration has been affected by thermonuclear bomb testing in the upper atmosphere. ^{14}C in groundwater is the result of dissolution of atmospheric and soil layer CO_2. Once carbonate species move below the water table, ^{14}C decays and there are no new sources, but minerals containing carbon may complicate interpretation. As with tritium, the radioactive decay of ^{14}C is used to determine the mean residence time (MRT) of the groundwater.

From the CAGE ^{14}C results (Table 3), the seven samples of groundwater have MRT ranging from about a few decades (i.e. sample UMV6 from Kunje, a TMG cold spring of probably very shallow flow path on the eastern side of the Middelberg Pass) to some two millennia (i.e. samples UMV1-UMV4). In general, all the above results reflect the presence of rather dynamic groundwater flow systems.

The Warmwaterkloof sample (UMV1) is from a hot spring source mixing with cold stream water on the western side of the Olifants River Syncline, approximately 10 km south of The Baths hot-spring resort. The mixed water has a temperature of 26.4°C, whereas the upstream surface water temperature is in the range 17-19°C. Neither the hot-spring source temperature nor the proportion of surface-ground water mixing at this site is known, which complicates interpretation of the ^{14}C result. Depending on the degree of mixing with the stream and shallow groundwaters of more localised flow path, the mean residence time of the hot groundwaters could be much greater than ~2 kyr (B. Verhagen, pers. comm.). Comparison of this result with ^{14}C data from the nearby hot groundwater at The Baths (Table 2-1) is instructive, as the later has a lower percentage relative to modern carbon.

The Eendekuil (UMV4) result, which is not significantly different from the UMV1 sample, is from a spring near the base of the Piekenierskloof Formation along the western limb of the major anticlinorium, to the north of the Piketberg Mountain range (Fig. 3). It is not a thermal spring, and its low ^{14}C value perhaps reflects a long, slow flow-path from the western slopes of the Olifantsberg range through an aquifer of relatively low transmissivity.

Boschkloof samples (UMV2 and UMV3) are from boreholes BK1 and BK2, drilled 666 m apart into the top part of the Peninsula Aquifer along a major fault zone following the contact with the overlying, steeply-dipping (>80°) Cedarberg shale aquitard. The ^{14}C results for both wells, which reach different depths (174 m and 314 m, respectively) and have different pumping-yield characteristics, are not significantly different.

The common ^{14}C results for BK1 and BK2, and the elevated groundwater temperatures for all three boreholes mentioned above, establish that there is definitely an influx of groundwater from a relatively deep flow path into these wells. What degree of mixing there may be between this deep water and cooler water of more localised origin, encountered at shallower strikes in the fractured-rock aquifer, is a possible complicating uncertainty for interpretation of the ^{14}C-derived MRT. The possible recharge area for groundwater following the deep flow path is ~40 km distant in a south-easterly direction along the main fault zone, which forms one of the strands of the TLM hydrotect.

The Ebenhaeser and Tharakamma samples (UMV5 and UMV7) are from locations along the south-eastern side of the Olifants River valley, the former representing a borehole sample from the Nardouw aquifer, and the latter sampled from an artesian borehole in the Peninsula aquifer. The ^{14}C results are practically identical, and indicate a residence time measured in centuries. Although the groundwaters from these sites have normal temperatures in the range 21-23°C, the radiocarbon results indicate that they have probably followed extended flow paths of intermediate depth.

The $\delta^{13}C$ results for four of the seven UMV samples (Table 3) indicate that there is relatively little involvement of carbonate mineral reactions along the groundwater flow paths, which is as expected in the highly siliceous TMG context.

Conclusion

The discovery of dramatically increased groundwater yields below a critical "threshold depth" is crucial to future exploration and drilling strategy in the Citrusdal region and elsewhere in the Western Cape. The potential added value to the water resource development and planning in the Western Cape warrants further scientific investigation.

The isotopic lightness of the deeper water is indicative of recharge to this part of the TMG Aquifer in higher and/or colder and/or more interior inland settings and support the conclusion that the deep confined Peninsula Aquifer is a regional aquifer with active recharge.

Current usage of the boreholes during and following an extremely dry period indicates that the yields recommended after wellfield testing are sustainable.

Acknowledgments

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Case Study: Hex River Valley

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Abstract

The Hex River Valley is situated in the syntaxis area of the Cape Fold Belt and is situated astride the N1 between Worcester and Touws Rivier. The area is one of the major centres of export table grape production in South Africa, with some 3500 ha under cultivation. The vines and associated citrus trees require irrigation during the hot, dry summer months. The estimated requirement of 30 million m^3/a is derived from groundwater (two thirds) and surface water (one third). The groundwater is mainly derived from the Table Mountain/Bokkeveld Group Aquifer system, via some 450 deep production boreholes. In years with below average rainfall, some areas of the Valley experience a decline in borehole yields and groundwater quality. The vines are sensitive to salinity, with the recommended upper limit for irrigation water being 80mS/m. Since the early 1960s, numerous hydrogeological investigations have been carried out aimed at conceptualising groundwater occurrence in the Valley and quantifying available groundwater resources. This paper gives an overview of the current understanding in this regard.

Introduction

The hydrogeology of the Hex River Valley was extensively investigated by the Geological Survey and Department of Water Affairs during the period 1960 to 1980. The investigations were initiated in response to deteriorating groundwater quality in parts of the Valley. The Valley is mainly concerned with export table grape production and there are ~3 500 ha under cultivation. The growing season coincides with the hot, dry summer months and the vines are irrigated with surface and groundwater, the latter providing about two thirds of the average requirements of 30 million m^3/a. The vines are sensitive to salinity and the recommended limit for EC of irrigation water is 80 mS/m. However, much of the groundwater occurring in the Valley is above this limit.

Geology

The Hex River Valley has developed along a synclinal fold axis developed in rocks of the Table Mountain Group (TMG) and Bokkeveld Group (Fig. 1). Within the accessible parts of the Valley, only the Bokkeveld Group and the Nardouw Subgroup of the TMG are represented. The Cedarberg Formation forms a prominent marker band in the Hex River Mountains and presumably acts as an aquitard between the underlying Peninsula Formation and the Nardouw Subgroup.

Extensive alluvial deposits cover the valley floor and flanks. These range from thick (~60 m), coarse alluvial fan deposits along the northern and south-eastern flanks of the valley to finer river alluvium in the central areas. The various alluvial types are shown in Fig. 1.

Hydrogeology

There are two aquifers present, the TMG/Bokkeveld Group fractured aquifer system and the overlying alluvium. The former is the most important in terms of recharge and direct groundwater abstraction and of the order of 20 million m^3/a is abstracted from about 450 production boreholes. A feature of the valley is that most of the production boreholes derive groundwater from the Bokkeveld rocks, although the main source of recharge is rainfall on the TMG rocks of the Hex River Mountains, during the winter rainfall months. Part of this groundwater then flows into the main abstraction area of the Valley under natural gravity and induced head differences caused by pumping. Borehole hydrographs show that there is generally a steep recovery of water levels during the rainy season, especially on the northern flanks of the Valley, but that this recovery is relatively short-lived (Fig. 2).

Alluvium derived from the TMG is an important reservoir for groundwater storage and of the order of 5 million m^3/a of this groundwater leaks into the underlying TMG/Bokkeveld Aquifer during the pumping season (Rosewarne, 1981). There is little direct abstraction of alluvial groundwater. Alluvium

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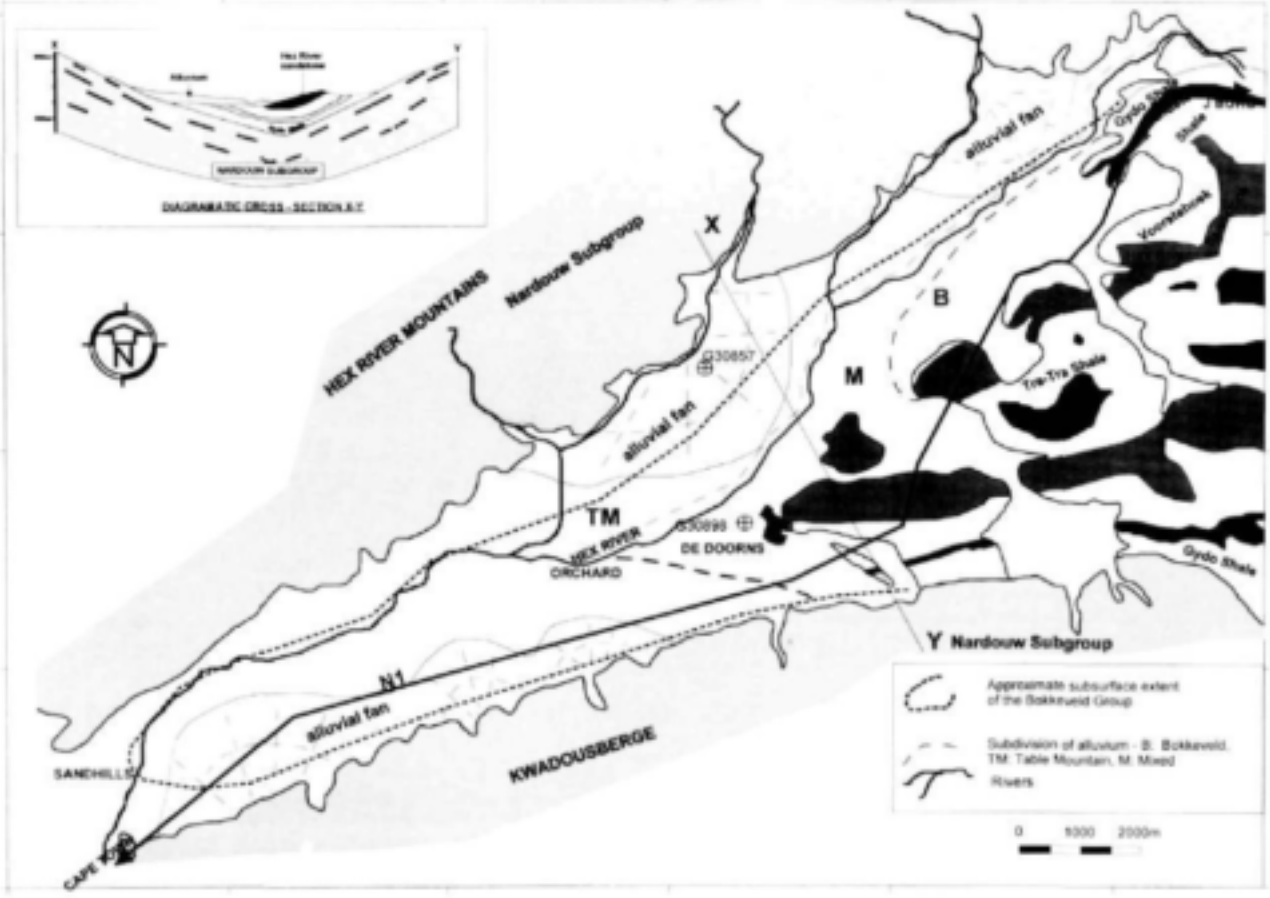

Figure 1
Hex River Valley: Geology

derived from the Bokkeveld Group rocks and mixed sources contains saline groundwater.

A feature of the Valley is a tongue-shaped intrusion of brackish groundwater (EC >80 mS/m) originating from the Bokkeveld rocks in the east and extending as far as Orchard (Fig. 3) The boundaries of this zone fluctuate according to recharge and groundwater abstraction patterns, extending further to the north and south-west in years of low rainfall. The best quality groundwater originates from the TMG Aquifer, where EC is <10 mS/m.

In years with above average rainfall, there is enough water to meet demands throughout the Valley. However, following below average winter rains, certain areas experience a drop in borehole yields and deteriorating groundwater quality. In this respect there is an uneven distribution of groundwater in the Valley rather than a general shortage. The areas experiencing shortages are generally those to the south of the Hex River and to the north-east of De Doorns. The reasons for the above shortage are a combination of the main recharge area being the Hex River Mountains, lack of saturated alluvium and poor water quality.

It is clear from past records and experience that total recharge to the Valley is not sufficient in "dry" years to meet demand for groundwater *under the present system of abstraction*. However, the total *potential* recharge to the Valley probably is.

Looking at borehole water level records, it appears that boreholes on the northern flanks of the Valley fully recover each year no matter what the rainfall, while those in the central and southern areas do not and show continual decline in response to below average rainfall. There is nothing practical that can be done to improve the performance of the latter boreholes and, in terms of a groundwater management plan for the whole Valley, reliance on these boreholes should be phased out (Rosewarne, 1997).

There is a relatively narrow zone of low drought risk north of the Hex River and paralleling the Hex River Mountains. Moving in a southwards direction the risk increases through medium to high, and very high in the central/eastern but largely unproductive area of the Valley. The medium risk areas will mainly be affected by decreased yields, while the high risk areas will be affected by both decreased yields and deteriorating water quality.

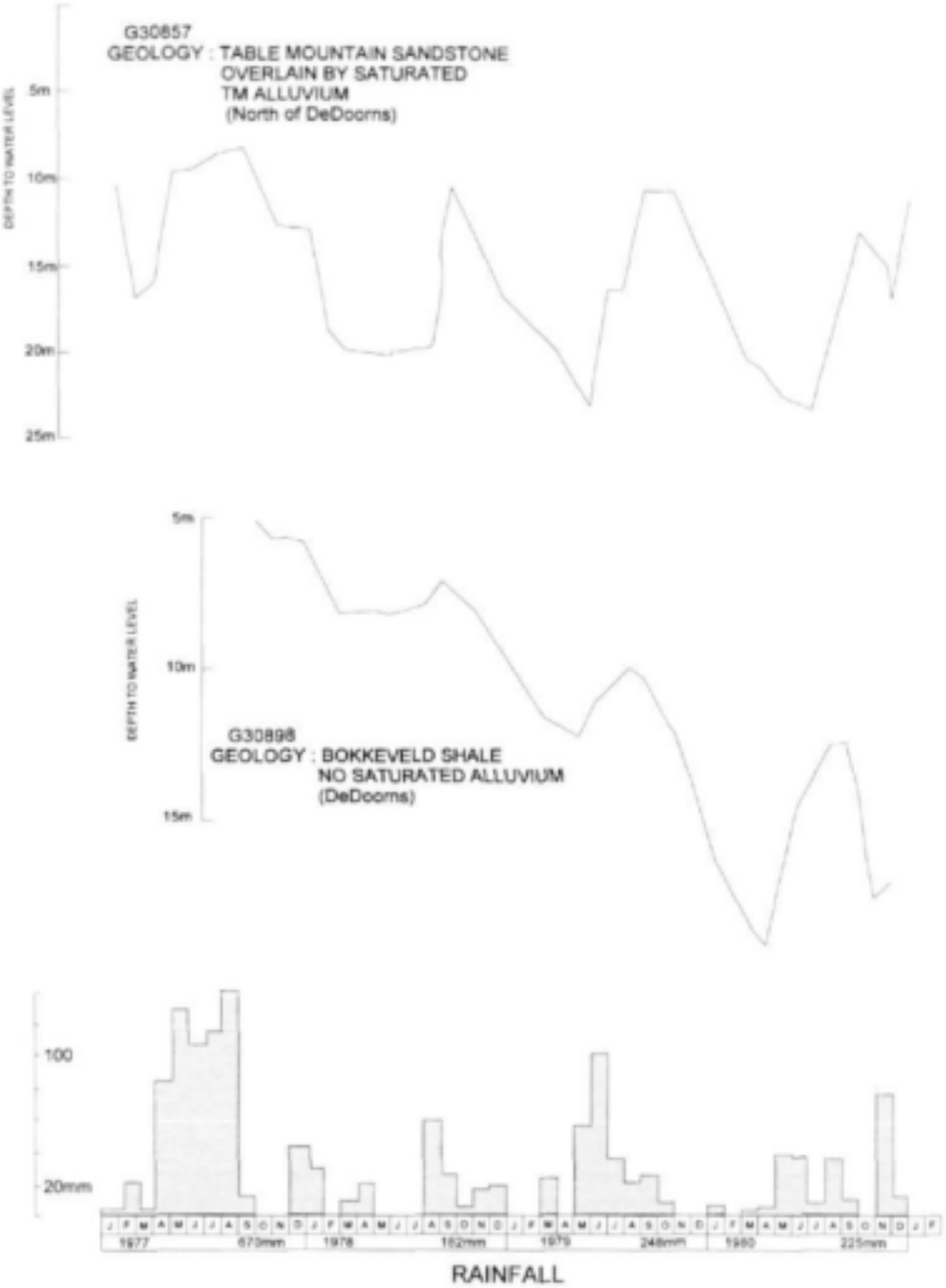

Figure 2

Borehole hydrographs

Groundwater management

The management of groundwater in the Valley is currently done on an individual farm basis, with the ~ 450 production boreholes pumped on an *ad hoc* basis and no metering of actual amounts pumped. To obtain the optimum assured yield from the aquifers, a first prerequisite is that the Valley is treated as a dependent unit in terms of groundwater management. A second prerequisite is that ground and surface water are managed on a conjunctive basis so that the separate yields of the former can be replaced by the larger and more economic joint yields of the latter.

The main components of a groundwater management plan in the Valley concern determining the optimum network of high yielding boreholes, artificial recharge and importing groundwater from outside the main Valley catchment.

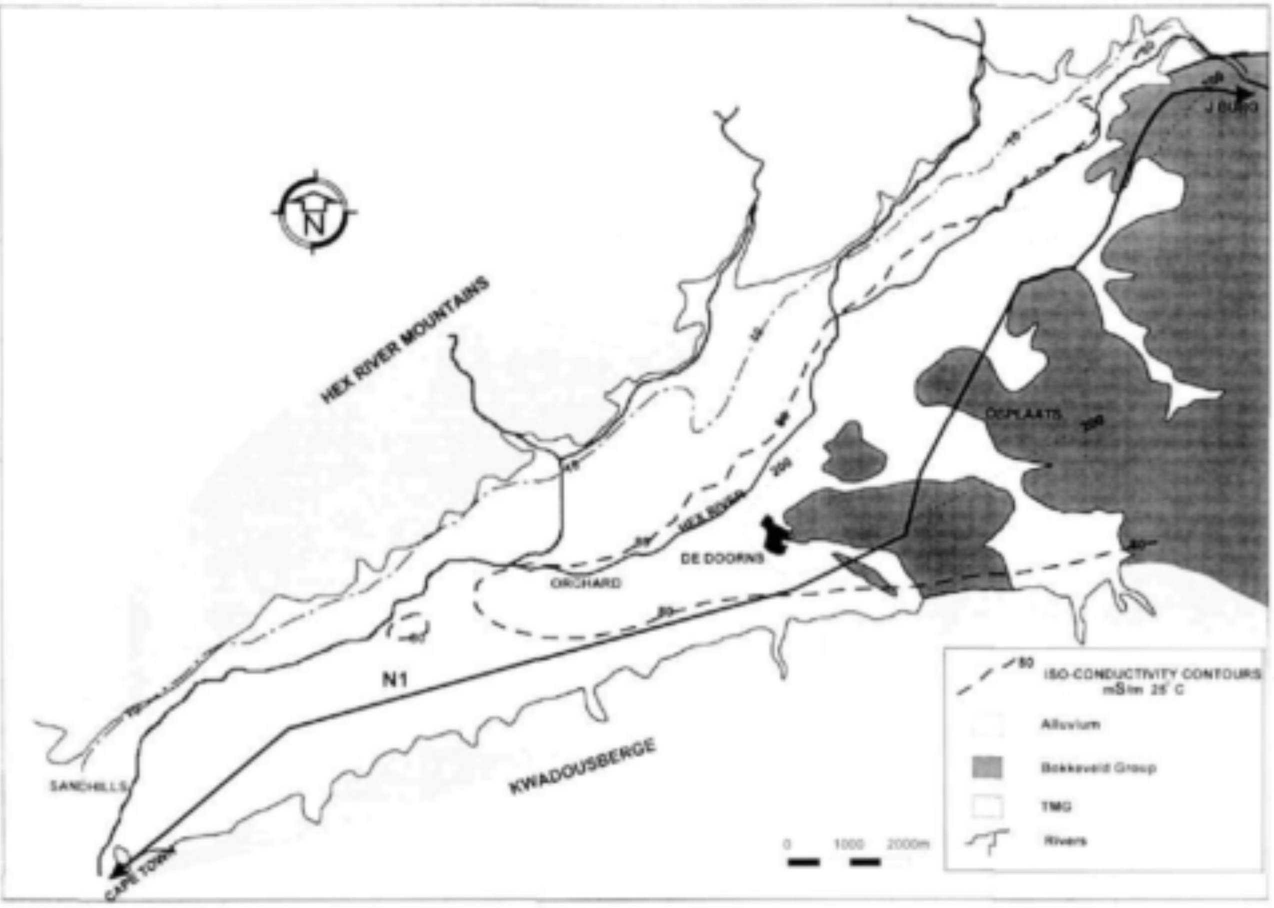

Figure 3
ISO-conductivity map: Summer 1980

Maximum mutual interference between pumping boreholes occurs in a NE-SW direction and a spacing of ~500 m should be allowed for between boreholes in this direction. The restructuring of the network of production boreholes will not necessarily increase the annual yield potential of the aquifers but will provide a more assured yield, with all abstraction taking place within the low risk drought hazard area.

If the figure for annual groundwater abstraction estimated by Rosewarne (1981) of 20 million m^3 is accepted as a reasonable "average", then this could be taken as the baseline annual yield of the Valley. This would require a network of 250 boreholes in the low risk drought hazard area, pumping at 5 ℓ/s during a six month pumping season.

Recoverable artificial recharge potential is estimated at 7 million m^3/a, once the available storage has been filled. The time required for this will depend on surplus water availability, recharge rates attainable and natural losses from the system.

In terms of imported groundwater, it is estimated that there is 10 million m^3 available from the catchment below the Roode Elsberg Dam and 25 million m^3 from the catchment of the Amandels River. These figures are based on surface areas of TMG and equivalent recharge rates as estimated for the TMG of the Hex River Mountains (Rosewarne, 1997). The latter figure takes into account summer surface water flows and so should represent sustainable yield without reducing summer low flow for surface water.

Conclusions

The main conclusions to be drawn from this case study are as follows:

- There are approximately 450 production boreholes abstracting about 20 million m^3/a to irrigate 3 500 ha of vines and citrus.
- Factors constraining groundwater use and development under existing management conditions are shale barriers within the TMG, spacing of production boreholes, areas of unsaturated alluvium and poor groundwater quality in the east and north-east.
- There is a relatively narrow zone of low risk drought hazard north of the Hex River, subparallel to the Hex River Mountains. The risk

increases to the south and east through medium to high and very high, although the latter area is largely uncultivated.

- There is about 16 million m^3 of storage available in alluvial fans for artificial recharge. Of this, possibly 7 million m^3/a could be recovered either directly from alluvial boreholes or indirectly by leakage into the underlying TMG / Bokkeveld Aquifer.
- Artificial recharge could decrease the high risk drought hazard area by about 1 700 ha.
- There is an estimated 10 million m^3 of groundwater available in the catchment below the Roode Elsberg Dam and a further 25 million m^3 from the Amandels River catchment.
- Under the present situation of management of groundwater on an individual farm basis, there is no prospect of significantly increasing overall availability of groundwater and a significant part of the Valley falls in the medium to high risk drought hazard areas.
- If the Valley is managed as a dependent unit, then there are sufficient groundwater resources to meet demand even in "drought" situations:

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Groundwater Prospecting on Verlorenvalley 334, Between Ceres and Touws River, Western Cape, South Africa

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Abstract

Hydrogeological prospecting around the Table Mountain Group (TMG)-Bokkeveld contact on the northeastern side of the Hex River mountain range produced a major groundwater strike of >60 ℓ/s air-lift blow yield. Previous development had focused on the Bokkeveld regolith aquifer and the immediately subjacent contact zone, close to the existing valley agricultural developments. In order to improve the hydrochemical character and dry-season sustainability of the groundwater development, an alternative exploration strategy was proposed. The new VV1 deep well (~250 m depth) targeted a deeper, more productive aquifer within the Skurweberg Formation close to a WNW-ESE-striking fault, connected via other major fractures to a high-mountain recharge area along the Hex River summit range. Lithological and geophysical logging of the completed well, together with rest water levels recorded during drilling, showed that the ~15 m thick, hitherto formally unrecognised, Verlorenvalley carbonaceous shale-bearing member at base of the Rietvlei Formation, is an effective confining mini-aquitard above the main Skurweberg Subaquifer. Because, for logistical and economic reasons, much TMG groundwater development has focused only on the uppermost TMG close to Bokkeveld-based agricultural lands, the detailed hydrostratigraphy and aquifer-aquitard structure of the ~200 m thick Skurweberg-Rietvlei interval is of regional hydrogeological importance in the Western Cape.

Introduction

In late 1998 the New Farmers Development Company commissioned an evaluation of the groundwater resources of the farm Verlorenvalley 334 (also known as "Verlorenvlei"), situated between Ceres and Touws River along the R46 main road (Fig. 1). The evaluation (Umvoto, 1999a-c) involved:

- a hydrocensus survey and water sampling over the farm and surrounding properties covering an area of ~280 km^2;
- a hydrogeological review and sustainability assessment of existing well-field yields through pump-testing of selected existing boreholes followed by a programme of water-level monitoring through the growing season; and
- recommendations relating to the potential for further groundwater development.

Verlorenvalley is a deciduous-fruit farm dependent on groundwater to a considerable extent since flood hydrology dominates the surface water flow patterns. The main focus of the evaluation was to provide a hydrogeological model for the farm, prepare a sustainable well-field and conjunctive water-use management plan, with emphasis on locating the most favourable aquifer at depth and on selecting one or more new target well-sites.

The investigations culminated in siting, drilling and geophysical logging of a single borehole in the southwestern part of the property (Figs. 2 and 3). The VV1 well was targeted at an evident fault structure, to intersect it in the range 200-250 m within the central fractured sandstone aquifer of the upper TMG. Smaller water strikes providing a cumulative air-lift blow yield of ~10 ℓ/s were achieved at relatively shallow depth, but the main strike occurred only at a depth of ~235 m. A blow yield in excess of 80 ℓ/s was thereafter achieved.

Physiography and rainfall

Verlorenvalley is situated ~150 km inland from the coast and landward of the regions highest mountain range, the Hex River mountains (Fig. 1). The highest mountain in this range is Matroosberg (2 249 m) and a prominent ridge known as Sonkliprug extends from this summit to a local prominence (1 422 m) ~2 km southeast of the Verloren Valley homestead (Fig. 2). The area is one of strong topographic and climatic gradients between the Medi-

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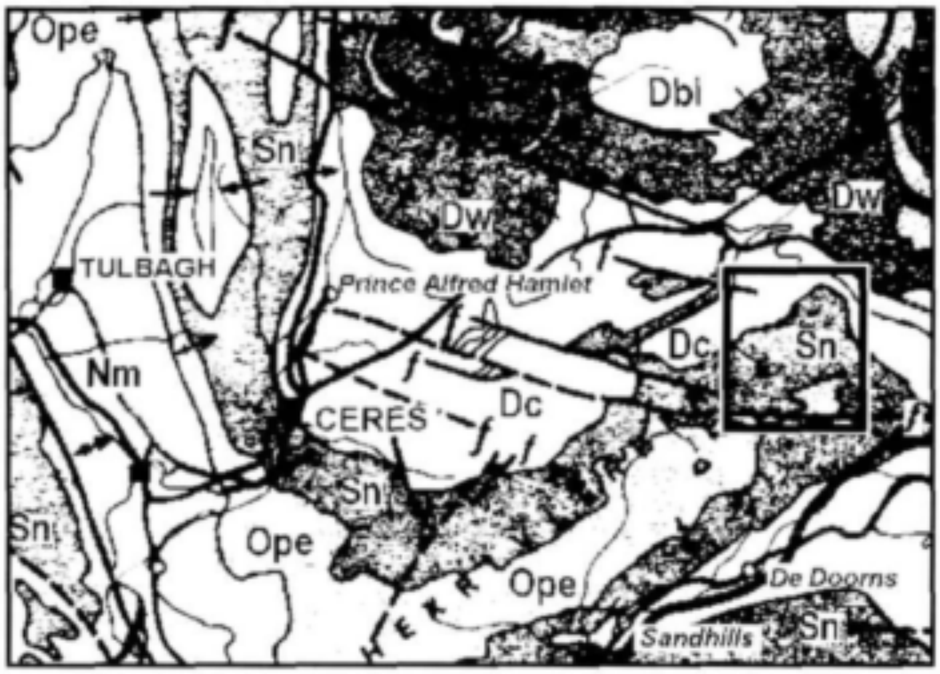

Figure 1

Location of the Verloren Valley project area on the northeastern end of the Hex River mountains. The area (rectangular box, east of Ceres and north of De Doorns) is underlain mainly by quartzitic rocks of the Nardouw Subgroup (lighter stippled unit; annotated Sn), bounded on the north by dominantly shaly rocks of the Ceres Subgroup, Bokkeveld Group (annotated Dc). Other stratigraphic units shown on this B&W geological map rendition are the Malmesbury Group (Nm), Peninsula Formation (Ope), Bidouw Subgroup (Bokkeveld: Dbi), and Witteberg Group (Dw). There is an en-echelon array of faults between the southern part of the Verloren Valley area (Bokkerivvier) and the Groenhof Fault between Prince Alfred Hamlet and Ceres. Another shorter fault of similar strike enters the northwestern corner of the Verloren Valley area.

terranean zone over the Hex River mountains and the Karoo arid zone further inland. The lowest point on the property is at ~880 m on the Smalblaarrivier stream (Fig. 3). This stream, a tributary of the Touws River, enters the property at its southwestern corner at ~1 150 m, and the main arable parts of its valley lie below 1 050 m.

April to September is the main period of rainfall, which accounts for 75-78% of the annual precipitation. This rainfall, associated with seasonally cool (winter) temperatures, contributes to the recharge of both surface- and groundwater. Discharge occurs during October to May when evapotranspiration is high.

The southeastern side of the farm occurs within the J12A subcatchment, draining into the Smalblaarrivier and Bokkerivier tributaries of the Touws River. The mean annual precipitation (MAP) for this subcatchment is 437 mm (Midgley et al., 1994, p. 8.5). The western side of the farm occurs within the H20C subcatchment, draining into the Spekrivier tributary of the Hex River. MAP for this catchment area is 643 mm (Midgley et al., 1994, p. 8.4). Model isohyets based on precipitation-elevation relations show that MAP over the farm averages 600-700 mm, and over the Hex River mountains to the south it exceeds 2 000 mm.

The mean annual evaporation (MAE) in the eastern subcatchment area (J12A) is 1690 mm (Midgley et al., 1994, map 2.3). This high rate of evaporation is caused by the arid conditions within the Karoo area.

Hydrostratigraphy

The farm is underlain mainly by formations of the lower Bokkeveld Group (Ceres Subgroup; Dc on Fig. 1 and units Dg to Dh on Fig. 2), with a thin fringe of the uppermost TMG (Rietvlei Formation of the Nardouw Subgroup; Dr in Fig. 2) along its southern boundary on the right bank of the Smalblaar River (Fig. 3). The geology of the area is comprehensively described by Gresse and Theron (1992) and covered in the 1:250 000-scale map compiled by Gresse (1997).

A superficial aquifer, consisting of unconsolidated alluvial deposits and a 50-100 m-thick, "fractured-and-weathered" or "regolith" layer of Bokkeveld strata, together with the upper TMG contact zone of the Rietvlei Formation, had been the main focus of previous well-field development close to the orchard areas (Weaver, 1995). Boreholes were drilled to a maximum depth of 156 m, i.e. No. 13 adjacent to the "Geeldam" reservoir (Fig. 3).

Figure 2

Annotated aerial photograph interpreted with fault (bold red line) and joint/fracture (thin red line) traces, covering area box-outlined in Figure 1. Table Mountain Group (Nardouw Subgroup) units annotated within the Sonkliprug mountain range are the Goudini Formation (Sg), Skurweberg Formation (Ss) and Rietvlei Formation (Dr). A conspicuous vegetated zone marks the Ss-Dr contact. Bokkeveld formations (blue line boundaries) shown are the Gydo shale (Dg), which underlies the developed agricultural lands along the Smalblaar River valley, the Gamka sandstone (Dga), Voorstehoek shale (Dv), and Hex River sandstone (Dh). Part of the Groenhof-Bokkerivier fault zone (not marked) is exposed in the deep E/W-trending valley along the southern border of this photograph. A subparallel WNW/ESE-striking fault branches from the northern part of the larger NE/SW-striking Kleinberg Fault , and formed the main structural target for a new deep borehole on Verloren Valley (blue triangle) at edge of ploughed onion fields (conspicuous white area).

Below the superficial or regolith aquifer zone, the bedrock hydrostratigraphy (Al-Aswad and Al-Bassam, 1997) consists of thick-bedded, quartzitic, fractured-rock aquifers, separated by thin-bedded siltstone and shale-bearing aquitards (Table 1). In the Verlorenvalley area, the thickest fractured-rock unit, the Peninsula Aquifer, is only exposed in steep cliffs along the upper reaches of the Bokkerivier (southern part of Fig. 2), and is located at too great a depth (~1 km) beneath the farm property to be accessible, at least under current limitations of South African groundwater drilling technology.

The higher Skurweberg Subaquifer (Table 1), however, is located at only ~200 m estimated depth beneath the farm. Considering its rugged, fracture-controlled microtopography on the northern slopes of the Sonkliprug, and widening area of high-altitude outcrop towards the higher rainfall areas to the south-west (Fig. 2), its recharge potential is significant. It therefore became the deep groundwater target of choice in this particular area.

A schematic structural cross-section (Fig. 4), oriented roughly NW/SE, was prepared through the Verlorenvalley property, in order to clarify the subsurface geometry of the aquifers tapped by various boreholes on the property.

Hydrocensus survey and hydrochemistry

Before any new groundwater targeting was considered, a systematic and regionally extensive hydrocensus survey was undertaken over an area of ~280 km² around the farm.

A total of 60 boreholes and springs were located and routine information, such as co-ordinates, water temperature and other physical properties, water usage, equipment, pumping rates, borehole drilling details, etc., was gathered. Wherever possible, rest water level in boreholes was measured and a clean water sample was collected. Samples from 54 out of the 60 boreholes were submitted to the CSIR, and analysed for calcium, magnesium, sodium, chlorides, sulphates, bicarbonate, iron, manganese, and for trace amounts of strontium. Laboratory measurements were also made for electrical conductivity (EC), pH, saturation pH, total dissolved solids (TDS), and hardness.

Table 1
Coincident Hydrostratigraphical Units of the TMG
(Verloren Valley and Hex River Mountains area)

Superunits	Units	Subunits
	Gydo Mega-aquitard	
Table Mountain Superaquifer	Nardouw Aquifer	Rietvlei Subaquifer Verlorenvalley Mini-aquitard Skurweberg Subaquifer Goudini Meso-aquitard
	Pakhuis-Cedarberg Meso-aquitard	
	Peninsula Aquifer	(no subunits)
	Saldanian Aquiclude	(Malmesbury Group and Cape Granite Suite)

The hydrochemical data showed that the groundwater is being drawn from two distinct aquifers. Of the thirteen wells, four (Nos 6, 9, 12, 13; Table 2 and Fig. 3) supply groundwater that is relatively low in EC, TDS, trace amounts of Sr (<0.1 mg/ℓ) and - No. 6 excepted - a low Fe concentration (<0.5 mg/ℓ). Chloride concentration ranges from 20 to 28 mg/ℓ. The wells in this set predominantly intersect and draw water from the TMG (Rietvlei Formation). The anomalous Fe concentration in the sample from No. 6 may be due to this being only dry, non-artesian well in this set, and could indicate contamination in a static water column.

The remaining nine wells are characterised by higher EC, TDS, Fe and Sr > 0.3 mg/ℓ, except for the Geelpomp sample, which is from a site (Fig. 3, No. 2) close to the mainstream channel. Chloride concentration ranges from 32 to 300 mg/ℓ. These wells are drilled into the Bokkeveld regolith aquifer beneath a thin cover of alluvial sands and gravel. The contrast in water chemistry between the two sets of samples indicates that the wells collared in Bokkeveld have not penetrated the TMG to any significant depth. The TMG-like Fe and Sr concentrations in Geelpomp are probably due to recharge of evaporated TMG-derived groundwater from the overlying alluvial aquifer along the valley axis.

