A HYDROGEOLOGICAL ASSESSMENT OF ACID MINE DRAINAGE IMPACTS IN THE WEST RAND BASIN, GAUTENG PROVINCE

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The "Lodge" spring rising in Government Subgroup quartzite west of the Ngonyama Lion Lodge in the Krugersdorp Game Reserve

PEER REVIEW

This report has been reviewed by the following colleagues and peers.

Dr. Pete Ashton	Principal Scientist and CSIR Fellow, CSIR–NRE, Pretoria
Dr. Kai Witthüser	Department of Geology, University of Pretoria
Prof. Dr. Frank Winde	North West University (Potchefstroom Campus)
Mr. Ewald Erasmus	Geotechnical Environmental Specialist (invited by Prof. Dr. Winde)
Dr. Nick Robins	British Geological Survey (NERC)

Their contribution of valuable time in providing thorough and constructive comment is gratefully acknowledged. The outcome of the review process is comprehensively dealt with in Annexure H of this report.

CITATION

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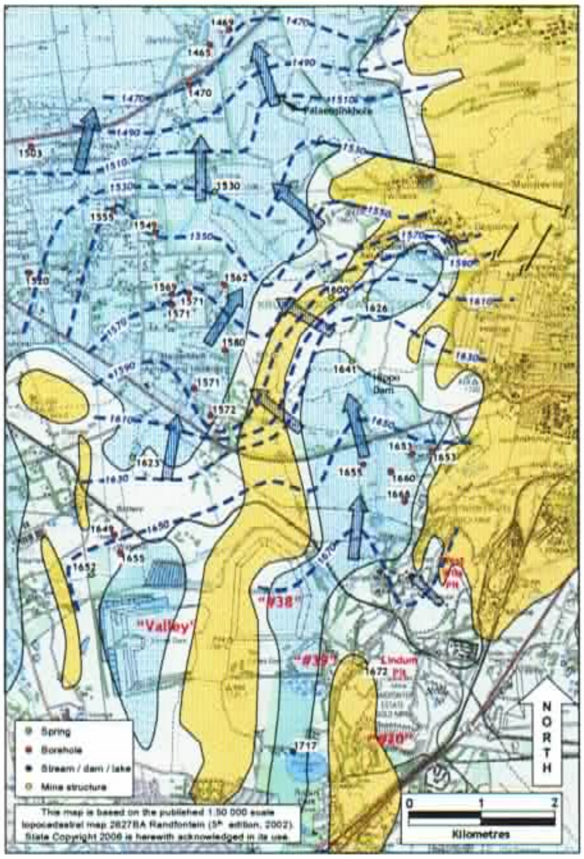
EXECUTIVE SUMMARY

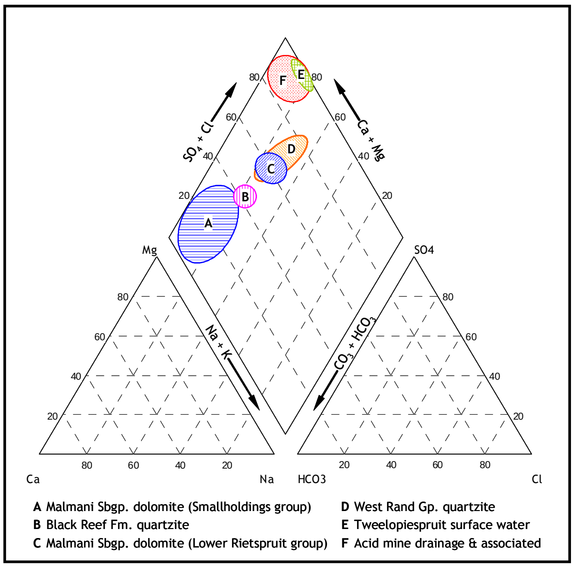
Acid mine drainage (AMD) from defunct and flooded underground gold mines in the West Rand Basin was first manifested during August and September 2002. Initial estimates of the decant rate ranged between 7 ML/d (winter) and 12.5 ML/d (summer). More recent estimates put the rate at between 18 and 36 ML/d, although an average of 15.5 ML/d is most often reported. The ramifications of AMD for the subregion are enormous. The greatest focus in this regard is the Cradle of Humankind World Heritage Site. Of no lesser concern, however, are the downstream landowners and agricultural activities that are largely or wholly dependant on groundwater for potable and economic use.

A review of the available relevant hydrogeological literature suggests that historically, greater attention has been afforded the surface water environment and the relatively "far-field" groundwater environment in the dolomitic Zwartkrans Compartment to the north of the locus of decant, and less to the hydrogeology of the decant area itself and the more immediate downgradient subsurface environment. In order to determine and implement the most appropriate acid mine water drainage management measure(s), it is necessary to first understand the hydrophysical environment that defines and informs the groundwater dynamic in the subregion. This dynamic includes the response of the groundwater regime to both natural and unnatural recharge mechanisms. The latter are predominantly mining related as might be associated with defunct underground workings, defunct and operational surface (opencast) workings and tailings dams. The interaction between surface water and groundwater represents another facet of this dynamic and, apart from AMD, also finds relevance in the discharge from at least one municipal waste water treatment works. This study, based mainly on field work undertaken in February and March 2007, seeks to further inform these aspects.

The groundwater environment that hosts the AMD occurrence comprises the karst aquifer associated with two outliers of Malmani Subgroup (MSbgp.) dolomite, and various fractured rock aquifers associated with the enclosing basin of Black Reef Formation (BRFm.) and older basement strata of the Central Rand Group (CRGp.) and West Rand Group (WRGp.). The dolomitic strata typically represent a karst aquifer characterised by modest (< 100 m^2/d) to extremely high (≈2 500 m^2/d) transmissivity values and, despite karstification, modest (in the order of a few per cent) storativity values. The BRFm. and WRGp. strata might conceptually be associated with fractured aquifers characterised by modest to low (< 10 m^2/d) transmissivity and low (< 1 %) storativity values. In all instances, however, heterogeneity prevails over homogeneity. In the case of the MSbgp. strata, this is defined mainly by zones of preferential dissolution, and in the case of the BRFm. and WRGp. strata, by fault and fold structures, fracture/joint patterns and bedding plane geometries. The reduction of 48 depth to groundwater rest level measurements to absolute groundwater elevation values, together with six spring elevations, forms the basis of the adjacent groundwater contour map. The map also shows flow vectors that describe groundwater movement in the study area.



The sourcing of field water quality parameters (electrical conductivity, pH and temperature) at 49 sites in the study area, and an equal number of more complete chemical analyses, served as basis to characterise the water chemistry in the subregion. This is exemplified in the adjacent trilinear diagram. Further analysis has elucidated the hydrochemical dynamic between the various water sources, especially that which characterises the influent sections of the Tweelopie Spruit and the Riet Spruit.



The study has generated a suite of physical and chemical hydrogeologic data and information that not only augments the growing volume of such material, but also contributes materially to an improved understanding of these components in the fabric that forms the groundwater regime in the subregion.

The following most salient conclusions are stated.

- An understanding of the groundwater environment in the subregion is obscured by complex geology. This study has produced sufficient evidence to seriously question the perception that the Government Subgroup strata form a comparatively low permeability “barrier” between the dolomitic outlier with its associated locus of mine water decant to the south, and the main dolomitic Zwartkrans Compartment to the north. This applies equally to the derivative of this perception, the Environmental Critical Level, as an absolute decant management solution.
- The threat to the quality of groundwater in especially the karst aquifer of the Zwartkrans Compartment derives from both acid mine drainage originating in the outlier and from effluent discharge originating at the Percy Stewart Waste Water Treatment Works. Whereas the former contributes elevated calcium, sulphate and heavy metal concentrations, the latter primarily contributes exceedingly high bacteriological concentrations to the karst environment.
- Although much effort and cost is expended by various organisations and parties in collecting hydrogeological data and information in the subregion, comparatively little of this data is subjected to wider scientific scrutiny and interrogation (either collectively or individually) with a view to further informing an understanding of the groundwater dynamic in the subregion.

The conclusions precipitate the following recommendations.

- There is sufficient cause to investigate in detail the structural geology in the subregion insofar as it informs the physical groundwater environment. The Krugersdorp Game Reserve provides the ideal terrain in which to execute the field-based components of this recommendation.
- The evaluation of the structural geology and geophysical data sets must be followed by intrusive investigations comprising the sinking of percussion-drilled exploration boreholes that target clearly identified geological/hydrogeological features. These boreholes must be constructed to provide technically unequivocal hydrogeological test facilities and vertically stratified groundwater quantity and quality monitoring stations.
- Under circumstances where the reticence of key role players to release important data sets impedes accurate judgement, it is imperative that such parties offer “proprietary” data sets up to objective independent scrutiny and application.
- There is an urgent need for all available existing data to be collated into a single data set that not only consolidates often duplicate sets, but also eliminates redundant monitoring stations.

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ABBREVIATIONS, ACRONYMS and SYMBOLS

~	approximate(ly)
<	less than
>	greater than
µg/L	microgram(s) per litre
%ile	percentile
A.H.	Agricultural Holdings
AMD	acid mine drainage
ARD	acid rock drainage
amsl	above mean sea level
bgl	below ground level
Bq/L	Becquerel per litre
BRI	Black Reef Incline
BRFm.	Black Reef Formation
bs	below surface
CGp.	Chuniespoort Group
CGS	Council for Geoscience
CoHWHS	Cradle of Humankind World Heritage Site
Comp.	compartment
CRGp.	Central Rand Group
CSIR	Council for Scientific and Industrial Research
DDS	DD Science cc Environmental Monitoring
DWAF	Department of Water Affairs and Forestry
EC	electrical conductivity
ECL	environmental critical level
ESE	east-southeast
Fm.	Formation
Ga	billion years
GA	General Authorisation
Gp.	Group
gph	gallon(s) per hour
GSbgp.	Government Subgroup
ha	hectare(s)
HGM	Harmony Gold Mine
I&AP	interested and affected party
JFA	Johan Fourie & Associates
JSbgp.	Johannesburg Subgroup
KGR	Krugersdorp Game Reserve
km^2	square kilometre(s)
L/s	litre(s) per second
m	metre(s)
m^3	cubic metre(s)
Ma	million years
MAE	mean annual evaporation
MAP	mean annual precipitation
MAR	mean annual runoff
MAT	mean annual temperature
m^3/a	cubic metre(s) per annum

m/d	metre(s) per day
m^2/d	square metre(s) per day
m^3/d	cubic metre(s) per day
m/km	metre(s) per kilometre
mg/L	milligram(s) per litre
ML	megalitre(s)
mL	millilitre(s)
ML/d	megalitre(s) per day
mm	millimetre(s)
Mm^3/a	million cubic metres per annum
MSbgp.	Malmani Subgroup
mS/m	milliSiemens per metre
n.d.	not determined
n.m.	not measured
no.	number
n.r.	not reported
n.s.	not specified
NRE	Natural Resources and the Environment
RSA	Republic of South Africa
SAWS	South African Weather Service
Sbgp.	Subgroup
Spgp.	Supergroup
SI	saturation index
SI_{cal}	calcite saturation index
SI_{dol}	dolomite saturation index
SI_{goe}	goethite saturation index
SI_{gyp}	gypsum saturation index
TDS	total dissolved salts
THRIP	Technology and Human Resources for Industry Programme
WMA	Water Management Area
WNW	west-northwest
WRB	West Rand Basin
WRGp.	West Rand Group
WWTW	waste water treatment works

1 INTRODUCTION

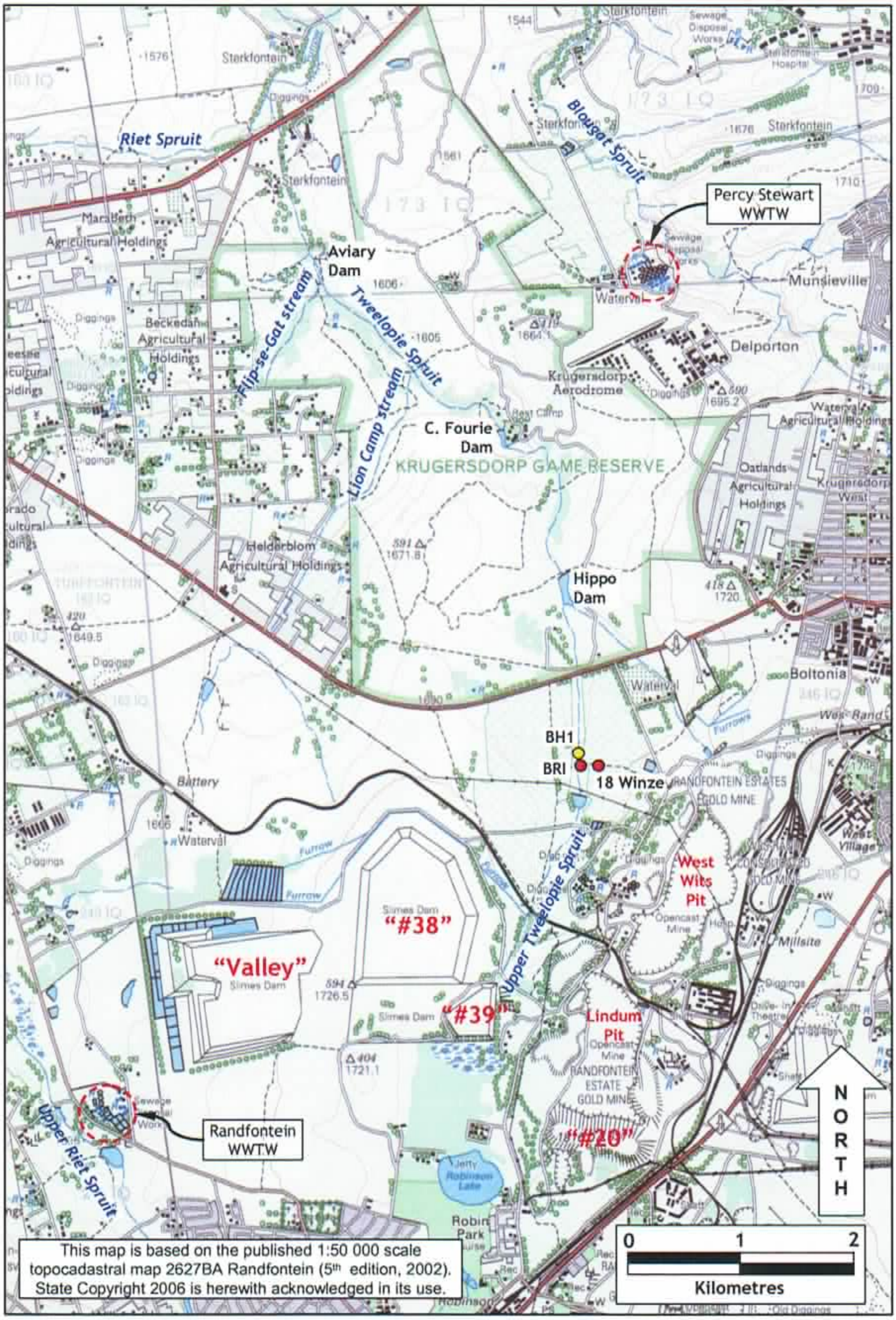
The comparatively short history of acid mine drainage (AMD) in the West Rand Basin (WRB) via mine water decant on the Randfontein Operations property (formerly Randfontein Estates Ltd) of Harmony Gold Mining Company west of Krugersdorp (Figure 1) is reasonably well documented (e.g. JFA, 2006; Coetzee, 2005). Decant first manifested on surface at a position very near borehole BH1 (Figure 1) on 27 August 2002 and later, on 3 September 2002, at the Black Reef Incline (BRI) shaft (Figure 1) some 200 m to the south (Du Toit, 2006). Initial estimates of the decant volume ranged between 7 ML/d in winter and 12.5 ML/d in summer (JFA, 2004). In early-2005, additional decant reported on surface at 18 Winze (Figure 1), an abandoned shaft to the east on the slope above the BRI (Coetzee, 2005). More recent estimates (Coetzee, 2005) put the rate of decant at between 18 and 36 ML/d. The subsequent development of a permanent water body in the Hippo Dam on the Tweelopie Spruit in the southern part of the Krugersdorp Game Reserve (KGR), together with the development of seeps and springs, reflects the more recent surface manifestation of mine void flooding and decant in the area. Prior to this, anecdotal evidence has it that the dam held water for only a few days before drying up, hence its other name of Dry Dam.

The ramifications of decant for the subregion are enormous. The greatest focus in this regard is undoubtedly the Cradle of Humankind World Heritage Site (CoHWHS), which includes the home of “Mrs Ples” in the Sterkfontein Cave system. Of no lesser concern, however, are the downstream landowners and agricultural activities that are largely or wholly dependant on groundwater for potable and business use. In order to determine and implement the most appropriate acid mine water drainage management measure(s), it is necessary to first understand the hydrophysical environment that defines and informs the groundwater dynamic in the subregion. This dynamic includes the response of the groundwater regime to both natural and anthropogenic recharge mechanisms. The latter are predominantly mining related as might be associated with defunct underground workings, defunct and operational surface (opencast) workings and tailings dams. The interaction between surface water and groundwater represents another facet of this dynamic and, apart from AMD, also finds relevance in the discharge from two municipal waste water treatment works (WWTW), viz. the Randfontein WWTW to the southwest in the headwaters of the Riet Spruit, and the Percy Stewart WWTW on the Blougat Spruit to the northeast (Figure 1). The study reported herein explores this dynamic and ancillary issues by consolidating and comparing readily available historical data with “new” data sourced in early-2007.

2 OVERVIEW DESCRIPTION OF THE PHYSICAL ENVIRONMENT

2.1 Morphology, Drainage, Climate and Rainfall

The terrain morphology in the area is characterised by undulating hills and lowlands with relief in the range of 130 to 450 m, a medium drainage density of 0.5 to 2 km/km^2, a low to medium stream frequency of 0 to 6 per km^2 and with 20 to 50 % of the area supporting slopes of < 5 % (after Kruger, 1983, in Schulze et al., 1997). The subregion straddles the subcontinental surface water divide between the Vaal River basin to the south and the Limpopo River basin to the north (Figure 2). These circumstances implicate the Upper Vaal and the Crocodile (West) and Marico Water Management Areas, respectively, in regard to catchment management agencies. More particularly, Quaternary basins C23D and A21D represent the associated locus of attention (Figure 2). The higher lying terrain on the subcontinental surface water divide to the south experiences a mean annual temperature (MAT) in the range 14 to 16°C, the lower lying terrain to the north being slightly warmer with an MAT in the range 16 to 18°C (Schulze, 1997).