The hydrophysical and hydrochemical data from Verlorenvalley (Table 2), placed within the wider regional context, confirmed the decision based on other hydrogeological considerations to focus future groundwater development on the deeper Skurweberg Aquifer.

Hydrotectonic interpretation

A systematic photogeological analysis (Fig. 2) of 1987 aerial photography, supplemented by the earlier photogeological map by Newton (1975), was used to map the boundary between the Skurweberg and Rietvlei formations in the Nardouw Subgroup (TMG), where it crosses the Laaste Drift property, south of Verlorenvalley. The stratigraphic subdivisions of the lower part (Ceres Subgroup) of the Bokkeveld Group were also mapped along the northern side of Verlorenvalley (Fig. 2).

In the aerial photographic interpretation (API), special attention was paid to the systematic mapping of fracture traces in the well-exposed quartzitic sandstones of the TMG, particularly the Skurweberg Formation. The mapped traces of two large faults, the E/W-striking Bokkerivier Fault and the NNE/SSW-striking Kleinberg Fault, are also prominent elements of the regional fracture pattern (thicker red lines in Fig. 2).

The Groenhof Fault near Ceres is one of an en-echelon group of WNW/ESE-trending fractures, arrayed E/W across the Ceres basin from Groenhof in the west to Bokkerivier in the east (Figs. 1 and 2). The eastern part of this zone crosses the southern part of the present study area near Matroosberg peak. Newton (1975, p. 28) notes that the "faults of the Groenhof-Bokrivier zone ... extend across the adjacent area ... south of Touws River, and may joint *(sic)* up with the fault south of Anysberg. This would make them part of the western termination of a major zone of E-W faults of which the Cango fault is the most important member". The entire, semi-continuous fault system extends for about 500 km from the Witzenberg Range in the southwestern Cape to the Baviaanskloof range in the eastern Cape, and may consequently be termed the "Cango Megafault".

The *Groenhof-Bokkerivier zone* has the typical appearance of a "horse-tail termination splay" system along a left-lateral strike-slip fault (Fig. 1). The present API interpretation shows greater continuity of the faulting, and high E/W fracture densities within the sandstone fault blocks surrounding the fault zone itself. A significant fault of similar WNE/ESE strike crosses the southern part of the Verloren-

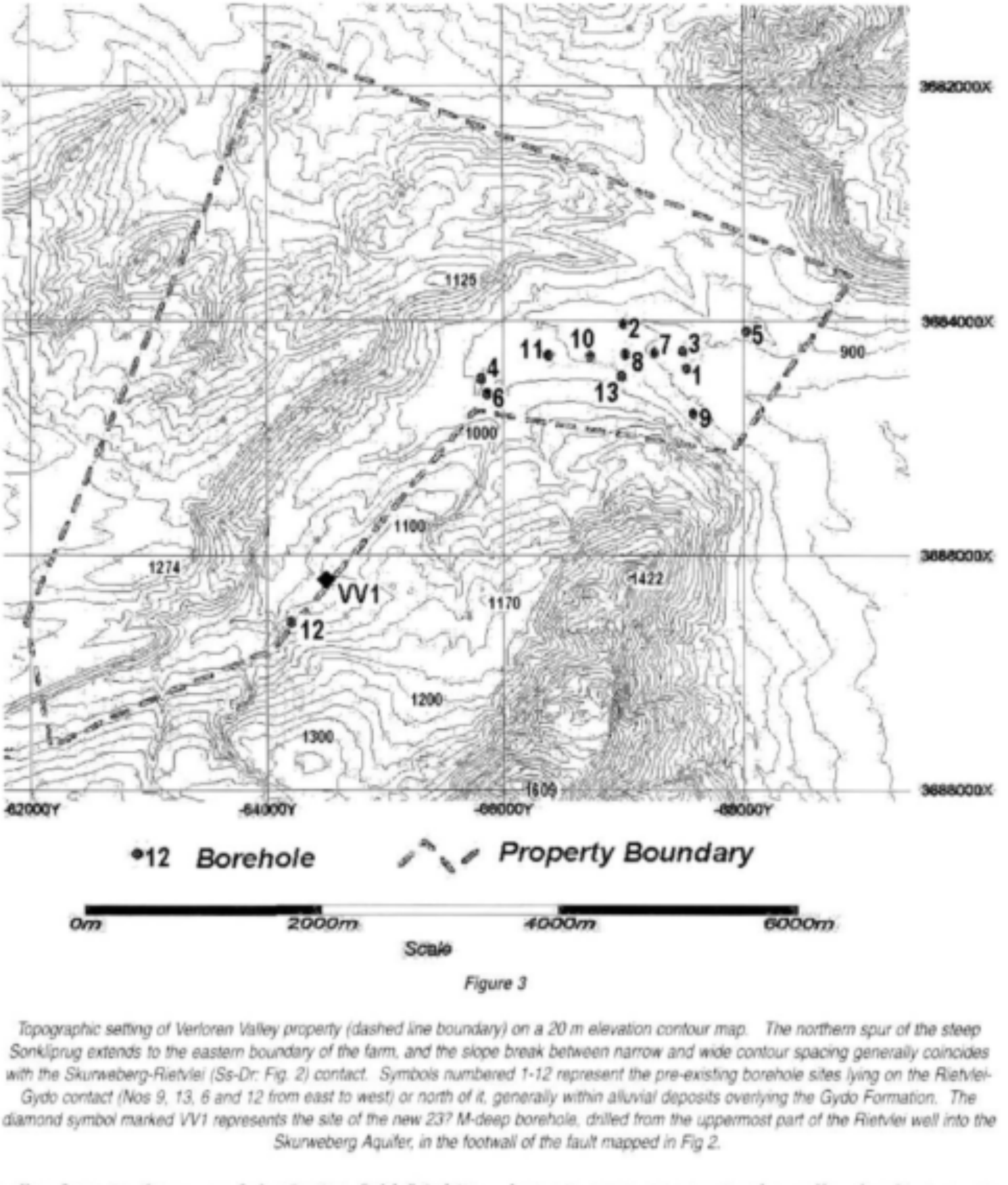

Figure 3

Topographic setting of Verloren Valley property (dashed line boundary) on a 20 m elevation contour map. The northern spur of the steep Sonkliprug extends to the eastern boundary of the farm, and the slope break between narrow and wide contour spacing generally coincides with the Skurweberg-Rietvlei (Ss-Dr: Fig. 2) contact. Symbols numbered 1-12 represent the pre-existing borehole sites lying on the Rietvlei-Gydo contact (Nos 9, 13, 6 and 12 from east to west) or north of it, generally within alluvial deposits overlying the Gydo Formation. The diamond symbol marked VV1 represents the site of the new 23? M-deep borehole, drilled from the uppermost part of the Rietvlei well into the Skurweberg Aquifer, in the footwall of the fault mapped in Fig 2.

valley farm in the area of the "onion fields" (white area on Fig. 2). It extends westwards across the southern part of the Sekelkoppe and may be continuous with a larger fault zone mapped across the area just south of the Theronsberg Pass (Fig. 1).

A NE/SW-striking fault structure crosses the area along the Sonkliprug (Fig. 2), and is continuously traceable from Kanetvlei in the south-western part of the Hex River valley, where a substantial fault-breccia zone occurs in the valley leading up to Kleinberg (Topo Sheet 3319BC). This *Kleinberg Fault* apparently displaces the hinge-line of the major syncline horizontally in a right-lateral sense, i.e. the SE fault block has moved southwestward.

The Kleinberg Fault and associated subparallel faults evidently represent an important "transfer zone", through which substantial displacement on the Touws River-Bokkerivier segment of the Cango

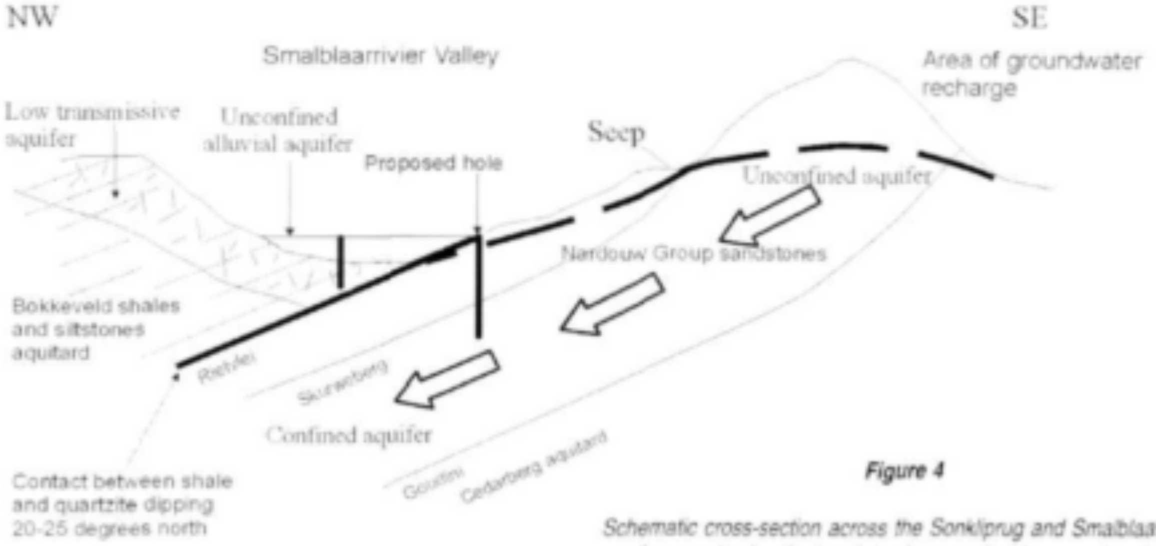

Figure 4

Schematic cross-section across the Sonkliprug and Smalblaarrivier valley, emphasing the break in slope marked by occasional seep zones at the Skurweberg-Rietvlei contact, discovered during drilling and logging of well VV1 (longer thick vertical line) to be due to a black shale-bearing mini-aquitard member. Also emphasised is the low-transmissive "regolith" aquifer formed by a fractured-and-weathered zone within the Bokkeveld Group beneath the valley and on its northern slopes. Earlier boreholes (shorter thick vertical line) targeted this aquifer, and are recharged mainly by infiltration from the overlying alluvial deposits and by overflow or "rejected recharge" from the Nardouw aquifers on the southern slopes of the valley.

Table 2
Summary of borehole and hydrogeochemical Information on Verlorenvalley

Borehole	Site ID No. (Fig. 3)	Depth (m)	Date	Blow yield (ℓ/s)*	Estimated Artesian flow (ℓ/s)	Rec. pump rate (ℓ/s)	EC (mS/m)	TDS (mg/ℓ)	Fe (mg/ℓ)	Sr (mg/ℓ)
TMG wells										
Geeldam	13	156	1997	6	2.0	5.0	10	64	0.1	<0.05
Kloofgat	12	100	?	-	0.5	5.7	12	77	0.2	0.06
17 Hectare	9	134	1997	?	0.25	5	13	83	0.4	0.06
Klipgat	6	?	?	-	0	-	16	102	12.4	0.10
Bokkeveld wells										
Fonteinbult	11	93	?	-	0	n.d	27	173	10	0.34
Woltemade	7	125	1997	11	0	15.0	29	186	6	0.30
Grenslyn	10	75	?	-	0	10.2	30	192	8.5	0.40
Drinkwater	4	83	?	-	0	n.d.	53	339	0.3	0.60
Geelpomp	2	99	?	-	0	2.7	58	371	0.4	0.06
Volstruis	8	124	1997	22	0	6.6	65	416	1.4	1.11
Willowtree	1	123	?	-	0	7.5	76	486	0.8	1.10
Oaktree	3	134	1997	6	0	n.d	146	934	10.2	0.91
Appelkoos	5	?	?	-	0	n.d.	158	1011	1.6	1.66

*Blow-yield information for 1997 provided by drilling contractor

Megafault is absorbed and relayed to the westerly continuation of the Worcester fault and to the set of en-echelon faults striking WNW/ESE across the Kouebokkeveld Mountains from the Theronsberg Pass area, northeast of Ceres (Fig. 1).

Groundwater targets

The focus of the geological interpretation was to delineate areas where the main TMG aquifer in this area (i.e. the Nardouw Aquifer and its deeper component Skurweberg Subaquifer) is economically accessible from the surface within the boundaries of the Verlorenvalley farm. Cost limitations placed a practical limit of ~250-300 m on the maximum depth of a new borehole.

Patterns of surface-water drainage and groundwater levels suggest that groundwater in the TMG flows mainly in a NNE to NE direction. Some fraction of it discharges into the "regolith aquifer" of the Bokkeveld Group, into the alluvial aquifer and, by means of springs and seep flow along both the Rietvlei-Gydo and Skurweberg-Rietvlei contacts, into the Smalblaar River.

A detailed comparison of the rainfall data with yields of boreholes on the farm (Table 2 and Fig. 3) and a study of surface discharge shows that recharge to the aquifer in the upper parts of the J12A subcatchment area is greater than that due to infiltration alone. The additional recharge is considered to come from the neighbouring H20C subcatchment, crossing the watershed divide at depth by means of major faulting and fracturing within the Nardouw Subgroup, which has a total surface area of ~55 km². The extended recharge area covers an area of 46 km² and is located within the mountainous region to the southwest of Verloren Valley.

Four prospective borehole sites were pegged but only one was drilled. This was priority target T1 (Umvoto, 1999d) sited on an ~E/W-striking fault, to be collared in the topmost part of the Rietvlei Formation. The required minimum depth of the borehole would be ~250 m to access the footwall side of the steeply SW-dipping fault, where it transected the top part of the Skurweberg Formation.

Drilling results

The "T1 target", near the existing "Kloofgat" borehole (No. 12, Fig. 3), is located along a significant ~E/W-striking fault that may in fact be continuous with another fault zone in the Theronsberg Pass area (Fig. 1), showing even greater displacement. This fault is connected also to the northern part of the NE/SW-striking Kleinberg Fault. Together these two structures are considered to provide a preferred groundwater pathway of higher hydraulic conductivity, leading from the higher parts of the Hex River mountain range near Matroosberg down to the upper part of the Smalblaarrivier valley.

The particular site and depth of this proposed borehole was dictated by its main objective, i.e. that the borehole should pass through the fault zone and intersect the highly fractured part of the Nardouw Aquifer on the northern or footwall side of the fault. The targeted part of the aquifer was preferably below the contact between the Skurweberg and Rietvlei formations.

The borehole was collared with an initial diameter of ~240 mm (~9.5 inches) in the topmost part of the Rietvlei Formation, not many metres below the Bokkeveld contact. The Rietvlei thickness in this area was estimated at ~200 m (Umvoto, 1999, p. 41), and the dip angle of the strata is ~25°. Consequently, the required minimum depth of the borehole was forecast at ~250 m, in order to properly access the top part of the Skurweberg Formation.

Immediately prior to the driller's establishment on site, reference vertical electrical soundings (VES) using the Schlumberger array method were undertaken over the target (Umvoto, unpublished results) to allow for possible siting refinement. The soundings showed a fall from a maximum apparent resistivity of 10^4 Ωm at 10 m depth in the dry unsaturated sand and weathered overburden to a minimum of ~450-500 Ωm at 50-70 m depth. Thereafter apparent resistivity rose to ~2000 Ωm at 250 m. These results actually gave no support to the Skurweberg target concept. After drilling and geophysical logging of the VV1 borehole, the observed VES minimum was found to correspond roughly to the contact between the thin-bedded, shale-bearing upper member of the Rietvlei Formation (where downhole resistivity measurements fell to <200 Ωm around 75-77 m depth) and the sandstone-dominated middle Rietvlei member below 84-85 m (Fig. 5).

The possibility "that the drill may encounter high-yielding fracture sets within the middle and lower parts of the Rietvlei Formation, and that the need for drilling deeper may thus be obviated" (*op. cit.*, p. 41), was considered in the target recommendations. Water strikes yielding up to 12 *ℓ*/s during air-lift blow testing by the driller were in fact found within fractured parts of the middle Rietvlei member at around 135 m depth, but did not distract from the deeper and potentially higher yielding objective within the Skurweberg Subaquifer.

Between 166 m and 181 m (Fig. 5), the geophysical logs show a zone of variable but localised distinctively low (<350 Ωm) resistivity, which the downhole video-camera record showed to be produced by layers of black shale up to ~2 m in thickness. Although thin (15 m total), this lower member, here provisionally identified as the Verlorenvalley Member and Mini-aquitard (Table 1), is an important hydrostratigraphic boundary. When the drill passed through this interval the rest water level in the borehole suddenly dropped from ~10 m below surface to over 20 m, indicating that the potentiometric surface for the uppermost Skurweberg Subaquifer was lower than the (locally perched?) water table in the Rietvlei Subaquifer.

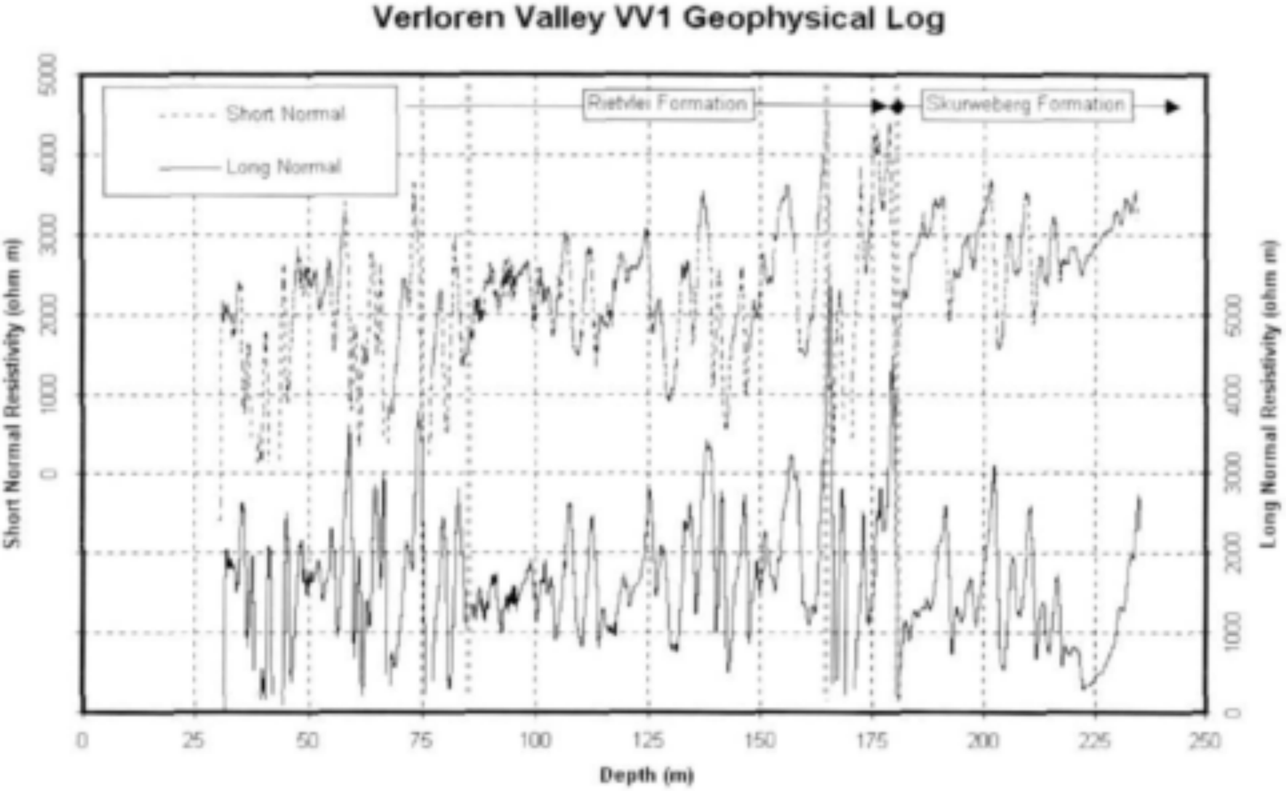

Figure 5

Example of a VV1 geophysical log, in this case "Short Normal" (SN; dashed line, left y-axis) and "Long Normal" (LN; continuous line, right y-axis) formation resistivity, here plotted together with 3 000 Ωm y-axis offset for depths > 28 m (rest water level is 24.2 m). Thicker bedded sandstone units within the Skurweberg and Rietvlei Formations have resistivity >3 000 Ωm, while thinner black shale interbeds within the upper Rietvlei member (0-85 m depth and the lower Rietvlei member (166-181 m depth) have resistivities <500 Ωm. The saw-tooth SN pattern in the upper Skurweberg (>181 m depth) probably represents thick (~10 m), upward-fining, graded sedimentary cycles in massive cross-bedded sandstone, with resistivity >2 000 Ωm except at cycle boundaries.

Within the upper Nardouw strata, Newton (1975, p. 24) previously identified an extensive, photogeologically mappable unit, which appeared "more susceptible to weathering and erosion than those above and below, with the result that it forms a slightly negative topographic feature". This "soft band" separates Rietvlei sandstones from Skurweberg sandstones over a wide area in the Hex River valley, the Waboomsberge south of Touws River, the Langeberg, and extends also to the Kammanassie area east of Oudtshoorn. The distinctive, vegetated and topographically recessive zone is also visible on aerial photography of the Verlorenvalley region (Fig. 2). The VV1 drilling results show that this thin unit has regional hydrostratigraphic significance as an effective aquitard separating distinct subaquifers within the larger Nardouw Aquifer (Table 1).

Below 181 m depth the drill passed through tight, relatively unfractured, quartzitic sandstones for over 50 m, provoking some tension about the wisdom of proceeding deeper in the section. In this stratigraphic interval the neutron-neutron log, an inverse proxy for porosity, shows a rising (decreasing water content or porosity trend from ~1 500 counts per second (cps) to ~1 750 cps at ~230 m. The BRD density log rises above 2 600 kg/m³, suddenly falling to ~2 000 kg/m³ on entering the deep water strike at 235 m. At this point the N-N log plummets precipitously from >1 500 cps to <1000 cps (Umvoto, unpublished data).

Conclusions

After intersecting a highly fractured, relatively porous zone at a depth of ~130 m within the middle Rietvlei Subaquifer, which produced a driller's blow yield of ~12 ℓ/s, the VV1 well might have been considered "successful", and could have been terminated at that stage. However, this well and its associated drilling strategy had been carefully designed to achieve a specific hydrostratigraphic target in a particular structural context, which would only be encountered after a further 100 m of drilling.

The achievement of a very high yield within the specified target zone justified this relatively high-cost and high-risk exploration strategy. The history of water level fluctuations during drilling, and a complete video and geophysical logging of the borehole revealed the hydrostratigraphic importance of a relatively thin (~15 m) contact member at the base of the Rietvlei Formation. In this area, and elsewhere within the Cape Fold Belt (judging from the extensive photogeological mapping of this same "soft band" by Newton, 1975), the Verlorenvalley mini-aquitard is expected to play an important controlling role on present and future groundwater developments around the usually accessible TMG-Bokkeveld contact zone, which is generally an area of great agricultural potential and frequently close to economically significant urban populations (e.g. Ceres and De Doorns) in the country districts of the Western Cape.

Further understanding of the hydraulic character and properties of the Skurweberg-Rietvlei interval will require the systematic lithological and geophysical logging of other groundwater wells similar in depth, structure and geological setting to the Verlorenvalley well VV1, with a view to detailed bed-resolution comparison and correlation.

Acknowledgements

Hannes le Roux and Steven Hobson of New Farmers Development Company (Pty) Ltd are thanked for their confidence, enthusiasm and determination to go for 'the big one', and for permission to publish. Nick Steven assisted with API and structural mapping during an early stage of this investigation. Andrea Amantia undertook water balance modelling and pump-test interpretations. Eric Manson undertook a review of surface-water development on the property, and acted as a critical referee for the entire project, in particular the conjunctive use approach proposed by Umvoto. BJ Cilliers & Kie (particularly Deon Cilliers) drilled well VV1 with utmost professionalism. Barry Venter of DWAF undertook downhole video recording and geophysical logging of the well soon after the main water strike was encountered. We thank all these persons.

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Experimental Deep Drilling At Blikhuis, Olifants River Valley, Western Cape: Motivation, Setting and Current Progress

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Abstract

A deep groundwater drilling experiment at the Blikhuis site, about 25 km north of Citrusdal on the east bank of the Olifants River has used a combination of percussion drilling (to 300 m depth) and diamond-bit core drilling (currently to over 600 m depth) to access the confined part of the Peninsula Aquifer (Table Mountain Group - TMG) along the faulted hinge zone of a major synclinal fold. Four experimental wells, one of which was aborted through technical problems, were drilled. At site BH2, away from the river bank the potentiometric surface in the Nardouw Aquifer (<165 m depth) is below ground level. This deepest borehole started flowing when water strikes in the Peninsula Aquifer were encountered below a depth of ~345 m. The physico-chemical properties of the artesian water differ from the shallow Nardouw groundwater, e.g. the higher Fe content of Nardouw groundwater is distinctive. The Blikhuis boreholes BH1, BH2 and BH4 provide a suitable location for further development of downhole experimental procedures to quantify the hydraulic properties of TMG aquifers and aquitards, for long-term monitoring of the impacts of large-scale abstraction, and for experimental practice in the conjunctive use of surface and groundwater resources, e.g. through artificial recharge of a deeply confined hard-rock aquifer system.

Introduction

The Olifants River is a main waterway that flows a long distance above the axis of a major, synclinal, artesian basin within the TMG, the Citrusdal Trough (Fig. 1) where an important hydraulically conductive structural feature ("hydrotect") obliquely transects both the deep groundwater reservoir and the river basin. Following an artesian groundwater exploration success by Umvoto in early 1995 at Tharakamma, in the southern end of the Citrusdal Trough, an eminent Israeli hydrogeologist, Prof. Arie S. Issar, advised the South African Department of Water Affairs and Forestry (DWAF) as follows:

> "It can be foreseen that the drilling of deep wells, of a diameter big enough to enable the pumpage of large quantities of water is going to play an important role in the future development of the water resources of the [R]epublic of South Africa. As this requires special investments in equipment and know how, it can be justified only if it involves a rather large number of wells" (Issar, 1995, p. 5).

More specifically with reference to the Western Cape Province, he also noted (*op. cit.*, p. 33):

> "As this semi-arid region is in the need of water, and most probably the solution sought will be in the direction of building a new dam, it is suggested to consider the possibility of launching a regional hydrogeological research project for this region ... The hydrogeological survey will be followed by a few deep exploration-exploitation wells along major fault lines, the results of which will be incorporated in a regional hydrological physical-mathematical model. ...".

Following the success of drilling and pump-testing at the Boschkloof well-field (Hartnady, 1998) between December 1997 and August 1998, an existing borehole site at Blikhuis was suggested to DWAF as one of four possible locations within the upper Olifants River (E10) subcatchment where deep exploratory drilling of an experimental nature might be carried out (fax from ER Hay to Z Dziembowski, dated 22/9/98).

Hydrogeological synopsis of the Blikhuis site

The Blikhuis site is perched on a high terrace overlooking the right bank of the Olifants River, approxi-

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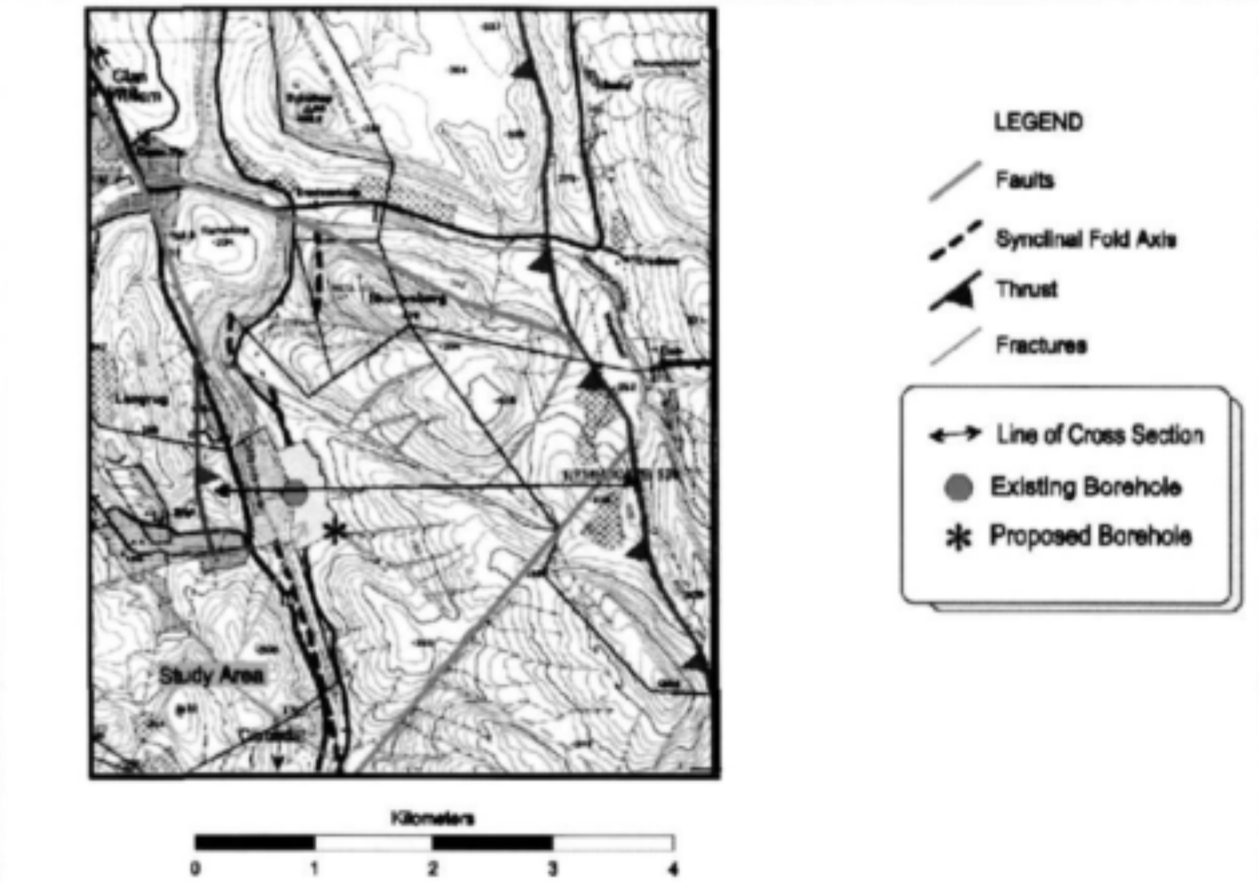

Figure 1

Structural map of the Blikhuis Experimental Deep Drilling (BEDD) Project site (for general location see Hartnady and Hay, 2001b, Fig. 2 in this volume), showing pattern of faults and fractures crossing the main synclinal hinge zone, and a line of cross-section (diagram below) through the existing, i.e. BH1 borehole site. The "proposed" borehole refers to the BH2 site. Further drilling has also occurred around the original BH1 site.

mately 30 m above river level (Fig. 1). It lies in the central hinge zone of the Olifants River Syncline (ORS, cf. Hartnady and Hay, 2001a). To access the main deep aquifer in the Peninsula Formation requires drilling through the lower part of the Nardouw Subgroup (Goudini Formation) and the underlying Cedarberg and Pakhuis Formations (Fig. 2).

The site lies along the Twee Riviere-Leipoldtville Megafault (TLM) hydrotect structure (cf. Hartnady and Hay, 2001a, Fig. 4), and recharge to the Peninsula Aquifer probably takes place in the Middelberg area between the Cold Bokkeveld and Cedarbarg mountain ranges.

Previous work

A borehole drilled in 1995 as part of a private groundwater exploration initiative, reached a depth of ~220 m, but was stopped before it had penetrated completely through the Cedarberg shale aquitard. This "BH1" well (red circle in Fig. 1) overflowed in a weakly artesian manner, and had a low driller's air-lift blow yield of only 2.5 ℓ/s. It was subsequently pump tested at a constant discharge rate of 5 ℓ/s, and results indicated a sustainable yield of 5 - 8 ℓ/s (Umvoto, 1995). The slightly elevated borehole-water temperature (23°C), and the well's response to pump testing, suggested the possibility of upward leakage of deeper groundwater from the top of the Peninsula Aquifer (Fig. 2).

Two main reasons were originally cited for using the BH1 site as a platform for deeper exploration in the underlying Peninsula Aquifer:

"a) *This borehole is sited in an optimum area for penetrating the Peninsula Fm in the central area of the valley ...*

b) *It would establish whether the axis of the syncline was in itself a target as are the hydrotects ...*"

(ER Hay to Z Dziembowski, 22/9/98). Acute chevron-folding of bedding planes in the Peninsula Formation, where the bed thickness-to-length ratio is large, leads to area change or dilation around the crests and troughs of folds, as "saddle-reef" openings form between thickly bedded members (Ramsay, 1967, p. 447). If flexural slip folding has

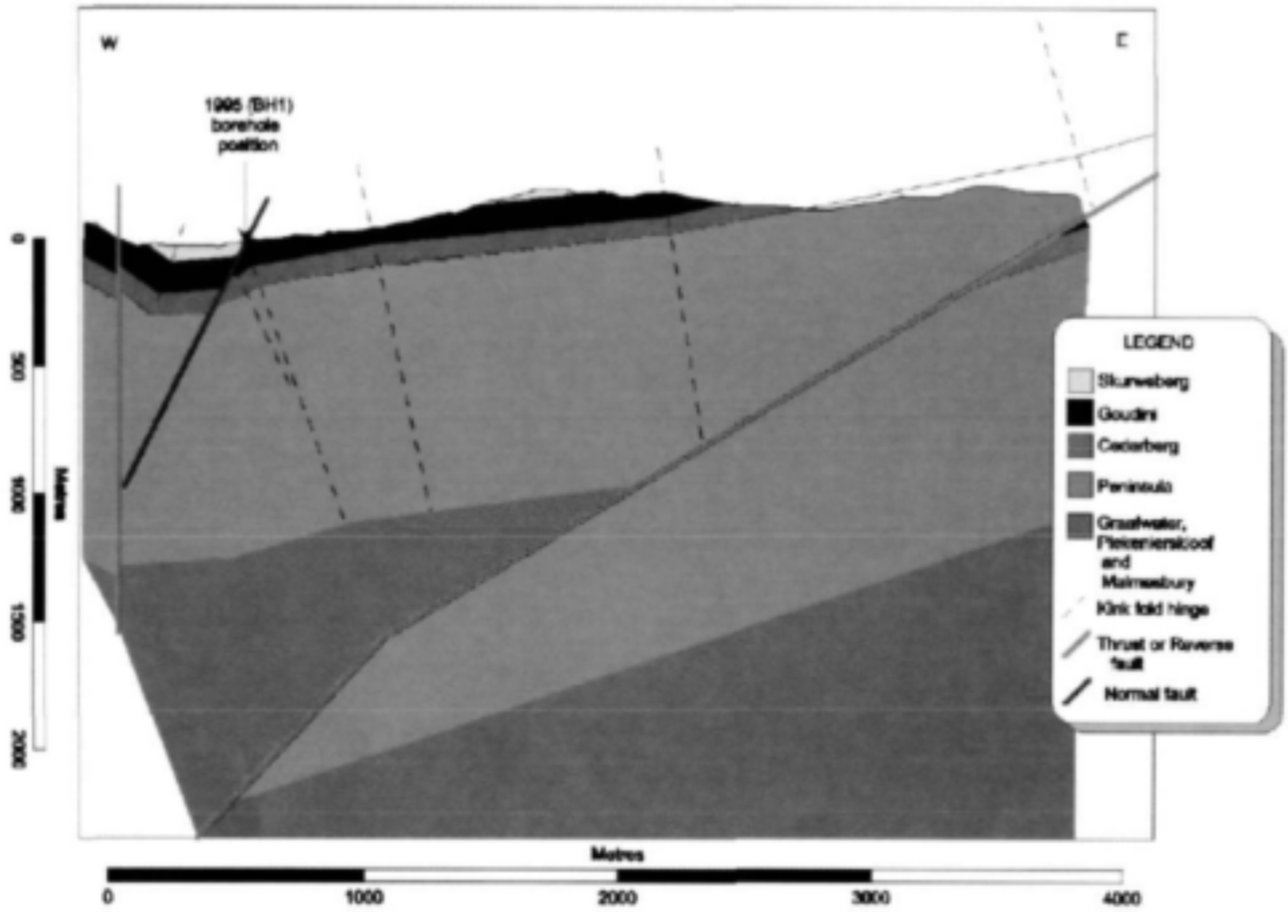

Figure 2

Preliminary geological cross-section through the BEDD Project area, based only on limited surface structural data and showing the true thickness and structural geometry of the Peninsula Aquifer and the overlying confining aquitard units, the possible projection of a low-angle thrust fault at depth, and fault-bend fold complexities in the hinge zone which enhance permeability in the aquifer. The 0 m level on the vertical scale refers to BH1 collar elevation at ~125 m above mean sea level. Drilling at BH2 shows that revision of the interpreted subsurface structural geometry is needed, and that a ~20 m thickness of Pakhuis Formation is present between the Peninsula and Cedarberg units.

occurred at shallow depths and at a relatively late stage in the orogenic-metamorphic history of the Cape Fold Belt, there may still be a residual high permeability although discrete hinge-zones in the fold axial plane.

Current operations and progress

Overcoming the typical TMG problems of hard abrasive rock and high water pressures requires the development of innovative drilling technologies, if the objective of developing an experimental groundwater well through the entire 1 300 m thickness of the Peninsula Aquifer is to be attained. In order to achieve this aim, presaged by Issar (*op. cit.*, p. 32) with reference to a "potential to get more groundwater in depths ranging from a few hundreds of meters to thousand meter, and even more", new groundwater well designs are being experimentally implemented at Blikhuis, initially involving deep core-drilling from the bottom of relatively wide-diameter air-percussion boreholes.

Original BH1 site

Clearing and deepening of the original private borehole was undertaken in late 1999 at the BH1 site and the upper contact of the Peninsula aquifer was intersected a few metres below the termination of the old well. However, further deepening by both percussion and core drilling proved to be impossible due to deviations from the vertical during the earlier drilling. In anticipation of the arrival of the core-drilling rig at Blikhuis, an alternative site was prepared by percussion drilling another site along the same NNW/SSE fracture trend, higher on the slope and some distance to the south-east. During the original private groundwater prospecting, this site had already been indicated as a possible productive target (Umvoto, 1995).

BH2 site

Air-percussion drilling

At the BH2 experimental site (blue asterisk in Fig. 1: lat. 32°23'42.4'S, long. 18°57'35.8"E), the new air-percussion hole was drilled between September 1999 and March 2000. This well was collared within the Nardouw Subgroup, close to the Goudini-Skurweberg contact, with an initial diameter of 204 mm, reducing to 165 mm at a depth of 84 m. It passed through the transitional Cedarberg-Goudini contact at ~160 m depth. After a further 140 m of drilling the chip samples showed that the borehole was still within the dark Cedarberg shales, against expectation as the regional thickness of the Cedarberg Formation is only ~90 m. The upper air-percussion section of borehole BH2 terminated in black carbonaceous shale at a depth of 304 m (and was later found to be within a few decimetres of the Cedarberg-Pakhuis contact).

A borehole-camera survey of the well to a depth of 280 m was undertaken by DWAF on 16 February 2000 (B. Venter, pers. comm.), augmented by a full-depth geophysical logging (natural gamma, self-potential, formation resistivity, neutron-neutron). A water quality (EC) and temperature log was also undertaken. At this stage the rest water level was ~5 m below collar, and the airlift blow yield was ~2 ℓ/s.

The EC log showed a constant value of 18 mS/m through the Goudini Formation, rising to 20 mS/m at 250 m depth within the Cedarberg Formation. A sharp rise to >40 mS/m at ~290 m, near the base of the well may have been due to drilling-fluid contamination. The temperature log shows a steady rise from 23.2°C at 20 m depth (~15 m below rest water level) to 24.9°C at 140 m depth, corresponding to a geothermal gradient (dT/dz) of 14.3 K/km. From this point there is a subtle inflexion to steeper dT/dz, which is roughly constant at 35.8 K/km between temperatures of 25.3°C at 180 m and 28.9°C at 280 m. The change in geothermal gradient coincides with the Cedarberg-Goudini transition, and is consistent with a change from lower thermal conductivity (K_t) in the Cedarberg shales to higher K_t in the Goudini sandstone, assuming uniform heat flow ($q = -K_t.dT/dz$).

There are no nearby heat-flow measurements in this part of the Cape Fold Belt, the nearest in a comparable geological and tectonic setting being from four deep boreholes in the Southern Karoo, between longitudes 21°E and 25°E, around latitude 30.5°S. Heat-flow (q) values here range between 51 and 61 mW/m^2, around an average of 56 mW/m^2 (Jones, 1992). If the same q value is assumed for the BH2 site, then K_t values for Goudini and Cedarberg lithologies are 3.9 $Wm^{-1}K^{-1}$ and 1.6 $Wm^{-1}K^{-1}$, respectively. As the Cedarberg value is lower than typical Karoo sandstone/shale (2.2 $Wm^{-1}K^{-1}$), and the Goudini value is also lower than typical Witwatersrand quartzite (6.3 $Wm^{-1}K^{-1}$; Jones, 1992, Table 2), the assumed Blikhuis q could be raised to 80 mW/m^2 and still maintain the Cedarberg-Goudini K_t values within the Karoo-Witwatersrand range. This comparison illustrates the need for future quantitative measurements of fundamental physical properties of the TMG rock types.

In the borehole-camera survey and geophysical logging of the top portion of the BH2 well, the reasons for the unexpectedly long section within the Cedarberg shale were revealed. Although sedimentary bedding dips in exposures around the well site were observed to be uniformly westward in the range 5-10°, the borehole-camera view showed a localised increase in dip to ~20° below 65 m within the Goudini Formation, and then a broader zone of steeper dips within the Cedarberg Formation below 165 m, generally in the range 35-60°. Evidently the borehole had intersected the hinge zone of a concealed fold structure, close to the Cedarberg-Goudini transition, and the apparently excessive thickness of Cedarberg shale is due to the increased obliquity of the angle between the borehole and the normal to bedding.

Diamond-bit rotary core drilling

In late June 2000, diamond-bit rotary core drilling at 122 mm diameter (NX) deepened the well through the Pakhuis-Peninsula contact at 324 m depth, into compact, quartz-veined and cemented pebbly sandstone. At a depth of 333 m, drilling was interrupted in order to insert 122 mm-diameter casing into the well. Drilling recommenced at slightly narrower diameter of 106 mm (NXC) to a depth of 349 m when a small water strike accompanied by core loss was made in highly fractured Peninsula quartzite. Further smaller strikes followed between 349 m and 352 m depth, until a main water strike at 360 m depth. At this point, in early August 2000, the rest water level rose in the borehole, and the BH2 well became mildly artesian. Further drilling to 372 m produced a maximum artesian flow of ~3.35 ℓ/s, and operations were soon thereafter halted for a change-over to the wireline mode of core retrieval.

On 13 September 2000, geophysical logging of the borehole was undertaken by DWAF (B. Venter, pers. comm.) between depths of 280 m and the current base of the borehole at 381 m. The main feature of these logs is the abrupt Peninsula-Pakhuis contact at 324 m depth. It is evident that the Pakhuis tillite and the overlying Cedarberg carbonaceous shale have similar geophysical properties, e.g. in respect of natural gamma and neutron-neutron (N-N; porosity proxy) characteristics, and that the Pakhuis Formation is as effective an aquitard as the Cedarberg. From the viewpoint of hydrostratigraphic classification, therefore, the "Cedarberg Aquitard" should perhaps rather be renamed the "Pakhuis-Cedarberg Aquitard".

Within the Peninsula Aquifer, the enhanced porosity of the fractured zone between 345 and 370 m depth is clearly evident in the N-N log. The water-strike and core-loss levels within this water-producing zone are also evident in the Long-range and

Short-range Density plots (L-DEN and S-DEN), and as also appear as discrete troughs in the resistivity plot.

After casing off all water strikes, drilling below 381 m proceeded at 76 mm diameter using the wire-line method of core retrieval. Further fracture intersections accompanied by core loss in the 434-444 m depth range recovered an artesian flow of ~1to 3 ℓ per minute at a constant temperature of 27.6°C (driller's own record). An apparently more "porous" zone of sandstone was intersected between ~475 and 485 m depth. By 490 m the artesian flow rate had recovered further to 0.31 ℓ/s (18 ℓ/min). Between 528 m and 544 m a complex fault zone in which bedding dips are steepened to become sub-parallel to the borehole core axis (i.e. sub-vertically dipping), was encountered. Below 500 m, there has been no notable increase in the artesian flow from the borehole(see Note 1 added in proof).

Geophysical logging below 381 m depth remains to be undertaken, whenever and provided drilling operations allow (see Note 2 added in proof).

BH3 and BH4 sites (close to BH1)

While the core-drilling rig was being mobilised, air-percussion drilling was continued at further sites close to the original BH1 borehole, as an insurance against failure at the BH2 borehole. The first of these "satellite" wells, BH3, had to be abandoned when the wider reaming bit became jammed at a relatively shallow depth (40 m) after the hole had first been drilled to 80 m at a narrower diameter. A later well, BH4, was drilled to a final depth of 195 m only a short distance to the northwest of BH3 along bedding strike. The BH4 well yielded a major water strike (blow yield of >50 ℓ/s) at 81 m, apparently within the Nardouw Aquifer.

After casing the borehole to 89 m, BH4 was deepened through a faulted zone by a further 100 m. The Cedarberg shales were not, however, intersected in this borehole: They are either still deeper than well bottom, or have been eliminated through loss of ground across the fault zone. Work remains to be done on reconciling the drilling logs and down-hole televiewer images, with surface structural data, in order to correctly interpret the subsurface structure in the BH1-BH4 area. The BH4 borehole cannot be further deepened into the Peninsula by core drilling, due to unstable drilling conditions in highly fractured rock in the bottom part of the air-percussion well, and consequent deviations from verticality.

Significance for future conjunctive use

Deepening of the BH2 experimental borehole by core drilling continues within the Peninsula Aquifer beyond a depth of 600 m (May 2001; but see Note 3 added in proof). If the project is successful in demonstrating the presence of open, hydraulically conductive fracturing at >500 m depth in this location, as predicted, it would represent a breakthrough in hydrogeological understanding of the deep confined parts of the Peninsula Aquifer. Confirmation of this deep groundwater resource, and the provision of the first access well to these depths would greatly improve the availability of water in the dry summer months when the Olifants River threatens to run dry. It would also mean that the information for long term planning with regard to accessing the Peninsula Aquifer in other areas away from the valley sides would become available; i.e. areas where the Nardouw Aquifer has potential and/or is being over-exploited could be supplemented by the Peninsula Aquifer for environmental protection or maintenance of the ecological Reserve in surrounding aquatic systems.

The Blikhuis site is hydrogeologically significant because of its close proximity to the full-supply-level (FSL) limit of the extended reservoir that would result were the wall of the Clanwilliam Dam to be raised by 7 m, as has recently been proposed in some schemes for the further development of surface-water supply in the Olifants River system (DWAF, 1998). A raised FSL reaching an elevation of 111 m above mean sea level would inundate upper parts of the Peninsula Aquifer exposed near the culmination of an anticlinal cross-fold on the ORS. Consequently, the Blikhuis area and its immediate downstream surroundings provide an unrivalled opportunity for a hydrogeological experiment in conjunctive usage of groundwater and surface water infrastructure.

It is therefore possible to envisage a future well-field in the extended Blikhuis-Kriedouwkrans area of the Olifants River valley acting as an artificial recharge source in the winter season, intercepting an upstream stormflow excess before it reaches the Clanwilliam reservoir and pumping it into the deep Peninsula Aquifer. In the summer season, on the other hand, the well-field would pump large volumes of groundwater out of the deep TMG Aquifer to maintain the stream baseflow and Clanwilliam reservoir volume at relatively stable levels consistent with water management, conservation, and environmental considerations.

Concluding remarks

Whether a scheme in conjunctive water management such as that outlined above is technically feasible, economically viable, and environmentally sound, remains to be determined through systematic hydrogeological and hydrological field research. The present CAGE project extension to deep borehole drilling at the Blikhuis site is a convenient and necessary starting point. Without the experimental deep boreholes through which can be systematically accrued various kinds of geophysical, petrophysical, pump-testing, and other hard scientific data, no real progress can be made in the practical development of the resource. This applied experimental research and borehole technology development must, however, proceed in tandem with a substantial component of "pure" or theoretical research in the academically demanding subject of fractured-rock hydrogeology, for the reason that a brute mass of empirical data has no ultimate value unless a sound interpretative framework exists within which to order and evaluate it.

Notes

1 According to driller's measurement records of artesian flow rate and emergent water temperature at the borehole collar, there was an abrupt doubling of flow rate (to ~0.7 ℓ/s) and a slight increase in temperature (to ~27.5°C) at a depth of ~650 m. A further increase to ~1 ℓ/s and 28.5°C occurred between 660-680 m. In late August 2001 after a major fracture zone intersection with significant core loss, the artesian flow rate suddenly rose to 3 ℓ/s and the water temperature to over 31°C.

2. Interim geophysical logging was undertaken in June 2001 when the BH2 borehole had reached a depth of 680 m, and the final logging in late October after the termination of drilling and the cleaning of all drilling contaminants from the borehole.

3 Drilling operations at the Blikhuis borehole BH2 were terminated in October 2001 at a final depth of 801.59 m.

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The Klein Karoo Rural Water Supply Scheme

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Abstract

The Klein Karoo Rural Water Supply Scheme supplies groundwater derived from boreholes drilled into the Table Mountain Group (TMG) rocks, to communities between Dysselsdorp and Calitzdorp. Approximately 25 boreholes were drilled during the development of the scheme, 18 of which have been used as production boreholes. Total abstraction from the Scheme varies seasonally. Normally the peak demand is between 110 000 and 120 000 m^3/month (Jan-Feb), while demand drops to approximately 70 000 m^3/month during June and July. This seasonal variation is equivalent to all of the scheme's production boreholes being pumped continuously at 50 ℓ/s in summer and 25 ℓ/s in winter. Total abstraction is approximately 1 Mm^3/a. Water levels in some of the wellfields have dropped by an average of 30 m over the last 7 years, suggesting over-abstraction. The water level decline and the potential effect on the environment (as yet unquantified) could be a factor that will control future abstraction from the scheme.

Introduction

The Klein Karoo area is situated in the Western Cape Province of South Africa, between the towns of Calitzdorp and Uniondale (Fig. 1). The Klein Karoo Rural Water Supply Scheme (KKRWSS) operates in the western half of this area. The KKRWSS was designed to supply up to 4.7×10^6 m^3/a of purified water. It is fed by an Eastern Sector (Kammanassie Mountains near Dysselsdorp comprising 13 boreholes of which 5 constitutes the Vermaaks River Wellfield, and a Western Sector at Calitzdorp with 5 boreholes. All but one of the boreholes has been drilled into TMG Aquifers. Some 400 km of pipeline delivers the abstracted groundwater to two purification plants at Dysselsdorp and Calitzdorp and to end-users.

Current groundwater abstraction from the KKRWSS is approximately 1.0×10^6 m^3/a, which is considerably less than the original designed capacity, but equal to the current demand. Poor wellfield performance in some areas can be attributed to a poor understanding of the groundwater flow regime and water balance, inadequate borehole construction and iron-reducing bacteriological clogging of borehole screens in certain parts of the TMG Aquifer.

Figure 1
Map showing the location of the KKRWSS

Study area and physiography

The scheme is situated between Calitzdorp and De Rust (Fig. 1). The study area comprises a broad valley, with an elevation of approximately 500 m above mean sea level (amsl), surrounded by a number of mountain ranges with altitudes ranging between 700 and 2 150 m amsl.

Rainfall and evaporation

Annual rainfall of up to 2 000 m/a occurs in the Swartberg and Outeniqua Mountains, while rainfall at the towns in the valley varies between199 mm at Calitzdorp and 329 mm at De Rust. Runoff from the mountains is captured in a number of dams (Kamanassie, Stompdrift and Koos Raubenheimer

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Figure 2
Water level decline - Eastern wellfield

dams) and utilised for irrigation supply or for supply to Oudtshoorn.
Average annual evaporation varies between 1 760 and 2 050 mm/a from the west to east. Evaporation is 50% less in the months of April to September than during summer.

Geohydrology

The following three major hydrogeological units together constitute the TMG Aquifer system:

- Nardouw Aquifer
- Cedarberg shale aquitard
- Peninsula Aquifer.

The Nardouw Aquifer has a relatively high shale and feldspar content, is prone to ductile deformation, and generally has lower hydraulic conductivity than the Peninsula Aquifer, which is more quartzitic with associated brittle deformation. Numerous springs originate on the contact between Peninsula Formation quartzites and the Cedarberg Formation shale, which constitutes an effective boundary to groundwater flow.

Generally the Nardouw Aquifer hosts lower yielding boreholes, with poorer groundwater quality and iron reducing bacteriological clogging of borehole screens is common. The Peninsula Aquifer is higher yielding, mostly because it is associated with the mountainous areas which have better recharge. The quality is also superior to that in the Nardouw Aquifer, with limited problems related to iron clogging.

Hydrochemistry and environmental isotopes

Groundwater in the Peninsula Aquifer is characterised by low mineralisation (TDS < 300 mg/ℓ), low pH (< 6) and very low TAL (<< 0.5 meq/ℓ). The low pH values in this formation show that the total dissolved inorganic carbon (TDIC) is present mainly in the form of free CO_2, whilst the narrow range of ^{13}C values (-19 to -22‰) is evidence of minimal carbonate dissolution. ^{14}C values for boreholes above the shale band in the Vermaaks River Valley (Fig. 2) range from 75-84 pMC (percent modern carbon), with practically no measurable tritium. The boreholes below the shale band in the Nardouw Aquifer give a much lower value of 53 pMC. The sudden "ageing" suggests that the band acts as an effective aquitard, inhibiting subsurface drainage further downstream. Surface drainage of mobile groundwater from upgradient of the shale band could also re-infiltrate to form less mobile groundwater below it. The results further suggest that the water pumped from the upper valley is derived from the Kammanassie Mountain catchment rather than from a regional fracture system.

Recharge

Recharge occurs principally in the highly fractured mountainous local catchments and average 9% of the total rainfall (Kotze, 2000). Recharge from these catchments feeds local subsurface drainage and surface runoff in mountain streams and feed the major regional fractures. Increased exploitation from the highly fractured catchment valleys appears to be the most economical solution to increasing water supply. This will be at the expense of the baseflow in mountain streams as a result of the local lowering of groundwater levels.

Abstraction and water demand

The Eastern Sector of the scheme

The Eastern Sector has a design capacity of 9 000 m^3/d (3.3×10^6 m^3/a) based on peak demand, with the Vermaaksriver wellfield being the most important abstraction area. This wellfield exploits the Peninsula Formation in a situation where the Cedarberg Formation shale cuts across the valley, thus acting as a dam wall retarding groundwater movement. Average monthly abstraction during 1999 was 45 000 m^3/month. During 1999 water levels continued their slow downward trend, dropping approximately 2 m in the wellfield and 1.5 m at a monitoring borehole 800 m downgradient of the wellfield. The water level reaction at the Cedarberg Formation shale contact area (0.5 km below the wellfield) also shows a continued decline, having dropped 0.8 m during 1999. The water level decline over the last 7 years has been approximately 20 m in the wellfield (Fig. 2). Even though the Vermaaksrivier Wellfield had a fairly good recharge from rainfall over the last six months of 2000 the monitoring holes continued to decline - this suggests that monthly rainfall totals in excess of 50 mm are required before water levels will recover.

The Western Sector of the scheme

The abstraction from the wellfield during 2000 was 137 000 Kℓ/a (4.35 ℓ/s, continuous pumping). Water is abstracted from five boreholes. The wellfield is in urgent need of augmentation as water levels continue to slowly decline, mostly as a result of low rainfall. Water levels have declined an average of 30 m over the last five years (Fig. 3).

Reasons for changes in suggested wellfield abstraction rates

From 1985 to 1998 the abstraction rates from the production boreholes have been changed considerably. These changes had to be made because important issues appear not to have been addressed initially. These include:

- **Differences in management scenarios between the Nardouw and Peninsula Aquifers**: This is probably the single most important aspect to impact on wellfield management. The Peninsula Aquifer is in general a much better aquifer in terms of groundwater quality, quantity and management (stable formation, limited iron-bacteria problems). However, only one of the scheme wellfields, the Vermaaks River Wellfield, is situated in this aquifer. The other wellfields are situated in the Nardouw Aquifer.
- **Interconnectivity between boreholes and wellfields**: Typical examples are the Varkieskloof, Bokkraal and Calitzdorp Wellfields, where three or more boreholes are sited on the same structure and fall within each others' area of influence.
- **Fear of negative impact of abstraction from the Peninsula Aquifer on springflow**: A water balance study is needed to define the relationship between recharge from rainfall, abstraction and springflow. A management decision should then be made on the relative importance of springflow or abstraction from deep wells.
- **Potential environmental impacts of groundwater abstraction from deep boreholes on near surface vegetation**: The best aquifer (Peninsula), coincides with the high mountain ranges in the Western Cape, which are normally included in Nature Conservation areas, e.g. Kammanassie Nature Conservation area.
- **Borehole construction and drilling**: Drilling in hardrock aquifers such as the TMG is difficult and careful borehole construction is essential to ensure sustainable groundwater production from deep boreholes. It is believed that poor borehole construction (ineffective screens) and shallow (<60 m) boreholes may have considerably reduced the supply capacity of several production boreholes, while unnecessary screens have promoted biofouling.

Figure 3
Water level decline - Western wellfield

- **Definition of the hydrogeological boundaries of the aquifers being exploited**: In order to optimally manage the aquifers, aquifer boundaries need to be defined so that non-Scheme boreholes do not abstract from the same aquifer. A considerable amount of groundwater abstraction by farmers takes place on the southern flanks of the Kammanassie Mountains adjacent to the Scheme's boreholes. To avoid conflicting interests, the hydrogeological system needs to be clearly understood in order to calculate the aquifer water balance.

Conclusions

The KKRWSS supplies approximately 1 million m^3 to the service area. Although the boreholes are being utilised at low rates compared to achievable pumping rates, water levels have declined in some of the areas by up to 30 m over the last 7 years. The Calitzdorp wellfield requires urgent augmentation, especially since recharge from rainfall has been very limited during the last 3 to 4 years. The Dysselsdorp wellfields are being under-utilised and more water can be abstracted from all of these wellfields. However, water levels in the Vermaaks River Valley continue to decline and environmental concerns may result in abstraction being decreased from this field.

Abstraction from the Scheme has provided valuable insight into the operation of large-scale TMG abstraction schemes. Future abstraction from TMG Aquifers will have to address environmental concerns related to lowering of water levels.

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Utilisation of the Table Mountain Group Aquifer at Plettenberg Bay (Eastern Cape)

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Abstract

The Plettenberg Bay Catchment Area is partly covered by rocks of the Table Mountain Group (TMG) which form a secondary aquifer. Development of groundwater in the aquifer is expensive, due to deep water strikes and difficult drilling conditions. Never-the-less, the aquifer is utilised by the Municipality and numerous private landowners. The Plettenberg Bay Municipality utilises groundwater from two areas - the Hillview ridge and the Airport plateaux, with a maximum abstraction of 300 000 m^3/a. The water quality of the TMG Aquifer is generally good although a low pH and high dissolved iron and manganese necessitated treatment. Over-abstraction, especially during the 1999-2000 peak holiday demand period, appears to have stressed the aquifer and current use from the aquifer is limited.

Introduction

Groundwater has been utilised as a supplementary supply at Plettenberg Bay since 1985. The Plettenberg Bay Coastal Catchments Study identified a primary aquifer adjacent to the lagoon and a secondary aquifer associated with the TMG rocks. The TMG Aquifer is by far the most important aquifer in the catchment, in terms of size and potential for development. The location of Plettenberg Bay is shown in Fig. 1.

Topography of the TMG area

The TMG in Plettenberg Bay area occurs in two main areas:

- An elevated ridge along which the Port Elizabeth
- Knysna main road runs
- An elevated terrace area between the Piesang Valley and the sea (adjacent to the airport).

The ridge is located at an elevation of approximately 140-190 m above sea level, while the airport terrace is 90-120 m above sea level.

Rainfall/evaporation

The rainfall in the area occurs throughout the year with a slight winter dominance. The annual average rainfall is approximately 710 mm.

Figure 1
Location of study area

Geology

Both the lithology and structural geology have a major bearing on the groundwater resources of the area. The rock units existing consist of the Table Mountain Group rocks, which are in areas overlain by the Gydo Formation (Bokkeveld Group), Uitenhage Group and recent sands of Tertiary and Quaternary ages. The lithostratigraphy is shown in Table 1.

The Table Mountain Group consists of the Peninsula, Cedarberg, Tchando, Kouga and Baviaanskloof Formations. Apart from the subordinate Cedarberg and Baviaanskloof Formations, the group consists predominantly of medium to course grained, cross-bedded units of quartzites and sandstones.

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Table 1
Lithostratigraphy of study area

Age	Group	Formation
Quaternary (30 Ma)		
Jurassic (140 Ma)	Uitenhage	Enon
Devonian (395 Ma)	Bokkeveld/Ceres	Gydo
Ordovician (500 Ma)	Table Mountain	Baviaanskloof Kouga Tchando Cedarberg Peninsula

Structural geology

The structural geology has a major bearing on the groundwater potential of the consolidated geological units. In their pristine state, the consolidated geological units have negligible groundwater potential. It is the secondary structural features that give the units groundwater potential. These secondary structures are usually associated with faults, fractures and weathering which gives rise to discrete zones of secondary permeability. Anticlines and synclines of parasitic asymmetrical folds characterise the succeeding less massive and relatively incompetent formations. In the Plettenberg Bay area the faulting has resulted in small elongate asymmetrical northward tilting half-grabens which are infilled with cretaceous sediments. Both the Bietou and the Piesang River basins are U-shaped, ESE plunging graben structures. The low permeability material in these graben structures effects regional groundwater flow patterns.

Hydrogeology

Siting procedure/exploration methods

Borehole siting undertaken by Groundwater Consulting Services took into account aerial photo interpretation and geophysical traversing. Geophysical traverses were undertaken across lineaments determined from the aerial photographs. The geophysical traverses were undertaken by utilising an Geonics EM-34 ground conductivity meter. In many cases the main water strikes in the Plettenberg Bay area is found at depths below 150 m. In these cases major lineaments were targeted and holes sited where the geophysics showed the features to be vertical. In the Hillview area, strong fracturing was encountered at depths of between 150 and 200 m.

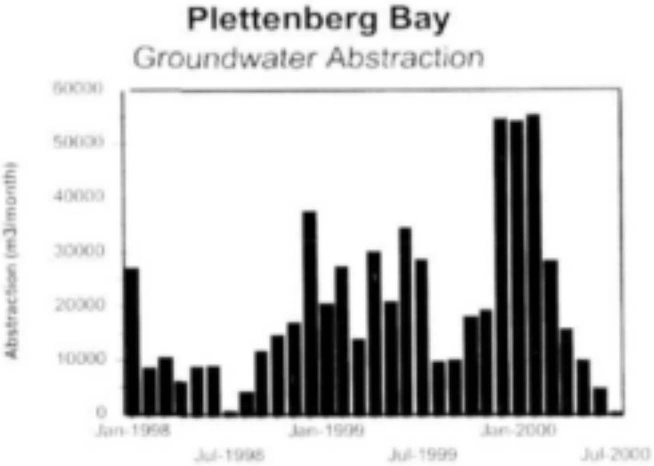

Figure 2
Abstraction at Plettenberg Bay

Borehole yields

During the Plettenberg Bay Catchment Study it was found that the average yield of the TMG boreholes is 2.1 ℓ/s with a range from 0.5 - greater than 15 ℓ/s. The average depth of boreholes is 100 m.

Groundwater quality

Groundwater of the TMG Aquifer is low in total dissolved solids, generally acidic and contains dissolved iron and manganese. There are however some variations in quality depending on the lithology. The Peninsula and Tchando Formations are the geological units which form the majority of the outcrop in the area. The Peninsula Formation groundwater has an average total dissolved solid content of 607 mg/ℓ and a pH of 6.1. Average iron and manganese concentrations in the groundwater are 3.61 mg/ℓ and 0.16 mg/ℓ respectively. The Tchando Fm groundwater, however, has an average TDS of 300 mg/ℓ and a pH of 5.7. Iron content, however, is much higher that in the Peninsula rocks with some holes yielding iron levels of between 14 and 16 mg/ℓ and manganese contents of 0.3 to 0.5 mg/ℓ.

Due to the low pH of the TMG Aquifer, a certain amount of iron and manganese is found dissolved in the groundwater. This leads to problems in the use of the water domestic consumption because of the staining and taste. In addition, the low pH and high iron content results in the water being corrosive.

Groundwater use

A number of Municipal production boreholes exist. From 1995-1998, four boreholes were used with an annual abstraction which decreased from 303 000 m^3/a in 1996 to 155 000 m^3/a in 1998. Two new boreholes were drilled in 1999 and abstraction increased to 287 000 m^3/a in 1999. The abstraction data shows a dramatic increase in abstraction during the 1999-2000 holiday period which appears to have stressed the aquifer. Since then water levels have dropped to pump levels in some of the boreholes. It is not certain whether this is as a result of a decline in regional water levels or as a result of iron clogging of the boreholes.

There is also considerable groundwater abstraction from the TMG Aquifer from all of the small holdings and developments which parallel the Plettenberg Bay-Knysna main road. This area is not serviced by the Municipal supply system and all of the resorts utilised groundwater abstracted from the TMG Aquifer.

Conclusions

TMG Aquifers at Plettenberg Bay are bounded by groundwater boundaries - either graben structures filled with low permeability, low groundwater potential sediments or by the sea. The aquifers have been utilised successfully since 1985, but water levels have reached pump suction at the beginning of 2000, mostly as a result of a dramatic 46% increase in use during the 1999 Christmas holiday peak demand period. It is unclear wether regional water levels have been lowered, or if iron bacterial clogging has reduced the efficiency in the boreholes. Currently the aquifer is being rested, while the option of aquifer storage and recovery (ASR) utilising surplus water from adjacent rivers during peak flow periods, is being considered.

Clear abstraction limits have been set for the TMG Aquifers at Plettenberg Bay and abstraction should not have exceeded these limits, no matter what the demand. In the future aquifer management must take cognizance of the abstraction limits and should manage the aquifer system based on abstraction and rainfall impacts on water levels.

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Case Study:
Port Elizabeth Municipal Area

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Abstract

Drought conditions and the imposition of water restrictions in the early 1990s lead to a proliferation of private boreholes being drilled into the Table Mountain Group (TMG) Aquifer in the Port Elizabeth municipal area. A research project was therefore initiated to investigate the number and distribution of boreholes, the volume of groundwater abstracted, its quality and legal options for the control of development and use of groundwater in the municipal area. It was estimated that there were ~300 boreholes in the municipal area abstracting ~370 000 m^3/a. Groundwater quality was found to be atypical of TMG Aquifers elsewhere, with extreme variation in quality. In terms of yield and quality, the TMG Aquifer in the Port Elizabeth urban area is not a potential source of municipal supply unless hitherto untapped aquifers exist at greater depths than so far exploited.

Introduction

The Port Elizabeth area experienced a downward trend in rainfall in the early to late 1980s, culminating in water restrictions being introduced from 1989 to 1992. In response to this, a proliferation of private boreholes were drilled into the sandstone aquifer underlying the municipal area, with much attendant publicity in the local press. Headlines such as "PE boreholes can go salty, expert warns," and, "Boreholes could drain groundwater", illustrate the concerns over extensive and uncontrolled use of groundwater in the municipal area.

In early 1992, SRK Consulting held discussions with Port Elizabeth Municipality (PEM) with a view to initiating a project to investigate the extent and effects of private groundwater abstraction in the municipal area. SRK and PEM then submitted a joint proposal to the Water Research Commission for funding, which was subsequently approved and the project commenced in January 1993. The original two year project duration was extended by six months in 1995 to facilitate gathering of further monitoring data. The principal research objectives were:

- to determine the number and distribution of boreholes in the PEM area;
- to assess the volumes of groundwater abstracted and its overall quality;
- to assess the potential for sea water intrusion; and
- to investigate legal options for PEM to control development and use of groundwater in the municipal area.

Geology

Port Elizabeth is situated at the eastern outcrop extremity of the TMG on a northwest-southeast trending anticlinal structure which forms part of the southern limb of the Cape Fold Belt (Fig. 1). Along the northern boundary of the study area, the resistant sandstones form an escarpment where they dip under the Uitenhage Group, while to the south, the sandstones form an elevated wave-cut platform. The main TMG formation underlying the PEM area is the Peninsula Formation.

Much of the southern part of the wave-cut platform that forms the Cape Recife headland is covered by a mantle of Tertiary to Recent deposits, such as the Nanaga Formation, a consolidated calcareous aeolian sand or dune rock. This formation is relatively resistant to weathering and forms topographic highs, e.g. Lovemore and Walmer Heights. Recent unconsolidated aeolian sand forms longitudinal sand dunes with crests trending east-northwest, west-southwest. Calcrete layers are commonly developed within the sand.

The rocks and sediments described above can be classified into two broad aquifer types. The TMG form secondary aquifers in which groundwater flows and is stored within fractures such as joints, bedding planes and faults. The Tertiary to Recent sands are primary aquifers in which groundwater flows and is stored in interstices within the constituent sand grains. Rocks of the Uitenhage Group are not classed as aquifers within the study area due to their generally low hydraulic conductivity and poor water quality.

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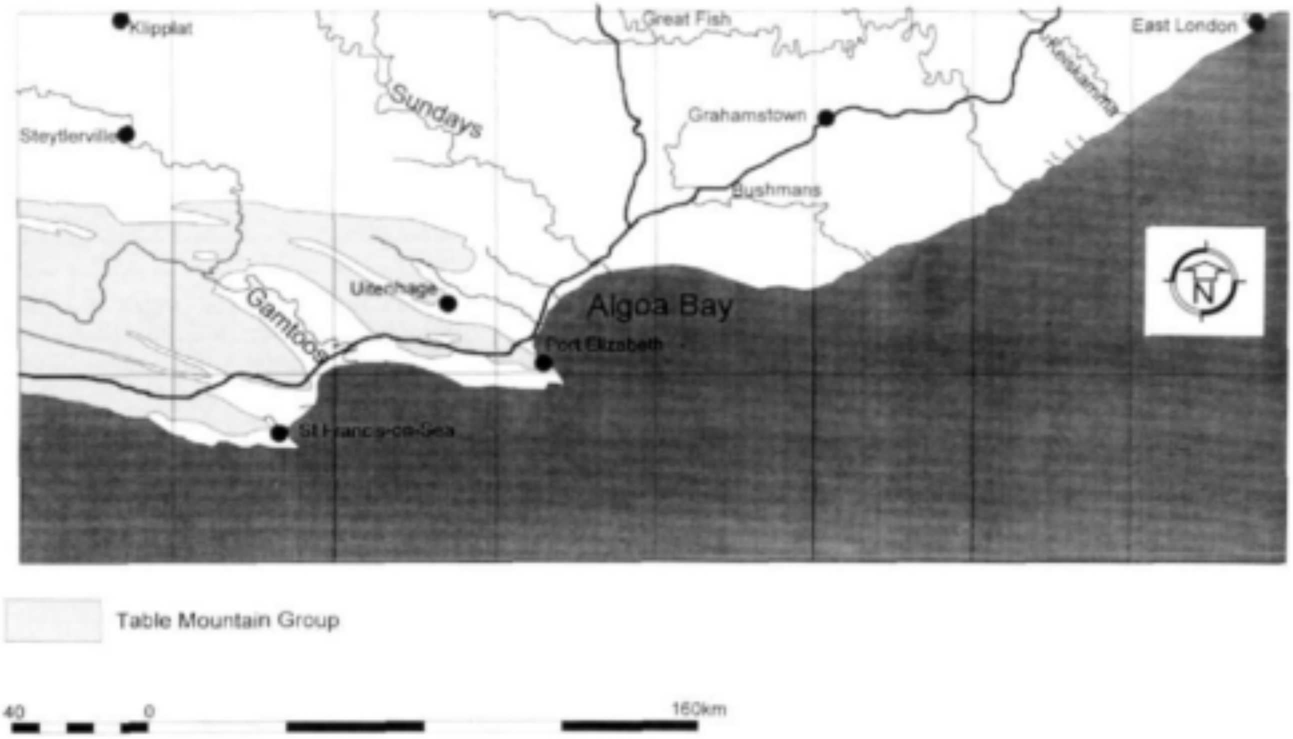

Figure 1
Locality plan

Figure 2
ISO-conductivity map

Hydrogeology

Borehole characteristics

There are two primary controls on the distribution of boreholes, the most important of which appears to be the socio-economic status of home-owners, while geological and hydrogeological factors are of secondary consideration. Although not all boreholes within the study area were located in the census, the borehole distribution and density recorded is considered to be representative of borehole occurrence in the area. Walmer and Summerstrand show the highest concentration of boreholes and major roads can be identified by the alignment of boreholes. Together these suburbs account for 65% of known boreholes and the distribution drops-off dramatically away from these areas.