This map is based on the published 1:50 000 scale topocadastral map 2627BA Randfontein (5th edition, 2002). State Copyright 2006 is herewith acknowledged in its use.

Figure 1. Locality map

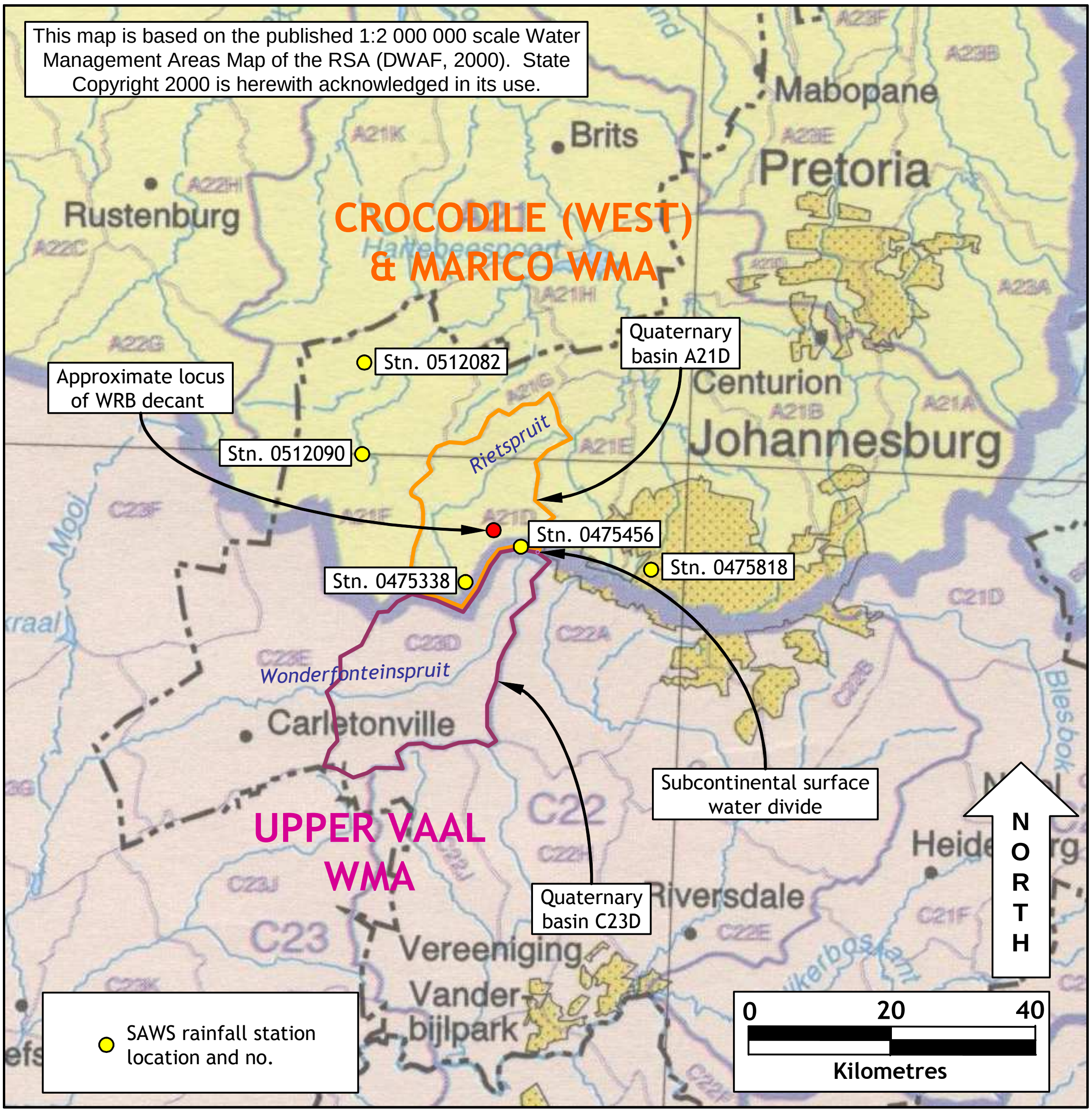


Figure 2. Regional surface water drainage map

Midgley et al. (1994) report the following salient information for Quaternary basins A21D and C23D.

	AREA	MAP	MAR	MAE	MAIN DRAINAGE
A21D	371.5 km^2	713.7 mm	56.3 mm	1700 mm	Riet Spruit
C23D	510.1 km^2	663.5 mm	29.5 mm	1650 mm	Wonderfontein Spruit

Monthly rainfall data for five climate stations in the wider region (Figure 2) were sourced from the South African Weather Service (SAWS). Information extracted therefrom is presented in Annexure B together with rainfall histograms, and add a more regional definition to the rather coarse mean annual precipitation (MAP) information presented above. For example, it would appear that precipitation per hydrological year at four of the five stations is decreasing. A roughly 10 % decrease in precipitation over the past some three to four decades is indicated. Such a reduction might have a potentially significant negative impact on the sustainability of the natural groundwater resource and, conversely, a potentially positive impact on the rate of mine water decant provided that a similar pattern applies to all of the area that contributes recharge to the defunct underground mine workings.

2.2 Geology

2.2.1 Regional geology

The region is underlain primarily by sedimentary strata (quartzite and shale) associated with the Witwatersrand Supergroup, and younger sediments (dolomite, quartzite and shale) associated with the older strata of the Transvaal Supergroup. The stratigraphic relationship of these strata to one another is shown in Table 1, and their distribution in Figure 3.

Table 1. Simplified lithostratigraphic subdivision of strata in the study area.

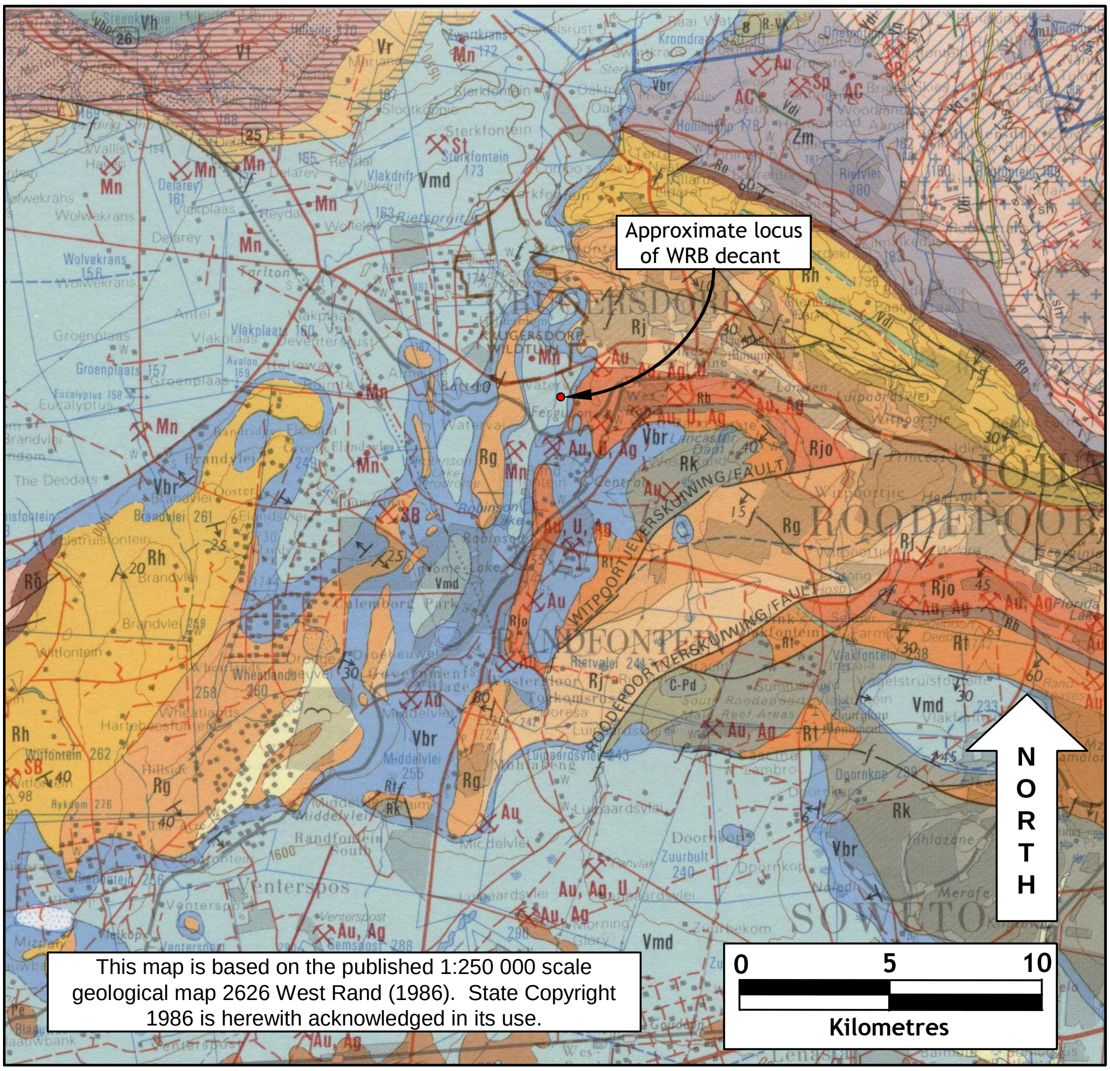
Basic Lithology	Lithostratigraphic Unit			Era (Age)	
Alluvium	Quaternary sediments			late Cenozoic (<10 000 yrs)	
Dolerite [Jd]	post-Karoo dyke / sill intrusive structures			early Mesozoic (150 – 190 Ma)	
Ferruginous shale & quartzite, hornfels [Vt]	Timeball Hill Formation	Pretoria Group	Transvaal Supergroup	(~2 225 Ma)	Vaalian
Quartzite, shale, chert breccia [Vr]	Rooihoogte Formation				
Dolomite [Vmd]	Malmani Subgroup	Chuniespoort Group		(~2 430 Ma)	
Quartzite, shale [Vbr]	Black Reef Formation			(~2 650 Ma)	
Quartzite, conglomerate [Rjo]	Johannesburg Subgroup	Central Rand Group	Witwatersrand Supergroup	(~2 750 Ma)	Randian
Shale, quartzite [Rj]	Jeppestown Subgroup	West Rand Group			
Quartzite, greywacke [Rg]	Government Subgroup				
Ferruginous shale, quartzite [Rh]	Hospital Hill Subgroup			(~3 000 Ma)	
Mafic & ultramafic rocks [Zm]	Undifferentiated			Swazian (>3 100 Ma)	

Notes: Lithology colours correlate broadly with those used in Figure 3.
Lithology symbols correlate with those used in Figure 3.
Ma = million years

2.2.2 Local geology

The dolomitic strata within which the decant from the West Rand (gold-mining) Basin (WRB) via the Black Reef Incline (BRI) and other features is manifested, are associated with the Vaalian (2.65 to 2.43 Ga) Chuniespoort Group, and in particular the Malmani Subgroup within this lithostratigraphic unit. These strata are encapsulated within Black Reef Formation quartzite which, in turn, is surrounded and underlain by older Randian (3 to 2.75 Ga) basement rocks associated with the Witwatersrand Supergroup. This relationship is illustrated in the local geological map presented in Figure 4, and the geological profiles presented in Figures 5a and 5b.

Numerous previous scientific and technical reports have incorrectly referred to the dolomitic strata as representing an inlier (e.g. Coetzee, 2005; JFA, 2006; Rison, 2006). These strata are completely surrounded by older rocks and, as such, represent an outlier (Allaby and Allaby, 1991). It is surprising that so basic an error in terminology such as described above has been replicated in scientific reports without question. The term outlier is used hence forward in this report to describe the area that hosts the locus of decant.



Approximate locus of WRB decant

This map is based on the published 1:250 000 scale geological map 2626 West Rand (1986). State Copyright 1986 is herewith acknowledged in its use.

Figure 3. Regional geology map (lithology colours correlate broadly with those used in Table 1)

The defunct underground mine workings in the West Rand Basin intersect the Johannesburg Subgroup strata that host the auriferous Main, Leader and South reefs, and the uraniferous Bird reefs. Older and much shallower mine workings exploited the near-surface gold occurrences in the Black Reef Formation (Coetzee, 2004) and the Kimberley reefs (Boulder/Lindum Reef and Battery/Horsham Reef) of the Turffontein Subgroup (Whiteside et al., 1976). Testimony to these mining activities are the large surface excavations in the form of the so-called West Wits and Lindum Pits of the West Rand Consolidated Gold Mining Company. The former are now used by Mogale Gold (Pty) Ltd, formed in late-2002 for the recovery of gold out of old mine dumps, as a sludge disposal facility.

2.2.3 Structural geology

The public participation process conducted by Naledi (2006) for Harmony Gold Mining (Ltd) records comments made by A. Jamison (a registered I&AP) at the public meeting held on 24 January 2006 in regard to the structural geology in the subregion. In particular, attention is drawn to the importance of geological structures (mainly faults) in establishing hydraulic continuity between various rock formations, and thereby determining the movement of groundwater. The published geological map 2626 West Rand at scale 1:250 000 (see Figure 3) indicates the larger and more prominent fault structures (e.g. the Witpoortjie and Roodepoort faults) in the subregion.

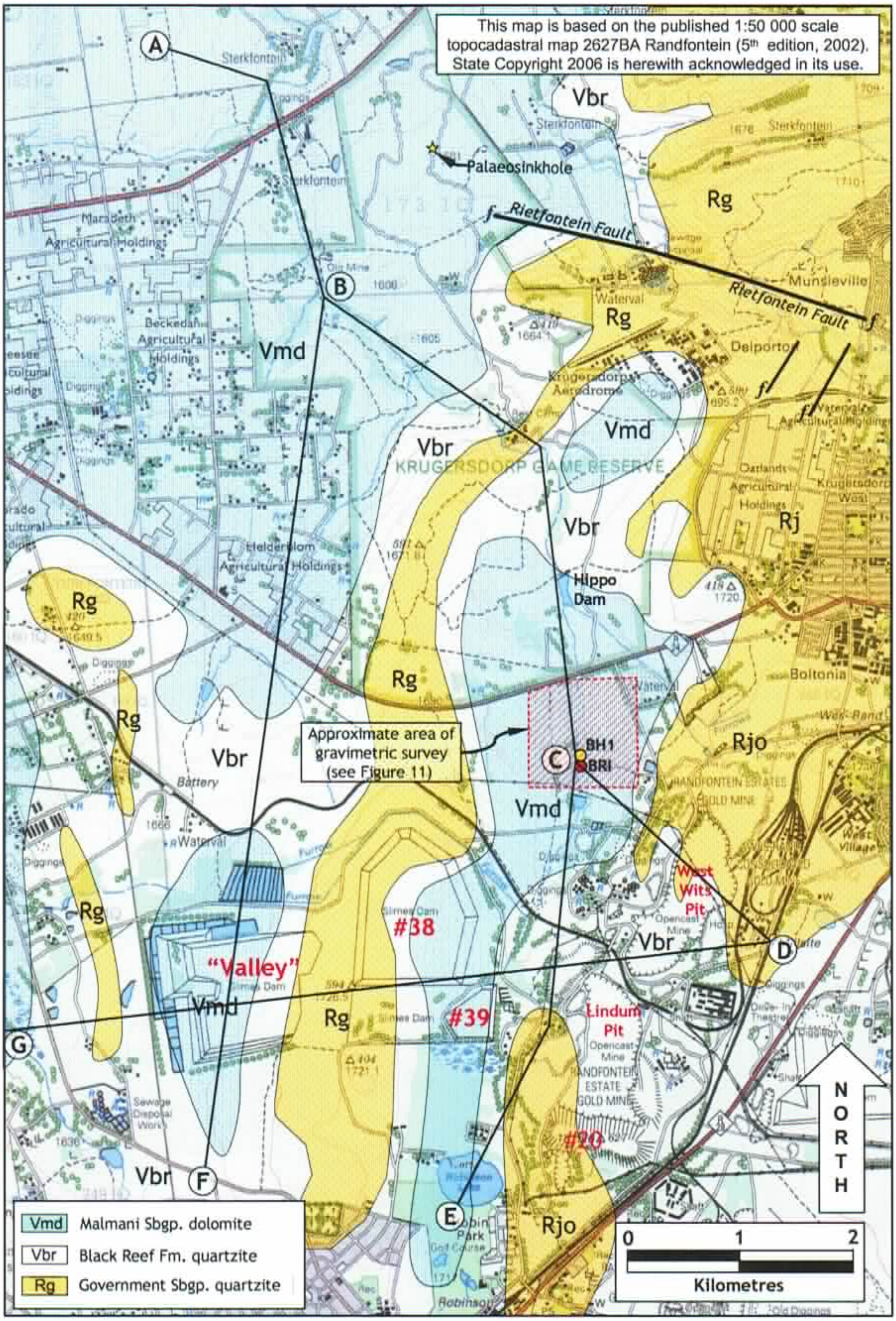


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Figure 4. Local geology map (after geological map 2626 West Rand, 1986)

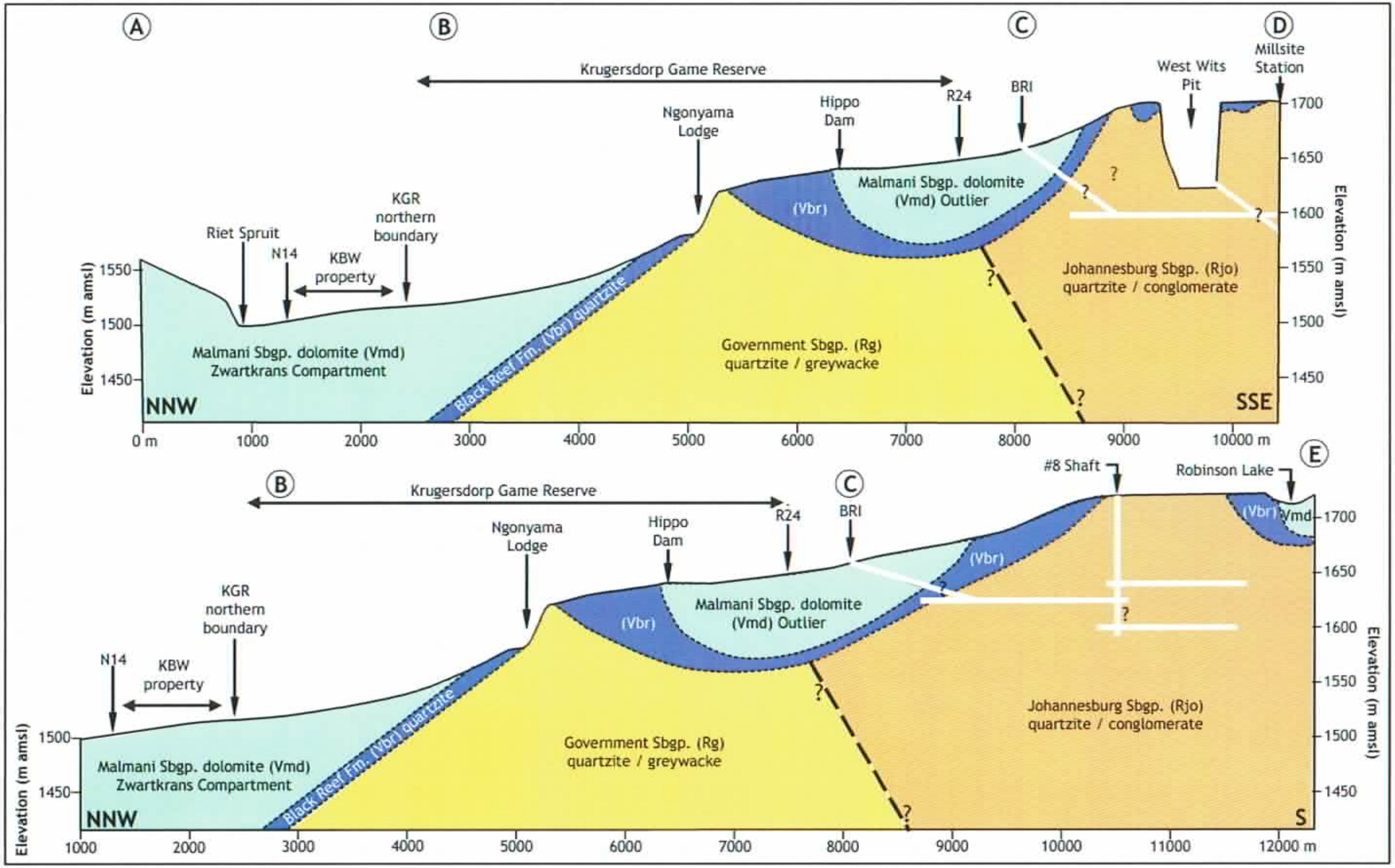


Figure 5a. Conceptual geologic profiles (see Figure 4 for profile positions)

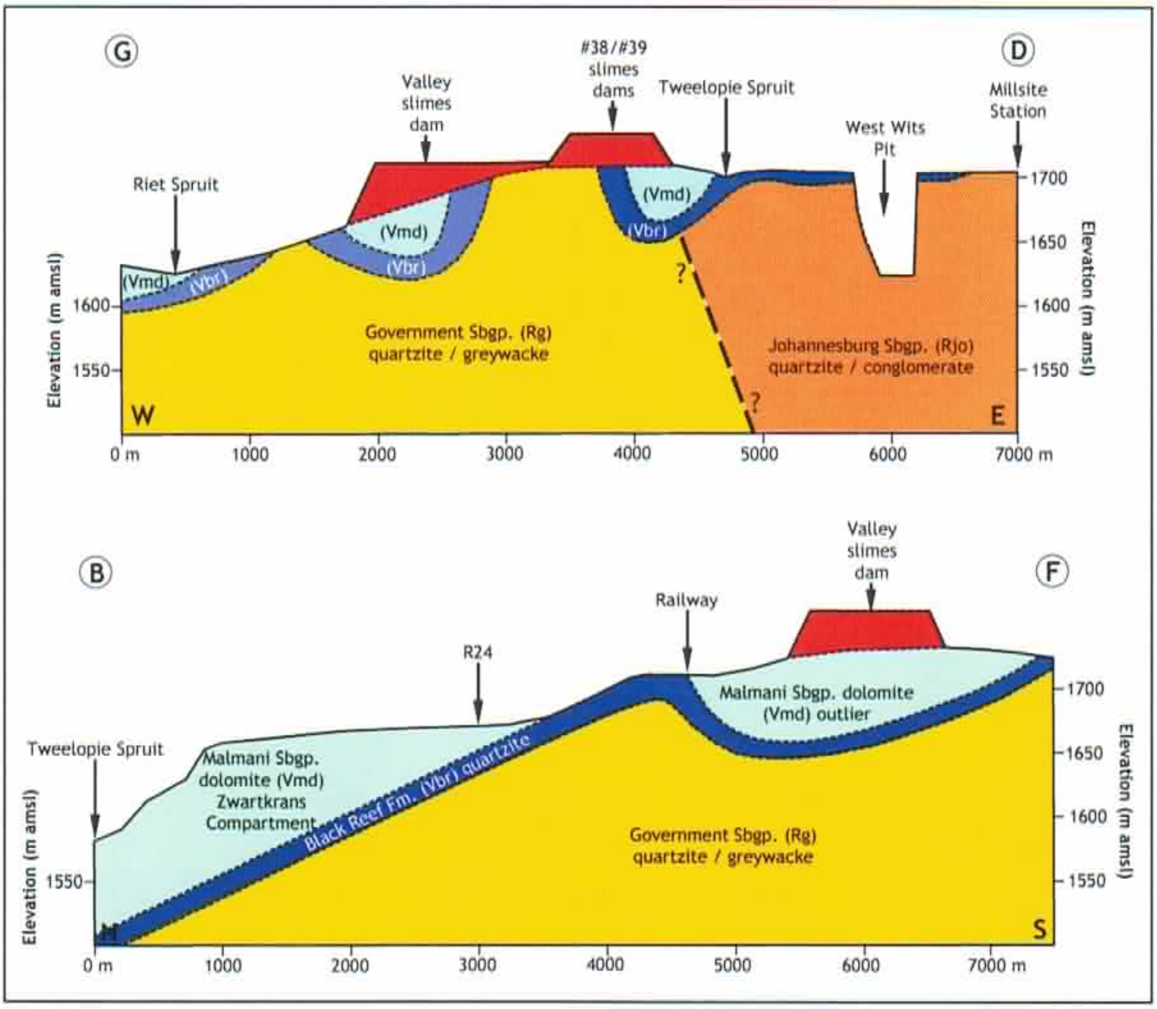


Figure 5b. Conceptual geologic profiles (see Figure 4 for profile positions)

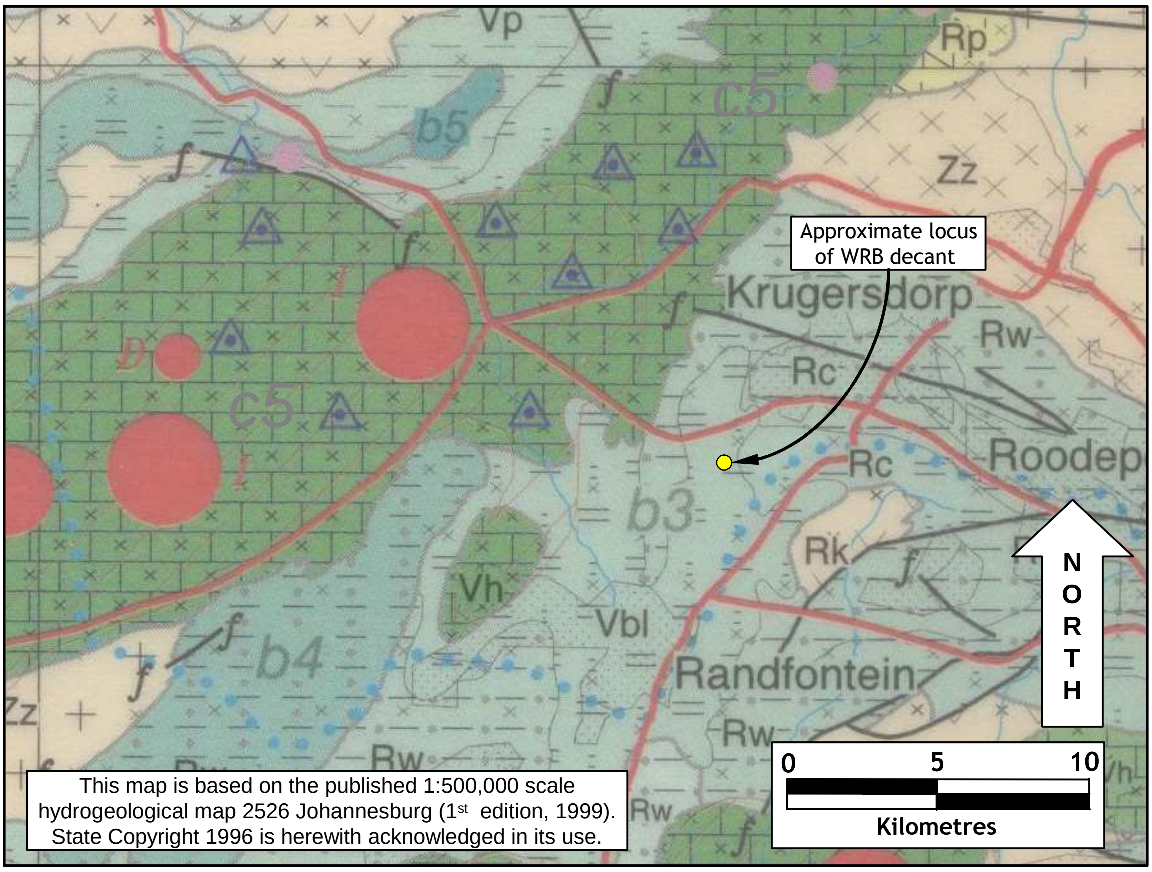
Closer to the locus of WRB decant, to the northeast thereof, Figure 4 indicates a WNW–ESE trending fault (the so-called Rietfontein Fault) cutting through the Witwatersrand strata and terminating in dolomite inside the northeastern boundary of the Krugersdorp Game Reserve (KGR). This strike direction characterises most faults and fracture systems in the subregion (Jamison, pers. comm., 2007). Under these circumstances, the structural geology of the Government Subgroup (GSbgp.) in the KGR, and its possible relevance to groundwater movement, needs to be determined as a matter of urgency. This concern finds support in the recognition, recorded in Section 10.2 of the Harmony Gold EIA Document (JFA, 2006), that "......... *an unqualified volume still escapes downstream into the Zwartkrans compartment via the Tweelopiespruit, mostly subsurface.*"

Dolerite intrusions mainly in the form of sub-vertical dyke structures, and occasionally in the form of sub-horizontal sills, represent equally significant structural geological features in the subregion. The role of the dyke structures in building compartments and subcompartments in the dolomitic formations is well documented (e.g. Bredenkamp et al., 1986; Rison, 2006), as is their concomitant role in controlling groundwater levels, discharge and flow. This influence is discussed in greater detail in section 3.2.

2.3 Hydrogeology

2.3.1 Regional hydrogeology

The region encompasses portions of the Karst Belt (#10) and Central Highveld (#17) groundwater regions as defined by Vegter (2001). The DWAF (1999) published hydrogeological map 2526 Johannesburg (portion replicated in Figure 6) indicates that these regions represent a karst and a fractured groundwater regime associated with the Malmani Subgroup and the Witwatersrand Supergroup, respectively. It also assigns the median borehole yield class *c5* (>5.0 L/s) to the karst aquifer, and *b3* (0.5 to 2.0 L/s) to the fractured aquifer in the region.



Approximate locus of WRB decant

This map is based on the published 1:500,000 scale hydrogeological map 2526 Johannesburg (1st edition, 1999). State Copyright 1996 is herewith acknowledged in its use.

Figure 6. Regional hydrogeology map

2.3.2 Local hydrogeology

The groundwater environment that hosts the acid mine drainage (AMD) occurrence comprises the karst aquifer associated with two outliers of Malmani Subgroup dolomite, and various fractured rock aquifers associated with the basin of Black Reef Formation strata and older basement rocks of the Central Rand and West Rand Groups (Table 1 and Figures 4, 5a and 5b). A more detailed description of these circumstances is given in section 3 of this report. Suffice at this stage to consider that a review of the available relevant decant-related hydrogeological literature (JFA, 2006; Rison, 2006) suggests that greater attention has been afforded the surface water environment and the relatively “far-field” groundwater environment in the Zwartkrans Compartment to the north of the locus of decant, and less to the hydrogeology of the decant area itself and the more immediate downgradient subsurface environment.

2.4 Hydrochemistry

The DWAF (2000) brochure that informs hydrogeological map sheet 2526 Johannesburg presents a synthesis of regional groundwater quality data for each of the rock types that occur in the subregion. These data provide a measure against which the chemistry of groundwater sourced locally from these strata can be assessed. The regional quality of groundwater per stratum is summarised in Table 2, and is illustrated graphically by means of Schoeller diagrams in Figure 7. Note that the Malmani Subgroup is here represented by the Chuniespoort Group.

Table 2. Summary of regional groundwater chemistry information per stratum (after DWAF, 2000)

Descriptor	Unit	West Rand Group	Central Rand Group	Black Reef Formation	Chuniespoort Group	SANS(1) Class I
Sample population	no.	81	18	52	223	
pH	pH units	7.2	7.3	7.0	7.6	5 – 9.5
Total Dissolved Salts	mg/L	254	207	238	444	< 1000
Electrical Conductivity	mS/m	37.3	29.3	34.3	62.9	< 150
Calcium	mg/L Ca	27.0	17.6	28.0	52.7	< 150
Magnesium	mg/L Mg	18.9	13.7	18.0	35.4	< 70
Sodium	mg/L Na	18.7	20.0	14.0	24.1	< 200
Potassium	mg/L K	1.8	2.6	1.7	2.3	< 50
Total Alkalinity	mg/L $CaCO_3$	117	85	98	177	n.s.
Sulphate	mg/L SO_4	16.1	33.5	36.0	70.5	< 400
Chloride	mg/L Cl	24.7	17.9	15.0	37.7	< 200
Nitrate	mg/L N	4.5	2.0	2.8	5.6	< 10
Fluoride	mg/L F	0.3	0.3	0.2	0.3	< 1

(1) SABS (2005) (see references)
n.s. not specified

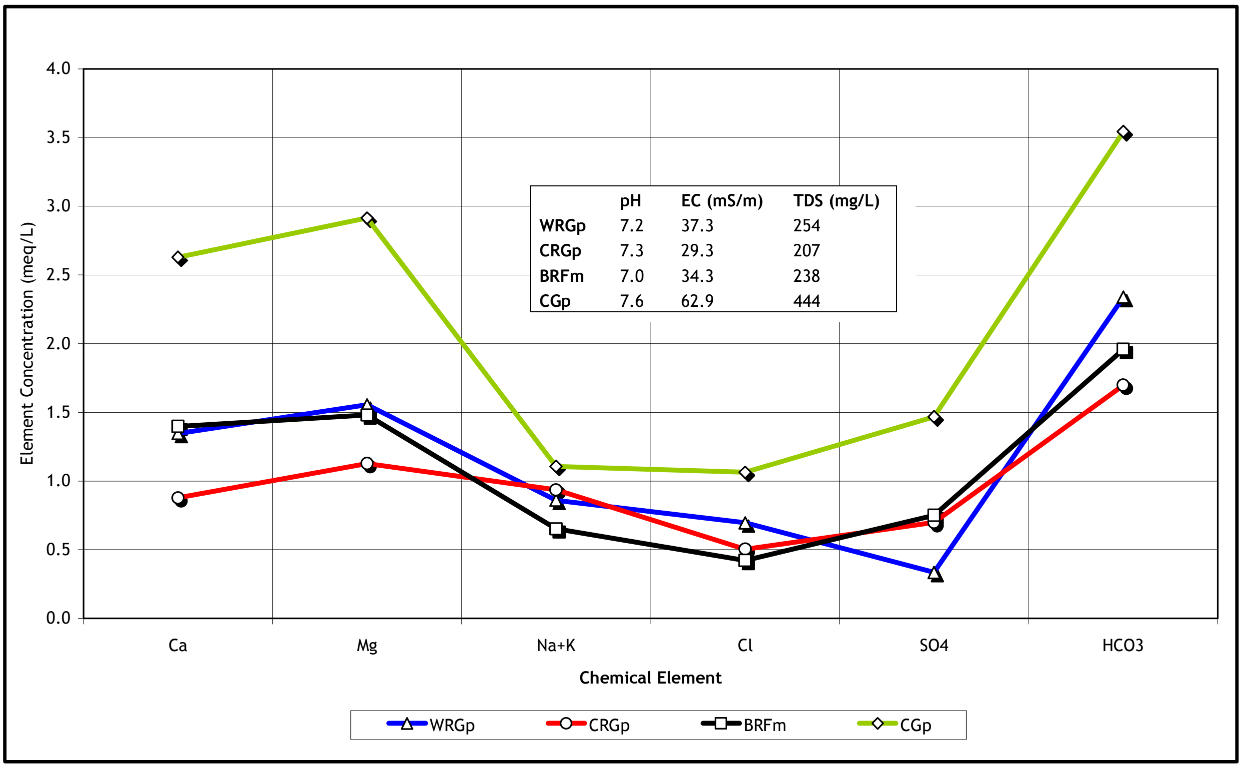


Figure 7. Schoeller diagram characterisation of stratum-hosted water chemistry (after DWAF, 2000)

It is evident from the regional groundwater chemistry data that the dolomitic strata exhibit a higher mineralisation and a more alkaline character than that of the other strata, although all appear to exhibit a magnesium-bicarbonate ($Mg—HCO_3$) composition. Figure 7 also shows the similar chemical composition of CRGp. and BRFm. groundwater, which might be expected given the lithologic and stratigraphic concordance between these strata, as is shown in Table 1.