The data indicate that the TMG Aquifer in the PEM area is relatively low yielding with >96% of recorded boreholes having a yield of <3 ℓ/s. Boreholes are generally 60 to 120 m deep. As a comparison, yields at St Francis Bay are in the range of 2 to 14 ℓ/s from depths up to ~90 m, while at Ceres, yields range from 5 to 12 ℓ/s from depths of 80 to 120 m. In both of the latter examples, the formation exploited is the Nardouw Subgroup.

Groundwater use

In times of average and above average rainfall, abstraction is minimal as groundwater quality is considered generally undesirable and municipal water relatively cheap. Records show that, for the majority of borehole owners, groundwater is used and considered as an emergency supply source only, with the potential for relatively short-term but high demand pulses to be imposed on the aquifer.

Total annual metered private groundwater abstraction amounted to 20 500 m^3 in 1993 from which, by simple proportion, it was estimated that total private groundwater abstraction amounted to about 240 000 m^3/a. A rough estimate of total corporate abstraction is estimated to be about 150 000 m^3/a. Combining figures for corporate and private abstraction, total annual groundwater abstraction in the PE municipal area is thus estimated to be ~390 000 m^3. This volume formed <1% of total municipal consumption at that time.

Groundwater quality

In the context of expected TMG Aquifer groundwater chemistry, the Port Elizabeth aquifer is atypical. For example, the range in conductivity is 50 to 820 mS/m, and in chloride, 100 to 2 800 mg/ℓ. The explanation put forward by the researchers is that expanding urbanisation in the PEM area over the outcrop of the TMG Aquifer has resulted in partial replacement of diffuse recharge by rainfall by the development of numerous point sources of recharge/contamination, such as old waste tips, leaking sewers and water mains, septic tanks, fertilizer application and stormwater. This would explain the frequent occurrence of groundwater with radically different chemistry from boreholes a few streets apart. Groundwater conductivity contours, potential sources of contamination and borehole positions are shown on Fig. 2.

Examples of conductivity-chloride contrasts are 475 mS/m to 1 463 mg/ℓ and 151 mS/m to 390 mg/ℓ in Walmer, and 247 mS/m to 559/mg/ℓ and 652 mS/m to 1 559 mg/ℓ in Walmer Heights. Historical reports of 'brackish' water in the Walmer area in the 1920s could also indicate a naturally elevated level of salts in the aquifer.

Examples of groundwater types are shown in a Piper Diagram in Fig. 3.

Groundwater from the central and inland suburbs is all of a sodium chloride type, particularly north of the Baakens River, whereas groundwater from the Summerstrand area has a greater Ca/Mg HCO_3 component, due to the influence of the lime rich coastal sands. This could indicate that the coastal boreholes are tapping the primary aquifer directly, or that a component of the secondary aquifer groundwater is derived by leakage from the overlying sands.

Although water types are consistent within the above two categories, there is a large spatial range in electrical conductivity and individual constituents within the sodium chloride type. There are also significant time variations in water quality within individual boreholes, as shown by the high standard deviation for many chemical constituents analysed for the same borehole at different times, although some are skewed by one analysis, which in many cases was the first of the monitoring period. The time variations do not appear to be seasonally related, with each borehole having its own pattern. Fluctuations also appear to be above and below a fairly constant level, with concentrations at the start and end of the monitoring period not being significantly different. The groundwaters generally comply with SABS 241-1984 upper limits for domestic water use, with some exceptions, including chloride, nitrate and iron.

With regard to saline water intrusion, the main area of concern is the coastal suburb of Summerstrand and, to a lesser extent, Humewood. The other coastal areas are either undeveloped or bordered by commercial or industrial areas. Inspection of the hydrochemical analyses of the four monitoring boreholes in Summerstrand shows no sign of any sea water intrusion. Of all the boreholes investigated for this project, the Summerstrand boreholes were some of the most consistent in terms of water quality. On the basis of these results, sea water intrusion is not regarded as a problem, although the drought ended shortly before the commencement of this project and the boreholes were not used as much as they would be in drought conditions.

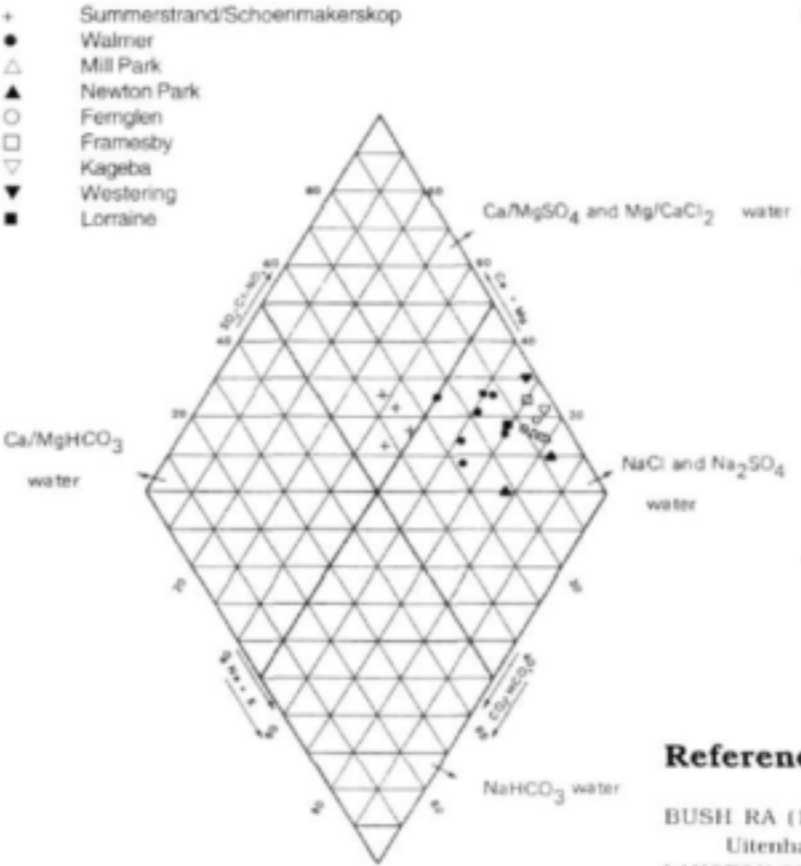

Figure 3
Modified Piper diagram

Conclusions

The main conclusions to be drawn from this study are listed below and follow the same order as the research objectives:

- There are an estimated 300 boreholes in the PEM area, of which 241 were located on the ground.
- Annual groundwater abstraction is estimated at 390 000 m^3.
- Over most of the study area the groundwater is a sodium chloride type. The only exception is Summerstrand where the groundwater has a greater Ca/Mg HCO$_3$ component.
- Groundwater quality in the PEM area is generally atypical of TMG Aquifers elsewhere in the Eastern and Western Cape. There is extreme spatial variation in groundwater quality, often over very short distances in the same suburb. Seasonal variation in groundwater quality is not seen as the rainfall patterns are so irregular. There is no "winter" or "summer" period of high or low rainfall as in Cape Town, for example.
- There is sporadic and short-lived intrusion of sea water in boreholes closest to the sea in the Summerstrand area. This is a local and non-permanent phenomenon at the moment but there is potential for a deeper incursion of saline water into the aquifer under higher pumping stress should drought conditions return.
- There is evidence of groundwater contamination in many areas on the basis of conductivity, chloride and nitrate levels, especially in the context of groundwater quality in TMG Aquifers elsewhere. The contamination is attributed to urbanisation and specifically waste dumps, fertilizer application, leaking sewers and stormwater runoff.
- In terms of yield and water quality, the TMG Aquifer in the PEM area is not a potential source of municipal supply, unless untapped aquifers exist at greater depths than so far exploited.

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Case Study:
St Francis-on-Sea

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Abstract

Extensive additional residential development at St Francis-on-Sea in the late 1980s led to a requirement for an additional 20 ℓ/s of potable water. The decision was taken to investigate whether this demand could be met from local groundwater resources. The subsequent hydrogeological investigation involved the siting, drilling and test pumping of 11 boreholes in the Table Mountain Group (TMG) Aquifer, in addition to 13 existing boreholes in the general area. The bulk of this work was carried out between May 1989 and February 1990. Two wellfields were developed, Santa and Airfield with a combined long-term yield capability of 24 ℓ/s and a peak capability of 60 ℓ/s to meet holiday season demand. A treatment plant was installed to remove iron from the groundwater. A two-year monitoring period after commissioning of the wellfields verified the above yield predictions.

Introduction

Extensive additional residential development at St Francis-on-Sea in the late 1980s led to the requirement for an additional 20 ℓ/s of potable water. Options included an expensive upgrade of the pipeline from Churchill Dam or exploiting local groundwater resources. The town is located on Recent sands and rocks of the TMG and some existing high yielding boreholes indicated good potential for further groundwater development. Consultants were accordingly appointed to investigate the groundwater potential and an initial exploration phase was followed by full wellfield development.

Geology

St Francis-on-Sea is situated on the eastern limb of the Cape Fold Belt and the rocks present here belong to the Table Mountain and Bokkeveld Groups. Their contrasting lithologies have had a strong influence on the form of the coastal and inland topography (Fig. 1).

The TMG mainly comprises resistant sandstones which form Cape St Francis, with the coastline paralleling the northwest-southeast strike of the strata. The Bokkeveld rocks are mainly shales, are less resistant to weathering and form the embayment extending north-east from the Krom River estuary.

The TMG is subdivided into two main formations, the Peninsula Formation and the Nardouw Subgroup. The latter comprises three sandstone horizons with closely spaced bedding plane openings, with dips of about 50° to the north-east. Jointing is well-developed at right angles to the bedding, as seen in exposures along the coastline and a number of fractures cut the bedrock, trending northeast-southwest. Borehole siting was related to these, where possible.

The Peninsula Formation in this area is a more massive formation with consequently less groundwater potential and is also further away from the town. It was therefore not targeted for groundwater supply.

A belt of Recent sand overlies the TMG, comprising both vegetated and mobile dunes of sand with calcrete lenses. These deposits are up to 40 m thick in the vicinity of the Airfield 3 borehole.

Hydrogeology

Borehole characteristics

All boreholes drilled into the Nardouw Subgroup struck groundwater, with blow-out yields ranging from 2 to 17 ℓ/s. Although earlier boreholes drilled by DWAF continued to depths of between 160 and 200 m, main water strikes in the more recent boreholes occurred between 40 and 80 m and drilling was generally not continued beyond 90 m.

Rest water levels are shallow, ranging between ~1 to 3 m below ground surface. For the main wellfield development areas, i.e. Airfield and Santa (Fig. 1), this translates into 60 and 47 m above mean sea level, respectively. Under maximum drawdown conditions, i.e. during step 4 of the test pumping

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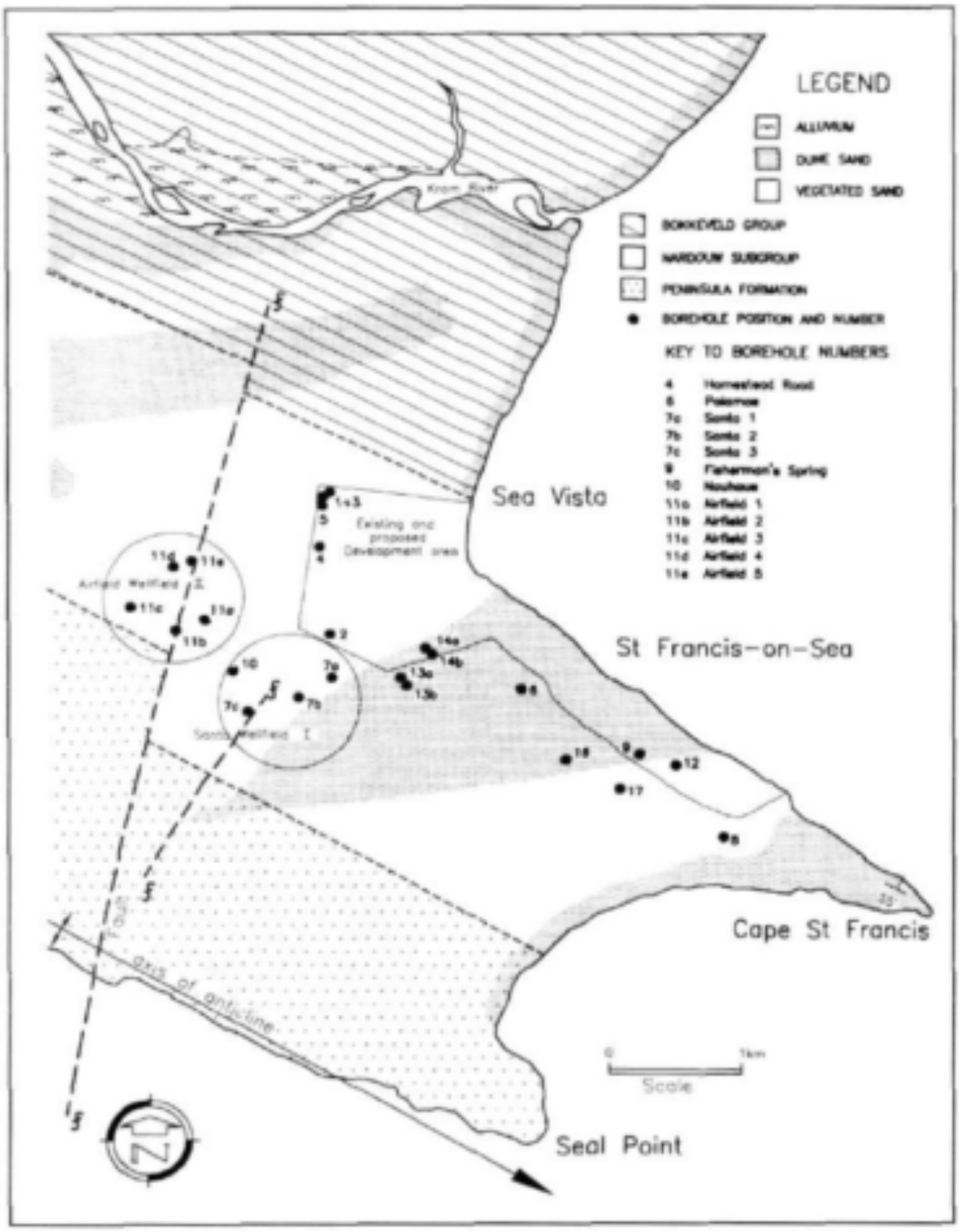

Figure 1

Locality plan showing geology and borehole positions

programme, water levels were generally not drawn-down below sea level.

The coastal rim of boreholes such as Palamos and Fisherman's Spring are at lower elevations and are closer to the sea. Sea water intrusion is a possibility here, aided by the jointing developed at right angles to the main structural trend and recommended pumping rates were reduced accordingly. If these boreholes are brought into production in the future they should be pumped continuously at a relatively low rate rather than intermittently at higher rates. This will minimise turbulence in fractures, a prime cause of expansion of the brackish water diffusion zone between fresh and sea water.

Aquifer types

The main aquifer is the Nardouw Subgroup, which has a width of about 1 500 m in the study area. It is bounded by the Peninsula Formation to the south, which is water-bearing but fractures are poorly developed and the Bokkeveld Group rocks to the north, which can be considered as being impermeable for all practical purposes. The degree of jointing in the Nardouw sandstones, mainly bedding planes, is such that boreholes can be sited almost anywhere within this formation and still strike water. The thick sand cover makes accurate borehole siting on specific features impossible anyway.

The overlying Recent sands also constitute an aquifer, although yields from shallow wells drilled into this formation were only of the order of 1 ℓ/s. More favourable conditions for exploitation of this aquifer exist in the vicinity of the Airfield, where sands are thicker and artesian flow was observed from Airfield 3 at the sand/sandstone contact. Although not directly utilised at present, the sand aquifer is of great importance as a source of recharge to the underlying sandstones. This mechanism will be particularly effective when bedrock water levels are drawn-down under pumping conditions and will thus aid recovery.

Test pumping data analysis for boreholes in the TMG Aquifer yielded transmissivity values of between 165 and 2 485 m^2/d and storativity of between 1.8 and 3.3×10^{-3}.

The main source of recharge to the TMG Aquifer is by throughflow from the Kareedouw Mountains to the north-west and, using Darcy's Law, this is estimated to be about 875 000 m^3/a (based on a conservative T value of 100 m^2/d). The main groundwater flow direction is to the south-east under natural conditions. Additional recharge under pumping conditions will be derived from leakage as described above and throughflow along strike. Based on the above recharge figures the following yields were recommended:

- A peak yield of 60 ℓ/s and 10 ℓ/s from the TMG and sand aquifers, respectively, sustainable for a maximum of 6 weeks per year over the holiday season.
- A long-term yield of 24 ℓ/s and 10 ℓ/s from the TMG and sand aquifers, respectively, for the remainder of the year.

Groundwater quality

The groundwater from the TMG Aquifer is slightly alkaline, low in total dissolved solids (TDS), is calcium bicarbonate in character and hard, complying with SABS 241–1984 limits for domestic water supplies. Problems were experienced with high iron content in the original supply boreholes (2 and 3), and all the newly drilled boreholes were accordingly sited further to the south and have a lower total iron content, within the SABS limits. An iron treatment plant was, however, installed to control overall iron content of the water supply.

Water quality of all the new boreholes in the sand aquifer is good and conforms to SABS recommended limits. This groundwater can be described as being slightly alkaline, moderate to low in TDS, and calcium bicarbonate in character. It is also hard (300 to 400 mg/ℓ $CaCO_3$) and softening of this water may be required.

Wellfield development

Two main wellfields have been developed, viz Santa and Airfield, designated Wellfield 1 and 2 on Fig. 1, respectively, consisting of the Santa 1 to 3 and Airfield 1 to 5 boreholes. The Homestead Road borehole was equipped at the same time as the Santa boreholes. Two other boreholes, Golf Course (3) and Reservoir (2) are already equipped to provide water into the reticulation system. Throughout the period of heavy drought from March to December 1989, these boreholes were the only source of supply to St Francis as the Churchill Dam Pipeline source was not used. Three other boreholes can also be equipped if required, namely Palamos, Fisherman's Spring and Harbour 1.

A three-year monitoring programme was implemented between December 1989 and December 1992, covering water levels, abstraction and water quality. Total abstraction during this period was 1.4 million m^3 and the wellfields met all long-term and peak requirements. Water levels fluctuated within the design limits, with those in the Santa Wellfield being within a +45 to 0 m amsl range and those in the Airfield Wellfield being + 60 to + 30 m amsl.

Groundwater quality remained good, with EC being in the range 60 to 90 mS/m. Periodic acid dosing has been required in the Santa boreholes to remove incrustation and restore performance.

Conclusions

The following conclusions can be drawn from this case study:

- The Nardouw Subgroup sandstones form the main aquifer, with significant recharge being derived from the overlying saturated Recent sand deposits. Within the bounds of these sandstones, boreholes can be sited at random with a >90% success rate.
- Two wellfields with a total of eight boreholes have been developed from which a peak yield of 60 ℓ/s and long-term yield of 24 ℓ/s can be obtained.
- Groundwater EC is in the range 60 to 90 mS/m and is a calcium bicarbonate type. A treatment plant was installed to deal with the typical 'iron-problem' characteristically associated with TMG Aquifers;
- A three-year monitoring programme from 1989 to 1992 confirmed the design yield and quality parameters of the wellfields;
- The St Francis-on-Sea case study has shown that scientifically sited and well managed groundwater abstraction schemes in the TMG Aquifer are a viable long-term water supply source for medium- to large-scale domestic purposes.

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The Table Mountain Group Aquifer Utilised at Steytlerville (Eastern Cape)

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Abstract

Groundwater is the sole or main source of potable water for many urban and rural communities in South Africa. More than 280 cities or towns, 5 million cattle, 26 million small stocks and 24% of irrigation water supplies depend on groundwater (Van Tonder and Dennis, 2000). Steytlerville is one of the communities that rely on groundwater and has done so for more than 10 years. The town has a peak demand of 15 000 m^3/month. This water is supplied predominantly from boreholes drilled into the Table Mountain Group (TMG) sandstone aquifers located 20km south of the town. At times the boreholes have been over-abstracted resulting in iron clogging of boreholes, but changes to the borehole design and scheme management have ensured sustainable groundwater utilisation.

Introduction

Steytlerville, a rural Karoo town located 150 km north west of Port Elizabeth, has a population of approximately 4 000 inhabitants. The municipal water supply is obtained solely from groundwater abstracted from two wellfields, namely the northern and southern wellfields. The southern wellfield is the stronger of the two wellfields and exploits the TMG Aquifer.

The water demand for Steytlerville in 1992 was 6 000 m^3/month during winter with an additional 3 000 m^3/month required during summer. Three boreholes in the southern wellfield supply 6 000 m^3, while the extra peak demand is provided by boreholes in the Northern Wellfield. The town demand has since increased to 15 000 m^3/month (source Town Clerk, Steytlerville) or 5.8 ℓ/s on a continuous basis. The increase in demand is as a result of the increase in the provision and extension of services to previously disadvantaged communities.

Topography

The topography of the town and surrounding area consists of broken hills, valleys and ridges associated with the inclined shales and sandstones of the Bokkeveld Group. Twenty kilometres to the south, the east/west trending TMG sandstones form the prominent Baviaanskloof mountains. Shallow incised valleys associated with north-south fractures occur along the edge of the mountain range.

Figure 1
Location of study area

Rainfall/evaporation

Steytlerville has a rainfall of approximately 240 mm/a, with the majority of precipitation occurring mainly in late summer. The month with the highest rainfall is March. Evaporation is nine times higher than the rainfall, being 2 246 mm/a. Rainfall along the northern flank of the Baviaanskloof mountains is higher than that of the town, being 500 mm/a. Even in the higher rainfall areas, the mean annual rainfall recharge to groundwater is low, expected to be approximately 6% of average rainfall.

Geology

The geology of the investigation area consists mainly of TMG sandstones in the south and the Bokkeveld Group shales in the north. Superficial alluvial de-

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Table 1
Stratigraphic Subdivision of the Cape Super Group South of Steytlerville

Bokkeveld Group	Traka Subgroup Ceres Subgroup
Table Mountain Group	Baviaanskloof Formation Skurweberg Formation Goudini Formation Cedarberg Formation Peninsula Formation

posits occur along the river courses, with some small colluvial fans occurring at the mouth of valleys incised into the Baviaanskloof mountains. The stratigraphy of the rocks found in the area is shown in Table 1.

Hydrogeology

Structures in the Table Mountain and Bokkeveld Groups play a large role in the availability of groundwater. In the west the nappe thrust created by the thrusting of the TMG over the Bokkeveld Group has produced a large number of small scale structures. Evidence of this is obtained from a number of incised north-south trending valleys. Some *small scale chevron folds are overturned to the north* of the study area. The TMG is highly jointed and fractured with fountains and seepages emanating from these fractures.

Springs also emanate from fractures in the mountains. Flow from these springs recharge the colluvial fans. High rainfall on the mountains recharges the fans and allows the streams to flow for periods of up to four months after the summer rains. The Bokkeveld Group rocks adjacent to the TMG mountains tends to deliver low yielding, poor quality water. There are definite notable exceptions where boreholes drilled in major west - east trending fractures in folds and kink zones coupled with horizontal fracture zones along bedding planes, caused by large scale structural deformation, produce extremely high yielding boreholes. The fact that these zones are recharged by long periods of run-off from fountains and the fans areas, allows for a better quality water than expected from the Bokkeveld. The groundwater conductivity for boreholes drilled in the TMG, varies between 35 mS/m and 53 mS/m, while boreholes drilled in the Bokkeveld Group shales have a conductivity of between 215 mS/m and 230 mS/m. Yields from production boreholes are variable with historical yields ranging from 10 to 15 ℓ/s for limited periods. In the eastern section of the investigation area, a major west-east trending anticline forms the Bloukop Mountain - this anticline plunges *below the Bokkeveld, with two of the production* boreholes drilled into the anticlinal axis.

Table 2
Step tests conducted on boreholes drilled in the TMG

		GCS 2	SBH 2
Step 1	Rate (ℓ/s) Drawdown (m)	3.38 2.31	2.12 0.91
Step 2	Rate (ℓ/s) Drawdown (m)	5.19 4.49	3.61 1.85
Step 3	Rate (ℓ/s) Drawdown (m)	8.14 7.73	5.46 3.10
Step 4	Rate (ℓ/s) Drawdown (m)	11.98 11.76	8.21 5.0
Step 5	Rate (ℓ/s) Drawdown (m)	15.3 16.16	

Borehole siting procedures

Electromagnetic traverses were undertaken along lines determined from aerial photographs. The geophysical traverses were undertaken using a Geonics EM-34 ground conductivity meter. In general the EM readings obtained over the TMG rocks vary between 10 mS/m and -2 mS/m. Anomalies identified for drilling had readings below -2 mS/m as seen in Fig. 2. The shales in the southern wellfield generally have low EM readings and layers of interbedded shales might be mistaken for fractured sandstone anomalies.

Drilling of the borehole

Drilling of the last few boreholes drilled involved drilling a small diameter pilot hole (165 mm), which was then reamed to the correct depth based on the position of the water strikes. After reaming (usually to a few metres above the deepest water strike which *was to be exploited) a plain PVC casing was grouted* into place, cutting off any upper water strikes. Most boreholes were drilled to a maximum of 100 m, although some attempted deeper boreholes (> 150m) were unsuccessful. Water strikes start as shallow as 25 m, but were normally in the range of 40 - 60m below surface. Blow yields range between 5 - 12 ℓ/s.

Aquifer testing of borehole

Evaluation of the step drawdown test data obtained from boreholes drilled in the TMG in the southern wellfield suggests that the TMG Aquifer is capable of very high yields over a short period of time (see Table 2).

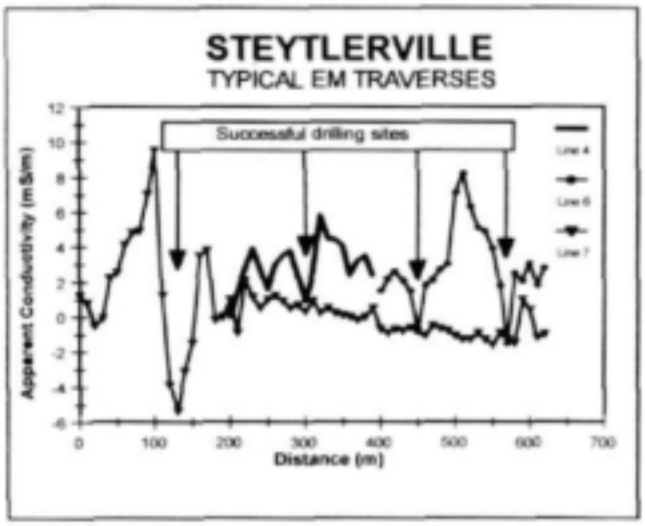

Figure 2

Typical geophysical traverses over anomalies drilled successfully

A 48 h constant rate tests conducted at rates exceeding 4 ℓ/s on these two boreholes, showed a continuous dropping in water levels during the test.

Water levels did not recover back to the pre-pumping static water levels after 48 hours of recovery, indicating that the aquifer was being mined. Measurement of water levels in surrounding boreholes during the test, together with Theis distance drawdown analysis, indicated that the cone of depression would extend approximately 1km with continuous pumping at 1.5 ℓ/s. The long-term sustainable yield of a borehole or a wellfield is determined ultimately by the recharge from rainfall or river flow to this cone of depression. Natural recharge into the 1km zone directly adjacent to each production borehole was determined as follows :

Natural recharge
= Area x Rainfall x % recharge to groundwater where: Area = 1 km radius around borehole; Rainfall = 499 mm/a; % recharge= 6% (Vegter's maps)

= 94 011 Kℓ/a.

The theocratical calculation suggest that the maximum abstraction rate for boreholes drilled into the TMG Aquifer at Steytlerville under the existing recharge conditions should not exceed 3 ℓ/s on a continuous basis (365 days per year). Any abstraction rates greater than this would result in a long term lowering of groundwater levels through out the area.

Since the initial estimates of sustainable yield were made in early 2000, monitoring of water levels in the aquifer has suggested that the 6% recharge figure utilised was too high. The harmonic mean of the two Cl values (Table 3) is 49 mg/ℓ - if the Cl value of the rain was 1 mg/ℓ the recharge would be 2%, while at 2 mg/ℓ, the recharge would be 4%. Lowering of the abstraction from the two boreholes to 1.5 ℓ/s per hole (47 304 Kℓ/a) has resulted in stabilisation of the water levels, suggesting that recharge is in the vicinity of 3 - 4 %.

Table 3
Groundwater quality of TMG Aquifer

Chemical parameter	SBH 2	GCS 2
Potassium as K mg/ℓ	3.5	2.4
Sodium as Na mg/ℓ	61	38
Calcium as Ca mg/ℓ	36	25.3
Magnesium as Mg mg/ℓ	7.3	4.2
Ammonia as N mg/ℓ	<0.1	<0.1
Sulphate as SO_4 mg/ℓ	50	22
Chloride as Cl mg/ℓ	68	38
Alkalinity as $CaCO_3$ mg/ℓ	124	89
Nitrite plus nitrate as N mg/ℓ	<0.1	<0.1
Iron as Fe mg/ℓ	2.5	2.4
Manganese as Mn mg/ℓ	0.53	0.2
Conductivity mS/m	53	35
pH	7.3	7.3
Saturation pH	7.9	8.2
Total dissolved solids mg/ℓ	339	224

Chemical sampling of borehole

A full chemical analyses was undertaken on two of the production boreholes (SBH 2 and GCS 2). The results are summarised in Table 3.

Groundwater quality of the TMG Aquifer is well within the SABS maximum allowable limits set for water for domestic supplies (SABS 241). Fe and Mn were detected at levels higher than allowed. Precipitation of Fe and/or Mn will probably take place on oxygenation of the water, which could result in the clogging of the pumps and pipes in the reticulation system.

Problems encountered and solutions

The majority of problems encountered are mainly related to over-abstraction of the aquifers. No monitoring program or abstraction program exist, and recommended pumping rates are routinely exceeded. Over-abstraction also caused an increase in the rates of iron clogging in some boreholes. To minimise clogging and to stop over-abstraction, the following measures were introduced:

- new boreholes were equipped with plain PVC casing to just above the main or deepest water strike, thereby reducing the cascading of water down the borehole;
- steel casing was removed, thereby preventing the introduction of corroded iron into the borehole;
- pumps were installed to a level of 1 m above main water strike, thereby maintaining upward inflow into the borehole; and

- pumping rates were lowered and pumping was changed to continuous pumping.

Conclusions

The TMG sandstones form a vital source of water for the town. Problems related to over-abstraction and iron clogging of boreholes have been reduced by developing more boreholes, utilised at lower abstraction rates. It is, however, still necessary to monitor the abstraction and the water level response to optimise wellfield management.

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The Hydrogeology of the Uitenhage Artesian Basin with Reference to the Table Mountain Group Aquifer

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Abstract

The Uitenhage Artesian Basin lies in the Eastern Cape and is South Africa's most important artesian groundwater basin, supplying approximately 1 400 Mℓ/yr (44 ℓ/s) of water from springs for domestic use to Uitenhage, as well as supporting large citrus irrigation schemes. Groundwater from this basin has been extensively utilised from the early part of the 20th century including periods of over-exploitation resulting in the declaration of a groundwater control area to limit abstraction to sustainable rates.

The aquifer comprises fractured Table Mountain Group (TMG) sandstones confined in the eastern part of the basin by overlying Cretaceous siltstones and mudstones, resulting in artesian conditions. The Coega Fault is a major structural feature dividing the basin into separate systems, viz. the southern Swartkops Aquifer and the northern Coega Ridge Aquifer, that are hydrogeologically independent from one another. The Elands River syncline divides the Swartkops Aquifer further into the Kruisrivier and Bethelsdorp Units.

Borehole yields commonly range from 5 to 10 ℓ/s and the groundwater quality is excellent with low salinities. Water hardening, however, is required due to the acidic and therefore corrosive nature of the groundwater, typical of other TMG Aquifers in South Africa. Using ^{14}C data, the age of the groundwater in the basin ranges from 1 500 to 28 000 years with a calculated flow rate of 0.8 m/a. From the chloride mass balance method, recharge rates are determined to be 25 to 55% of annual rainfall. Groundwater temperatures generally show that depths of groundwater strikes do not necessarily correspond with depth of origin, indicating a complex groundwater circulation pattern within the basin.

Whilst the Uitenhage Artesian Basin has been locally well studied, a basin-scale hydrogeological characterisation is considered necessary followed by recommendations and formulation of a management plan to ensure the continued sustainability of groundwater supply from this national asset.

Introduction

The Uitenhage Artesian Basin (UAB) is South Africa's largest and hydrogeologically most important artesian groundwater basin, supplying surface-water and groundwater for agricultural, domestic, commercial and industrial uses. It covers an area of about 3 700 km², occurring mostly within the Port Elizabeth and Uitenhage Districts in the Eastern Cape, and is recharged by rainfall on the Groot Winterhoek and Zunga mountain ranges to the west. Groundwater from this basin currently supplies approximately 15% of the total municipal requirements of Uitenhage, one of the Eastern Cape's largest industrial areas, indicating the strategic importance of this basin. However, by the same token, the urbanised nature of the central and eastern portions of the UAB has resulted in pressure on this vulnerable water resource. Increasing demand on the resource has resulted in an increase in the potential for over-exploitation and contamination.

Hydrogeological conditions along the Coega Ridge and in the Kruisrivier region in the basin changed after 1908 from a free-flowing artesian system to a sub-artesian system. This was due to the arrival of drilling machines in the area and the resultant rapid increase in the number of boreholes drilled to augment the yield from the artesian basin for irrigation. In 1950 the Hall Commission heard evidence regarding the weakening flow conditions in the UAB. As a result of substantial pressure from farmers in the region, the basin was declared a Subterranean Government Water Control Area (SGWCA) in 1957. The Uitenhage SGWCA that encloses the central and

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eastern portion of the UAB is shown in Fig. 1 and covers an area of 1 125 km^2.

Since and as a result of the declaration of a control area, the UAB has been extensively researched with various groundwater studies having been conducted during the latter half of the 20th century. These studies were commissioned primarily to characterise the hydrogeology of the basin and to determine the effect of various influences affecting the flow conditions within the aquifer. This paper is a synthesis of the characteristics of the UAB with reference to the hydrogeology of the TMG.

Physiography

The western part of the basin is dominated by high west-northwest striking mountain ranges (viz. the Groot Winterhoek, the Elands and the Zunga Berge) comprising the main catchment area and the lower-lying Van Stadens Berg to the south. Towards the east, the mountain ranges are fringed by low-lying terraced coastal plains that dip gently seawards and surround an extensive alluvial floodplain and estuary. Isolated koppies – formed by inliers of TMG sandstone – project through the soft Cretaceous strata in the coastal area and along Coega Ridge.

The basin enjoys a moderate mean annual precipitation of 636 mm with rain during all seasons, mostly due to orographic influences. The rainfall is, however, variable over the whole basin with the highest falls in the mountainous catchment (760 mm/a) decreasing to 435 mm/a at Uitenhage. The region has a temperate climate with warm summers and mild winters and annual evaporation in the region of 1 650 mm.

The easterly flowing Swartkops River and its two main tributaries, viz. the Kwa-Zunga and Elands Rivers, are the major perennial drainage features of the basin with minor ephemeral rivers draining the southern catchment area. The predominant drainage features follow structural weaknesses in the west of the basin grading to an open-valley floodplain and estuary in the east.

Geology

The geologically dominant feature in the study area is the WNW-ESE striking and plunging depositional trough delineated by Van Eeden (1952). The present-day UAB was an open basin in the Jurassic period (120 m. years ago), ringed by mountains to the north, south and west (Mountain, 1955). Pebble and boulder alluvial deposits were washed from these mountains under a high-energy environment of deposition and accumulated mainly along the western margin of the basin to form the Enon Formation conglomerate and sandstone. Clays were then deposited unconformably on the Enon Formation - under a basin-entry depositional environment to form the mudstones and siltstones of the Kirkwood Formation. Subsequent invasion of the basin by the sea deposited marine to estuarine clays to form the Sundays River Formation.

During the Tertiary Period, numerous periods of marine transgression formed terraces in the Cretaceous sediments of the UAB and deposited a veneer of calcareous sandstones (Algoa Group) with sea-level retreat.

The west and southern portion of the basin – comprising the Groot Winterhoekberge, the Kwa-Zunga River valley and the Elands and Van Stadens Berge – is formed by quartzitic TMG sandstones. Bokkeveld Group shales underlie a large part of the Elands River catchment, in the central west of the basin. The central portion of the basin consists mainly of Uitenhage Group deposits with river alluvium in the valley and floodplain areas. Quaternary floodplain and Cretaceous terrace deposits of the Algoa and Uitenhage Groups comprise the eastern part of the basin, with mudstones and sandstones of the Kirkwood Formation forming the rolling hills southeast of Uitenhage.

Structure

Post-Cape lateral compression during the Cape Fold Belt orogeny produced zones of intense folding that produced the dominant, regional east-southeast trending folds in the Cape Supergroup rocks, forming the mountain chains in the UAB. Two large ESE-striking regional folds form the Elands River Syncline in the south and the Swartkops River Anticline in the north (Toerien and Hill, 1989). Figure 1 shows simplified geological profiles through the study area and illustrates the geometry of the aquifer units.

The Coega Fault is the major structural feature in the region and is the eastern extension of the regional scale Coega-Baviaanskloof Fault Zone (Hill, 1988). The Coega Fault is traceable from west of Groendal Dam eastward to the coast and is a normal tensional fault with an average vertical southward displacement of the Cretaceous sediments of 550 m (Marais and Saayman, 1965).

The downthrow on the fault is hydrogeologically significant since:

- It makes aquifer penetration logistically and economically unfeasible for small-scale drill rigs on the southern side of the fault, in the central regions of the study area.
- The aquiclude overlying the Swartkops Aquifer is juxtaposed against the artesian Coega Ridge Aquifer (see below for aquifer delineation detail).

Hydrogeology

The UAB is a complex, fractured rock aquifer with the basin configuration controlled by post-depositional faulting in the north and folding in the south. The UAB's natural boundaries are the Indian Ocean to the east, the TMG-Bokkeveld Group contact in the vicinity of the Coega River to the north, the Groot

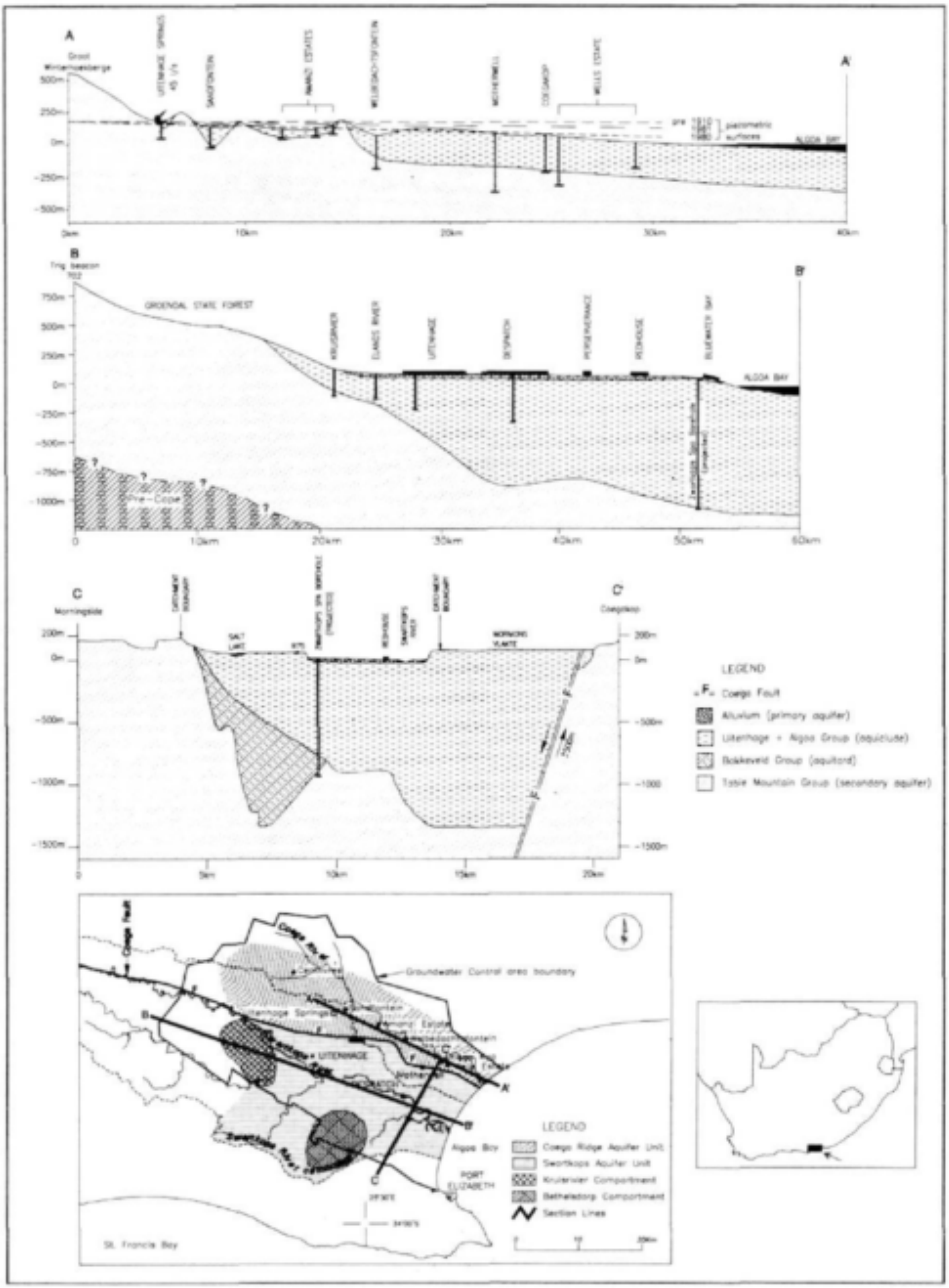

Figure 1

Aquifer delineation and hydrogeology of the Uitenhage Artesian Basin (from Maclear, 1996)

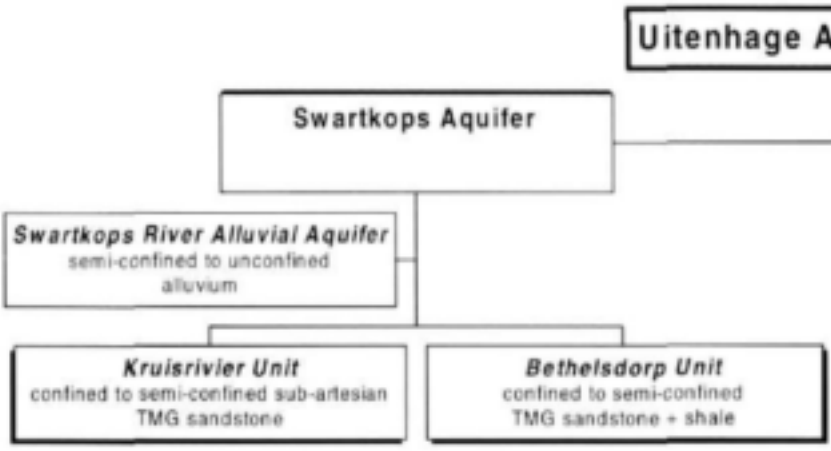

Figure 2
Subdivision of the Uitenhage Artesian Basin

Table 1
Hydrogeology of the aquifer units within the Uitenhage Artesian Basin

Aquifer	T m^2/d	S	Q ℓ/s	TDS * mg/ℓ	Water temp. °C	Abstraction Mm^3/a	Size km^2
Coega Ridge:	50 – 400	2 x 10^4	3 – 23	170 av.	23 – 33	4.7	470
Swartkops:	-	-	-	-	18 – 55	-	-
Kruisrivier unit	2 – 90	5 x 10^2	0.4 – 16	200 – 8 800	-	3.3 (1995) 1.7 (1993)	110
Bethelsdorp unit	-	-	1 – 4	500 – 30 000	-	0.8 (1961) 0.01 (1993)	150

* TDS is variable depending on the geology of the source rock, with low salinity in the TMG and moderate to high salinity in the Uitenhage Group.

Winterhoekberge to the west and the St. Albans Flats (west of Port Elizabeth) to the south. The potential sustainable yield of the UAB aquifer was estimated at 80 ℓ/s by Venables (1985), with individual borehole yields generally greater than 5 ℓ/s.

Uitenhage Artesian Basin - Aquifer delineation

The UAB is subdivided hydrogeologically by the Coega Fault into two major aquifer systems, viz. the relatively shallow Coega Ridge Aquifer (CRA) north of the Coega Fault and the deeper Swartkops Aquifer (SA) to the south of the fault (Fig. 2). The two aquifer systems function independently from one another, i.e. abstraction from a borehole in one unit only affects the yield of boreholes or springs in that unit, and not in the neighbouring unit.

The Swartkops Aquifer is further subdivided into the Kruisrivier Unit and Bethelsdorp Unit by the low permeability to impermeable Bokkeveld Group infill of the Elands River Syncline and the Swartkops River Alluvial Aquifer that occurs as a thin narrow unit over most of the Swartkops Aquifer. The characteristics of the aquifers within the Uitenhage Artesian basin are summarised in Table 1.

Aquifer types

Two aquifer types occur in the UAB, viz. the minor, shallow semi-confined to unconfined, primary Swartkops River Alluvial Aquifer; and the deeper major artesian to sub-artesian, fractured secondary aquifer, in quartzites of the TMG, and basal sandstone and conglomerate layers of the Enon Formation. Most of the artesian groundwater within the secondary aquifer is restricted to relatively narrow, well-defined zones of intense fracturing.

The alluvial aquifer is separated vertically from the fractured TMG Aquifer in the central to eastern parts by confining layers of Uitenhage Group sediments (primarily Kirkwood Formation mudstones), which form an aquiclude and result in artesian conditions in the TMG Aquifer. The Elands River Syncline striking east towards Port Elizabeth, exposes the Bokkeveld shales (aquitard) below the Cretaceous rocks. The syncline is hydrogeologically significant in the study area where the shales form an impermeable barrier, dividing the SA into the southern Bethelsdorp and the northern Kruisrivier units (Marais, 1965). The majority of abstraction in the SA occurs in the Kruisrivier Unit, where groundwater is pumped for irrigation purposes.

To the south and west, the secondary TMG Aquifer is separated horizontally by low-permeable sediments of the Bokkeveld Group (Fig. 1). The Coega Fault marks the boundary in the UAB between artesian conditions in the SA in the southern downthrown side, and the CRA in the northern upthrown side.

Groundwater quality

Groundwater in the TMG fractured aquifer is of an excellent quality with salinities generally less than 15 mS/m and is fit for drinking in its raw state. Due to its low fluoride content, however, addition of fluoride, and/or blending of groundwater with surface water is needed if it is to be used as a sole long-term drinking supply. In addition, water hardening is required due to low pH as is the case at the Uitenhage Springs.

Groundwater flow rates and recharge

All groundwater samples analysed from the confined zones of the CRA, have zero tritium (Venables, 1985), indicating that the water being pumped from the sampling boreholes is older than 55 years and that no recent recharge is occurring at the sampling sites. No intensive study on aquifer recharge has been undertaken for the basin. Utilising the chloride mass balance method, Maclear (1996), determined recharge to the TMG Aquifer feeding the Uitenhage Springs to range from 25 to 55% of annual rainfall.

In a study by Talma et al. (1982) a recognisable trend of increasing ages of groundwater with increasing distance eastward along the strike of the Coega Ridge was identified from ^{14}C data. The age of the groundwater ranges from 1 500 years at the Uitenhage Springs immediately east of the recharge area, to 28 000 years at the Coega Kop discharge area (Heaton et al., 1986). From these dates, the flow rate along the flow-path in the CRA is calculated at 0.8 m/a.

Groundwater temperature

The available groundwater temperature data from boreholes drilled into the TMG Aquifer in the UAB show little correlation between groundwater temperature and borehole depth, to be expected in a confined aquifer system. The groundwater temperature is a function of the depth of circulation of the groundwater system rather than the depth of the water-strike in a borehole.

From the temperature, the circulation depth of the groundwater in the aquifer can be determined, although the differing thicknesses of the overlying Cretaceous sediments in different portions of the basin makes interpretation difficult with respect to applying a simple geothermal gradient to the TMG. For example, the 160 m deep borehole drilled into Eye 2 at the Uitenhage Springs was drilled directly into the TMG and has a groundwater temperature of 23° C, whereas the Amanzi Estate borehole is only 55 m deep, has a Cretaceous overburden of 38 m, and a temperature of 33°C. Using a geothermal gradient of 37 m/°C (from Jones, 1992) and an ambient temperature for the recharge water of 18° C, the temperature of Eye 2 at Uitenhage Springs indicates a groundwater circulation depth of 185 m compared with 555 m for the Amanzi Estates borehole. In contrast, the circulation depth of the 54°C artesian groundwater that flowed out of the old Zwartkops Spa borehole (discussed in a following section) is estimated at 1 330 m.

Coega Ridge Aquifer

The CRA occurs in the north-central portion of the study area. This aquifer is comprised of quartz arenites of the TMG overlain by impermeable mudstones and siltstones of the Uitenhage Group, which forms an aquiclude. The aquifer stretches from immediately west of the Uitenhage Springs, eastward along Coega Ridge, to the coast. The steep (50°) northerly dipping TMG-Bokkeveld Group contact to the north forms the northern boundary to this aquifer.

The CRA is economically significant as the source of the artesian to sub-artesian groundwater at points of large-scale abstraction, viz. Uitenhage, Sandfontein, Amanzi Estates, Coega Kop and Wells Estate (Figs. 1 and 3), where groundwater is used for irrigation of citrus (for export) and lucerne, as well as for domestic use.

A strong degree of hydraulic connectivity exists between the boreholes along the Coega Ridge, discussed in detail by Maclear and Woodford (1995). The nature of this relationship is, however, unpredictable and is a function of the degree of interconnection of the water-bearing structures, as well as the differing depths of groundwater circulation.

Uitenhage Springs

The Uitenhage Springs (Fig. 1) daylight from fractured TMG sandstone at the foot of the Grootwinterhoekberge, approximately 8 km north-northeast of Uitenhage in the west of the CRA. The cumulative artesian flow rate from nine eyes is 45 ℓ/s. The springflow rate has varied over time (Fig. 3), especially in the period from the early 1900s to the 1960s due mostly to over-abstraction (Maclear and Woodford, 1995). The effect of this reduction in flow at the Uitenhage Springs (from 82 ℓ/s at the turn of the century, to 35 ℓ/s in the late 1950s) resulted in the call for the declaration of a control area, since the Springs provided Uitenhage's main water supply at the time.

It is of interest to note that the major increase in boreholes drilled in the CRA during the period men-

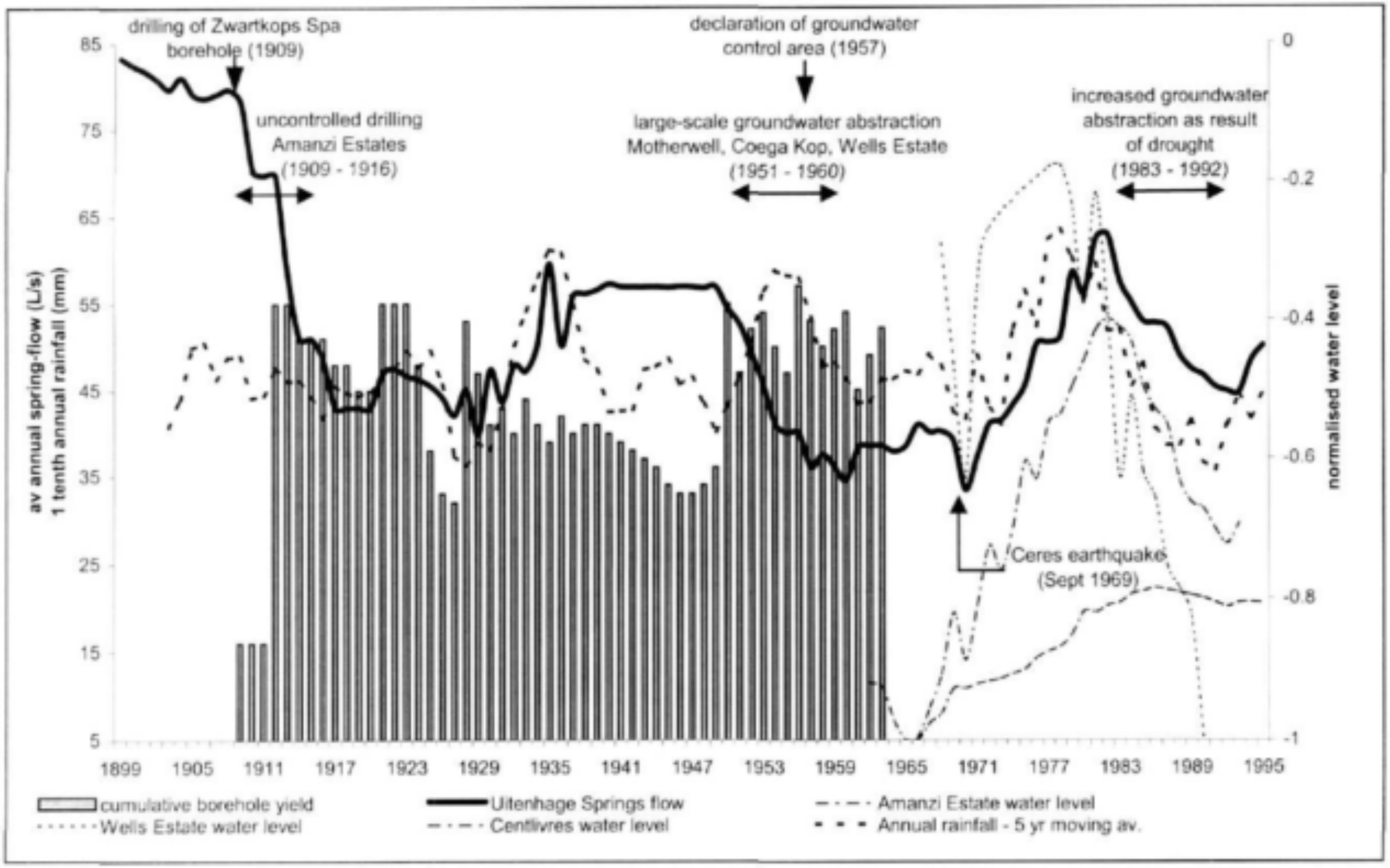

Figure 3

Flow variations at Uitenhage Springs (1899 to 1995) from Maclear (1996) tioned above did not increase the total yield of the unit, which remained relatively constant at 80 ℓ/s, but rather increased the depth to the piezometric level (Fig. 1), thus changing pressure conditions from artesian to sub-artesian. If anything, the yield from the unit decreased slightly towards the end of the 1960s, as a result of increased leakage (through rusted borehole casings) of groundwater - under artesian pressure - into the confining overlying Cretaceous sediments.

Swartkops Aquifer

The Swartkops Aquifer (SA), shown in Fig. 1, comprises the area south of the Coega Fault and stretches from Groendal Dam in the west to below Port Elizabeth in the east. It has similar hydrogeological conditions to the Coega Ridge Aquifer, with the only major difference being the much greater depth to the TMG Aquifer in an easterly direction – a function of a thicker overburden of Cretaceous sediments. The SA is not hydraulically linked to the CRA and is semi-confined to unconfined on its southern boundary, with a piezometric level (and thus hydrostatic pressure) 100 to 120 m lower than that of the CRA.

The two hydrogeological units of the Swartkops Aquifer are discussed in more detail below.

Kruisrivier Unit

Drilling is generally successful to the west of the Kruisrivier Unit due to the relatively thin deposits of overlying Cretaceous sediments to be penetrated, before the TMG quartzites or basal sandstone layers of the Enon Formation are intersected.

As a result of observations by Marais (1965) that artesian pressure increases with increasing depth in the sandstone, this researcher deduced that there is no direct surface recharge to the artesian sandstone aquifer. Groundwater from the TMG Aquifer (recharged by rainfall on the upper basin catchment) instead recharges the basal sandstone unit of the aquifers in the Kirkwood and Enon Formations by lateral and vertical pressure leakage to these formations from the bounding quartzitic sandstone unit.

This observation was supported by findings by Bush (1985), where groundwater quality analyses, carried out during pumping tests on exploration boreholes in the Kruisrivier Unit, showed that there was a decrease in salinity and an increase in acidity of the groundwater with increasing duration of the test. This is considered to be a function of progressively increasing groundwater contributions from the TMG quartzites and decrease in groundwater derived from the overlying mudstone.

High TDS concentrations in the Kruisrivier groundwater are a result of mixing of water derived from localised TMG sandstone outcrops and overlapping Cretaceous formations. Comparison of borehole hydrochemistry in this portion of the basin shows that boreholes abstracting groundwater from an aquifer of mixed provenance have a higher salinity than those from a quartzitic provenance.

The areas of Kruisrivier with low salinity groundwater, and consequently the areas of large-scale abstraction, correspond to areas obtaining their recharge directly from the Groot Winterhoekberge and Elands River Forest Reserve, rather than from seepage from the overlying clayey mudstones of the Uitenhage Group.

Bethelsdorp Unit

The Bethelsdorp Unit (Fig. 1) is located in the Swartkops Aquifer on the southern margin of the UAB and is bounded by the Cape Supergroup outcrop to the south, the Elands River Forest Reserve and Groot Winterhoekberge to the west, the shale-filled syncline to the north and Algoa Bay to the east. The major aquifer in the Bethelsdorp Unit is situated beneath the low-lying foot of the Bethelsdorp escarpment in fractured TMG quartzites, which are overlain by low-permeability, confining layers of the Bokkeveld Group sediments. Where the TMG Aquifer has not been penetrated by drilling, the Kirkwood Formation sandstone and the Enon Formation conglomerate are considered as the aquifer, with the Kirkwood Formation mudstone acting as the aquiclude.

The Bethelsdorp Unit is under-utilised compared with the Kruisrivier Unit. It is artesian to sub-artesian in places and has not been a focus of intensive study in the past. Boreholes of variable, moderate yields can be drilled with some degree of success. The boreholes drilled into this unit are relatively shallow (25 to 200 m) with the highest yields being obtained from boreholes which first penetrate the confining Bokkeveld Group before intersecting TMG quartzites, thereby resulting in artesian conditions, with a general increase in yield with an increase in depth of TMG penetrated (Marais, 1965).

Zwartkops Spa borehole

A discussion of the Zwartkops Spa borehole – located in the Swartkops River Valley on the northern outskirts of Port Elizabeth – is relevant, since this famous borehole (location shown on Fig. 1) provides the only geohydrological information available for the deep discharge portion of the Swartkops Aquifer to the east of the basin.

The borehole was originally commissioned for oil exploration and drilling commenced in 1906 with the arrival of a drill crew from the oil fields of Poland. Drilling ceased in 1909 at a final depth of 1 082 m below surface (1 075 m b.s.l.) when hyperthermal (54.5°C) artesian groundwater, flowing at a rate of 13 ℓ/s was struck and the upward artesian pressure balanced the total weight of the drill-string, thereby making deepening of the borehole impossible.

The artesian flow of the Zwartkops Spa borehole is associated with a regional fault of similar character to that of the Coega Fault. Whilst the sandstone encountered at final depth was of uncertain geological origin, the hydrochemical nature of the groundwater indicates it to be a mixed sample of at least two major rock types: high Fe typical of TMG, but relatively high TDS (560 mg/ℓ) indicative of the Bokkeveld Group.

The thermal properties of the TMG Aquifer host-rock in this part of the basin are a result of an increase in groundwater temperature with depth. This temperature increase is a function of the geothermal gradient of the host-rock, as well as residual heat from the structural deformation (specifically Mesozoic folding) which the Cape Supergroup underwent. Maclear (1996) calculated a depth of groundwater circulation for the Zwartkops Spa borehole at 1 330 m. Accordingly, the groundwater that fed the Spa borehole for 50 years originated from at least 250 m deeper than the depth of the thermal water-strike. This illustrates the structural complexity of the basin and the effect this has on the groundwater circulating conditions within the fractured TMG sandstone comprising this aquifer.

Due to the reported medicinal properties of the artesian groundwater, a hotel and health spa was built around the borehole, viz. the Zwartkops Spa. The claimed medicinal properties of the spa water were a function of the high Fe content and hypotonic nature of the groundwater, which was used consumptively, mainly in the treatment of anaemia. The Zwartkops Spa subsequently became one of the leading resorts of its type in the country. In 1965, however, the borehole became defunct as the steel casing rusted through due to the corrosive nature of the groundwater and groundwater subsequently leaked under artesian pressure at a rate of approximately 410 000 m^3/a (13 ℓ/s) into the Cretaceous sediments and overlying surficial alluvial deposits. In 1969 the borehole was eventually grout-sealed by the Drilling Division of the Department of Water Affairs and Forestry to prevent loss of groundwater from the Swartkops Aquifer and the Zwartkops Spa closed down.

Discussions and recommendations

The Uitenhage Artesian basin is the only extensive aquifer with free-flowing artesian conditions of its type in South Africa. Whilst it has been locally well studied, a need exists for basin-scale hydrogeological characterisation. The UAB is considered an ideal 'working model' of a fractured TMG Aquifer, since it contains all the variables found in similar Cape Fold-belt aquifers within a relatively small and well-defined area, such as artesian and sub-artesian conditions, cold to hyperthermal water and macro- to micro-scale fracturing. Such a study would produce a better understanding of TMG Aquifers in South Africa to the benefit of groundwater users and advance the science of hydrogeology.

Since groundwater from this basin is an important supply of water for domestic and large-scale irrigation purposes, it is vital that a groundwater-resource awareness campaign is initiated and encouraged to ensure water conservation in the future. Since all groundwater resources only have a finite supply potential, demand-based abstraction from the basin should be planned and carried out on the advice of hydrogeological specialists, for the ultimate benefit of the groundwater users and the community dependent on this resource.

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Springs in the Table Mountain Group, With Special Reference to Fault Controlled Springs

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Abstract

One of the characteristics of the Table Mountain Group (TMG) is the numerous springs issuing from it. According to the mode of occurrence, three types of springs can be identified, namely shallow circulating springs, lithology controlled springs and fault controlled springs. The basic characteristics of the first two spring types are discussed briefly, while the characteristics of the fault controlled springs are dealt with in more detail. The multitude of springs emanating from the Table Mountain Group can be considered the region's most valuable natural asset and should be protected from indiscreet groundwater development.

Introduction

The TMG is a largely arenaceous rock group, extending from Cape Town northwards to beyond Clanwilliam and eastwards as far as Port Elizabeth. It is of Ordovician to Silurian age, and overlies the metamorphic rocks of the Namibian erathem, viz. the Malmesbury Group in the west, the Kaaimans and Kango Groups in the central region around George and Oudtshoorn and the Gamtoos Group, which outcrops mainly west of Port Elizabeth. The TMG is conformably overlain by the predominantly argillaceous rocks of the Bokkeveld Group. A product of the intensive folding which the rocks had undergone is the number of scenic fold mountain ranges which host numerous geological features such as folds, faults, fractures, fissures and intricate joint systems. Many of these features give rise to one of the distinct characteristics of the TMG, namely the abundance of springs issuing from it.

Springs according to mode of occurrence

Based on their mode of occurrence, the following spring types have been differentiated:

Shallow circulating springs

The shallow circulating springs seep from a network of joints, small, irregular fractures and from bedding planes within the TMG. These springs are draining generally small subterranean reservoirs, notably during and following rainy spells. They are generally low-yielding, many being seepages only. Their yields are highly seasonal, and most of them cease to exist with the onset of dry weather conditions. In view of their generally intermittent behaviour, it is debatable whether many of these springs can in fact be considered proper springs.

Lithology controlled springs

Lithology controlled springs (Fig. 1) issue due to the presence of impeding or impervious layers. Three types of lithology controlled springs can be identified, namely:

Springs issuing from contacts with interbeds

The Cedarberg Formation is the most important and well-known interbedded shale layer in the TMG and due to it's relative imperviousness it probably accounts for the bulk of the perennial springs in the TMG terrain. This shale unit is furthermore hydrogeologically important as it almost invariably divides the TMG into two separate groundwater systems. Saturation of the Peninsula Formation commonly results in the rise of springs on the Peninsula Formation/Cedarberg Formation contact at suitable topographical levels, from where it overflows onto the Nardouw Subgroup.

The following are a few well-known Cedarberg Formation related springs, to name but a few: the Hoeksberg Spring (south of McGregor), Vermaaks (currently dry) and Marnewicks Springs (in the Kammanassie Mountains), the Meiringspoort Spring (upstream from the waterfall), the Swartberg Spring (feeding the Dorps River at Prince Albert) and the Humansdorp Spring. Other unnamed interbedded

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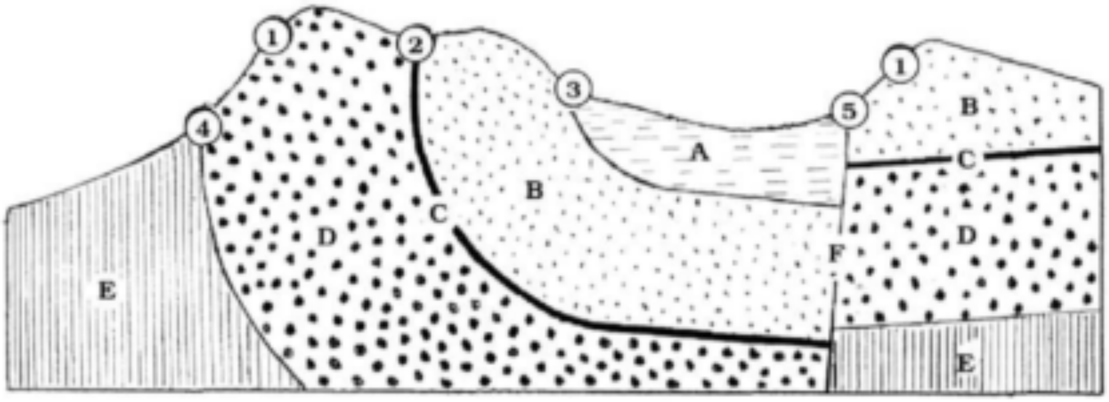

Figure 1

Schematic profile to illustrate spring occurrence in the Table Mountain Group (TMG)

A = Bokkeveld Group
B = Nardouw Subgroup (TMG)
C = Cederberg Formation (TMG)
D = Peninsula Formation (TMG)
E = Pre-Cape Namibian age rocks
F = Fault

1 = Shallow circulating spring
2 = Spring issuing from contact with interbed
3 = Spring on the TMG/Bokkeveld Group contact
4 = Spring issuing from an unconformity
5 = Fault controlled spring

shale layers may also account for spring occurrences, especially towards the east of Uniondale. The Kareedouw Spring, providing the town with water, is an example of a spring most probably issuing from an unnamed interbedded shale layer within the Peninsula Formation.

Springs on the TMG/Bokkeveld Group contact

One would expect the TMG/Bokkeveld Group contact to be a likely locality for the emanation of lithology controlled springs. However, except for a few scattered springs emanating on that contact along the northern foothills of the Kammanassie Mountains (Water Research Commission, 2000) and possibly the springs at Dysselsdorp (dry since the late 1970s probably due to groundwater development in that area), no other springs issuing on the TMG/Bokkeveld contact have so far been reported.

Generally speaking, springs emerging on the TMG/Bokkeveld Group contact can be linked to faults in the TMG and can thus be termed fault controlled springs.

Springs issuing from unconformities

The discordant contact between the often fractured quartzitic-sandstone of the Peninsula Formation of the TMG and the underlying impervious argillaceous units of the Malmesbury, Kaaimans, Kango and Gamtoos Groups (Fig. 1), is an important locality for some of the lithology controlled springs. The series of springs emanating on the western side of the Kasteelberg west of Riebeek West, and the numerous springs issuing on the southern foothills of the Outeniqua Mountains north of George exist, due to the presence of impervious argillaceous rocks of the Malmesbury and Kaaimans Groups respectively. These springs are being fed by groundwater from the overlying fractured TMG rocks. Even the springs in the limestone units of the Kango Group north of Oudtshoorn reveal distinct TMG groundwater fingerprints (Barnard, 1993) from the nearby TMG of the Swartberg.

One of the distinguishing characteristics of the lithology controlled springs is their relatively wide-ranging yield fluctuations. The yield of the Marnewicks Spring (Cedarberg Formation related) for instance generally varies between 9 and 19 ℓ/s and that of the Rooi River Spring north of George (Kaaimans Group related) fluctuates between 0.4 and 4 ℓ/s. The groundwater quality of the lithology controlled springs is almost without exception excellent. ECs generally range between 10 and 35 mS/m, and no record of any chemical determinants exceeding recommended limits for human consumption have been received. The groundwater from these springs has a pronounced sodium-chloride nature.

Fault controlled springs

The eleven more important and well-known fault controlled springs occur from Citrusdal in the west to Uitenhage in the east. The alignment of these springs follows a remarkable incurvature (Fig. 2), which appears to mimic the shape of the Cape Fold Belt. The alignment of these springs may be meaningful in terms of the deeper Cape Fold Belt structure.