3 DESCRIPTION OF THE GROUNDWATER ENVIRONMENT

A total of 61 geosites (Figure 8) were enumerated in February and March 2007 according to the scope, methodology and approach outlined in Annexure A. The sites were sourced for hydrogeological information (mainly rest water level and water quality) that might inform a better understanding of the groundwater environment and its inter-dependant components. The sites comprised 41 boreholes, 6 springs, 7 surface water (river/lake) sites and 7 mine sites (mainly shafts). The analysis and reduction of the data presented in Annexures D and E form the basis of a more informed description of the groundwater environment as documented hereunder.

3.1 Groundwater Occurrence

An inspection of Figure 4 suggests that groundwater occurrence in the study area is associated with three formations, viz. the Malmani Subgroup (MSbgp.) dolomite, the older Black Reef Formation (BRFm.) quartzite and the still older West Rand Group (WRGp.) strata. Of these, the dolomitic strata typically represent a karst aquifer characterised by modest (< 100 m^2/d) to extremely high (> 1 000 m^2/d) transmissivity values (Bredenkamp et al., 1986; Leskiewicz, 1986; Hobbs, 1988; Kuhn, 1989) and, despite karstification, modest (in the order of a few per cent) storativity values. The BRFm. and WRGp. strata might conceptually be associated with fractured aquifers characterised by similar modest to low (< 10 m^2/d) transmissivity and low (< 1 %) storativity values. In all instances, however, heterogeneity prevails over homogeneity. In the case of the MSbgp. strata, this is defined by zones of preferential dissolution (see section 3.2.2), and in the case of the BRFm. and WRGp. strata, by fault structures, fracture/joint patterns and bedding plane geometries.

Information obtained for two boreholes (sites 002 and 003, Figure 8) of different depth on Plot 37, Helderblom Agricultural Holdings, indicates the complex nature of groundwater occurrence in the MSbgp. dolomite. The boreholes some 120 m apart exhibit very similar depths to groundwater rest level (± 45 m), but differ in the chemical composition of the groundwater each produces (see section 3.3). Suffice to report here that in February 2007, the shallower (83 m deep) borehole (site 002) produced groundwater with a field EC of 18 mS/m, pH of 7.3 and temperature of 21.4°C, and the deeper (136 m) borehole (site 003) water with an EC of 32 mS/m, pH of 7.9 and temperature of 22.9°C. These observations indicate that heterogeneity in the karst aquifer is three-dimensional.

3.2 Groundwater Flow Pattern

3.2.1 Regional scale

Bredenkamp et al. (1986) state that "*Ground-water in the Zwartkrans compartment drains north-east to the Danielspruit and Kromdraai springs.*" Although not mentioned, it must be presumed that the much stronger Zwartkrans Spring delivering 258 L/s (Bredenkamp et al., 1986) also drains this compartment under circumstances where the Daniel Spruit and (3 L/s), and Kromdraai springs deliver only 3 L/s and 28 L/s respectively (Bredenkamp et al., 1986). All three these springs are located outside the present study area.

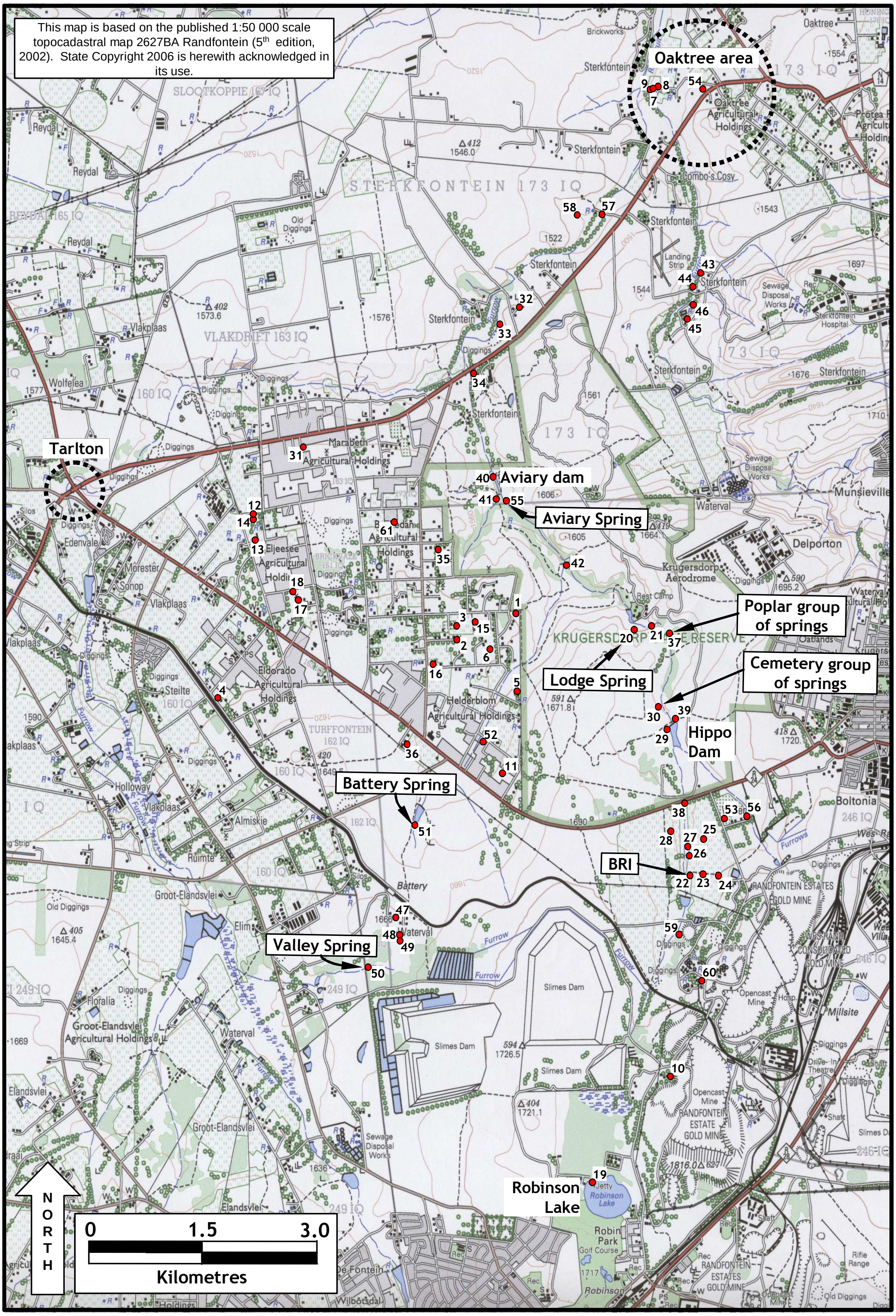


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Figure 8. Geosite locality map

Bredenkamp et al. (1986) subdivide the Zwartkrans Compartment into nine subunits based mainly on sharp transitions in water level over short distances, with partial verification of bounding dyke structures using ground and airborne geophysical information. This reasoning rests on the premise of very weak (essentially flat) hydraulic gradients in each subunit. Flat hydraulic gradients within subunits was also put forward as the reason for not contouring water levels (Bredenkamp et al., 1986). It is also notable that the difference in "representative water level" between the five subunits B, C, D, E and F located north of the study area, is only some 70 m over a distance of roughly 8 km, i.e. little more than 10 m/km or 14 m per subunit. These circumstances, and the comparatively sparse set of water level data employed, raises doubt over the recognition of an overly disrupted groundwater flow pattern due to barrier boundaries and associated sub-compartmentalistion.

3.2.2 Subregional and local scale

The reduction of 48 depth to groundwater rest level measurements to absolute groundwater elevations based on surface elevations interpolated to ± 1 m accuracy from 1:10 000 scale orthophoto maps, together with six similarly-derived spring elevations, forms the basis of the groundwater contour map presented in Figure 9. This map also shows flow directions that describe groundwater movement in the study area. These flow directions are replicated in the conceptual hydrogeologic profiles presented in Figures 10a and 10b, which further show the potentiometric surface that defines the hydraulic head in the various aquifers and the hypothetical flow directions associated therewith.

The potentiometric surfaces shown in Figure 10a clearly indicate a separation of some 20 m between the potentiometric surface and the streambed elevation along the course of the Riet Spruit in the vicinity of the confluence with the Tweelopie Spruit. It is in this vicinity that the Tweelopie Spruit becomes an influent stream, i.e. it loses water to the groundwater environment. For most of its reach upstream of this position, the Tweelopie Spruit is an effluent stream receiving dolomitic groundwater mainly from the MSbgp. outliers to the south, e.g. via the Cemetery and Poplar groups of springs (see Figure 12) and the Zwartkrans Compartment, e.g. via Flip-se-Gat stream and the Aviary Spring. The Riet Spruit is also a dry stream upstream of its confluence with the Tweelopie Spruit, having lost the flow from its upper reaches (sustained mainly by the treated effluent discharge from the Randfontein WWTW) to the westerly Steenkoppies Compartment (Barnard, 1996a) by the time it reaches Tarlton. Only the former of these circumstances have been investigated and verified during this study.

The influent nature of the Riet Spruit downstream of its confluence with the Blougat Spruit and past the Sterkfontein Cave system is recorded in stream flow gaugings reported by Bredenkamp et al. (1986). These gaugings reflect a decrease in stream discharge from 200 L/s in the Blougat Spruit immediately downstream of the Percy Stewart WWTW, to a discharge of only 13 L/s in the Riet Spruit north of (opposite) the Sterkfontein Caves and about 1 km upstream of the Zwartkrans Spring. Immediately downstream of the Zwartkrans Spring, these gaugings reflect a surface flow of 258 L/s in the Blaauwbank Spruit, most of which must be equated to the discharge of the spring. This value is replicated in the 2004 water balance for the Zwartkrans Compartment presented by Rison (2006).

A more detailed "final" water balance reported in JFA (2006) reflects a discharge of 208 L/s (18 ML/d) in the Blaauwbank Spruit (presumably in the vicinity of the Zwartkrans Spring), comprising a 172 L/s component described as "*Canal leaving stream at Danielsrust*" and a 36 L/s component described as "*River flow leaving compartment*". It is not clear how these components relate to the Zwartkrans Spring. A DWAF meeting held on 28 February 2007 at HGMs Office Complex in Randfontein was informed that the Zwartkrans Spring was dry, and that any flow in this vicinity represented surface runoff. This was in response to a query regarding the potentiometric level of groundwater in the Sterkfontein Caves (reportedly 1436 m amsl) *vis-à-vis* the elevation of the spring (reportedly 1439 m amsl). These circumstances were put forward as evidence that the water level in Sterkfontein Cave could not rise more than 3 m, i.e. up to the level at which the dolomitic compartment would overflow via the Zwartkrans Spring.

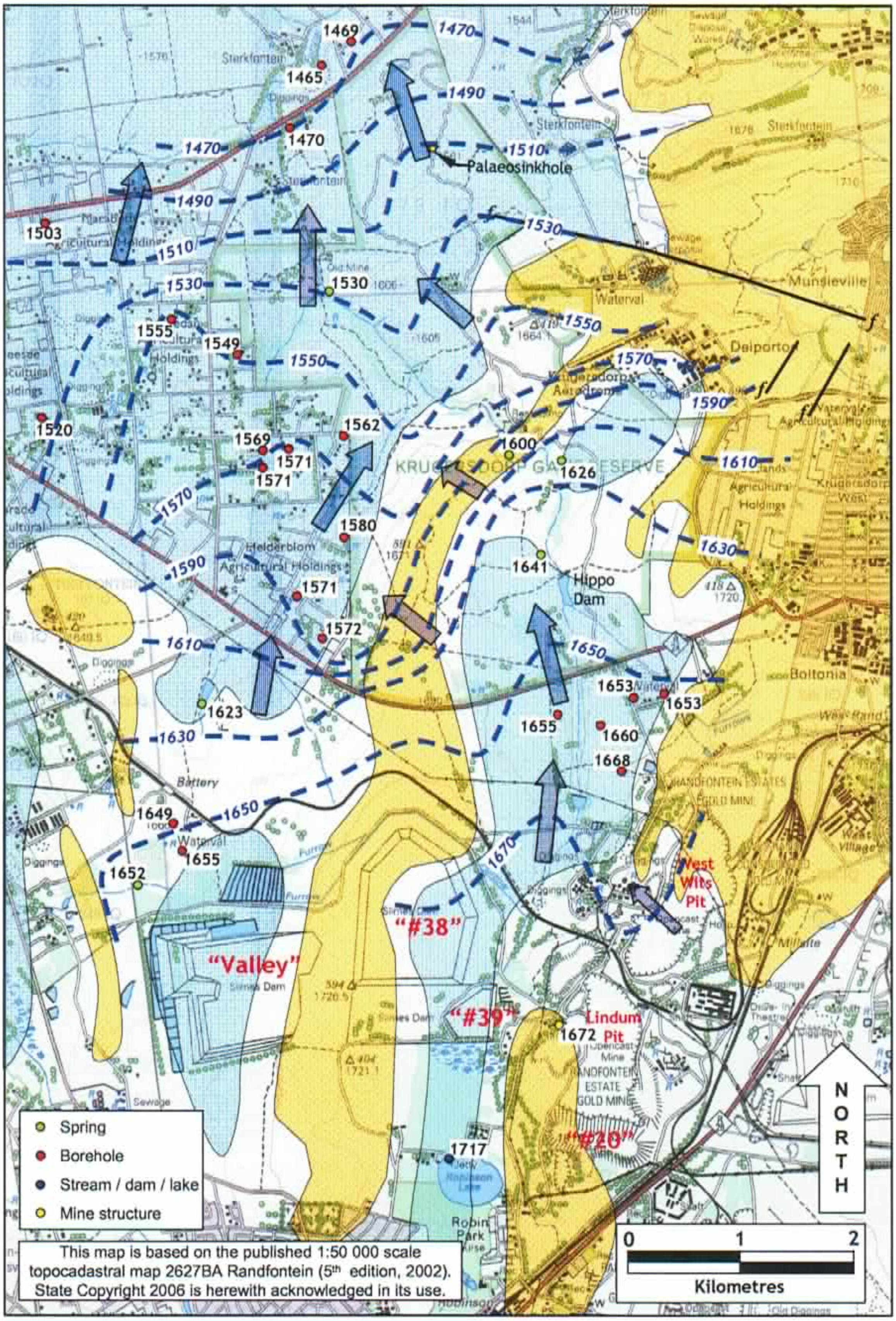

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Figure 9. Groundwater contour map, February/March 2007 (geology as per Figure 4)

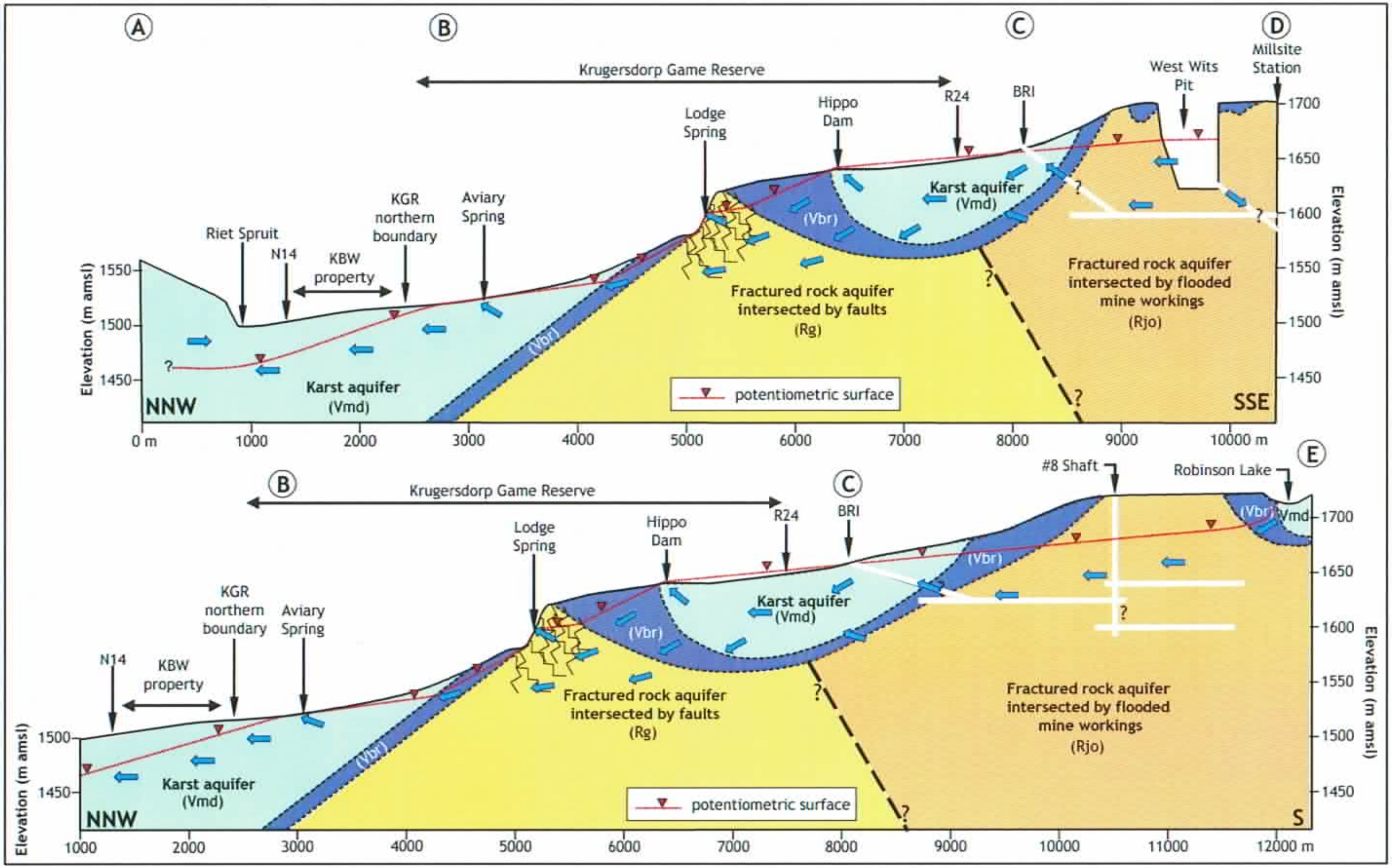


Figure 10a. Conceptual hydrogeologic profiles (see Figure 4 for profile positions)