It is interesting to note that five (or 46%) of the major fault controlled springs are situated in the relatively limited syntaxis domain (Fig. 2), which is indicative of a greater frequency of deep fracturing in that domain compared to the rest of the occurrence area. It is also notable the area east of 23°E is

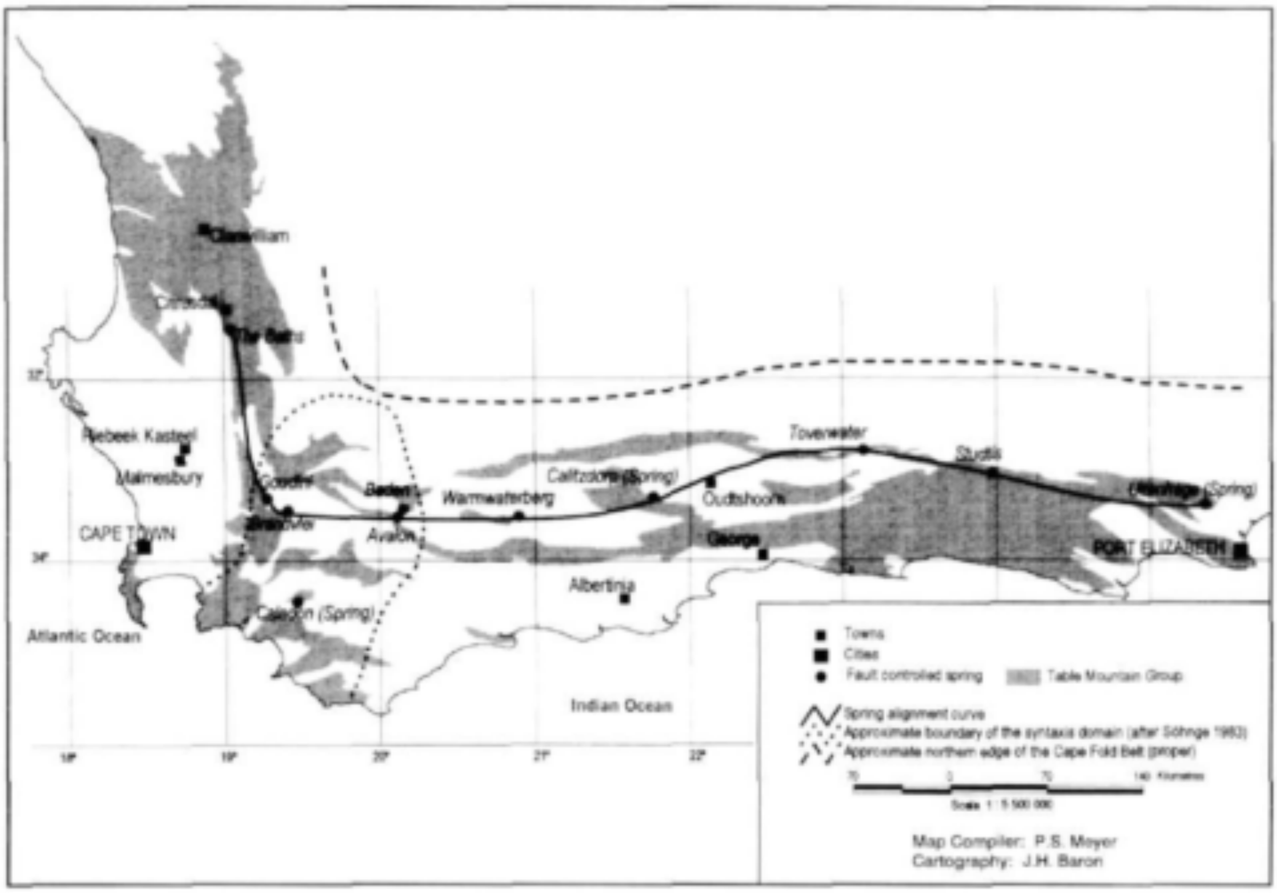

Figure 2

The positions of the most important and well-known fault controlled springs in the Table Mountain Group relative to the broader Cape Fold Belt realm

devoid of thermal and hyperthermal springs, indicating a region of less deep groundwater circulation. It would be interesting to determine whether this phenomenon could be linked to the prevalence of thrust faulting in the area east of 23°E (Booth and Shone, 1999; and Murray, 1996).

The major fault controlled springs have the following characteristics (Table 1):

- They all rise from conduits in competent, fractured and fissured quartzitic–sandstone of the TMG which are in all instances faulted against, or are in contact with incompetent Cedarberg Formation and Bokkeveld and Uitenhage Groups aquicludes.
- They are all at least hypothermal springs, with water temperatures in excess of 20°C. They are thus all relatively deep circulating springs.
- They are all strong yielding (yields range between 9 and 127 ℓ/s) and seasonal fluctuations are limited.
- The groundwater quality of all of them is excellent, and ECs do not exceed 35 mS/m.
- The dominant chemical determinants of the groundwater are sodium and chloride.
- Hydroxides of iron and/or manganese, ranging between 0.1 and 2.0 mg/ℓ, have been recorded in most of them.

Brief discussion and outlook

The Table Mountain sandstone terrain is generally mountainous, rough and often inaccessible. As a result, many springs in the TMG, particularly those issuing from interbed contacts, are largely situated where the influence of human activities is unlikely to be felt. Some springs, however, especially those bordering on or located within reach of areas with development potential, would be vulnerable in terms of groundwater abstraction and groundwater pollution. The reduction and even ceasing of spring-flow at a few localities subjected to groundwater development and subsequent large-scale abstraction, is proof of this danger.

The multitude of springs emanating from the TMG support numerous established communities and play an important role in the agricultural sector. These springs can thus rightly be regarded as one of the region's most valuable assets and warrant careful protection. To protect the springs from injudicious exploitation, any extensive groundwater de-

Table 1
Salient information on the major fault controlled springs

Name of spring	***Co-ordinate***		***Temp.*** **(°C)**	***Yield*** **(ℓ/s)**	***Cond.*** **(mS/m)**	**Probable depth of circulation (m)***	**Classification of thermal water #**	**Remarks**
	South	**East**						
The Baths (Citrusdal area)	32° 44' 22"	19° 02' 06"	43	29	8	2000	Hyperthermal	Geological setting: situated on an E-striking fault in Peninsula Formation (TMG) sandstone, on the western limb of a deep syncline on the contact with the Cedarberg Shale Formation. Dominant chemical determinants: sodium and chloride. Utilisation: recreation.
Goudini	33° 24' 00"	19° 15' 53"	40	11	7	1700	Thermal	Geological setting: situated on a NNW-striking fault in Peninsula Formation (TMG) sandstone near the contact with Bokkeveld Group shale. Dominant chemical determinants: sodium, sulphate and chloride. Utilisation: recreation.
Brandvlei	33° 43' 46"	19° 24' 58"	64	127	8	3600	Hyperthermal	Geological setting: situated on a NE-striking fault in Nardouw Subgroup (TMG) sandstone on or close to the contact with Bokkeveld Group shale. Dominant chemical determinants: sodium and chloride. Utilisation: under-utilised, partly used for domestic supply.
Caledon	34° 13' 20"	19° 26' 18"	37	9	20	1600	Thermal	Geological setting: situated on an E-striking fault. Peninsula Formation (TMG) sandstone faulted against Bokkeveld Group shale. Dominant chemical determinants: sodium and chloride. Utilisation: recreation.
Avalon (Montagu)	33° 45' 57"	20° 07' 02"	43	38	11	2000	Hyperthermal	Geological setting: situated on an E-striking fault. Nardouw Subgroup (TMG) sandstone faulted against Bokkeveld Group shale . Dominant chemical determinants: sodium and chloride. Utilisation: recreation.
Baden	33° 42' 20"	20° 07' 33"	38	37	10	1500	Thermal	Geological setting: situated on an ill-defined E-striking fault in Nardouw Subgroup (TMG) sandstone on the contact with Bokkeveld Group shale. Dominant chemical determinants: sodium and chloride. Utilisation: recreation.
Warmwater-berg	33° 45' 57"	20° 54' 08"	45	9	26	2100	Hyperthermal	Geological setting: situated on a NE-striking fault. Nardouw Subgroup (TMG) sandstone faulted against Bokkeveld Group shale. Dominant chemical determinants: sodium and chloride. Utilisation: recreation.

Table 1 (continued)								
Name of spring	**Co-ordinate**		**Temp. (°C)**	**Yield (ℓ/s)**	**Cond. (mS/m)**	**Probable depth of circulation (m)***	**Classification of thermal water #**	**Remarks**
	South	**East**						
Calitzdorp	33° 39' 38"	21° 46' 24"	50	8	31	2500	Hyperthermal	Geological setting: situated on a NE-striking fault. Nardouw Subgroup (TMG) sandstone faulted against Bokkeveld Group shale. Likely dominant chemical determinants: sodium and chloride. Utilisation: recreation.
Toverwater	33° 24' 00"	23° 09' 10"	44	11	15	2000	Hypothermal	Geological setting: situated on the E-striking Cango fault. Peninsula Formation (TMG) sandstone faulted against Enon Formation (Uitenhage Group) conglomerate. Dominant chemical determinants: sodium and chloride. Utilisation: irrigation.
Studtis	33° 32' 48"	23° 57' 50"	24	31	18	480	Hypothermal	Geological setting: situated on a NE-striking fault. Nardouw Subgroup (TMG) sandstone faulted against Bokkeveld Group shale. Likely dominant chemical determinants: sodium and chloride. Utilisation: irrigation.
Uitenhage	33° 42' 05"	25° 26' 18"	23	45	34	400	Hypothermal	Geological setting: situated on an ESE-striking fault (Maclear 1996) in Peninsula Formation (TMG) sandstone, on or close to the contact with Kirkwood Formation (Uitenhage Group). Yield fluctuates in accordance with abstraction from aquifer (Maclear 1996). Dominant chemical determinants: sodium and chloride. Utilisation: municipal use.

* Average geothermal gradient of 1°C/80 m was derived from relatively deep geophysical borehole logging data of six scattered boreholes in the TMG, assuming the downward rate of increase continued uniformly. Ambient water temp. 18°C.

\# Italian classification (Kent 1969):
Water temp. below 20°C = cold
Water temp. between 20°C and 30°C = hypothermal
Water temp. between 30°C and 40°C = thermal
Water temp. above 40°C = hyperthermal

Note: For information on isotopes, see in this issue: "*Thermal Springs of the Table Mountain Group*" by C. Harris and R.E. Diamond.

velopment in the TMG should be preceded by a study to assess the impact of this development on the springs, taking into account, amongst others, the mode of occurrence of springs in the proposed development area.

To fully understand the hydrogeological complexities of the TMG, a knowledge of the distribution and mode of occurrence of springs in the TMG is necessary. Relatively little is, however, known about springs in the TMG and a comprehensive study, including aspects such as spring distribution, mode of occurrence, yield sustainability and vulnerability to exploitation is highly recommended.

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The Thermal Springs of the Table Mountain Group: A Stable Isotope Study

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Abstract

Thermal springs ranging in temperature up to 64°C issue from rocks of the Table Mountain Group (TMG) which indicate deep (in some cases > 2 km) circulation of groundwater. The δD and $\delta^{18}O$ values of the springs range from -46 to -18‰ and -7.3 to -3.9‰ respectively. Although the thermal springs have isotope compositions that plot close to the local meteoric water line, their δD and $\delta^{18}O$ values are significantly lower than ambient meteoric water, or groundwater. It is therefore suggested that recharge of most springs is at significantly higher altitude than the spring. The isotope ratios decrease with increasing distance from the west coast, which is in part related to the continental effect. However, a negative correlation between spring water temperature and $\delta^{18}O$ value in the springs closest to the west coast indicates a progressive increase in the average altitude of recharge away from the coast.

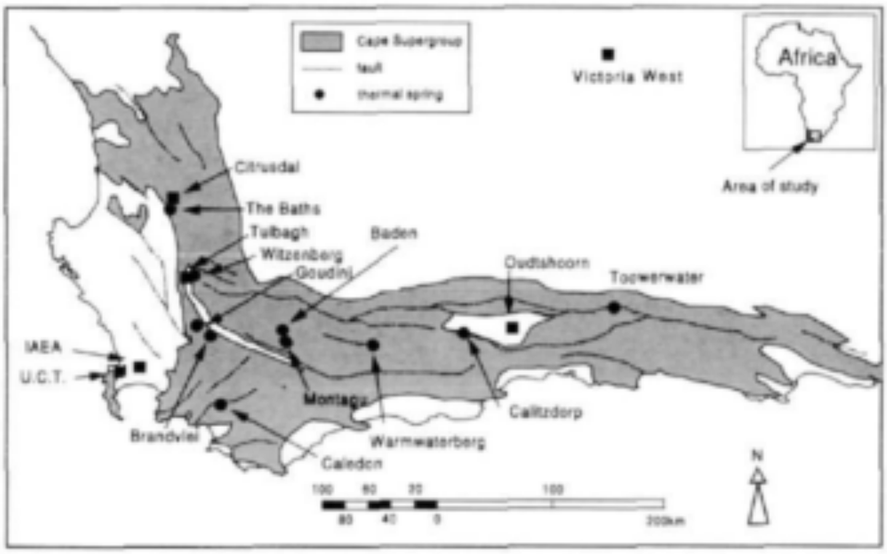

Figure 1

Sketch map of the Western cape showing the location of thermal springs sampled. The location of rainfall monitoring stations at the University of Cape Town (UCT), Cape Town International Airport (IAEA), Citrusdal, Tulbagh and Oudtshoorn are also shown. The thermal spring at Citrusdal is known as "The Baths" but to avoid confusion it is referred to as Citrusdal in the text. The area of outcrop of the Cape Supergroup forming the Cape Fold Belt mountains is indicated (taken from Theron et al., 1991).

Introduction

There are over eighty seven thermal springs in South Africa ranging in temperature from 25-64°C. They are not associated with recent volcanic activity, which is unknown in this part of Africa. The geology and chemical composition of the springs have been described by Kent (1949), Hoffmann (1979) and Meyer (2001). Most Western Cape thermal springs issue from rocks of the TMG where faulted and highly jointed quartzites and sandstones of the Cape Fold Belt act as the main deep aquifer. In this case study, we review hydrogen, oxygen, tritium and ^{14}C isotope data, and some trace element data for TMG thermal springs from existing publications by Mazor and Verhagen (1983), Diamond (1997) and Diamond and Harris (2000). The aim is to show how isotope data have been used to constrain the nature of the recharge and mechanism(s) of heating of the thermal springs.

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Table 1
General information about thermal springs sampled

Spring	Temp (°C)	Flow (ℓ/s)	Alt. (m)	Dist. (km)	Geological environment
Baden	37	38	280	150	TMG-Bokkeveld Group contact, near regional fault
Brandvlei	64	126	220	90	TMG-Bokkeveld Group contact, regional fault
Caledon	50	9	360	100	TMG-Bokkeveld Group contact, near regional fault
Calitzdorp	52	27	200	310	TMG-Bokkeveld Group contact, near regional fault
Citrusdal	43	29	250	80	Fault in Nardouw Subgroup of TMG
Goudini	40	11	290	80	Regional fault in TMG
Montagu	43	38	280	155	TMG-Bokkeveld Group contact, near regional fault
Towerwater	44	11	800	455	Regional fault in TMG
Warmwaterberg	45	9	500	225	Near top of Nardouw Subgroup, near regional fault
Witzenberg	~28	~1	800	105	Peninsula Formation

Distance = distance from the West Coast measured in a straight line with an E-W orientation.
Modified from Diamond (1997).

All groundwater that sinks to any appreciable depth will become heated because of the geothermal gradient. Mazor (1991) suggested a purely arbitrary temperature divide between cold springs and thermal springs of 6°C above average annual surface temperature. The Western Cape valleys and coastal plains experience annual average temperatures between 15°C and 20°C, so any water discharging at or above about 26°C can be classified as a thermal spring. In the Western Cape, there is a full gradation from cold (<20°C) to the hottest spring in the country, Brandvlei, 64°C. Data from all of the well known thermal springs in the area were sampled during this work (Table 1). The majority are above 40°C, with one spring, Witzenberg (28°C) just falling within the classification of thermal. Most of the springs are found at relatively low altitude (<300 m), with two springs found at 700 m or above (Towerwater and Witzenberg). The spring with the highest yield (Brandvlei) is also the hottest, whereas most of the springs with low discharge are relatively cool. This may in part be due to more effective cooling by heat loss to the surrounding rock in the case of the springs with low yield. Diamond (1997) and Diamond and Harris (2000) suggested on the basis of the likely geothermal gradient that the thermal water at Brandvlei must come from an average depth of 2.35 km. This estimate is in agreement with geological cross sections (Diamond and Harris, 2000).

Results

Chemistry

Chemical data for three TMG springs (Goudini, Brandvlei and Calitzdorp) were presented by Mazor and Verhagen (1983). Compared to hot springs located in other source rocks in South Africa, these springs have low total dissolved ions (< 200 mg/ℓ) with no group of ions dominating.

Carbon isotope data and tritium

Mazor and Verhagen (1983) obtained a range of $\delta^{13}C$ values from -18.9 to -24.5‰ for dissolved bicarbonate in some Western Cape springs (Montagu, Caledon, Brandvlei, Goudini and Citrusdal). Diamond (1997) measured the $\delta^{13}C$ values of CO_2 gas discharged with the spring water at Brandvlei and Calitzdorp and obtained $\delta^{13}C$ values of -22.7 and -21.5‰ respectively. Mazor and Verhagen (1983) determined the ^{14}C content of five of the springs (Table 2) which vary from 47 to 78 pmC (per cent modern carbon). These authors also measured the tritium content of five of the springs and found that only Citrusdal and Goudini have tritium slightly above 1 TU (tritium unit; 1 TU = $^{3}H/^{1}H$ of 10^{-18}). Because of the possibility of contamination at the time of sampling (Mazor and Verhagen, 1983), values below 1 TU can be regarded as tritium-free.

Hydrogen and oxygen isotopes

Water δD and $\delta^{18}O$ values are presented in Table 1 and are plotted against altitude and temperature in Fig. 2. The $\delta^{18}O$ vs. temperature plot shows two distinct groups of samples with negative correlation. The springs plotting in the upper group are Goudini, Caledon, Citrusdal and Brandvlei all of which are found in the belt of mountains closest to the coast (the "coastal group"). The springs which plot on the lower group are found in the mountain belts further inland (Fig. 1). This negative correlation is less strong for δD vs. temperature. There is no correlation between isotope ratios and height above sea level. For those springs less than 200 km from the west coast (Fig. 3), there is a good correlation between isotope ratios and distance from the west coast.

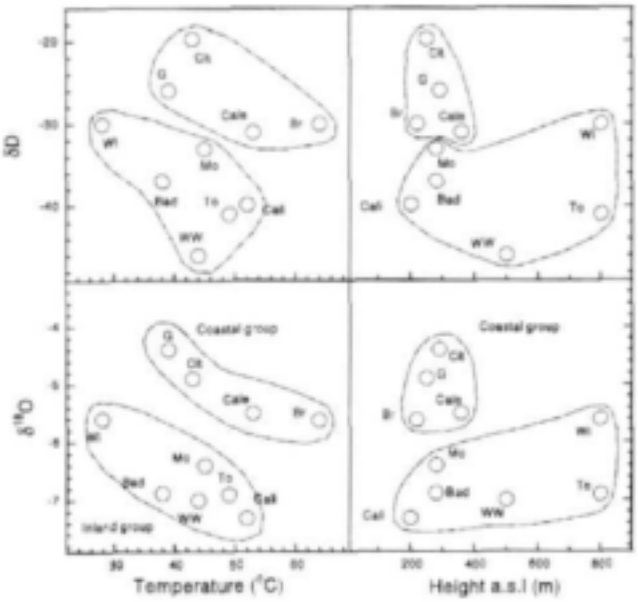

Figure 2

Plot of δD and δ¹⁸O values of thermal springs vs. temperature and height of spring above sea level. Cit = Citrusdal, G = Goudini, Cale = Caledon, Br = Brandvlei, Wi = Witzenberg, Bad = Baden, WW = Warmwaterberg, To = Toowerwater, Cali = Calitzdorp.

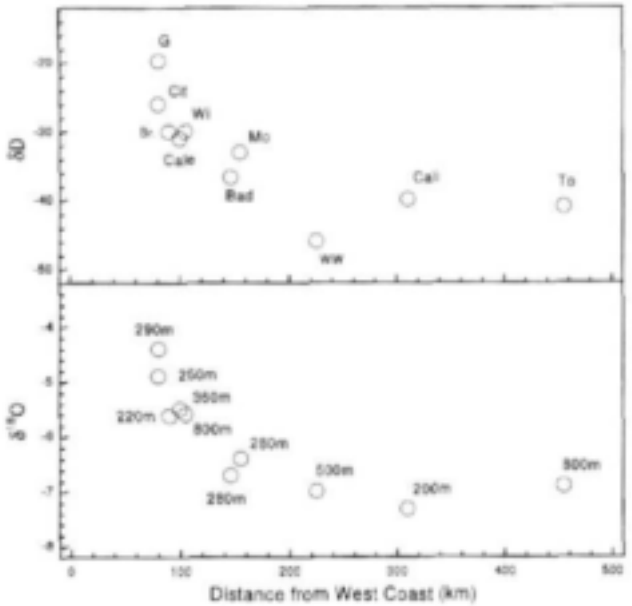

Figure 3

Plot of δD and δ¹⁸O of thermal spring water vs. distance from the west coast of southern Africa measured in an E-W direction. Abbreviations for springs in upper diagram as for Fig. 2. In lower diagram, height above sealevel for each spring is indicated.

Table 2
Isotope data for thermal springs

Spring	TDI (mg/ℓ)	δD	$\delta^{18}O$	$\delta^{13}C$ gas	$\delta^{13}C$ HCO_3^-	TU	^{14}C (pmC)
Baden		-37	-6.9				
Brandvlei	100	-30	-5.6	-22.7	-18.9	0.5±0.3	70.7
Caledon		-31	-5.5		-21.6	0.8±0.3	47.2
Calitzdorp	170	-40	-7.3	-21.5		0.3±0.3	
Citrusdal		-20	-4.9		-20.0	1.1±0.3	70.7
Goudini	91	-26	-4.4		-24.5	1.1±0.3	78.2
Montagu		-33	-6.4		-21.3		49.1
Toowerwater		-41	-6.9				
Warmwaterberg		-46	-7.0				
Witzenberg		-30	-5.6				

Notes: TDI = total dissolved ions, TU = tritium units, pmC = percent modern carbon. TDI, bicarbonate $\delta^{13}C$, tritium and ^{14}C data from Mazor and Verhagen (1983) on samples collected in 1971-2. Oxygen, hydrogen and gas $\delta^{13}C$ data from Diamond and Harris (2000). H, O and C isotope data are reported in the familiar δ notation, relative to SMOW, where $\delta = (R_{sample}/R_{SMOW} - 1)*1000$, and R = $^{18}O/^{16}O$, D/H or $^{13}C/^{12}C$.

Discussion

Carbon isotopes and tritium

The gas and the dissolved bicarbonate $\delta^{13}C$ values (-18.9 to -24.5‰) clearly label the carbon as being of organic rather than volcanic origin. The $\delta^{13}C$ values of the gas samples of -21.5 and -22.7‰ are much lower than the typical $\delta^{13}C$ values for volcanic and geothermal CO_2 of 0 to -11‰ (Taylor, 1986). The most likely source for the carbon is soil and vegetation at the area of recharge (Diamond, 1997; Diamond and Harris, 2000).

The low tritium content indicates that the water in all the springs (except perhaps Citrusdal and Goudini) contains little or no recent (post 1952) water. The ^{14}C data are harder to interpret because the initial ^{14}C content at recharge is not known. Mazor

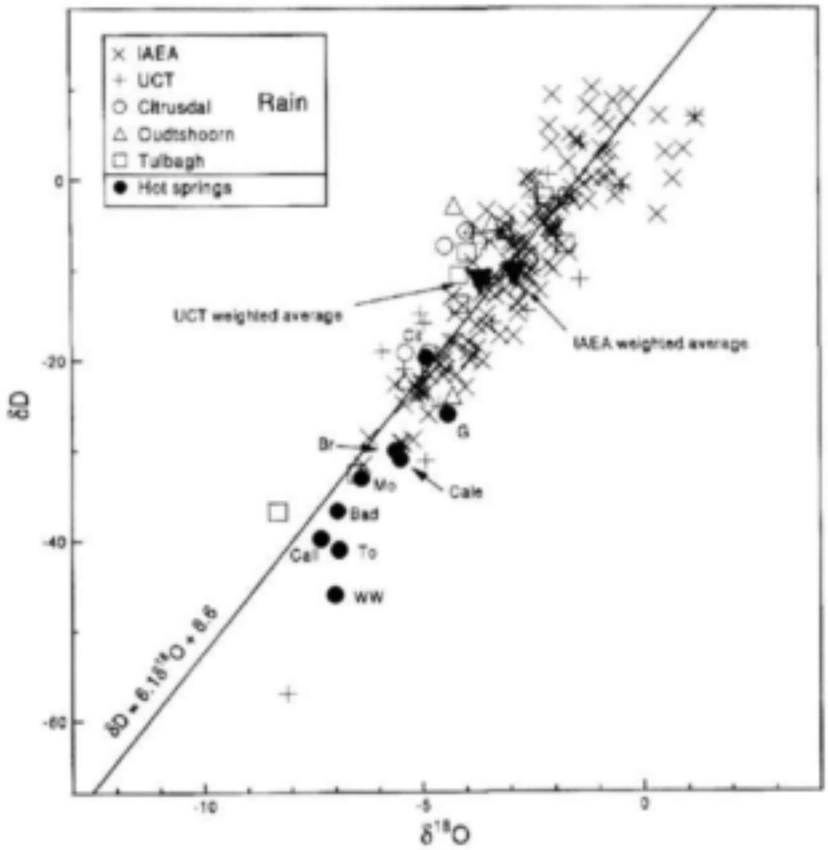

Figure 4

Plot of δD vs. $\delta^{18}O$ for thermal springs and rain water from various places. All rain data are integrated monthly samples; the UCT data are for a two-year period (Diamond and Harris, 1997) and the IAEA data for most (but not all) months between 1962 and 1974 (IAEA, 1997); the Citrusdal, Oudtshoorn and Tulbagh data are for March-October 1995. The weighted annual mean values for the UCT and IAEA collection stations are shown and the line of best fit through the rain data is from Diamond and Harris (1997).

and Verhagen (1983) suggest, on the basis of low $\delta^{13}C$ values, that the initial ^{14}C contents were high and that no exchange with ^{14}C carbonate material took place. Brandvlei, Citrusdal and Goudini have 71-78 pmC which Mazor and Verhagen interpret to represent short turnover times. Montagu and Caledon have lower ^{14}C content (49 and 47 pmC respectively) which led Mazor and Verhagen to suggest turnover times of several thousand years.

Comparison with meteoric water

One of the main conclusions of both Mazor and Verhagen (1983) and Diamond (1997) was that the thermal springs have systematically lower δD and $\delta^{18}O$ values than expected for ambient meteoric water. The ideal comparison would be with rainwater collected at the spring site over a period of several years, but such data are not available. The International Atomic Energy Agency database (IAEA, 1997) has a monthly rainfall isotope record for Cape Town International Airport from 1962-1974, and a five year record (1995-2000) exists for the University of Cape Town (Harris, unpublished data). The rainfall data are compared to the thermal spring data on Fig. 4 and it can be seen that the springs have systematically lower δD and $\delta^{18}O$ values compared to the rain, and the weighted mean annual δD and $\delta^{18}O$ values for UCT and the IAEA data. Also plotted on Fig. 4 are rain data from inland stations at Oudtshoorn, Citrusdal and Tulbagh (Diamond and Harris, 1997). These are not complete annual records, nevertheless they all include the winter months when rainfall is highest, temperature lowest.

The average spring δD and $\delta^{18}O$ values for Citrusdal are -20 and -4.9‰ compared to the weighted mean for rain at Citrusdal (Diamond, 1997) of -11 and -4.4‰. The average spring δD and $\delta^{18}O$ values for Witzenberg are -30 and -5.5‰ compared to the weighted mean for rain (Diamond, 1997) for Tulbagh of -20 and -5.1‰. These data are consistent with the Citrusdal and Witzenberg springs being recharged by ambient rain water. The Calitzdorp spring has the lowest δD and $\delta^{18}O$ values of all the springs analysed and these values (δD and $\delta^{18}O$ = -40 and -7.3‰, respectively) are considerably lower than rainfall at Oudtshoorn 40 km east of Calitzdorp Spa, at the same altitude (weighted mean δD and $\delta^{18}O$ = -11.6 and -4.1‰, respectively). No data for rainfall in the vicinity of Montagu, Baden, Warmwaterberg, Towerwater and Rietfontein exist, but there is no reason to suppose that it should be significantly different from the analysed rainfall samples. It is therefore concluded that some of the thermal springs have isotope ratios that are significantly lower than ambient rainfall.

Comparison with groundwater

We have chosen to compare the thermal spring data with data (Harris et al., 1999) from cold springs issuing from the lower slopes of Table Mountain (next to UCT in Fig. 1), and water sampled from boreholes in the area around Victoria West (altitude 1 200 m; Fig. 1) in the SW Karoo (C. Harris, unpublished data). These data give some idea of the range of δD and $\delta^{18}O$ values of unheated ground water compared to the thermal springs. The Victoria West water samples were taken from various depths (0-250 m) from a number of boreholes drilled by the Department of Water Affairs and Forestry in the area. The Table

Mountain springs plot close to the local meteoric water line (Diamond and Harris, 1997) whereas the Victoria West borehole waters form an array through which the line of best fit has the equation $\delta D = 6.9^{*}\ \delta^{18}O - 1.8$. The negative intercept value is uncharacteristic and may reflect significant evaporation in the near surface environment during recharge. The thermal springs plot between the lines of best fit through the Table Mountain and Victoria West data. They have significantly lower δD and $\delta^{18}O$ values than and generally have lower $\delta^{18}O$ values.

Origin of low δD and $\delta^{18}O$ values

The comparison of δD and $\delta^{18}O$ values between the thermal springs and meteoric and groundwater data indicates that the thermal springs have significantly lower δD and $\delta^{18}O$ values than expected for ambient rain. Various combinations of the following may be responsible for these low δD and $\delta^{18}O$ values:

- The continental effect (e.g. Dansgaard, 1964)
- Selective recharge during periods of abnormally high rainfall (as suggested by Mazor and Verhagen, 1983)
- Recharge during a earlier period of colder climate
- Recharge at altitudes significantly higher than the springs.

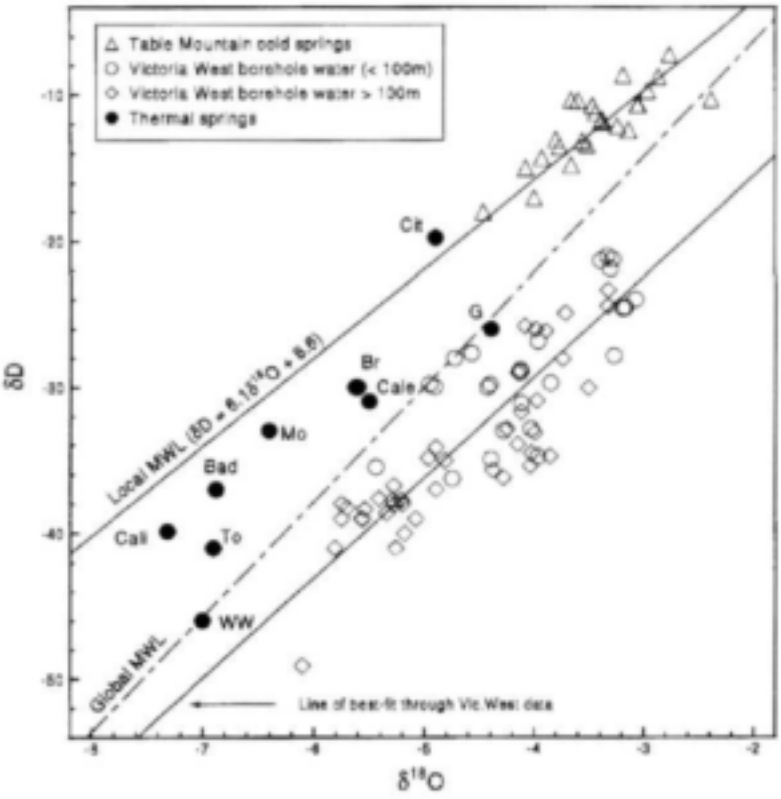

Figure 5

Comparison of thermal spring δD and $\delta^{18}O$ values with those of cold springs on the lower slopes of Table Mountain (Harris et al., 1999) and water sampled from various levels from deep boreholes in the area around Victoria West (Harris, unpublished data). Water collected from < 100 m depth and from > 100 m depth are distinguished. The local meteoric water line (MWL) for the Western Cape is from Diamond and Harris (1997). The line of best-fit through the Victoria West data was calculated using the reduced major axis method. The Global Meteoric Water Line of Craig (1961) is shown for reference.

Figure 5 suggests that the continental effect, alone, cannot account for the low δD and $\delta^{18}O$ values of the thermal springs. Selective recharge during heavy rains is unlikely to explain the difference in isotope composition between the cold groundwaters and the thermal springs. The possibility that the springs were recharged during a colder climate regime was rejected by Mazor and Verhagen (1983) because of the lack of correlation between ^{14}C data (as a proxy for time) and oxygen and hydrogen isotope ratios.

There remains the possibility that high average altitude of recharge is the cause of the low isotope ratios of the thermal springs. It is well known that the δD and $\delta^{18}O$ values of rainfall decrease as altitude increases (Dansgaard, 1964). Midgley and Scott, (1994) reported an altitude effect on $\delta^{18}O$ of -0.32‰ per 100 m for the Jonkershoek Mountains, about 70 km east of Cape Town. At Calitzdorp, the possibility exists that the zone of recharge of the spring could be in the Klein Swartberg mountains to the north, which rise up to 2 000 m (Fig. 2). The difference between the $\delta^{18}O$ value of the spring and Oudtshoorn rain is 3.2‰ which could be interpreted as the recharge zone being on average 1 000 m higher than the spring that is at about 1 200 m. Geological cross-sections presented by Diamond (1997) and Diamond and Harris (2000) show that this interpretation is hydrologically reasonable.

Regional variation

The small number of thermal springs precludes a detailed discussion on the regional variation of their δD and $\delta^{18}O$ values. Nevertheless the stable isotope data present several interesting features. The most obvious feature is the apparent effect of continentality whereby the δD and $\delta^{18}O$ values decrease with increasing distance from the west coast. The difference between the Table Mountain springs data and the Victoria West groundwater data illustrate a second effect, that is a much lower "deuterium excess" d, where $d = \delta D - 8^{*}\delta^{18}O$ for a given data point (Dansgaard, 1964; Whelan, 1987), for the inland groundwater. Regardless of whether the low y-axis intercept value for the line of best fit through the Victoria West data is indicative of evaporation prior to recharge, the thermal springs also show a similar decrease in deuterium excess as their distance from the west coast increases.

The apparent grouping of thermal springs into coastal and inland groups (Fig. 3) which both show a negative correlation between $\delta^{18}O$ and water temperature is more difficult to explain in the light of the observations made above. Within each group, higher temperatures of spring water can only be explained by circulation of water to greater depths. As discussed above, lower δD and $\delta^{18}O$ values can generally be explained by recharge at higher altitude, thus the data are consistent with the higher temperature springs being recharged at higher altitude. This is to be expected as a greater depth of circulation would be expected in aquifers with greater hydraulic head. The correlation between $\delta^{18}O$ value and distance from the west coast in the coastal group must, therefore, reflect an increase in the average altitude of recharge with increasing distance from the coast and is not simply due to the continental effect. The inland group of thermal springs shows a negative correlation between $\delta^{18}O$ value and water temperature with a similar gradient, but with $\delta^{18}O$ values about 2‰ lower for a given temperature. This offset is presumably due to the greater continentality of these springs. The lack of correlation between distance from the west coast and isotope ratios in those springs > 200 km from the west coast (Fig. 3) may in part be due to the change in geometry of the Cape Fold belt from east to west. The coastal group of thermal springs is located in mountain belts which trend N-S, perpendicular to the movement of weather systems, whereas the inland group is situated in mountain belts which trend E-W.

Conclusions

The source of water in the Western Cape thermal springs is meteoric in origin, and the high temperature of some of the springs can only be explained by deep circulation. Low tritium contents show that the water is pre 1952 in age, and ^{14}C data suggest variable turnover times of up to a few thousand years. The thermal springs differ from ambient meteoric water in their significantly lower δD and $\delta^{18}O$ values. Although the isotope ratios of the thermal springs become progressively more negative with increasing distance from the west coast (for the first 200 km), it appears that high average recharge altitude is the most important factor responsible for the low δD and $\delta^{18}O$ values.

Acknowledgements

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Part 7:

Summary

Potential of Table Mountain Group Aquifers and Integration into Catchment Water Management

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Introduction

The interest and belief in the Table Mountain Group (TMG) as an important aquifer is a relatively recent phenomenon of the South African hydrogeology scene. In 1937 the Geological Survey (Frommurze, 1937) published a definitive overview of groundwater in South Africa. In this volume he stated (p. 115) "In view of the fact that the underground water is generally located in the above mentioned structures (vertical joints, folds and faults), contacts of the quartzites with shale bands, coupled with its habit of building mountains or rough country, which is generally well watered by streams or springs, this formation is of little importance from the boring aspect".