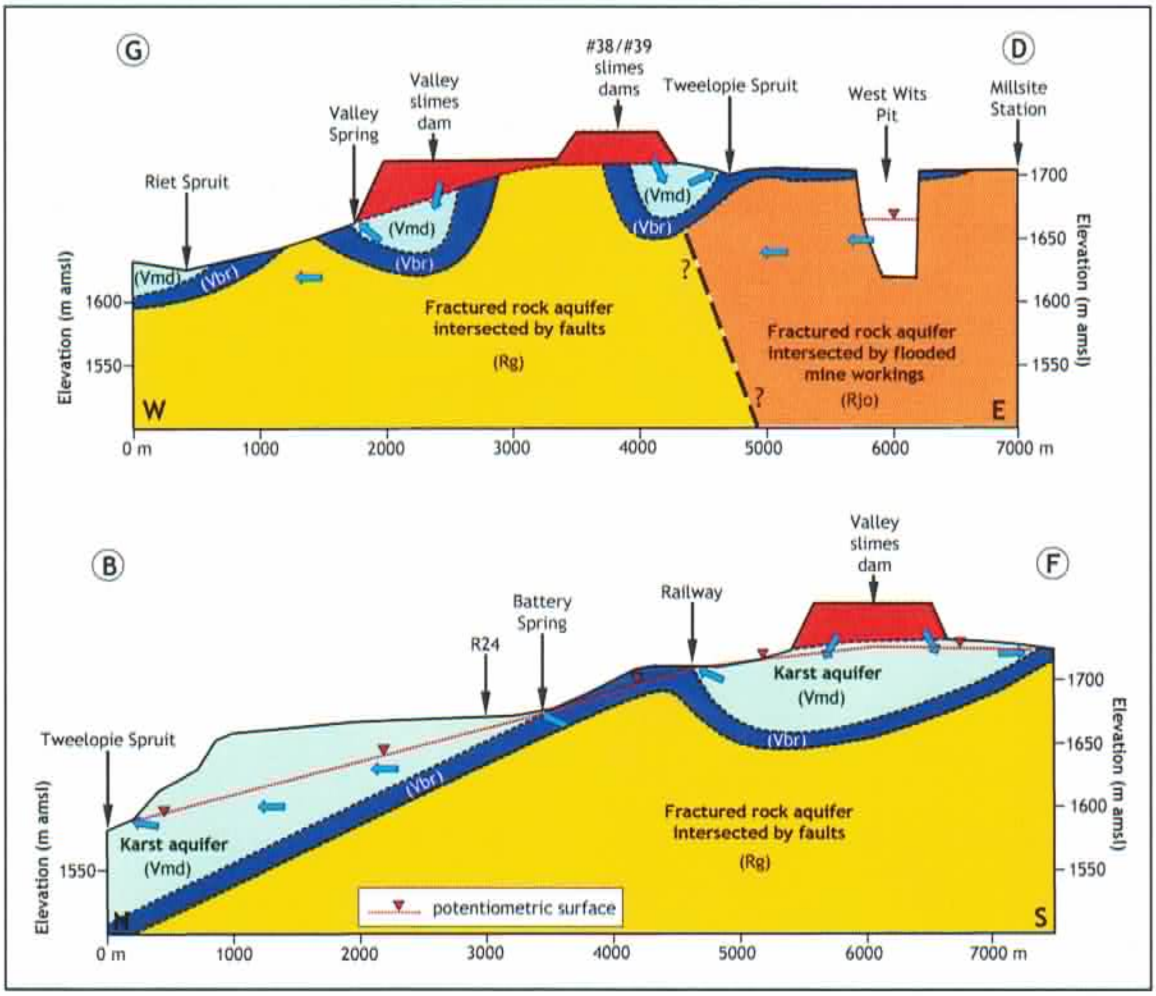
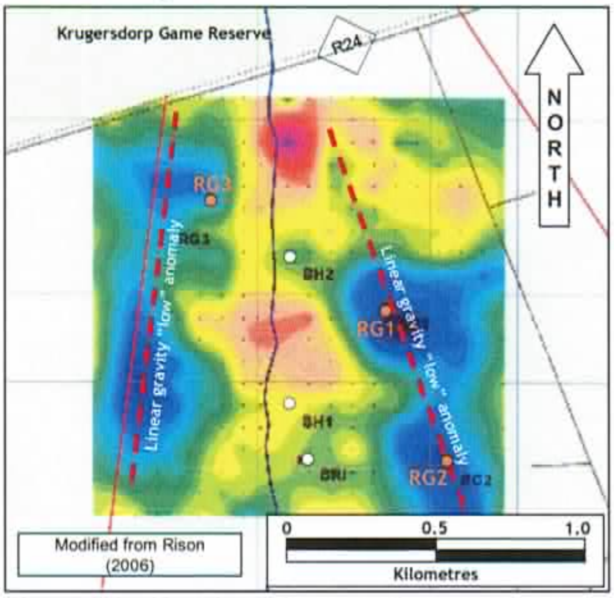


Figure 10b. Conceptual hydrogeologic profiles (see Figure 4 for profile positions)

The footprint of a gravimetric survey carried out for Harmony Gold Mine (HGM) around the Black Reef Incline (BRI) is shown in Figure 4. The outcome of this survey, encompassing some 90 ha (±950 m x 950 m at a station interval of 50 m), is presented in Figure 11. It shows that the two older "scavenger boreholes" BH1 and BH2 are located within a gravity "high" zone ostensibly associated with more dense (less leached) dolomite. Three newer boreholes (RG1, RG2 and RG3) are located within gravity "low" zones ostensibly associated with less dense (more leached) dolomite flanking the gravity "high". These zones pose a hydrogeological concern, since they define routes of preferential and accelerated groundwater movement conjointly with their roughly north-south strike. This interpretation needs, however, to be qualified under circumstances where the source diagram does not indicate the scale of density variation represented by the applied shading. Nevertheless, the possible extension of these features northwards into the KGR needs to be established as a matter of urgency.



Modified from Rison (2006)

Figure 11. Gravimetric map of an area around the locus of original decant

3.3 Water Quality

The sourcing in February and March 2007 of field water quality parameters (electrical conductivity, pH and temperature) at 49 sites (mainly boreholes and springs) in the study area, and an equal number of more complete chemical analyses, serves as basis to expand on the generic evaluation presented in section 2.4. The reader is referred to Figure 12 for the position of most of these sites in relation to the geology of the study area — attention is also drawn to the names assigned the various springs enumerated during this study. These data augment similar information sourced from the DWAFs National Groundwater Archive (NGA) and other “local” monitoring initiatives such as that by Mr. Stephan du Toit of Mogale City for and on behalf of the latter, and Mr. Dave Dorling of DD Science (DDS) for and on behalf of Harmony Gold Mine (HGM). The DWAF data exhibits a fair distribution between groundwater level and groundwater quality information. Whereas the latter include sources located within the outlier, groundwater level data is limited to the karst aquifer in the Zwartkrans Compartment.

3.3.1 Malmani Subgroup

The quality and chemical composition of groundwater currently produced by the karst aquifer, both in the Zwartkrans Compartment immediately north of the KGR and in the dolomite outlier, is represented by 21 recent analyses associated with the sites listed hereunder. The relevance of these sites informs their contribution to the results of this study. Note that the list excludes sites such as 024 (HGM exploration borehole RG2), 034 (the KBW borehole), 043 (the Travers borehole), 052 (the L. Fourie borehole), 053 (the A. Jacobs borehole) and 055 (the Aviary spring) which exhibit patently anomalous chemical compositions due to impacts from extraneous sources. These sites are addressed separately in section 3.4.6. Perhaps surprisingly under these circumstances, the list includes site 028 (Figures 8 and 16) located within the main dolomite outlier and not too far from the locus of decant, viz. the BRI and surrounds.

GEOSITE*	DESCRIPTION	RELEVANCE OF SITE LOCATION TO THE STUDY
001	Garden irrigation supply	Helderblom A.H. upgradient of Lion Camp drainage
002	Irrigation supply	Helderblom A.H. west of KGR
003	Potable & irrigation water supply	Helderblom A.H. west of KGR
004	Potable water supply	Eldorado A.H. near Upper Riet Spruit
006	Potable water supply	Helderblom A.H. upgradient of Lion Camp drainage
007	Irrigation water supply	Oaktree A.H. ± 150 m from the Riet/Blougat Spruit
008	Potable & irrigation water supply	Oaktree A.H. ± 350 m from the Riet/Blougat Spruit
009	Potable & irrigation water supply	Oaktree A.H ± 25 m from the Riet/Blougat Spruit
013	Potable & irrigation water supply	Eljeesee A.H.
014	Irrigation water supply	Eljeesee A.H.
016	Potable & irrigation water supply	Helderblom A.H.
018	Potable water supply	Eljeesee A.H.
028	HGM exploration borehole RG3	Main dolomite outlier ± 630 m northwest of the BRI
031	Potable water supply	Marabeth A.H.
032	Potable & nursery water supply	Downstream of KGR where Riet Spruit is influent
035	Potable water supply	Beckedan A.H. upgradient of “Flip-se-Gat” drainage
036	Potable & irrigation water supply	Helderblom A.H.
054	Potable water supply	Oaktree A.H. ± 550 m from the Riet/Blougat Spruit
057	Potable water supply	Alongside Riet Spruit between Môrester and Oaktree

* CSIR ID See Figures 8 and 12 for the position of these sites

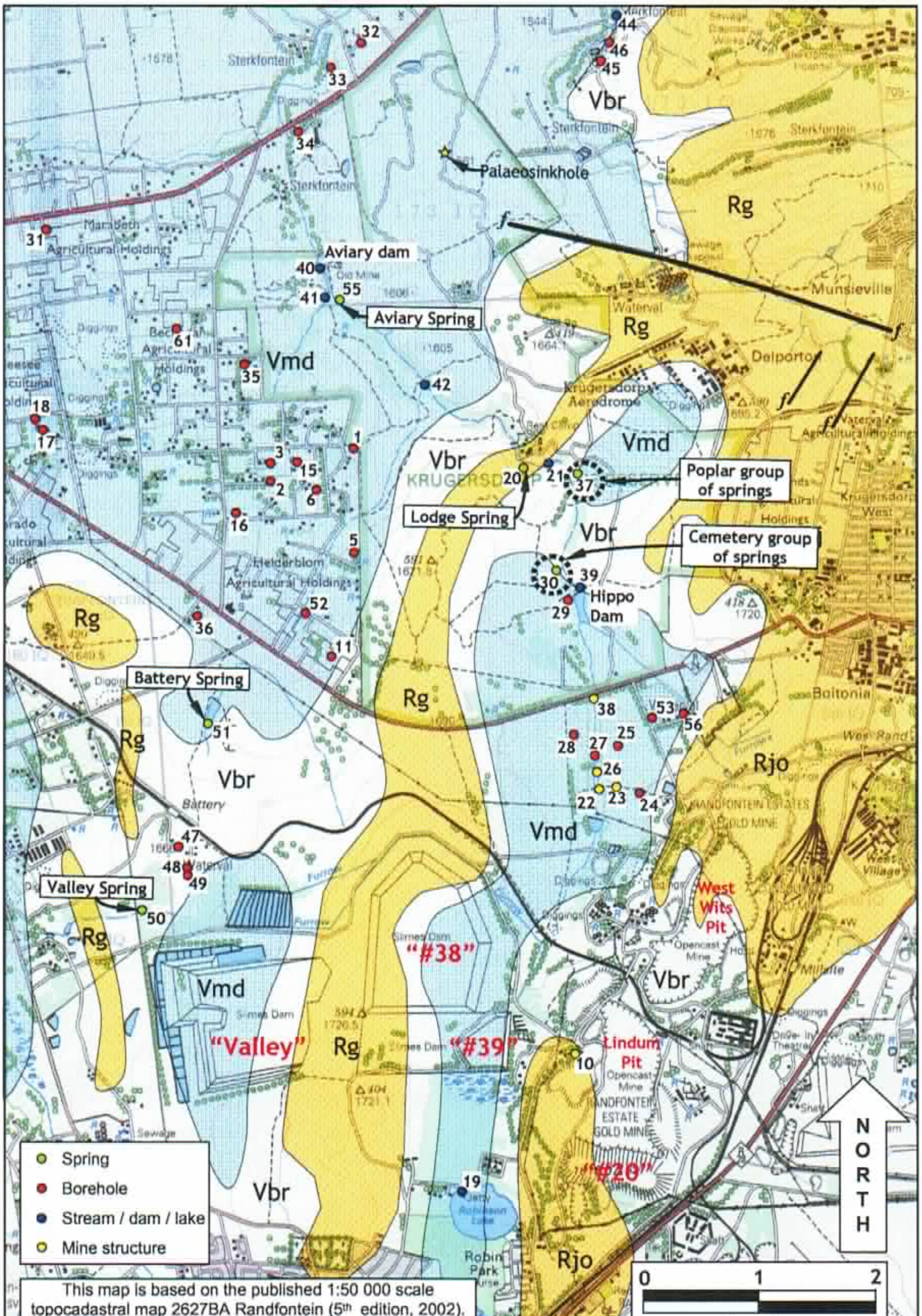


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Figure 12. Distribution of surface, mine and groundwater quality sampling stations (geology as per Figure 4)

The groundwater quality and chemical composition at the above-listed sites is illustrated in Figures 13 and 14. The following aspects warrant mention.

- The groundwater demonstrates two distinct groupings that are provisionally identified as the “Smallholdings” and the “Lower Riet Spruit” groups on the basis of their geographic location within the Zwartkrans Compartment (Figure 15). The former generally exhibit the characteristic calcium-bicarbonate (Ca—HCO_3) chemical composition and lower mineralisation of natural dolomitic groundwater, whereas the latter exhibit an anomalous calcium-sulphate (Ca—SO_4) composition and higher mineralisation. The right ternary diagram (Figure 14) shows the measure of sulphate increase from the Smallholdings Group to the Lower Rietspruit Group.

- The differing plotting positions of sites 002 and 003 suggest the existence of vertical variation in groundwater quality in the MSbgp. dolomite (at least in the Smallholdings area). These sites, both boreholes on Plot 37, Helderblom A.H., represent drilled depths of 83 m and 136 m respectively The chemical difference is more clearly defined in Figure 16, which includes minor and trace element levels.

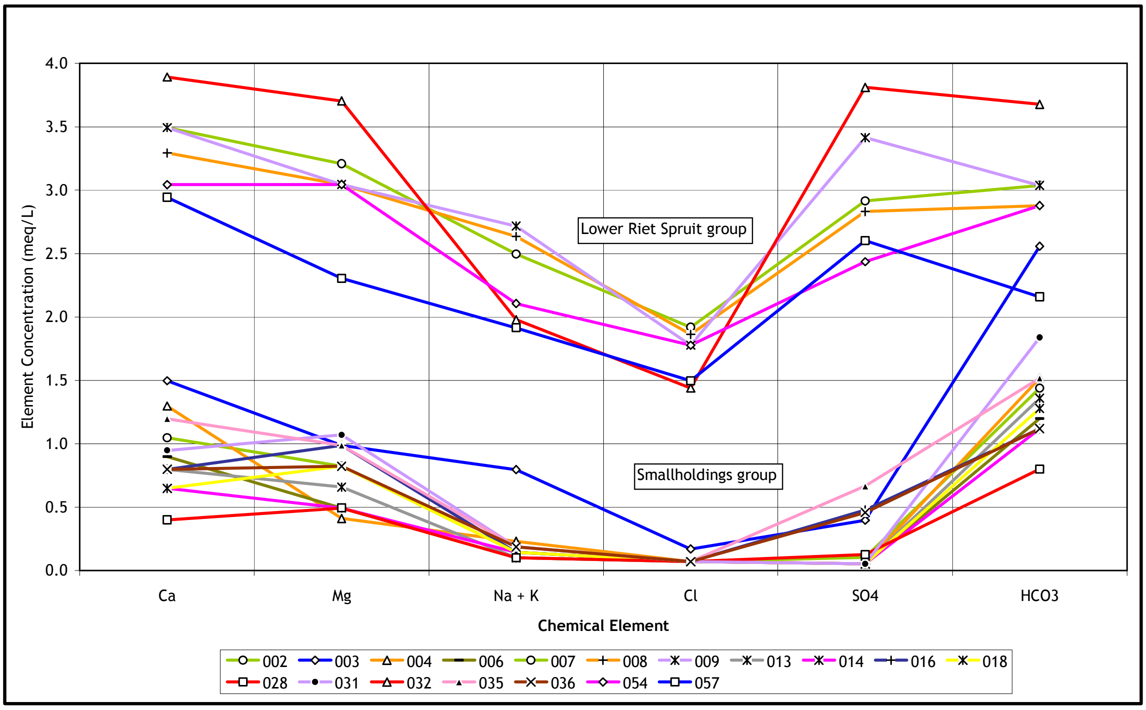


Figure 13. Schoeller diagram characterisation of Malmani Sbgp. water chemistry

Figure 16 reveals that the shallower groundwater (site 002) has an elevated nitrate (NO_3-N) and boron (B) concentration that is readily attributable to its closer proximity to the active practice of irrigated maize cultivation on the property and surrounds. The deeper groundwater (site 003) exhibits elevated sodium (Na), chloride (Cl), sulphate (SO_4), fluoride (F) and manganese (Mn) levels relative to that of the shallower groundwater. The difference extends to temperature, pH and EC values [the deeper source (003) exhibits a warmer, more alkaline and mineralised character] as well as the calcite and dolomite saturation index values (see Annexure G). One possible explanation is the mixing of the deeper dolomitic groundwater with quartzitic (BRFm. and WRGp.) groundwater. This finds support in the greater ^{222}Rn concentration of 15.4 ± 0.8 Bq/L in the deeper dolomitic groundwater compared to the 5.0 ± 0.31 Bq/L in the shallower groundwater (Kotze, 2007), under circumstances where the highest ^{222}Rn concentration (65.1 ± 3.3 Bq/L) was sourced from the Lodge Spring draining WRGp. strata.

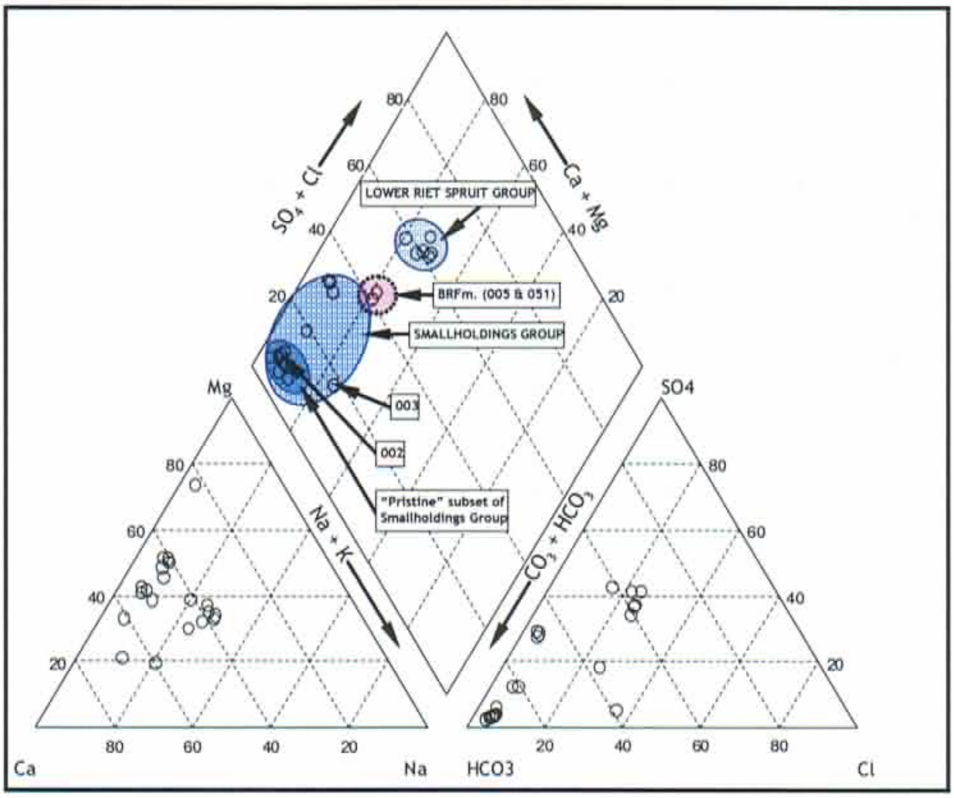


Figure 14. Piper diagram characterisation of Malmani Sbgp. and BRFm. water chemistry

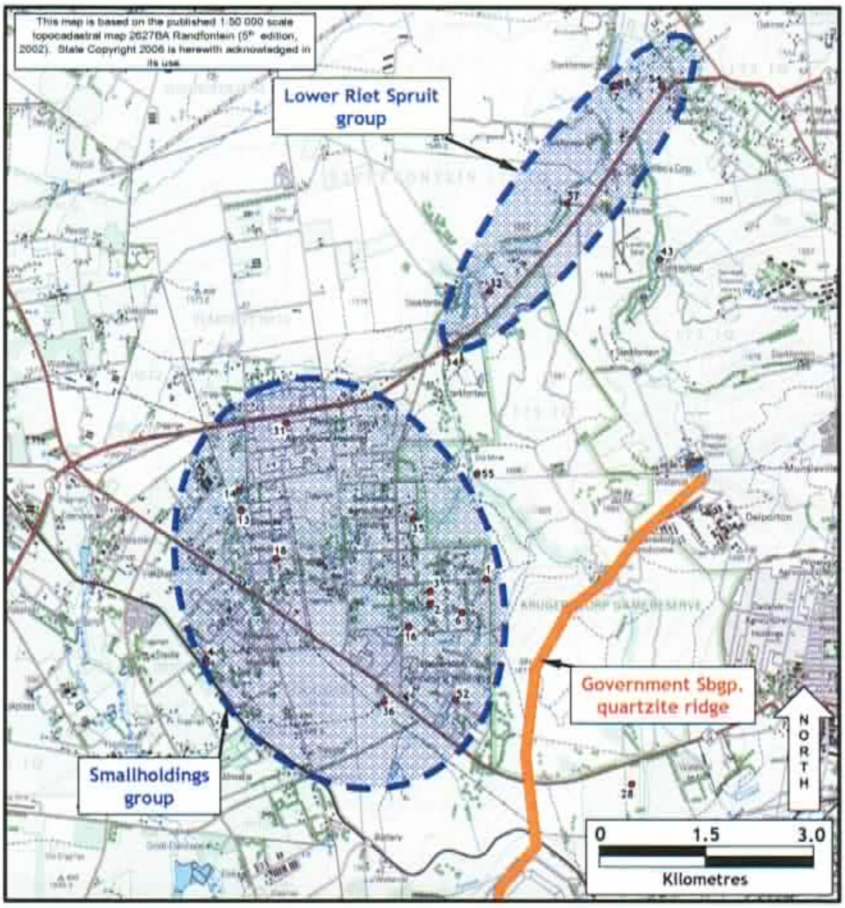


Figure 15. Locality map of Malmani Sbgp. water chemistry groupings

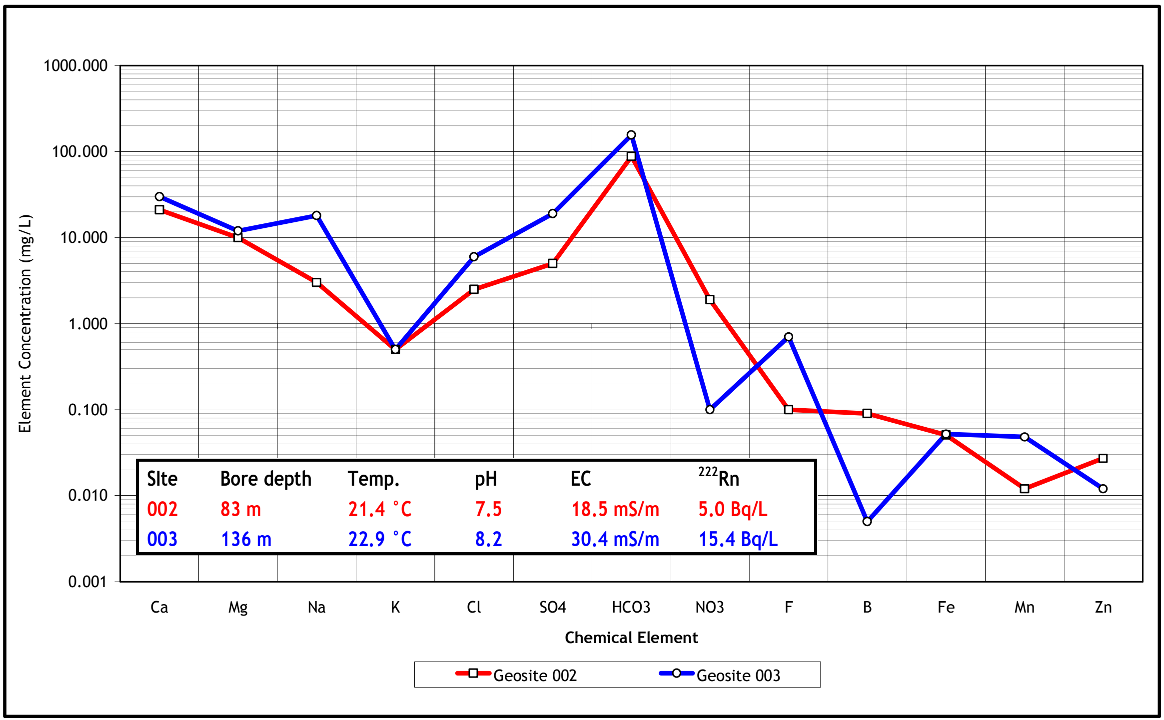


Figure 16. Difference in dolomite water chemistry between adjacent boreholes of different depth

3.3.2 Black Reef Formation

The study enumerated five geosites ostensibly producing groundwater from the BRFm. quartzite. These are identified hereunder as sites 005, 045, 047, 051 and 056. The reader is referred to Figure 12 for the position of these sites in relation to the geology of the study area. Of these, sites 005 and 051 may be considered the most representative of ambient natural groundwater associated with this stratum due to their geological setting and comparative remoteness from potential contamination sources. Further, it is shown in section 3.4.3 that the groundwater obtained from sites 045 and 056 show a similarity to West Rand Group groundwater. The chemical composition of the groundwater from these sites is illustrated in Figure 17. Under circumstances where the groundwater quality associated with site 047 exhibits, amongst others, an anomalously elevated sulphate concentration of 326 mg/L, it is not considered representative of Black Reef Formation groundwater.

GEOSITE*	DESCRIPTION	RELEVANCE OF SITE LOCATION TO THE STUDY
005	Potable water supply	Helderblom A.H. close to MSbgp./BRFm. contact
045	Potable water supply	Elevated position east of Blougat Spruit on BRFm.
047	Potable water supply	On BRFm. within cattle kraal north of Valley slimes dam
051	Spring	Natural drainage from BRFm. north of Battery railway station
056	Potable water supply	Close to MSbgp./BRFm. contact east of BRI in main outlier

* CSIR ID See Figures 8 and 12 for the position of these sites

Figure 17 indicates that the BRFm. groundwater exhibits a calcium-bicarbonate (Ca–HCO_3) chemical composition similar to that of natural dolomitic groundwater. This finds support in the Piper diagram plotting position of these samples (Figure 14) in proximity to the Smallholdings grouping of Malmani Sbgp. samples.

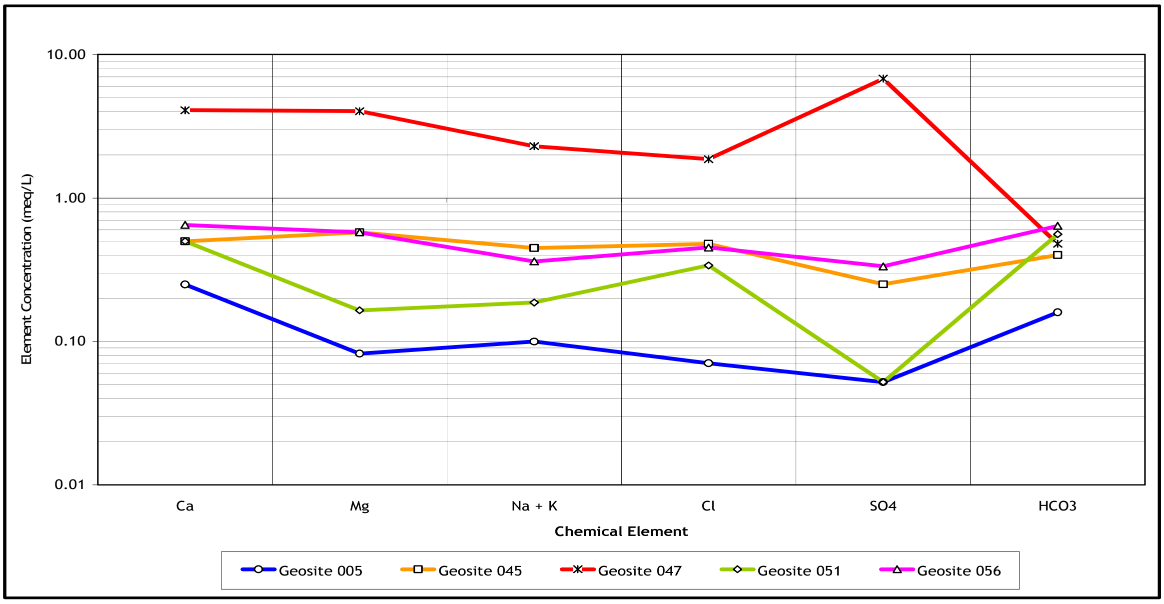


Figure 17. **Schoeller diagram characterisation of BRFm. water chemistry**

3.3.3 West Rand Group

The Lodge Spring (site 020) in the KGR ostensibly produces the single most representative groundwater from these strata, and in particular the Government Subgroup (GSbgp) quartzite. It is likely that the borehole identified as site 011 in the Helderblom A.H. (Figure 12) also draws water from this lithology, but is probably compromised in this regard by its prior intersection of the overlying BRFm. quartzite at this location. It is also likely that sites 045 and 056 (Figure 12) already associated with BRFm. strata (section 3.4.2), also penetrate the underlying GSbgp. strata. This possibility finds support in the comparative chemical compositions, especially the Mg—Cl character associated with site 045 as illustrated in Figure 18. The Piper diagram characterisation of this groundwater is shown in Figure 19, which also shows that the site 056 plot position lies closest to that which characterises BRFm. groundwater.

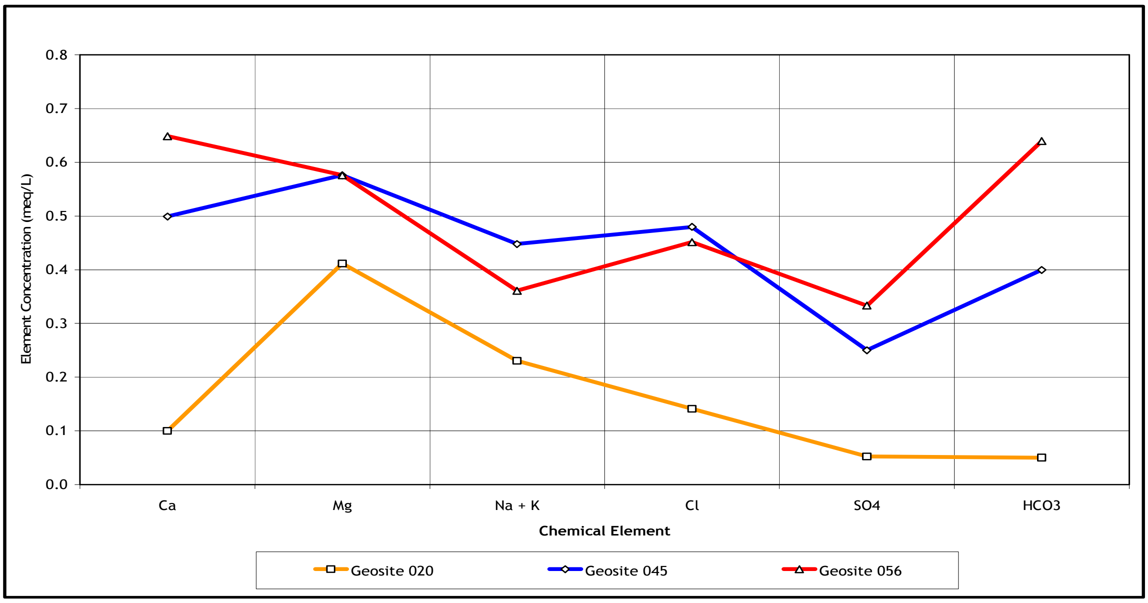


Figure 18. **Schoeller diagram characterisation of WRGp. water chemistry**

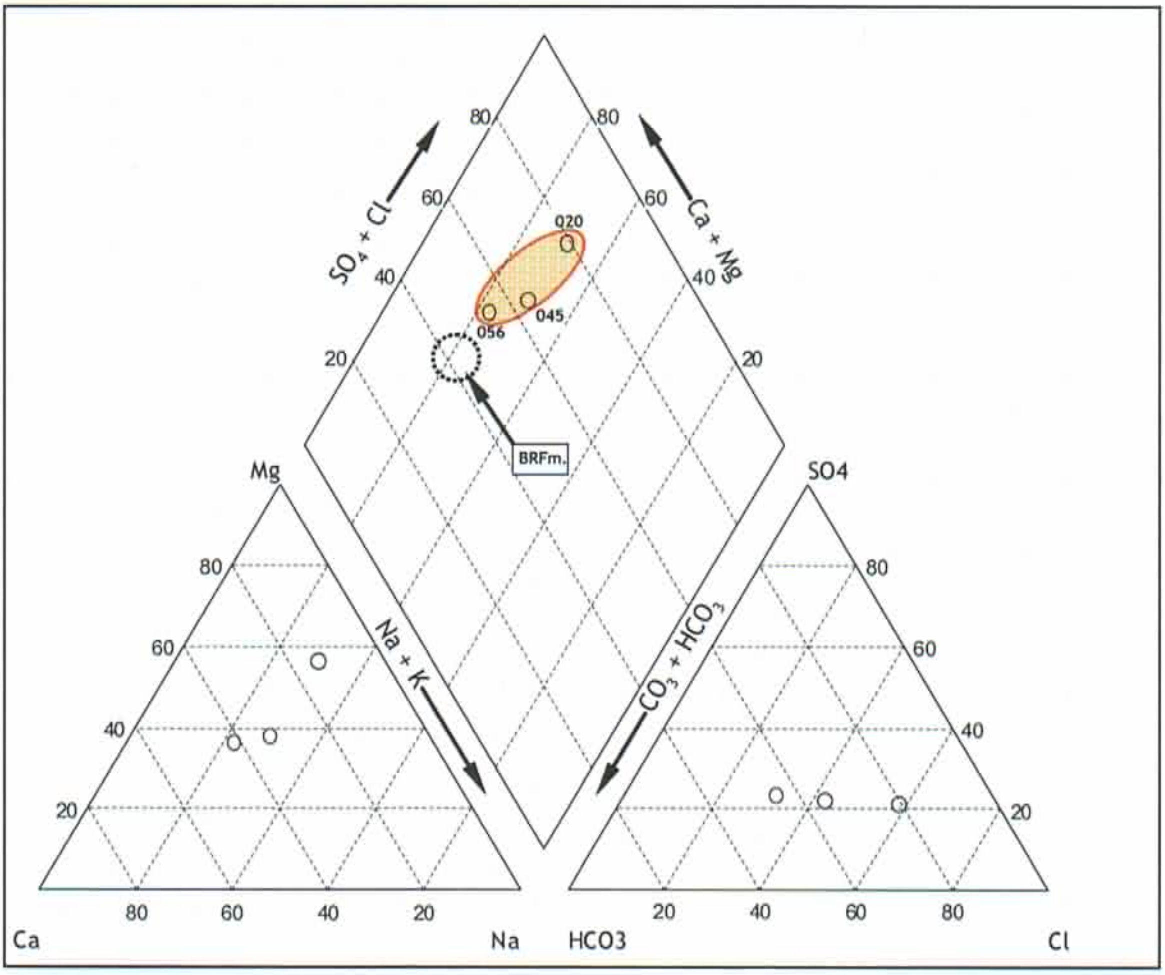


Figure 19. Piper diagram characterisation of WRGp. water chemistry

3.3.4 Mine water

Point sources of mine water (in essence acid mine drainage or AMD) that were sampled for this study are represented by the following stations.