Similarly du Toit (1954, p. 248) also dismissed the groundwater potential of the TMG as follows, "On account of the low porosity of the strata boreholes rarely give good supplies of water. Nevertheless the highly jointed character of the hard sandstones is favourable to the passage of water, wherefore the numerous little springs that flank the sandstone ranges".

The belief that TMG was an aquifer of little potential persisted until fairly recently. In 1992 the retired Director of Geohydrology, DWAF in a discussion of the TMG potential said "it is of no great importance as a regional aquifer. The farmers are merely exploiting the shallow skin of fractured rock" (Vegter, pers. comm., Oct 1993). This belief was reflected in the study titled "Western Cape System Analysis" (Ninham Shand, 1994) which examined all the possible sources of water for this area. Twenty-four possible methods of increasing the water-supply were identified, ranging from building the Skuifraam Dam through to importing water with tanker-ships, and it included two groundwater resources. None of these 24 options considered groundwater from the quartzites of the TMG.

This lack of belief in the TMG as an aquifer of regional importance had the knock-on effect of lack of support for research and investigation work in the TMG aquifer. As an example, in 1995 the Water Research Commission commissioned a state-of-knowledge report (Bredenkamp et al., 1995) on groundwater recharge. There are thirty investigations listed, not one of which is in the TMG, yet the "dolomite aquifer", the largest South African aquifer, has nine listed investigations.

In April 1992 the WRC held a workshop on Fractured Rock Aquifers. The purpose was to review past research, to identify gaps in knowledge and develop a strategy of co-ordination. Ten papers were presented, in which the TMG aquifer did get some minor passing mention. Proceedings of that workshop listed fourteen current WRC research projects which incorporated aspects of fractured rock research, one of these (subsequently published as Weaver et al., 1999) was entirely restricted to the TMG, one was partially based in the TMG (subsequently published as Anderson, 1996) and the remainder were either based in other geological formations, or were not specific to a geological formation.

However, as with any scientific postulate, there will always be colleagues who question the postulate. Joubert (1970) is the first person who proposed that there are substantial reserves of groundwater in the TMG and that this water is at greater depths than is commonly thought to be.

In the late 1980s to early 1990s various hydrogeologists become more vociferous in promoting the TMG as a regional aquifer.

- In the early 1980s the Klein Karoo Divisional Council identified a severe shortage of water in the southern area of the Klein Karoo. They commissioned the Institute of Groundwater Studies, University of Orange Free State, to investigate the groundwater resources of the area. Initial drilling concentrated on the Upper Nardouw close to the contact with the Bokkeveld shales. Due to shortages of water at peak demand times, a second phase of drilling commenced in 1989 under the supervision of Schalk Meyer of DWAF. The target aquifer was the "window" of Peninsula Formation in the Kammanassie Mountains. This was highly successful and a production wellfield was developed.

- In 1988 Peter Rosewarne submitted a research proposal to WRC entitled "Feasibility study on large scale groundwater abstraction from the

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TMG sandstones", but the proposal was not accepted.

- In 1991 John Weaver put forward a proposal to the WRC "Geochemistry and Isotopes for resource evaluation in the fractured rocks of the TMG". This was accepted, commenced in 1992 and completed in 1998 (Weaver et al. 1999).

- In 1992 Umvoto submitted to the WRC a proposal dealing with the structural controls and fractal analysis of joints, faults ands folds in the TMG, but the proposal was not accepted.

- In 1994 Umvoto submitted further proposals to the WRC but these were not accepted.

- In 1995 Ari Issar, a prominent Israeli hydrogeologist, was contracted by DWAF to review work and make recommendations on the TMG aquifer (Issar, 1995). He visited various ongoing projects at Klein Karroo, Agter-Witzenberg and Citrusdal and as a result strongly promoted the TMG. Subsequent to this endorsement, there is wide-spread acceptance that the TMG has potential as a regional water-supply source.

- In 1995, Umvoto submitted a proposal to the DWAF Western Cape Region for a regional hydrogeological study in the Olifants-Doring. This proposal was not accepted.

- In September 1997 Umvoto provided the groundwater component to the Olifants-Doring Basin Study, a study-project for DWAF by BKS-Ninham Shand. As a follow-up the consortium Umvoto-SRK proposed a more detailed regional study in the Olifants-Doring catchment. Initially this was resisted but after lobbying, this was accepted by DWAF in 1997, field work commenced in 1998 and the final report was handed over in October 2000. This was later called the CAGE (Citrusdal Artesian Groundwater Exploration) Project.

- In 1997 John Weaver initiated a TMG information sharing workshop, which was subsequently held in early 1998 as a Western Cape Groundwater Division mini-seminar at which a number of TMG experiences were presented by hydrogeologists who had done groundwater work in the TMG.

- Recent activity around investigating the TMG for its groundwater potential has substantially increased:
  - IAH2000 has a TMG focus.
  - The opening address for IAH2000 by Minister Ronnie Kasrils notes the potential of the TMG for regional water-supply.
  - The WRC in 2000 commits funds to a TMG research thrust.
  - The WRC initiates this volume of existing TMG knowledge.
  - The WRC holds a workshop in 2001 which focuses on identifying TMG research priorities.

The structure of this paper deviates from that of a normal paper. What follows are three free-standing contributions by hydrogeologists who were part of the movement to promote the TMG as a regional aquifer. These three papers reflect the authors experience and current understanding of the TMG aquifers.

References for introduction section

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Paper 1

Potential of TMG Aquifers and Integration Into Catchment Water Management

P Rosewarne

Introduction

The winter rainfall area of the Intermontane Domain of the TMG Aquifer offers a unique opportunity to maximise/optimise groundwater yield from this aquifer. This area is characterised by reliable precipitation often in excess of 1 000 mm/a, which is mainly concentrated during the period June to September. Even in a 'dry' winter, as 2000 started out to be, there were still the highest snowfalls in 40 years on the TMG mountains. Whether global warming/climatic change will lead to a significant reduction or loss of this winter precipitation in decades to come is beyond the scope of this paper.

Groundwater management

The main demand for irrigation water is in the dry summer months and for peak domestic supplies, over the Christmas and Easter holiday periods. The management scenario advocated is for boreholes/wellfields tapping the TMG Aquifer to be heavily pumped during the summer months – even exceeding average recharge estimates - in the knowledge that there will be sufficient winter precipitation to recharge the aquifer.

This approach acknowledges that there will be increased drawdown in groundwater levels and decreased surface water low flows but that the dynamic use of groundwater storage and recharge will produce a higher catchment yield than the *status quo*. It is proposed that this groundwater management approach be termed **Summer Overdraft.**

In many parts of the Intermontane Domain there are catchments where water allocations/availability from springflow or surface water low flows are regarded as 'cast in stone', eg the lower Hex Valley and Klein Karoo. Any perceived interference in such flows is met with swift recourse to litigation. However, springflow and surface water low flows or baseflow represent gravity overflow of groundwater from compartments and is a minimum catchment yield. This can be increased significantly by pumping boreholes to exploit groundwater in storage and creating increased reservoir volume to absorb excess precipitation.

For example, the baseflow or overflow available from the Sanddrif-Amandels catchments of the lower Hex Valley is of the order of 19.5 million m^3/a (Kotze and Rosewarne, 1999). Modelling has indicated that this could be increased to 26 million m^3/a by establishing suitably sited boreholes. Any reduction in base/springflow would be compensated for by allocations from the groundwater pumped. This would be returned to the system to maintain the ecological reserve and any licensed water use.

Heavy pumping of TMG/Bokkeveld Aquifers during the summer months is practised in areas such as the Hex River Valley (Rosewarne 1984) and the Agter Witzenberg (Weaver 1999). However, problems of partial recovery and saline water intrusion can occur in 'dry' years because many boreholes tap the Bokkeveld Aquifer, away from the main recharge zone.

The quantity and rate concept of aquifer yield applies here, where total recharge to a catchment may be equal to or exceed the annual groundwater abstraction but the rate at which the water moves into the area of withdrawal does not (Rosewarne *op cit*). Because of this, the summer overdraft approach to groundwater management will only work consistently where the following conditions collectively exist:

- Exploitation is directly from the TMG Aquifer;
- Intermontane Domain of the TMG Aquifer;
- Winter rainfall area;
- TMG Aquifer either within or directly connected to an area with mean annual precipitation of >800 mm.

The new Water Act also allows for a more dynamic approach to catchment water management rather than the blinkered approach of the past. However, there are valid concerns about the unknown effects of large-scale groundwater abstraction from the TMG Aquifer on the environment. These must be understood and quantified before new large-scale schemes for bulk supply purposes can be developed. Clearly, realising the full potential of the TMG Aquifer in catchment management and planning is still some way off and will require close co-operation and understanding of each other's positions between the various interested and affected parties.

Recent initiatives by the Water Research Commission, Department of Water Affairs and Forestry and the Cape Metropolitan Council indicate that serious efforts are now being made to address these problems and pave the way for releasing the full potential of the TMG Aquifer.

Conclusions

Evidence presented in papers within this volume supports the contention that the TMG Aquifers constitute a major regional groundwater resource.

Assuming that catchment managers and water supply policy makers are in agreement with the Cape Hydrogeological Community, these resources need to be integrated into catchment water management. An approach put forward in this paper is to 'overpump' the TMG Aquifer in suitable areas to replace existing, passive water use with a dynamic use of groundwater storage and recharge. A proposed name for this approach is Summer Overdraft. A modelling exercise in the lower Hex Valley has indicated that water availability in a catchment could be increased by a third using this approach.

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Paper 2

Potential of TMG Aquifers and Integration Into Catchment Water Management

CJH Hartnady and ER Hay

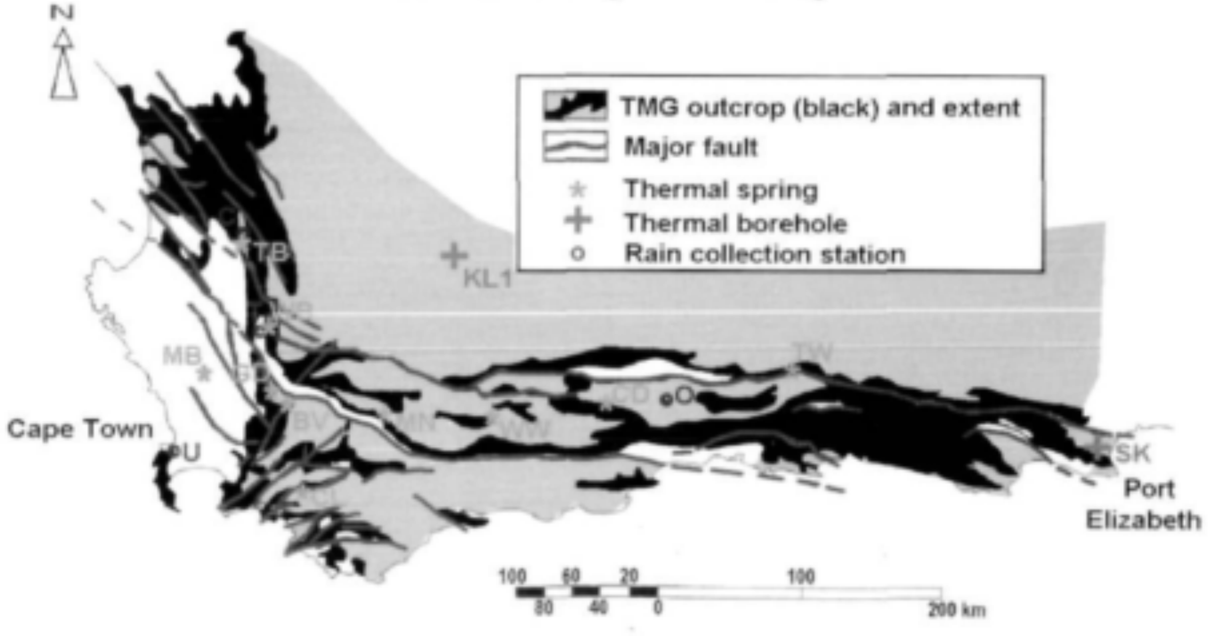

Figure 1

Distribution of the TMG aquifers in the Western and Eastern Cape Province, South Africa (black = mountain exposures; grey = deep suboutcrop in synclinal basins). The current Umvoto study area covers the western, roughly N-S trending region between Cape Agulhas at the southern tip of Africa and the northern basinal limit along the West Cape coast.

Introduction

Water is *the* crucial limiting resource to social development and economic growth in the Western Cape Province. The storage and supply capacity of many surface water drainage basins is stretched to the utmost. Serious doubts are expressed about whether further riparian development is sustainable in the long term. Fractured-rock groundwater systems of the tectonically folded Table Mountain Group (TMG) constitute a unique super-aquifer of vast areal extent and - evidenced by several powerful hot-spring sources with outflow temperatures up to 64°C - great subsurface depth (Fig. 1). Because of conceptual and practical difficulties confronting the exploitation of fractured-rock aquifers, this potential resource has been largely overlooked in recent South African water-resource evaluation and forecasting exercises.

There are now mounting pressures to build further large dams in ecologically sensitive mountain areas of the Cape Fold Belt (CFB), host to an astonishingly diverse but threatened floral kingdom. It is therefore a matter of both economic and environmental importance that a quantitative approach to water-resource evaluation is extended also to the adequate description and understanding of the deep artesian groundwater component in the overall hydrological cycle.

The occurrence of deeply confined artesian conditions in the TMG aquifer(s), particularly the remarkably thick (>1 km) Peninsula Formation, over wide areas is the focal issue in the modern approach to resource appraisal. The orthoquartzitic sandstone formations are exposed within an extensive area between Cape Town and Port Elizabeth (Fig. 1). The full volume of the aquifer rocks in this whole region is on the order of 100 000 km^3 (500 km x 200 km x 1 km), the greater part of which is concealed in the subsurface. If a representative fracture porosity in the range of 0.1 to 1% is accepted for upper continental crust (Brace, 1984), this equates to a maximum potential groundwater volume of 10^{11} to 10^{12} m^3, a figure far in excess of all possible surface-water storage capacity in the CFB.

TMG aquifer characteristics

Not only is the subsurface fluid volume exceedingly large, it is also of exceptionally high quality. Being almost entirely constituted of the mineral quartz, the host sandstones are highly resistant to chemical weathering and erosion, in contrast to the enclosing clay-, mica- and feldspar-bearing shales, or underlying granitic and phyllitic rock types. The TMG aquifer rocks thus form topographically high-standing (>2 000 m elevation in some parts) mountain ranges (black areas in Fig. 1). These ranges exert a powerful control on rainfall patterns in the generally Mediterranean climate (warm dry summers, cold wet winters) of this region. Rainfall on the summit peaks and ridges can be several times greater than the mean annual precipitation in the lower-lying areas (MAP ~500 mm), the South African record for the highest annual rainfall being 3 974 mm (156.5") at Jonkershoek in 1950. Locally up to 40% or 50% of MAP may infiltrate in the summit recharge areas, but because of the inert, highly siliceous character of the aquifers the groundwater composition is very little changed from pure rainwater compositions by prolonged contact with and hydraulic transport through the TMG.

Limited chemical and mechanical weathering of the high-standing TMG sandstone surfaces tends to exploit and accentuate its internal fracture networks, thus determining the micro-geomorphology of the mountain landscape. It has locally generated a pseudokarst - a "piped and tunnelled landscape", superficially resembling a carbonate-rock karst terrain, but developed chiefly by subsurface grain-by-grain erosion of largely insoluble quartz materials.

In a few places, such as the mountains of the Cape Peninsula near Cape Town, the TMG pseudokarst hosts some of the world's largest sandstone cave systems, e.g. Wynberg Cave on Table Mountain or Ronan's Well near Kalk Bay, some hundreds of metres in subsurface extent. In parts of the Cederberg and Cold Bokkeveld mountain ranges, strange arches and bizarre sculptures have been weathered out of a network of eroded crack systems. The development of these open crack and cave systems is evidently due to a form of "spring sapping", caused by the mechanical effects of concentrated groundwater flux along joint surfaces.

Locally, the effects of chemical weathering may have also contributed to pseudokarst development. The solubility of quartz is markedly increased by the presence of organic molecules, particularly alginic acid and amino acids, released in abundance by algae lichens) which coat the rock surfaces, and by bog vegetation within enclosed depressions. Elsewhere in the world, e.g. the Roraima Formation of southeastern Venezuela, pseudokarst in orthoquartzitic sandstones has been ascribed largely to chemical weathering under a humid tropical environment.

The climate in the CFB was most recently subtropical only in Early Tertiary times (during and before 35-65 Ma). The pseudokarst may therefore be a relict chemical-weathering feature of Early Tertiary or Late Cretaceous age. However, present-day surface waters in the higher TMG terrains have a characteristic brown colouration imparted by soluble or colloidal organic compounds derived from the soils or from biosphere processes in the streambeds. Various humic acids may even now aid the process of chemical weathering along the sub-surface fracture systems. They may also provide nutrients to microbial "biofilms" that derive energy from non-photosynthetic metabolisms (e.g. Fe(III) reduction) and have potential for biochemical and biomechanical corrosion of the subterranean environment. The high hydraulic conductivity of particular features within the TMG sandstone, and the development of cave systems in the vadose zone, may therefore have a modern, partly biogenic origin.

Hydrotectonic controls

The TMG units are relatively high-permeability aquifers by virtue of a network of pervasive fracture sets, including bedding-parallel fractures, bedding-orthogonal and bedding-oblique jointing at various scales, and fault zones with variable length and displacement characteristics. Progress towards a full understanding of TMG hydrogeology must involve accurate characterisation of the fractured structure within the aquifers, and consideration of its implications for fluid flow (permeability), and fluid storage. The contribution of fractures (faults and joints) to the permeability of fractured sandstone aquifers depends on:

- properties of the individual fractures, i.e. aperture, roughness, presence/absence of mineralisation or fault gouge, preferred flow channels; and
- properties of the fracture system as a whole, i.e. orientation and length distributions, geometry, connectivity (Odling, 1997).

The essential approach is called "hydrotectonics", defined broadly as the science of structural controls on large-scale fluid flow and storage. Within the boundary constraints provided by the large-scale structural geometry of confining aquitards, major tectonic features, such as fold axes, regional "mega-fault" structures (Fig. 1), and - rarely in the CFB- intrusive dykes, constitute either barriers or preferred paths (hydrotects) for groundwater flow.

Fracture spatial density and connectivity

Fracture spatial density d is defined as $d = 1/l_0^2 \Sigma_{i=1}^{n} a_i^2$, where l_0 is the side-length of a square sampling area, and a_i is the half-length of fracture i from a sample of n fractures within the area. A minimum d of 1.5 is required to ensure that an entire fracture network percolates. Many natural networks have d over the percolation threshold, such that the "hydrogeology of many fractured sites is controlled by a finite number of major conductors" (Renshaw, 1996, p.1526).

Derived from percolation theory, the concept of *connectivity* describes the properties of groups of objects arranged in space. As these objects intersect to form clusters, at a certain density of objects a supercluster of theoretically infinite extent is formed. This condition, identified as the "percolation threshold", arises where the largest cluster connects opposite sides of an area, regardless of its size. In rock masses where fractures intersect to form a fracture network, connectivity expresses the degree to which this network provides continuous pathways through the rock. Such a continuous pathway is described as a "backbone", another concept used in percolation theory (Odling and Webman, 1991).

Based on both field data and theoretical analysis of fracture growth, it is argued that many natural fracture networks in the earth's crust are close to the percolation threshold (Renshaw, 1996, 1997; Crampin, 1994; Crampin and Zatsepin, 1996). On the other hand, results from percolation theory (Stauffer and Aharony, 1992; Bour and Davy, 1997) and from numerical simulation of fracture growth (Renshaw, 1996) indicate that fracture networks near the percolation threshold show decreasing conductivity with increasing scale.

Table 1
Hydraulic conductivity (K) related to fracture spacing (N) and aperture (b)

$K = \rho_w g N b^3/12\mu$ [equation from Snow (1968)]
where:
fluid density $\rho_w = 1\,000$ *kg/m³*,
gravitational acceleration $g = 9.8$ *m/s²*,
viscosity $\mu = 10^{-3}$ *Pa s*

Fracture spacing N	Fracture aperture b	Planar porosity Nb	Aperture-cubed b^3	Hydraulic conductivity K	
m^{-1}	m		m^3	m/s	m/d
100	1.0E-04	1.0E-02	1.00E-12	8.17E-05	7.056
50	2.0E-04	1.0E-02	8.00E-12	3.27E-04	28.224
20	5.0E-04	1.0E-02	1.25E-10	2.04E-03	176.400
10	5.0E-04	5.0E-03	1.25E-10	1.02E-03	88.200
5	2.0E-04	1.0E-03	8.00E-12	3.27E-05	2.822
2	5.0E-04	1.0E-03	1.25E-10	2.04E-04	17.640
1	2.0E-04	2.0E-04	8.00E-12	6.53E-06	0.564
0.5	2.0E-04	1.0E-04	8.00E-12	3.27E-06	0.282
0.2	5.0E-04	1.0E-04	1.25E-10	2.04E-05	1.764
0.1	1.0E-03	1.0E-04	1.00E-09	8.17E-05	7.056

The "somewhat surprising observation that the importance of fracture networks in terms of bulk permeability generally decreases with increasing scale" (Renshaw, 1998, p.124) is implied by results from percolation theory and numerical models of fracture growth for equally conductive (uniform aperture) fractures. At the laboratory scale, however, the average aperture of fracture networks will be a function of the size of the sample. When this "sample bias" is accounted for, hydraulic conductivity is found to increase with increasing scale (*op cit.* p. 123-124).

Fracture aperture, spacing and hydraulic conductivity

There is a cubed-power dependence of hydraulic conductivity on fracture aperture (Snow's Law; see Table 1), hence an intensely fractured zone (spatial density N = 100 m^{-1}) with moderate average fracture aperture (100 μm) and correspondingly high fracture porosity (1%), may have the same hydraulic conductivity as a sparsely fractured zone (N = 0.1 m^{-1}) with high average fracture aperture (1 mm) but low fracture porosity (0.1%). For a wide range of fracture spacing and aperture conditions, the hydraulic conductivity of the TMG Aquifers may lie within the range between 0.2 m/d and 200 m/d (Table 1).

Combined acoustic imaging and flow-meter logging of a borehole on the property Boontjiesrivier, near Citrusdal, was used to obtain a quantitative estimate of fracture aperture distribution (Hartnady and Hay, 2000). The general or background fracture spacing in the Nardouw (upper TMG) Aquifer is

Table 2
Variations of specific storage with porosity and compressibility

Pore compressibility βp [range after Domenico & Schwartz (1990, Table 4.1)]							
m^2/N	3.00E-10	4.00E-10	5.00E-10	6.00E-10	7.00E-10	5.00E-09	
Porosity n		**Specific storage S_s m^{-1}**					
Range from Talwani & Acree (1985, p.959), Brace (1984)	0.01	2.99E-06	3.97E-06	4.95E-06	5.93E-06	6.91E-06	4.90E-05
	0.005	2.96E-06	3.94E-06	4.92E-06	5.90E-06	6.88E-06	4.90E-05
	0.001	2.94E-06	3.92E-06	4.90E-06	5.88E-06	6.86E-06	4.90E-05
lower range	0.0005	2.94E-06	3.92E-06	4.90E-06	5.88E-06	6.86E-06	4.90E-05
	0.0001	2.94E-06	3.92E-06	4.90E-06	5.88E-06	6.86E-06	4.90E-05

~1 m^{-1} (98 fractures observed in 100 m length of borehole). With a most likely range of fracture aperture estimated between ~20 µm and 200 µm on different models of head distribution, the upper limit of hydraulic conductivity for the TMG Aquifer "matrix" is ~0.5 m/d, but could be as low as 0.001 m/d (~6.5×10^{-9} m/s). Conversely, there are little more than 5 productive fractures in the lower ~50 m of the borehole, corresponding to a local "hydrotect" fracture spacing of ~0.1 m^{-1}. If the corresponding fracture aperture is taken near the upper limit of the estimated range, i.e. ~550 µm, then a hydraulic conductivity of ~1 m/d is obtained for the deeper fractured zone in this particular well.

Specific storage and storativity in TMG Aquifers

A storativity (S) of <0.001 is generally estimated for TMG Aquifers on the WRC "Saturated Interstices" map (Vegter and Seymour, 1995, Sheet 2). An S value of 10^{-3} is a reasonable *a priori* estimation for the deeper confined parts of the TMG Aquifers, being at the upper end of the 10^{-5} to 10^{-3} range usually given (e.g. Driscoll, 1986, p. 737). This is equivalent to regarding the whole TMG Aquifer as an "effective porous medium" of clean- coarse-sandstone character on the ~1 000 m thickness scale.

In a confined aquifer *specific storage* Ss is defined as the volume of water that a unit volume releases from or takes into storage when the pressure head in the unit volume changes a unit amount. This property has units of length^{-1} (m^{-1}). The relationship between Ss, porosity (n), and fluid/matrix compressibilities (Table 2) is:

$$Ss = \rho w g(\beta p + n\beta w)$$

where ρw is the density of water (~1 000 kg/m^3), g is gravitational acceleration (~9.8 m/s^2), βw is the vertical compressibility of water, and βp is the pore volume compressibility (Domenico and Schwartz, 1990, Eq. 4.34, p. 113).

The water volume derived in the above expression is equivalent to the volumetric expansion of water as the pressure is lowered (function of $\rho w g n \beta w$) plus the volumetric contraction of the pore space as the porosity is reduced (because the matrix expands, function of $\rho w g \beta p$). The coefficient of vertical compressibility of water βw at 25°C is 4.8×10^{-10} m^2/N. The compressibility coefficient of materials equivalent to the TMG fractured-rock aquifers βp probably lies between the textbook ranges given for "Rock, fissured" (i.e. 6.9×10^{-10} to 3.3×10^{-10} m^2/N) and "Dense, sandy gravel" (i.e. 1×10^{-9} to 5.2×10^{-9} m^2/N; Domenico and Schwartz, 1990, Table 4.1, p. 111). The latter, higher compressibilities probably apply within intensely fractured parts of the aquifer, along some of the major hydrotects.

Experience of intersecting a large fault at ~300 m depth below surface along the Franschhoek tunnel route (Forbes, 1978) showed that rock material along the fault zone flowed into the excavation like an unconsolidated sandy gravel. However, for the initial purposes of the CAGE modelling, the upper limit of TMG compressibility is conservatively set at 7×10^{-10} m^2/N (Table 3, cases 4, 6 and 8), except for two models where it has been raised further to 5×10^{-9} m^2/N (Table 3, cases 9 to 10). Application of fissured rock βp coefficients to the estimation of S_s for TMG aquifers within the middle portion of the E10 catchment (Table 3, cases 1 to 8) leads to values that lie between 2.94×10^{-6} m^{-1} (i.e. for $\beta p = 3\times 10^{-10}$ m^2/N), 6.91×10^{-6} m^{-1} (i.e. for $\beta p = 7 \times 10^{-10}$ m^2/N). The porosity range appropriate to upper-crustal rocks is taken as 10^{-2} to 10^{-3} (from Talwani and Acree, 1985, after Brace, 1984).

Table 3
TMG (Peninsula Aquifer) storage modelling
E10C-G subcatchments of area 1 687 km^2

Case	Thickness (Ope unit) b m	Dip factor[1]	Rock volume m^3	Fracture porosity n	Pore volume m^3	Specific storage[2] S_s m^{-1}	Effective storativity S	Storage volume		
								1 m head drop m^3/m	20 m head drop m^3	50 m head drop m^3
1	1100	1.00	1.86E+12	0.001	1.9E+09	2.9E-06	3.2E-03	5.5E+06	1.1E+08	2.7E+08
2	1100	1.00	1.86E+12	0.01	1.9E+10	3.0E-06	3.3E-03	5.5E+06	1.1E+08	2.8E+08
3	1100	1.00	1.86E+12	0.001	1.9E+09	6.9E-06	7.6E-03	1.3E+07	2.5E+08	6.4E+08
4	1100	1.00	1.86E+12	0.01	1.9E+10	6.9E-06	7.6E-03	1.3E+07	2.6E+08	6.4E+08
5	1300	1.10	2.42E+12	0.001	2.4E+09	2.9E-06	4.2E-03	7.1E+06	1.4E+08	3.6E+08
6	1300	1.10	2.42E+12	0.01	2.4E+10	6.9E-06	9.9E-03	1.7E+07	3.3E+08	8.4E+08
7	1300	1.15	2.53E+12	0.001	2.5E+09	2.9E-06	4.4E-03	7.5E+06	1.5E+08	3.7E+08
8	1300	1.15	2.53E+12	0.01	2.5E+10	6.9E-06	1.0E-02	1.7E+07	3.5E+08	8.7E+08
9	1300	1.15	2.53E+12	0.001	2.5E+09	1.0E-05	1.5E-02	2.5E+07	5.1E+08	1.3E+09
10	1300	1.15	2.53E+12	0.01	2.5E+10	1.0E-05	1.5E-02	2.5E+07	5.1E+08	1.3E+09

Notes

1 The **dip factor** provides a thickness correction based on a average dip (α) for both eastern and western limbs of the Olifants River Syncline and is equal to $1/\cos\alpha$ (e.g. 1.15 where $\alpha = 30$).

2 Values for **specific storage** are derived from ranges of fractured-rock porosity (0.001-0.01) and vertical compressibility for "fissured" rock, provided by Talwani and Acree (1985, p.959) and Domenico and Schwartz (1990, Table 4.1, p. 111), respectively.

As the dimensionless product of S_s and aquifer thickness, *storativity* S is "the volume of water an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of pressure head normal to that surface" (Domenico and Schwartz, 1990, p. 115-116). The bedding normal thickness (t) of the Peninsula Aquifer in the Citrusdal area was measured during the CAGE fieldwork as 1 300 m (compare previous estimate of ~1 100 m), which can be corrected upwards to an effective vertical thickness of ~1 495 m, assuming an average limb dip of 30° in the major synclinal fold structure. The original thickness, uncorrected by a dip factor has also been used in the scenario modelling (Table 3, scenarios 1 to 4), in order to provide a conservative lower range of storage. Thus relatively high Peninsula aquifer storativity ($S = S_s t$) values in the range 3.24×10^{-3} (Table 3, model scenario 1) to 1.50×10^{-2} (Table 3, model scenario 10) are calculated.

Quantification of TMG groundwater resource potential

In a relatively small area of <2 000 km^2 within the central portion of the E10 catchment, the storativity modelling exercise for the Peninsula Aquifer (Table 3) leads to an estimated range of groundwater resource potential between 5 and 25 million cubic metres (Mm^3) per unit (1 m) drop in hydraulic head, integrated over the surface area this part of the confined aquifer. In the context of a valley floor elevation <200 m above mean sea-level and an overlying confining aquitard which is generally exposed at elevations around 300-350 m along the surrounding mountain slope, a regional average lowering of the potentiometric surface for the Peninsula Aquifer by 20 m is probably technically feasible and without adverse environmental consequences. This degree of groundwater development would yield approximately 100 to 500 Mm^3. The challenge is to formulate management strategies that permit sustainable exploitation of this resource.

The elevation difference between the top of the aquifer and the potentiometric surface may be in the order of hundred metres over wide areas, so that drawdowns much larger than 10 m are locally possible without in any way impacting on the aquifer's saturated thickness. Furthermore, with sufficient knowledge of other aquifer properties such as *hydraulic conductivity* K, well field sites can be strategically selected to ensure that, during the summer pumping season, the surrounding cones of depression only rarely, and generally intentionally, diffuse to exposed aquifer boundaries where base flow from springs and seepage zones can be affected.

A previous analysis of TMG resource potential by the "Western Cape Systems Analysis" (WCSA) that recharge to the aquifer system would need to exceed a combined quantity of ~300 Mm^3/yr (DWAF, 1993, Table 20.11.1, p. 64), estimated for the TMG-sourced base flow contribution to the surface water runoff from Berg River, Palmiet River and Riviersonderend catchments. The naturalised summer mean annual runoff (MAR) formed the basis for this base flow calculation. In the case of the upper Riviersonderend catchment (500 km²), the annual loss of recharge capacity to base flow is calculated at 90.68 Mm³ (DWAF, 1993), i.e. only 16% of mean annual precipitation (MAP) in the area, and 31% of the MAR (Midgley et al., 1994).

Groundwater recharge to most South African aquifers is generally taken to be less than 10% of MAP, with Cenozoic sand aquifers being regarded as exceptional in that recharge may be in the range of 15-20% of MAP. *In the upper TMG (Nardouw) aquifer* of the Agter Witzenberg area between the towns of Tulbagh and Ceres, however, a comparison of the chloride (Cl) content and ^{18}O oxygen-isotope signature between rainfall, spring and borehole samples indicated an extraordinarily high recharge of 50% (Weaver et al., 1999).

In estimating the storage capacity for the TMG, the WCSA calculations (DWAF, 1993) focus on the outcropping area of the aquifer formations (DWAF, 1993, Fig. 20.10.1). These areas are, for the most part, relatively inaccessible, high-lying zones of groundwater recharge to the TMG aquifer systems. The proportion of the recharge that is "rejected", in the sense that it overflows from the aquifer into the surface water system at springs, provides for the base flow to rivers arising in the mountains. Hence there is a concern that a significant groundwater abstraction from precisely these parts of the aquifer would lower the water table by amounts on the order of 100 m (DWAF, 1993), and therefore detract from the base flow to rivers and dams.

In contrast, our focus is specifically on the parts of the TMG aquifer that are low-lying on the limbs of major synclinal folds. Over wide areas, the bulk of the aquifer volume in these folds even lies below sea level. Because they are well confined by the thick, overlying shale aquitard(s) of the Bokkeveld Group, these synclines are artesian basins. The potentiometric surface of pressure head for the confined TMG aquifers is above the land surface in these valleys, hence the observed artesian flow from marginal wells that are sufficiently deep to intersect them. The actual potentiometric level is constrained in the case of the Peninsula Aquifer by the elevation of the Peninsula-Cedarberg contact, and in the case of the Nardouw Aquifer by the Bokkeveld basal contact.

The original WCSA assessment (DWAF, 1993), which dismissed the TMG groundwater option, dealt with an aquifer area that was much less than 984 km². There is, however, a larger area of ~1 500 km² in the surroundings of the Theewaterskloof reservoir, almost entirely underlain by TMG rocks at some depth, except for a few, small, anticlinal windows of pre-TMG basement in the Wemmershoek and Stettynsberg mountains. The WCSA study only considered the upper 200 m of the "saturated thickness" within the smaller surface area of actual TMG outcrop, but another approach premised on a deep-drilling capability in the intervening synclinal basins would take into account the full thickness of both TMG aquifers (~2 km) over the larger area. The total volume of fluid stored within the fracture porosity (0.1%) of the deeper, ~1.2 km-thick Peninsula Aquifer may be estimated at ~2 000 Mm³, which amounts to over four times the present annual safe yield of 436 Mm³ of the whole WCSA surface water system. Using conservative assumptions in storativity calculations, a groundwater volume of 150 Mm³ could be abstracted from this source for an area-averaged drawdown of only 10 m.

Catchment and aquifer management policy

The aquifer management strategy generally proposed for the TMG Aquifers is that of summer pumping and winter recovery. This groundwater management method is currently applied on a localised scale in various parts of the Western Cape, including the Agter-Witzenberg where borehole hydrographs show that end-summer drawdowns of 30 to 50 m are recovered by the end of the following winter-recharge season (Weaver et al., 1999, Section 4.2).

When normal winter recharge and aquifer recovery does not occur fully during exceptional drought periods, and surface water reservoirs are seriously depleted or empty, the deep well fields should in principle also be capable of "mining" the TMG groundwater resource over several summer-winter cycles. Such mining of the deep strategic groundwater reserve should be effected with minimal or no impact on the surface environment, until the drought is broken and full recovery is assured. In order to accomplish this form of water resource management, the time lag between onset of pumping and the radial expansion of the induced depression in the potentiometric surface to the borders of the recharge area should be on the order of months or years. Such extended time lags in (spring or well) discharge responses to recharge from distant precipitation are indeed possible where deep regional flow systems exist (Domenico and Schwartz, 1990, p. 262).