GEOSITE*	OTHER IDENTIFIER	TYPE	MOST PROBABLE SOURCE
010	#8 Shaft	Mine shaft	Defunct underground workings
019	Robinson Lake	Surface water body	Occasional process water dam
022	Black Reef Incline	Mine shaft	Defunct underground workings
023	18 Winze	Mine shaft	Defunct underground workings
025	RG1	Exploration borehole	Intrusion of mine water
026		Artesian discharge	Defunct underground workings

* CSIR ID See Figures 8 and 12 for the position of these sites

The essentially calcium-sulphate (Ca$-$SO$_4$) chemical composition of mine water sourced from the above-listed sites is illustrated in Figures 20 and 21. Figure 20 includes the chemical composition of Robinson Lake water which, although a surface water source, is used as an "occasional" process water dam by HGM. These stations fall within the core grouping of AMD water illustrated in the Piper diagram (Figure 22). The following aspects warrant mention.

- The groundwater from borehole RG1 (site 025), which is only 36 m deep, shows a similar overall chemical composition as that obtained from #8 Shaft (site 010).
- The RG1 and #8 Shaft mine water is noticeably different in chemical composition from that produced by the BRI (site 022), 18 Winze (site 023) and the artesian discharge (site 026), which all show a greater similarity with Robinson Lake water.

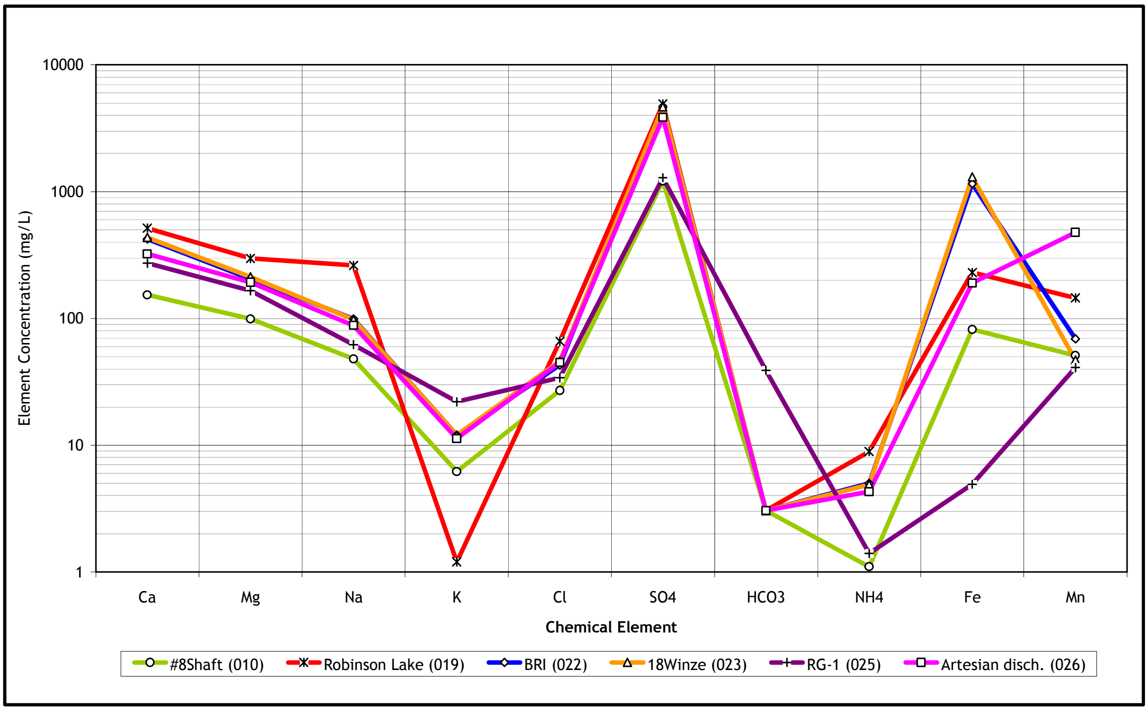


Figure 20. Parts per million characterisation of local mine water (AMD) chemistry

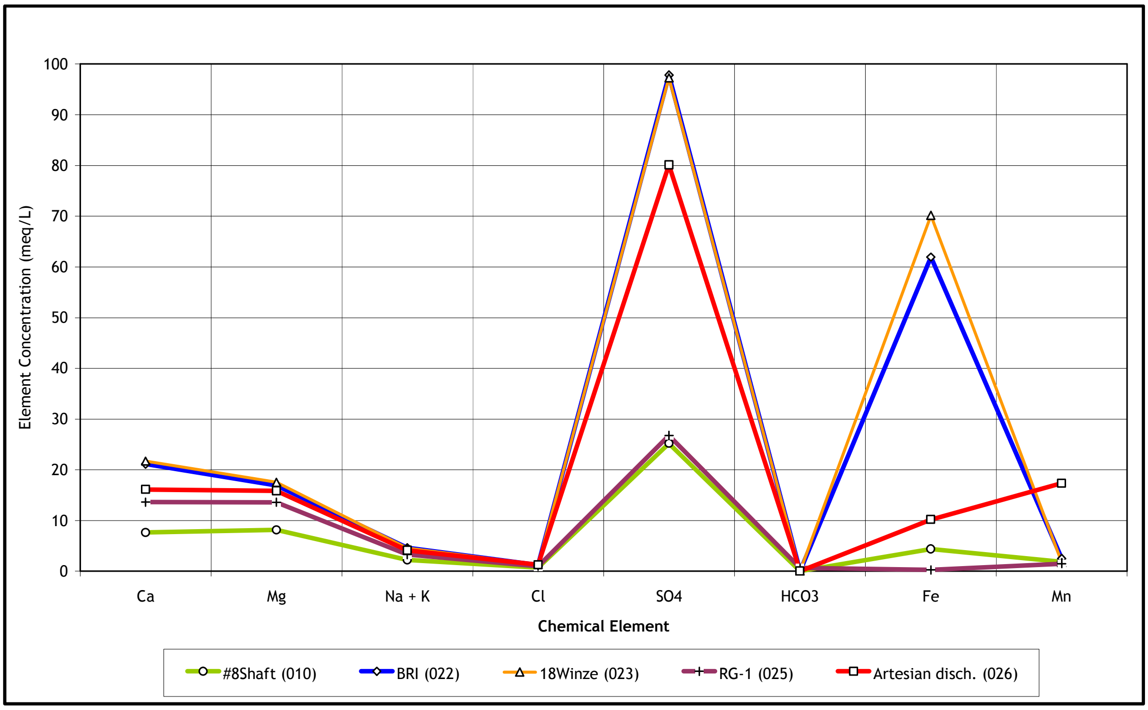


Figure 21. Schoeller diagram characterisation of local mine water (AMD) chemistry

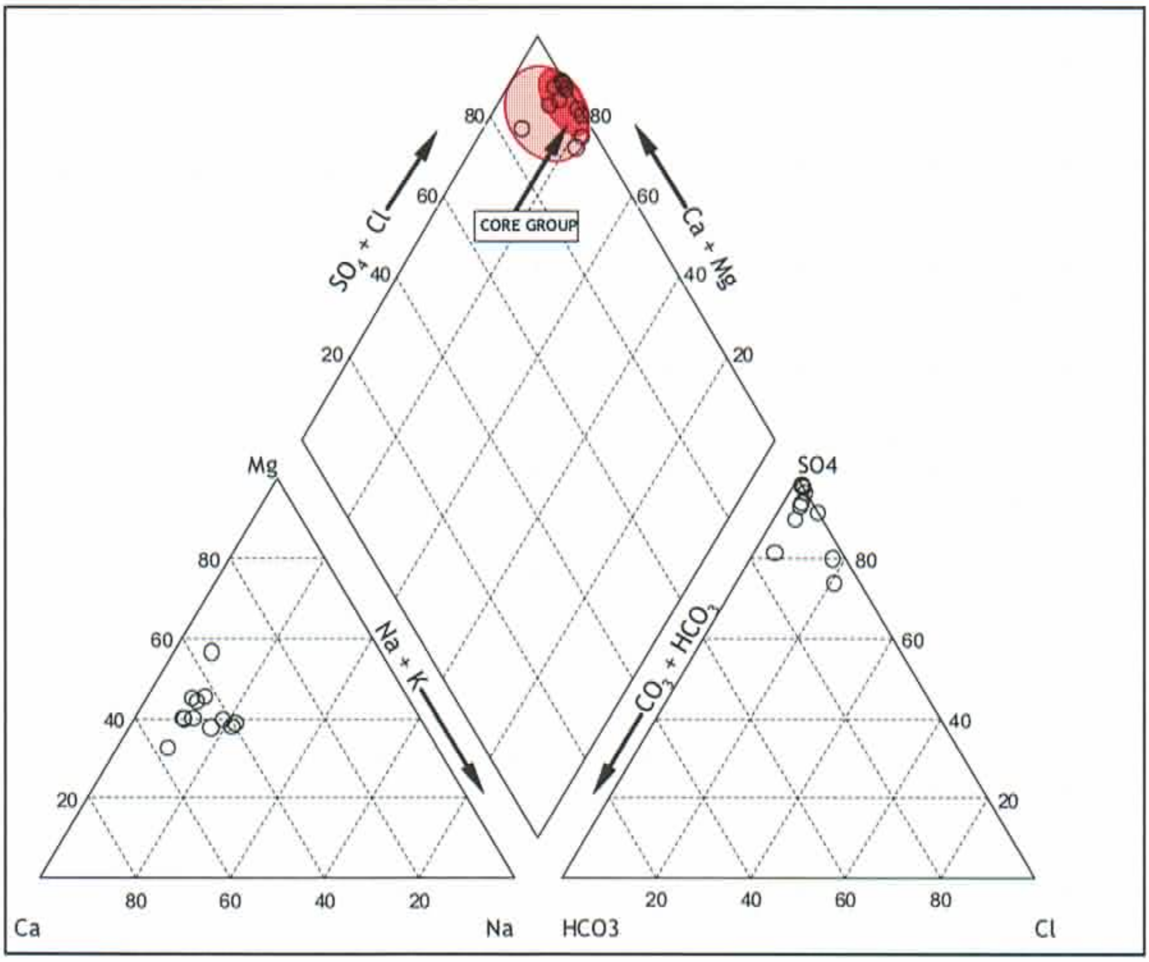


Figure 22. Piper diagram characterisation of AMD and associated water chemistry

Sources of groundwater that exhibit signs of contamination by mining activity, by virtue (amongst others) of their "anomalous" quality when compared to ambient natural stratum-specific groundwater quality, are listed as follows.

GEOSITE*	OTHER IDENTIFIER	TYPE	MOST PROBABLE SOURCE
030	Spring 2	Spring in Cemetery group, KGR	Mine water intrusion into MSbgp.
037	Poplar Spring	Spring in Poplar group, KGR	Mine water intrusion into MSbgp.
047		Water supply borehole	Valley slimes dam
049		Water supply borehole	Valley slimes dam
050	Valley Spring	Spring	Valley slimes dam
055	Aviary Spring	Spring	Mine water intrusion into MSbgp.

* CSIR ID See Figures 8 and 12 for the position of these sites

The predominantly calcium-sulphate ($Ca-SO_4$) chemical composition of the water sourced from most of the above-listed sites is illustrated in Figures 23 and 24. These stations fall within the larger grouping of AMD and associated water shown in the Piper diagram (Figure 22). Figure 23 includes the chemical composition of borehole RG1 (site 025) groundwater which lies in the conceptual flowpath between the mine water and the Cemetery and Poplar groups of springs (see Figure 12) in the KGR.

In light of the above, an interesting aspect to the characterisations is the similar chemical composition of groundwater produced by Spring 2 (Cemetery group) and the Poplar Spring (Poplar group), to that which characterises the borehole RG1 groundwater. With the exception of "depressed" iron and manganese levels (Figure 23), the spring waters represent a muted replica of the RG1 dolomite groundwater.

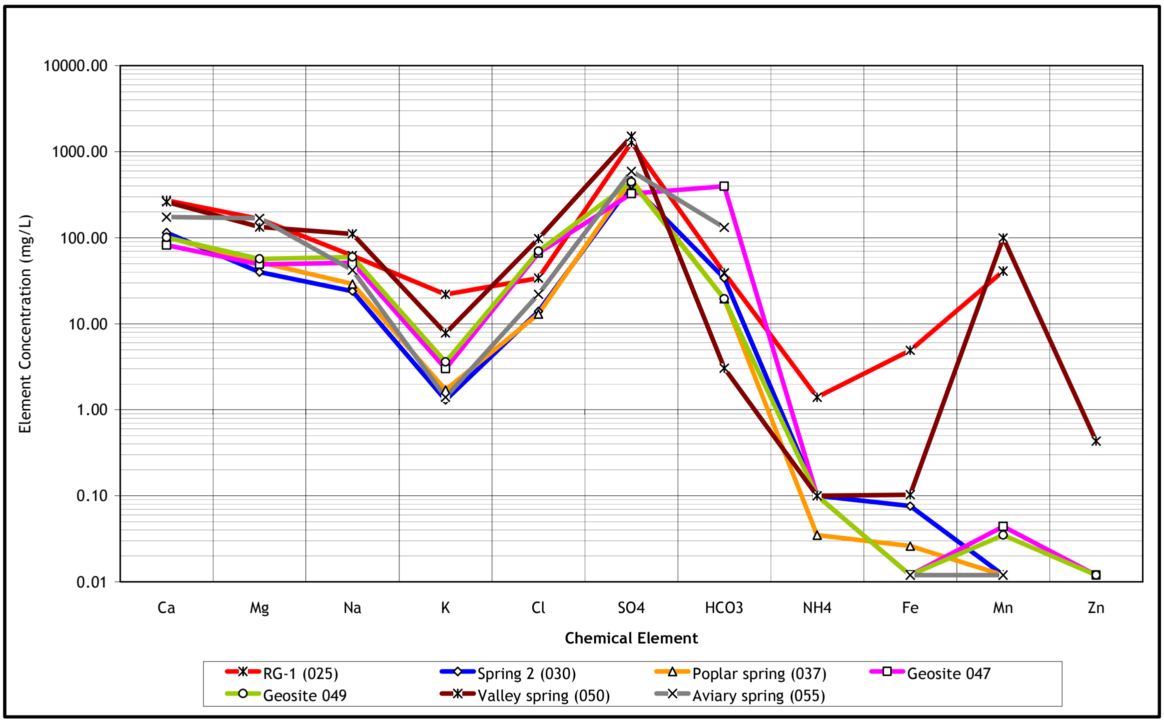


Figure 23. Parts per million characterisation of local "impacted" water chemistry

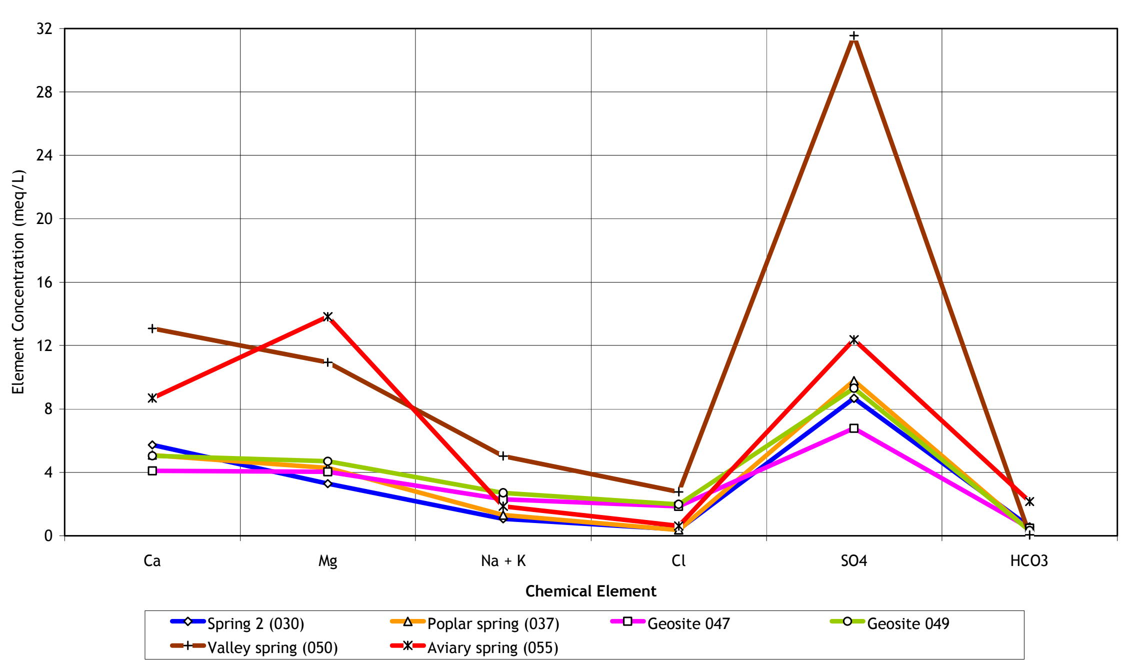


Figure 24. Schoeller diagram characterisation of local "impacted" water chemistry

3.3.5 Surface water

The close interaction between surface water and groundwater in the study area has already been described in section 3.2 on the basis of influent/losing and effluent/gaining stream segments. It is further manifested in the existence of numerous 4th order (discharge range 6.3 to 28.3 L/s) and 5th order (discharge range 0.6 to 6.3 L/s) springs as per Meinzer's Classification (Meinzer, 1923). Under these circumstances, the mutual influence of water quality on the respective surface and subsurface environments dictates the inclusive discussion and assessment of surface water quality. It must also be recognised, however, that surface water quality is subject to a much greater temporal variability than groundwater.