Such a sophisticated level of conjunctive surface- and groundwater resource planning and management in the TMG aquifers and their recharge catchments will involve using deep drilling technology which exists, but is not usually accessed by the groundwater industry in South Africa. It is undoubtedly required to access the storage capacity of the deeper *confined aquifers. The current technology* can be innovatively adapted to the abrasive rock conditions and high water pressures that are likely to be encountered deeper in the TMG.

Even with the various technological adaptations and innovations that may be required, the capital cost of deep groundwater wells of adequate supply capacity is likely to be only a fraction of the cost of future large dams in the Western Cape (e.g. the Skuifraam Scheme at ~R700 million in 1997 costing). Furthermore, the damming of the Berg River and possibly other mountain streams represents an inevitable disruption and devaluation of the as yet unvalued "ecosystem services" that the freely flowing rivers provide to the whole natural and social environment. On the other hand, the development of the deep groundwater capacity can be considered as a perspicacious investment in the "natural capital" of the Western Cape's unique water resource, and one that actually replenishes and magnifies its stock (Lovins et al., 1999).

In view of the evident potential for adverse global climate change in the 21st Century, there is a long-term strategic importance in developing the deep groundwater reserve. It is an added insurance against losses consequent on prolonged drought cycles, which - as has happened in the 20th Century and earlier eras - could trigger disastrous economic downturns. In the longer run, such episodic losses could potentially dwarf the cumulative recurrent costs of operation (e.g. pumping) and maintenance, which are greater for the TMG groundwater development option compared to most surface water schemes. Aside from this future scenario, it is anticipated that the lower capital cost of groundwater development and resultant reduction in finance/ amortisation charges will favour this option in terms of the cheaper cost of water delivered.

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Paper 3

Potential of TMG Aquifers and Integration Into Catchment Water Management

JMC Weaver

Introduction: porosity, storativity, specific yield and the conceptual model of how water is held and released from the TMG Aquifer

Porosity of a rock mass is the difference between the total volume and the solid volume. Based on the genesis of the porosity various porosities are defined, such as primary porosity, secondary porosity, single porosity, microfissure porosity and double porosity (Kruseman and De Ridder, 1990). In fractured rocks a proportion of water is held in dead-end porosity and does not play a role in yield calculations. When discussing the potential groundwater yield of an aquifer, the term *effective porosity* describes the water that is available or the water that is released when the aquifer drains or is pumped. For the TMG the effective porosity is a combination of storativity and specific yield.

The concept of *storativity* was developed primarily for the analysis of well hydraulics in confined aquifers and is well defined for two-dimensional horizontal flow towards a well. Storativity ranges from $5x10^{-3}$ to $5x10^{-5}$. For unconfined aquifers *specific yield* is used to describe the storage term and the usual range is $3x10^{-1}$ to $1x10^{-2}$, or 30% to 1% (Freeze and Cherry, 1979). Hydrogeologically, a significant difference between confined and unconfined aquifers is that the volume of water stored in an unconfined aquifer relates to the rises and falls of the water-level (table); whereas for a confined aquifer, water level fluctuations reflect primarily changes in pressure, rather than changes in volume of water stored. The example regularly used is that of an inclined fracture that is drilled and intersected at depth. This fracture is open at surface so the fracture is effectively an unconfined aquifer (specific yield applies). However, when the drilling intersects the fracture, water rises in the borehole, which is the behaviour of a confined aquifer (storativity applies).

There are no confining units in the TMG. This of course excludes local conditions where Bokkeveld shales or Cedarberg shales overly the TMG. So assuming that one is studying a block of sandstone of the Peninsula Formation with neither of these confining units present, the question is: What is the conceptual model of flow in this aquifer? My experience and observations lead me to view the TMG as a multiple porosity aquifer, which on a regional scale should be regarded as unconfined. At the local scale such as a wellfield test-site it will display different facets and combinations of confined to unconfined behaviour, depending on where the borehole is drilled, or which zone of the borehole is being tested. Thus a borehole drilled into a fracture will show apparent confined conditions, and when tested will behave as a confined aquifer during the initial stages of pumping and will show semi-unconfined or leaky behaviour during later stages of pumping. But if that same borehole had stopped a few metres short of the fracture it will be damp and would be called dry by the driller. If left for a week, water will slowly seep into the borehole and the two boreholes would show the same or very similar water levels. Figure 2 illustrates the various scenarios that can be obtained depending on the positioning of a borehole.

The effective porosity in the TMG will vary depending on the local geology and geomorphology. For alluvial material along rivers, alluvial fans and hillwash it will be high. For the upper weathered zone it will also be high, and if pseudo-karst is present this will increase the effective porosity. Zones of intense folding, faulting and fracturing will have quite a high effective porosity and this will persist at depth. Away from these zones, e.g. some areas on the western or eastern limbs where tectonic activity was less intense the effective porosity would be lower, of the order 10^{-4}.

The available water from the TMG is a combination of what can be obtained from both storativity and specific yield ($S + S_y$), with spatial variation of the relevance of each at a regional scale. This possibly means that the available volume of groundwater available for the TMG is the order of 0.5% (0.005) as opposed to 5% (which is applicable to unconfined primary aquifers) or to 0.05% (which is applicable to confined aquifers).

Some of these aspects are discussed at length and detail in Woodford (2001) and Hartnady and Hay (2001 - Paper 2 in this article). Methods of pumping test analysis are discussed in Murray (1996), Van Tonder and Bardenhagen (2000) and Woodford (2001).

Necessary conditions for groundwater exploitation

The potential of any aquifer for water-supply depends on:

- It being a sustainable resource, which is a function of recharge
- It being an accessible resource, which, for the TMG is a function of thickness of the aquifer and accessibility by boreholes
- Management options
- Restrictions on exploitation.

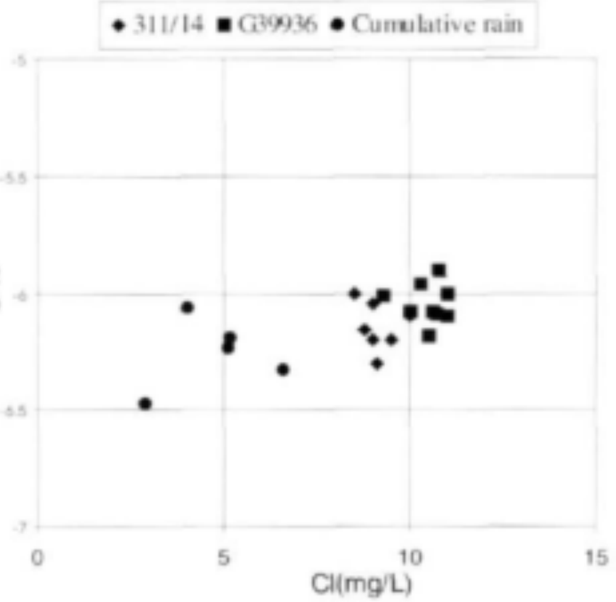


Figure 1

Agter-Witzenburg. Chloride and $\delta^{18}O$ for cumulative rain collecters and mountain boreholes G39936 and 311/14

Necessary condition 1: TMG Aquifer and sustainability

The prime controller of an aquifers' sustainability is recharge. And recharge in the TMG is one of the least studied in the country. The WRC recharge manual (Bredenkamp, 1995) lists 30 investigations – not one of these is in the TMG, yet the "dolomite aquifer" the largest in South Africa", has nine listed investigations.

Weaver et al. (1999) measured chloride and $\delta^{18}O$ in five cumulative rain samplers and compared the results to groundwater quality analyses from two boreholes in the mountains of the Agter-Witzenberg. These boreholes are located in the recharge area of the local TMG Aquifer, more specifically they are in rugged mountains of the Nardouw Formation. The data implies a recharge potential at this site of up to 50% using a chloride mass balance. Figure 1 shows this data, with the rain having about 5 mg/ℓ of chloride and the groundwater about 10 mg/ℓ. The slight shift of $\delta^{18}O$ from rain to groundwater shows the effect of evaporation.

Recharge percentage will vary from one local area to the next. For instance, flat low-lying areas with a thicker overburden of finer-grained sediments will probably have a lower recharge percentage than adjacent higher-lying areas which are covered with a thin veneer of coarse sand. For the CAGE project, Hartnady and Hay (2000) developed a relationship between rainfall, topography, area of Peninsula and of Nardouw exposed and temperature such that the areal distribution of recharge was modeled without spatial averaging. Recharge was considered as zero in low rainfall zones (<200 mm/a), regardless of whether this rain fell entirely within the winter (May to September) time period. The results varied from ~8% in the low lying and lower rainfall areas to 43% in the high mountains, with a spatially weighted average of 23%.

Taking a ramble over the TMG mountains, any keen observer will note two features which are conducive to high recharge. The rock is fractured and jointed and these are often open at surface. Secondly the soil is usually a medium to coarse sand with clay very rarely being found. Both these features support the premise of a high recharge potential. The Cape fynbos vegetation from the TMG mountains is adapted to these conditions. Many of the mountain fynbos species cannot be grown in soil which does not drain freely.

In order to establish the sustainable yield of TMG Aquifers a better understanding of recharge is required. The recharge potential of the TMG requires further research.

Necessary condition 2: TMG Aquifer and accessing the water

There are two considerations.

- The rough terrain makes it difficult to transport a drill-rig to the preferred drill-site. Drill-sites can be made accessible by road-building, but quite often such road-building may be unacceptable because of the impact.
- Once on-site it is difficult to drill to depths much greater than about 400 metres.

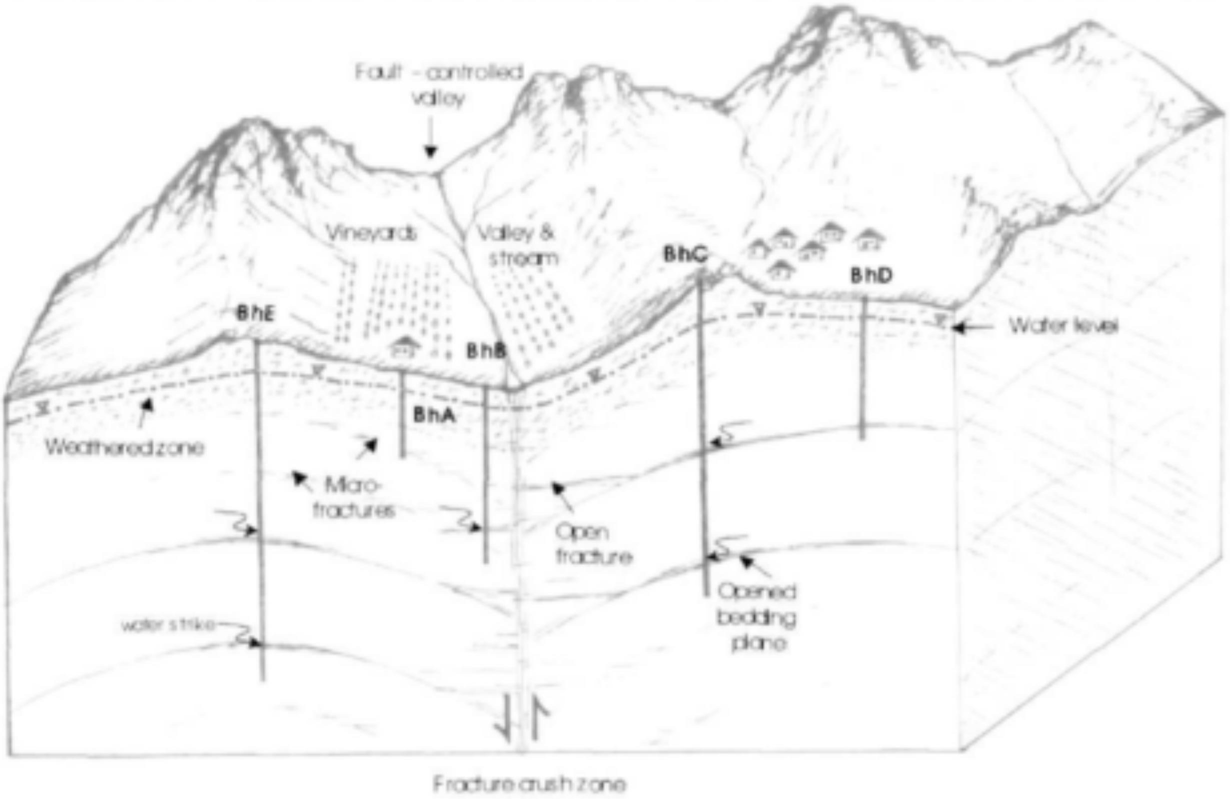
Some practical considerations of drilling deep boreholes in the TMG

To drill a deep borehole in any environment requires in-depth planning in order to manage potential problems which could prevent completion of the boreholes. The TMG presents significant additional challenges to drilling a deep borehole. One reason is that the sandstone is hard and abrasive which results in severe wear on the drill tools.

The main problem that needs to be overcome when drilling a deep borehole is the capacity of compressors. Compressors are used to drive the drill-bit and to lift water and drill cuttings at the face of the hole to surface. The normal large capacity compressors with attached in-line boosters deliver about 40 bar of pressure, which effectively limits the depth of drilling to around 400 m.

To achieve greater depths will require drilling with either rotary tricone or diamond bit. Rotary tricone bits are used in the oil industry, but their usage in the TMG quartzites is untested. They should be tested as using rotary tricones may be a practical method of achieving large diameter deep boreholes.

Extending the depth of the large diameter percussion boreholes with diamond drilling is a feasible method which has been tested. The method was used to good effect for deep drilling of Witwatersrand gold exploration boreholes. Depths of over 900 me-



TMG - Potential figure description

Figure 2 shows some of these various aspects of yield and confined/unconfined conditions. BhC and BhE are sited on the axis of anticlines and have intersected two major water strikes. BhB has been sited adjacent to the major fault, which is clearly visible to the naked eye as well as on air-photos and satellite photos. BhB is a few metres to one side of the crush zone to avoid the severe drilling problems of collapsing conditions. BhB has intersected an open fracture directly connected to the fault zone and thus also indirectly to BhC and BhE. These three boreholes are high yielding and are used to irrigate the vineyards seen on the sketch. BhD has not intersected any large aperture open fractures, but has intersected an extension of the upper water strike fracture of BhC. This fracture has a smaller aperture, thus lower yielding than at the axis of the anticline, but has sufficient yield to supply the group of houses for domestic water supply. It is also sustainable throughout the year because of its areal connectivity. BhA has not intersected any major or large fractures, but has intersected some minor fissures and thus is able to supply the single house with water, but not much more. BhA and BhD behaved like unconfined aquifers when drilled i.e. an accumulation of dampness and small minor water strikes, slowly increased the yield. BhE, BhB and BhC reacted similarly, but when the first major water-strike was encountered, the water-level rapidly rose in the borehole to the rest-water level, which is a few metres below surface.

ters of percussion drilling in Ventersdorp lava were achieved, after which the drilling was completed by diamond drill. For these boreholes all water-strikes were cemented off, enabling the compressors to lift the cuttings to surface without the need to overcome the weight of the water. DWAF Drilling Division has also employed the same method successfully (without cementing the water-strikes), when drilling some of the circular structures in the Karoo for Alan Woodford. Two boreholes were percussion drilled to 340 m and extended to 500 m and 800 m with NW-diameter diamond drilling. This method has also successfully been combined with casing off of the water by the DWAF Drilling Division in the TMG on the Blikhuis Experimental Deep Drilling (BEDD) project designed and run by Umvoto Africa, where depths of ~600 m have currently been reached with cumulative artesian yields of ~5 ℓ/s. A limitation of this method is the amount of water that can actually flow through the completed narrow diameter of the diamond drilled section of the borehole. Diamond

Table 1
Approximate flow obtainable through diamond drill boreholes of varying diameter

Diamond drill borehole diameter		Approximate flowrate at 20 bar (ℓ/s)
Drill size	Diameter of hole (mm)	
AW	48	~4
NW	76	~10
HW	100	~16
PW	120	~23
SW	146	~33

drilling is expensive, thus the diameters tend to be minimised.

With this type of borehole construction, the borehole pump will be installed in the large diameter of the percussion drilled section. Below the pump will be the narrow diameter diamond drilled section. Water struck at depth will rise in the borehole (since it is under pressure) and will thus be available for abstraction for a pump placed at the bottom of the large diameter percussion-drilled section of the borehole. Table 1 shows the maximum flow rates through various diamond drill hole sizes. The flow rate at 20 bar implies that water is intersected by the diamond drill at 200 m below the end of percussion drilling. For the AW diameter the pressure loss over 200 m is 2.5 bar, while for the SW it is 0.5 bar. The flow rate at 20 bar is about 2 m/s, which is at the upper limit of efficiency.

The possible solution to the 400m compressor capacity limitation is the development of a hydraulic powered hammer bit. The prototype has been demonstrated in Germany, but as yet a freely available commercial product is not yet on the shelves.

Drilling to 400 m requires changes to the normal design of shallower boreholes. The important rule is to start at a large diameter. If one starts at a smaller diameter, say 210 mm then after a hundred or so meters the drill size will need to reduce to 165 mm. As soon as any reasonable water-strike is obtained drilling will no longer be able to continue because of back-pressure. Back-pressure is created when the gap between the drill-rod and the side wall (the annulus) is small and a resistance to flow is created. An example of this back-pressure limiting the depth of drilling was a borehole sited in the Agter Witzenberg (Weaver et al., 1999) to intersect the Bokkeveld/Nardouw contact at about 250 m. At 118 m about 25 ℓ/s was obtained. The drilling was discontinued at 141 m because of combination of 14 bar needed to lift the water to surface, plus the back-pressure nullified the capacity of the compressors.

Large diameter boreholes also mean that large delivery volume pumps can be installed. It would be very frustrating to drill a borehole with a potential of more than 50 ℓ/s and only be able to install a 20 ℓ/s pump.

To make deep drilling a practical reality the feasibility of using rotary tricone bits must be tested. The development of hydraulic percussion drill bits must be stimulated.

Necessary condition 3: Managing the aquifer

To develop a proper management regime for a TMG Aquifer will require an understanding of both to what depth does groundwater occur and what the likely storage conditions are. The depth of flow is needed in order to understand at what depths groundwater can be accessed from. The storage is needed so that one can understand that if one were to pump from these depths, then what would be rate of lowering of the water-levels in the wellfield. If there is a high storativity, then this can be used to advantage for the Summer Overdraft management scenario as described by Rosewarne (this group of papers) and also to buffer periods of lower than normal winter rainfall.

The TMG sandstone is reputed to have virtually no primary porosity (H. Theron, pers. comm. 2001, and De Beer, 2001). Porosity is secondary and is a function of weathering and of fractures, joints and other openings (hydrogeologically speaking, the TMG could be termed a quartzite and not a sandstone, as for a sandstone one visualises some primary porosity). There is some limited storage in the weathered zone and in areas where transported sands are thicker, but this is limited to a thin skin. Another feature which has high storage potential if proved to be areally extensive, is the development of karst environment. Traditionally associated with limestone and dolomite the concept of karst in quartzite may seem rather left-field to traditional hydrogeologists. However there are a number of observations that give glimpses into the tantalising possibility of a zone of very high and unexpected storage potential. Wynberg Cave on Table Mountain and Ronans Cave above Kalk Bay are well-known examples of pseudo-karst caves in the TMG. Another example is from the Keerom Dam in the Nuy Valley, about 25 kms NNE of Worcester. After excavating about 13 metres into the sidewall of the valley for keying in the dam-wall, a void 1.5m high and about 6m square was exposed and which showed evidence of water erosion (Falla in Brink, 1981). This cave was about 15 metres above stream level. At Sanddrift Dam, which is 6 km NW of the Hex River Valley, a similar cave was encountered when digging the foundations for that dam. This cavern was lined with manganese, which is an indicator of groundwater flow (pers comm. H Theron, 2001).

Most of the folding in the Cape Fold Belt was characterised by brittle folding. The sandstone was cemented and thus the rocks did not fail by slip, but by brittle failure. These openings are unlikely to be filled (by precipitation of minerals from oversaturated solutions) as groundwater in the TMG is undersaturated. Silica is the only exception and silica does not readily precipitate, thus openings once formed will not be filled by mineralisation. At the discharge zone, when conditions are suitable and when exposed to the atmosphere, iron and manganese will oxidise and precipitate. This however is not expected to occur in the subaqueous environment.

Rocks such as dolomite and granite, under normal temperatures and pressures will tend to undergo plastic flow, and at depths greater than 200 to 300 m fractures will tend to close. Quartzite however is competent and even at great depths fractures will tend to remain open.

Deep flow of groundwater has been regularly measured and is accepted as a feature of TMG. From the above discussion open fractures to great depths are possible, and groundwater from the fractures have the character of deep flow. The remaining question is what is the storage capacity of the TMG.

Shallow TMG certainly has a high storage capacity. A specific yield of 10^{-2} for the upper 200 m is quite feasible. If the pseudokarst terrain is widespread this would be even higher, closer to 10^{-1}. More detailed discussion is presented in Weaver and Talma (2000). For the lower zone storage is probably lower because of the lack of weathering. A storativity value of 10^{-3} can be considered a reasonable estimate for the deeper zone. See tables in paper 2 of 3 above.

A question regarding yield potential for the TMG is "what is the potential yield away from zones of fracturing and faulting?" Water-supply projects tend to be located in zones where fracturing and faulting are prominent features and it is from these projects that most knowledge is gained about storage. It is not common practice to deliberately drill boreholes away from target areas, and thus knowledge of storage in unfractured areas of the TMG is minimal. An example of drilling carried out away from fractures is the Agter-Witzenberg project (Weaver et al, 1999). Drilling was done on a geological cross-section deliberately chosen where no lineaments could be seen on air-photographs. All the boreholes that were drilled yielded water, the highest yield being ~25 ℓ/s. These yields are probably related to bedding plane slip and fracturing resulting from competence differences between the shales and quartzites during formation of the syncline in which the valley is situated. In a geological environment similar to the TMG, namely the Windhoek aquifer, Murray (pers com) has deliberately drilled boreholes some distance from production boreholes drilled on prominent lineaments. These boreholes have been drilled to test hydraulic conductivity and storativity away from the fracture zones for a research project on artificial recharge in fractured rocks. The experiments are still underway.

The consideration of deep flow and storage is necessary because the storage capacity will influence both the management options as well as the potential for increasing recharge. The management option for the TMG Aquifer is that of conjunctive use. Thus for an average summer overpumping will deliberately be allowed to occur and the water table will be lowered hundreds of metres, and full recovery will occur in winter. This has been proposed in the past and is also proposed in this volume. The second consideration is that this method makes space available for recharge water. At present most of the recharged rain merely daylights lower down the mountain as ephemeral springs and does not actually recharge the aquifer, probably because the aquifer is already full and there is no space for further recharge water. This method is proposed mainly for the Peninsula Formation for two reasons. In order to be able to lower the water table by a hundred metres or more the pumping borehole needs to intersect high yielding fractures at depths of 200 to 300 m or more. This condition of open fractures at depth is more likely to be encountered in the Peninsula Formation because the ortho-quartzites are relatively more competent than the felspathic sandstones of the Nardouw Formation. The second condition favouring the Peninsula Formation for this management scenario is that the Peninsula is relatively free of dissolved iron in the groundwater. High iron levels are commonly encountered in the Nardouw, for example the high-iron groundwater boreholes supplying the Klein Karoo Rural Water Supply Scheme on which some research has been done (Jolly and Engelbrecht, 2001). When high-iron groundwater is pumped there is a danger that the boreholes can become clogged by iron precipitating in the fractures when cascading water increases dissolved oxygen and converting the soluble ferrous iron to insoluble ferric iron. In contrast the four pumping boreholes of the Klein Karoo Scheme, which are in the Peninsula Formation, have no iron present (Weaver and Talma 1999) and thus do not have a borehole clogging threat.

In order to develop proper aquifer management scenarios the determination of storage capacity of the TMG needs additional research. The research needs to be directed towards the four zones of expected differing storage character, namely the upper weathered zone, the lower zone, fracture zones and zones where no obvious fracturing occurs. Also, the proposed method of lowering water levels by a few hundred metres during the summer peak water demand period and allowing water levels to recover during the high rainfall and low water demand winter period, needs careful investigation before implementation.

Necessary condition 4 : Restriction on exploitation

The main challenge that needs to be overcome before implementing large-scale exploitation of the TMG, is the effect that this will have on the fynbos biome and the mountain environment. The areas of particular concern are high altitude marshes, low

Table 2
Annual sustainable yield in m³ per square kilometre of recharge area as a function of recharge percentage and annual rainfall

Annual rainfall (mm)	Annual sustainable yield (recharge) per km² at varying recharge percentages (m³)			
	15% recharge	20% recharge	30% recharge	40% recharge
400	60 000	80 000	120 000	160 000
600	90 000	120 000	180 000	240 000
800	120 000	160 000	240 000	320 000
1 000	150 000	200 000	300 000	400 000

Table 3
Yield potential (in m³) per square kilometre of accessible aquifer as a function of pumpable saturated thickness of the aquifer and storativity of the aquifer

Pumpable saturated thickness of the aquifer (m)	Storativity			
	10^{-2}	$5x10^{-3}$	10^{-3}	$5x10^{-4}$
400	$4x10^6$	$2x10^6$	$0.4x10^6$	$0.2x10^6$
500	$5x10^6$	$2.5x10^6$	$0.5x10^6$	$0.25x10^6$
600	$6x10^6$	$3x10^6$	$0.6x10^6$	$0.3x10^6$
800	$8x10^6$	$4x10^6$	$0.8x10^6$	$0.4x10^6$

altitude wetlands and the flora and fauna associated with these wetlands. Cape Nature Conservation have adopted the precautionary principle and will not support the development of a bulk water supply project developed in the TMG unless it can be shown that there will be no negative impact on the fynbos.

Potential

The preceding four chapters have described the four necessary conditions, but the question that remains unanswered is "How much water can a TMG catchment yield on a sustainable basis?" To properly answer such a question to a reasonable degree of accuracy will require an intensive hydrogeological investigation. However, the following two exercises can be done to obtain a first order estimate of the amount of water available.

Annual sustainable yield

As discussed earlier, this is dependent on the percentage recharge to the aquifer and the amount of rain falling in the recharge area. Firstly, define the recharge area. The suggested method is to delineate the catchment boundaries and measure the area of the catchment which has Peninsula Formation and Nardouw Formation exposed at surface. Determine the rainfall for these recharge areas. Make an estimate of the expected recharge percentage which could be expected to occur in the catchment. Using the annual rainfall and expected recharge percentage as the two variables, the following table shows the annual sustainable yield in cubic metres that is potentially available from the catchment per square kilometre of TMG outcrop. Having obtained the recharge (in m³/a) that occurs per square kilometre of TMG outcrop, multiply this by the area of outcrop of the recharge zone and the result is a rough estimate of the annual sustainable yield of the catchment under consideration.

The recharge percentages used in Table 2 range from conservative (15 and 20%) to optimistic (40%). The rainfall is realistic, however on the high mountains higher rainfall will be experienced. This table serves to demonstrate the range of sustainable yield that can be potentially obtainable for the TMG.

Weaver and Talma (2000) used this method to estimate the annual yield of water available to the City of Cape Town within a radius of 200 km from Cape Town. The area of TMG outcrop was measured using GIS and, allowing a 1km buffer for the area of TMG sandstone dipping under the Bokkeveld, the exploitable area (only the outcrop area), is 13 200 km². Using a 33% recharge rate (realistic to optimistic) and 600 mm rain per annum (conservative), the potential recharge is 2 600 million cubic metres. The current annual consumption of water by Cape Town is 500 million cubic metres. Even if a recharge rate of 15% is used it is fairly obvious that the TMG has the potential to satisfy future increase of water demand for Cape Town.

Yield potential

As discussed earlier, the yield potential is dependant on the storativity of the rock formation and the depth that the volume of rock mass that can be utilised. To obtain the yield potential of a catchment, similar to the previous exercise, calculate the area in square kilometers of the aquifer that is potentially exploitable. The result should be slightly more than the area calculated for the recharge area, as deep boreholes will be able to access portions of the aquifer lying below the shales of both the Cederberg Formation and the Bokkeveld Formation. Using the two variables "pumpable saturated thickness of the aquifer" and "storativity of the aquifer", from the table below calculate the groundwater yield potential per square kilometre of accessible aquifer.

This table serves to show the potential of the TMG if deep pumping boreholes can be drilled. This amount of water in stored in the aquifer will provide an excellent buffer if used to summer overpump the aquifer and winter recharge. A storativity of 10^{-3} is regarded as optimistic, while 10^{-3} is conservative. Borehole depths or pumpable saturated thickness, will be dependant on the ability to develop methods of drilling deep boreholes.

Weaver and Talma (2000) used this method to estimate the amount of water in storage in the TMG within a radius of 200 km of the city of Cape Town. The area of potential exploitation is 13 200 km^2. Taking a storativity of 10^{-2} and an average pumpable saturated aquifer thickness of 500 m, they calculated the groundwater yield potential to be 66 000 million m^3.

When these boreholes are drilled in the future, the amount of available water in storage may be higher than estimated by the above method. This method has assumed a horizontal land surface. In practice most TMG production boreholes will be drilled at access points into the mountains, which will tend to be in ravines or lower lying areas. Thus, where there are areas at higher altitudes than the borehole, and because the water-table tends to follow the surface topography, more water in storage will be accessible.

Future research needs

The four priority areas for further research that are identified are:

- Recharge.
- Storativity.
- Ecological dependencies on groundwater which may inhibit exploitation of groundwater from the TMG.
- The influence that structural geology has on determining yields of individual boreholes and also on wellfields. Included in this topic could be the influence that lithology has on yields from the Nardouw Formation versus the Peninsula Formation.

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Hydrogeological Research Needs and Priorities for the Table Mountain Group Aquifer Systems

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Abstract

This paper outlines hydrogeological research needs and priorities for the Table Mountain Group aquifer system. These needs and priorities were identified during the preparation of this volume and during a workshop attended by contributing authors. The following aspects were identified and are presented in an order of importance (a) environmental and ecological impacts of groundwater abstraction (b) recharge (c) flow conceptualisation (d) storage (e) exploitability (f) tools and technologies (g) water quality (h) economics and (i) management plans. Based on the outcome of the workshop, a research programme is being designed to ensure current limitations in our understanding of the Table Mountain Group Aquifer systems can be addressed.

Introduction

The Water Research Commission (WRC) initiated a project during 2000 to synthesize current knowledge of Table Mountain Group (TMG) aquifer system. The project relied on the knowledge and experience of hydrogeologists familiar with TMG aquifers and resulted in a document entitled "Hydrogeology of TMG Aquifers" (this volume). A series of technical issues and case studies were identified and authors were invited to submit written contributions. This volume hence represents a *status quo* of our current understanding of the TMG aquifer system. To realise the full potential of this source of water, many uncertainties and barriers have to be overcome. These include:

- A deficient understanding of the occurrence, attributes and dynamics of TMG aquifer systems
- A lack of understanding of the environmental impacts of groundwater exploitation
- Uncertainties about how best to manage the resource within a multi-objective environment.

Appropriate research of a multi-disciplinary nature is required to find answers to the many questions relating to the water resource potential of TMG aquifers and the optimal management and protection of these aquifers. The research also needs to facilitate implementation of integrated water resource management in the region. This paper outlines the need for an appropriate research programme on the occurrence, attributes and dynamics of groundwater systems in the TMG.

Priority issues

Identification of issues

A number of research issues were identified during the preparation of contributions for this volume. These, and other issues, were discussed at a workshop to determine research priorities for the TMG aquifer system held on 3 April 2001 in Gordons Bay (Wroe-Street, 2001). Major role players involved in the research, exploration, development and management of TMG aquifer systems attended the workshop (Appendix 1). The following research issues and needs were identified for investigation (in order of priority):

- Environmental and ecological impacts of groundwater abstraction
- Determination of recharge
- Conceptualisation of different flow paths
- Storage capacity of the TMG aquifer system
- Exploitation potential of TMG aquifers
- Tools and technologies required to develop and manage the TMG aquifer system
- Water quality impacts
- The comparative costs of exploiting TMG aquifers
- Integration of knowledge into management plans for TMG aquifers.

It was agreed the first four issues require priority attention. As most of the other priority issues are to some extent dependant on the outcome of research into the first four issues, only the priority issues are addressed below.

Environmental impact of abstraction

Promulgation of the National Water Act (Act 36 of 1998) and the National Environmental Management Act (Act 107 of 1998) has highlighted the need to understand and consider the impacts of groundwater abstraction on the surrounding environment. This is an issue being addressed throughout the world, with South Africa being no exception. One of the problems in this country is that no documented and scientifically evaluated case studies exist where groundwater abstraction has been shown to impact the surrounding environment. The WRC is currently funding two related research projects:

- The impact of groundwater abstraction on the ecology of the Kammanassie Mountains
- Dependence of vegetation on groundwater.

The impact of groundwater abstraction from TMG *aquifers on fynbos is also currently a topic of heated* debated. Until such time all parties are properly informed regarding groundwater dependence and impacts of abstraction, this debate is likely to continue. Proper investigation of these issues is hence urgently required. From this, tools and procedures need to be developed for mapping groundwater-dependent ecosystems and sensitive environments.

Recharge

Recharge is a key consideration in any groundwater resource assessment. It is therefore surprising that no proper assessment of recharge of TMG aquifer systems has been undertaken. Currently practitioners base their assessments of recharge on historic rule-of-thumb approaches supported by some recent short-term studies. Sound research is required to facilitate a better understanding of recharge processes and the quantification thereof. Specific tools for measuring or estimating recharge of TMG aquifer systems are also required.

Flow conceptualisation

Conceptualisation of the different flow paths in TMG aquifers was ranked as the third most important area of research. Improved understanding of this topic will require the following aspects be addressed:

- Possible differences in flow dynamics and paths in specific geographical areas and geological domains
- Interactions between surface and groundwater
- Use chemical tracers and geothermometers to trace groundwater flow.

The notion of deep groundwater flow in the TMG (greater than 200 m) is also being debated by the hydrogeological community. To date, little proper investigation of this phenomenon has been initiated. Because of the perceived advantage of developing deeper groundwater resources, the investigation of deep groundwater in the TMG aquifer system also needs to be specifically addressed.

Storage

The fourth priority area of research identified was an improved understanding of storage in these fractured hard-rock aquifer systems. Consensus was that our understanding and quantification of storage is limited. In addition to improving our understanding of how much storage capacity exists in TMG aquifers, verification of existing theories and knowledge regarding storage capacity in relation to the position and depth of various TMG formations is required. Methods of quantifying storage are also required.

Programme implementation

The WRC recognises the need to implement an appropriate research programme to improve current knowledge of TMG aquifer systems. Such a programme is to be in keeping with WRC principles of research funding, including:

- The research is to be demand-driven and should address specific problems
- The research should lead to human resource development and strengthening of institutional capacity to undertake water research
- Promotion of inter-disciplinary and inter-institutional research and collaboration
- Involvement of stakeholders to maintain focus and gain acceptance and application of research products.

Given the identified research priorities and needs related to the TMG aquifer system, the following overall objectives for a TMG aquifer system research programme have been developed:

- Develop an understanding of the occurrence, attributes and dynamics of TMG aquifer systems
- Develop of understanding of environmental impacts of exploitation from TMG aquifer systems
- Integration of groundwater into the broader water management framework (multi-objective analysis).

It is envisaged four subprogrammes will be implemented, with each focussing research on a priority issue related to the TMG aquifer system. The start of each each subprogramme will be phased to accommodate WRC budget contraints. The first subprogramme will address ecological and environmental impacts of large-scale groundwater abstraction from TMG aquifer systems. The programme is expected to start in 2002 and will last about 4 years.

Conclusion

The TMG aquifer system has the potential to be a significant source of water. Though the aquifer system is used to some extent, a number of aspects relating to the aquifer system are poorly understood and unquantified. A number of areas of research have been identified which require priority attention. These include the ecological and environmental impacts of groundwater abstraction, recharge, groundwater flow and the conceptualisation thereof and storage. The WRC plans to implement a research programme to research these issues. The first subprogramme will address the ecological and environmental impacts of groundwater abstraction and is expected to start in 2002. The remaining TMG aquifer system research subprogrammes will be scheduled according to WRC budget constraints.

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Appendix 1

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