3.3.5.1 Tweelopie Spruit

The Tweelopie Spruit represents the most direct route for AMD to reach the Zwartkrans Compartment. Its path through the KGR also assigns to it even greater ecological importance and sensitivity. The surface water sampling localities are listed and described, in order of encounter downstream along the Tweelopie Spruit, as follows.

GEOSITE*	DESCRIPTION	RELEVANCE
038	Final discharge from HGM treatment plant	Upstream "artificial" input
039	Outlet of Hippo Dam in Tweelopie Spruit, KGR	First (upstream) output
021	Waterfall above Ngonyama Lodge in Tweelopie Spruit, KGR	1st blend with groundwater
042	Tweelopie Spruit above confluence with Lion Camp stream	2nd blend with groundwater
041	"Flip-se-Gat" stream before joining Tweelopie Spruit	Natural groundwater input
040	Outlet of Aviary Dam in Tweelopie Spruit, KGR	Final blend & output

* CSIR ID See Figures 8 and 12 for the position of these sites

The dominant calcium-sulphate ($Ca—SO_4$) chemical composition of the surface water sourced from the above-listed sites (except site 041) is illustrated in Figures 25 and 26. The following aspects of the characterisations warrant mention.

- The similar inorganic macro-element (Ca, Mg, Na, K, Cl, SO_4 and HCO_3) compositions of the Tweelopie Spruit surface water chemistry is clearly evident, and the "downward" trend described by the respective element concentrations indicates an improvement in water quality in a downstream direction.

- The comparatively tight grouping (circled in Figure 25) of elevated manganese concentrations in the Tweelopie Spruit surface water again serves as an indicator of the presence and influence of mine water on this resource. This indicator is virtually absent in the "Flip-se-Gat" stream discharge.

- The very different calcium&magnesium-bicarbonate ($CaMg—HCO_3$) chemical composition (Figure 26) and considerably better quality of the "Flip-se-Gat" stream discharge reflects the karst aquifer source of this water. The benefit of this excellent quality water in improving that of the Tweelopie Spruit is, however, severely limited by the relatively small discharge (estimated at some 10 L/s in mid-February 2007) of this stream compared to that of the Tweelopie Spruit (estimated at some 100 L/s in mid-February at site 042).

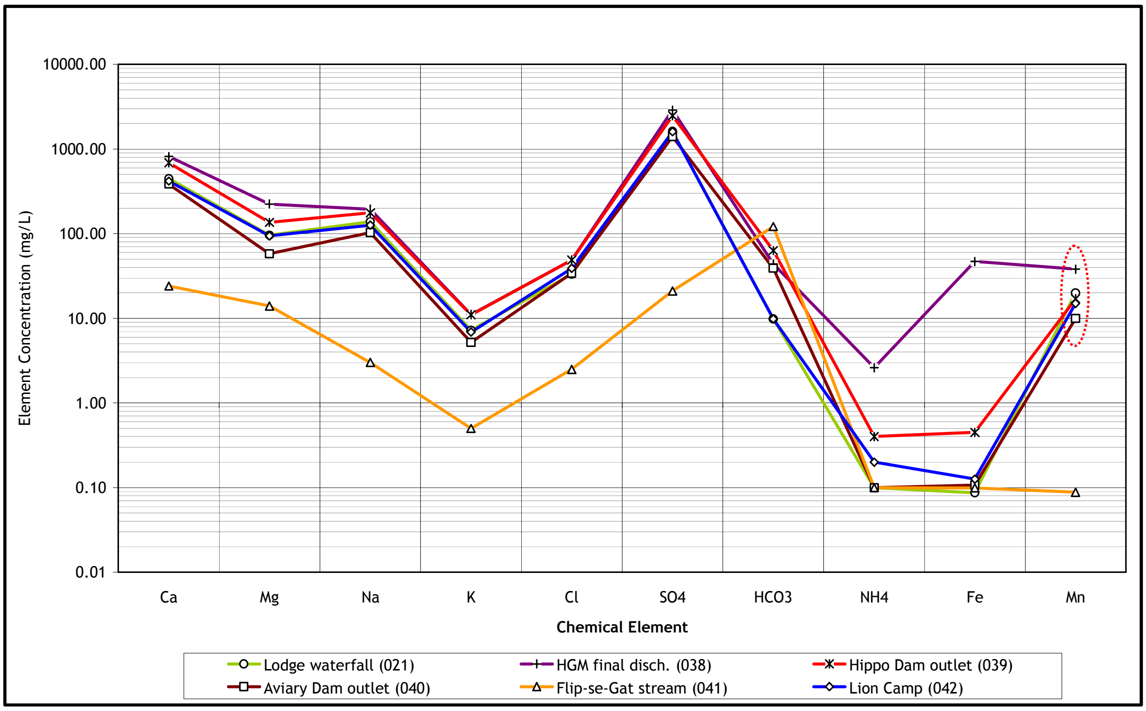


Figure 25. Parts per million characterisation of Tweelopie Spruit water chemistry

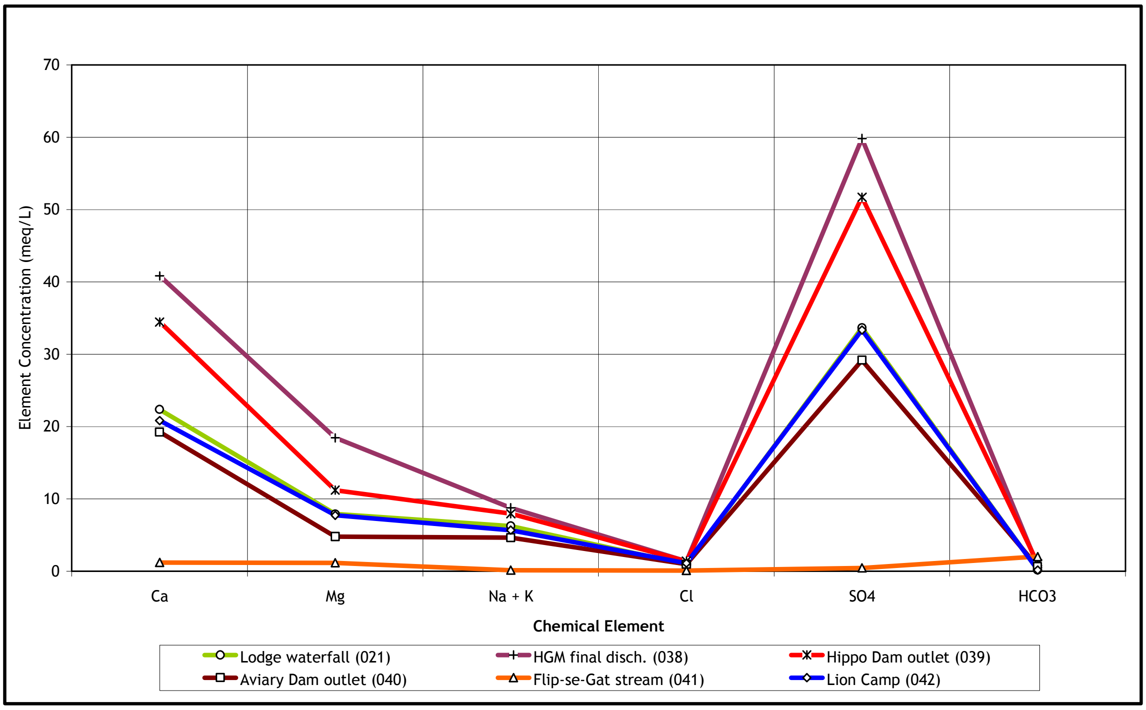


Figure 26. Schoeller diagram characterisation of Tweelopie Spruit water chemistry

The improvement in water quality (decrease in element concentrations) along the Tweelopie Spruit from site 038 (the HGM treatment plant final discharge) to site 040 (Aviary Dam outlet in KGR) in mid-February 2007 is illustrated in Figures 27 and 28. Geosite 041 (Flip-se-Gat stream) does not appear in these figures under circumstances where, as described above, it is associated with a "fresh" tributary of the Tweelopie Spruit.

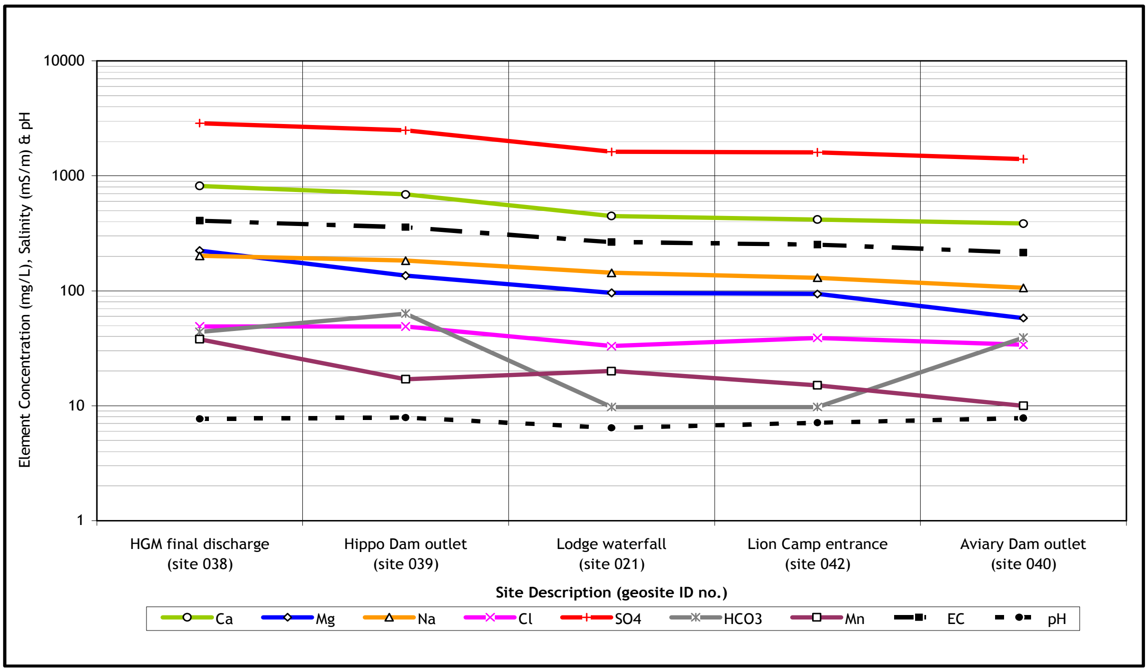


Figure 27. Parts per million improvement in water quality in the Tweelopie Spruit

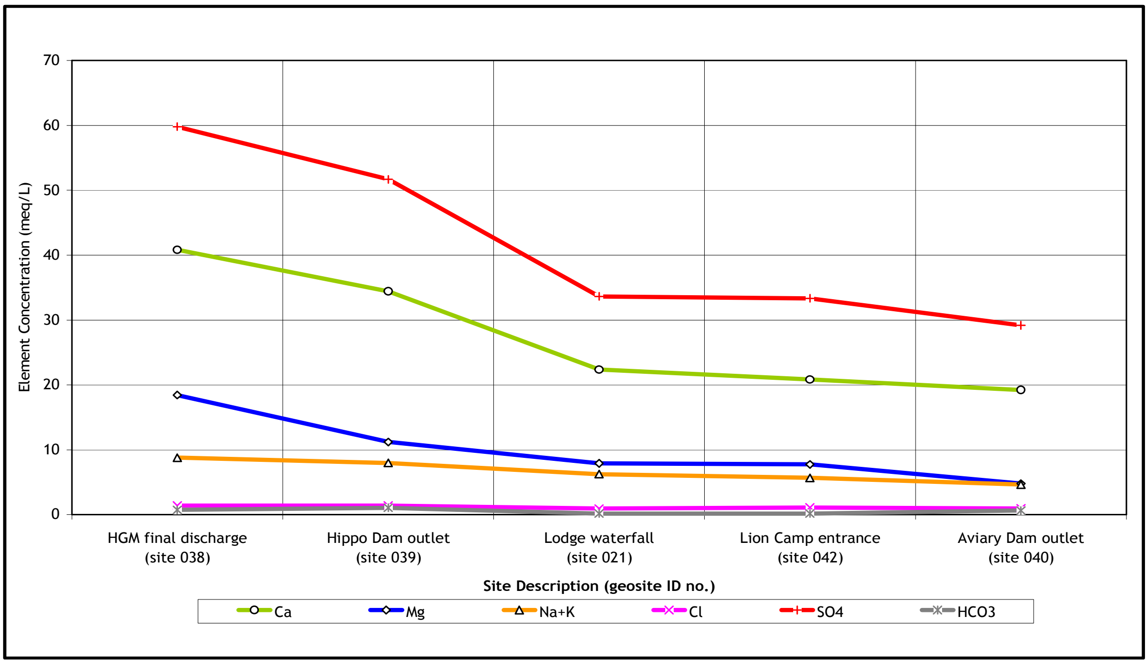


Figure 28. Equivalents per million improvement in water quality in the Tweelopie Spruit

The following aspects of these graphs warrant mention.

- The halving of Ca and SO_4 concentrations between the “endpoint” sites 038 and 040, some 80 % of which is already manifested at site 021. This is attributed mainly to the contribution from the Poplar and Cemetery groups of springs.
- The slight increase in Mn concentration from site 039 (Hippo Dam outlet) to site 021 (base of Lodge waterfall) is anomalous, and warrants further investigation.

3.3.5.2 Blougat Spruit

A further aspect of surface water quality in the subregion is that associated with the Blougat Spruit. This drainage receives effluent discharge from the Percy Stewart WWTW. Concerns in this regard were investigated some 10 years ago by DWAF (Barnard, 1996b), who found that flood irrigation with Percy Stewart WWTW effluent in the KGR as well as its discharge into the Blougat Spruit contributed to groundwater pollution in the Oaktree area (see Figure 8) of the Zwartkrans Compartment. According to riparian landowners, the situation has deteriorated since then (Travers, pers. comm., 2007). DWAF's water quality record for this drainage has been augmented with a sample collected at site 044, a weir located on Ptn. 10 of Sterkfontein 173 IQ. This site is immediately upstream of site 043, a water supply borehole located on the right (east) bank about 100 m from the river. The samples collected at these sites were also subjected to bacteriological analysis, viz. total coliform, faecal coliform and E. coli values.

The water quality results presented in Figures 29 and 30 indicate the Na—HCO_3 (sodium bicarbonate) character of the riverwater with elevated ammonia (NH_4), iron and manganese levels compared to the adjacent Na—SO_4 (sodium sulphate) type groundwater. Nevertheless, the chemical compositions are sufficiently similar to provide clear evidence for the existence of hydraulic continuity between the Blougat Spruit and the groundwater environment tapped by the borehole. Although the bacteriological results (Figure 31) support this observation, caution must be exercised in postulating a direct link on this evidence under circumstances where the on-site sanitation facilities that serve this property have not been considered. Of greater concern, however, are the high coliform counts associated with the river water.

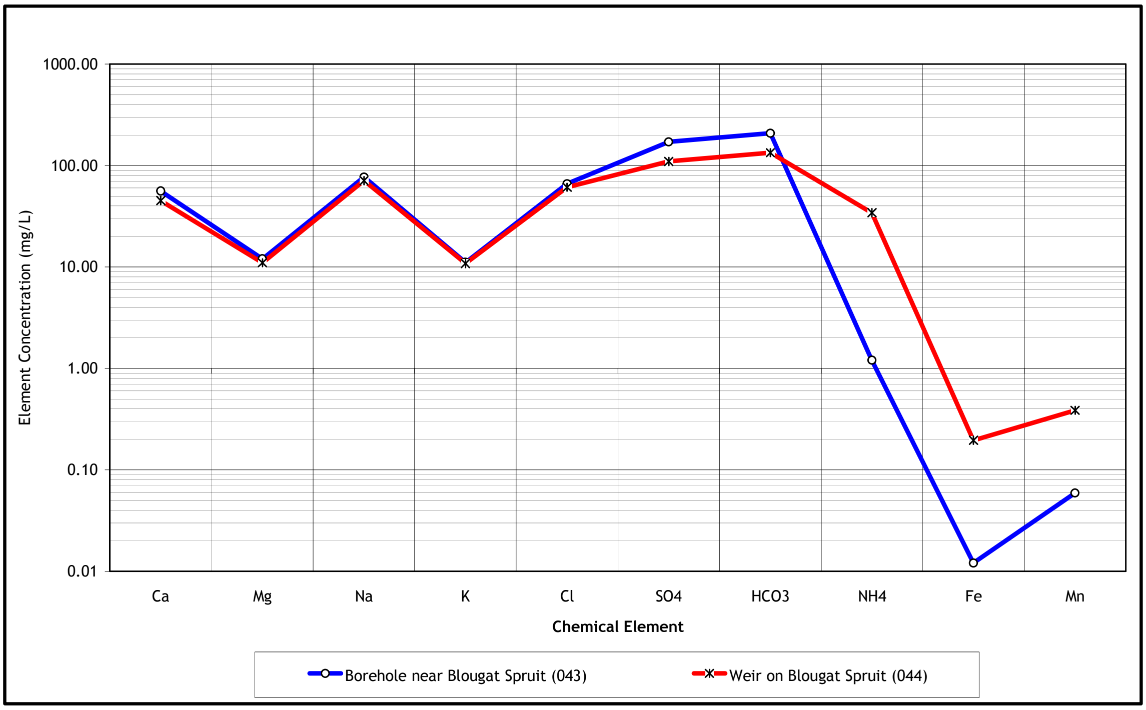


Figure 29. Parts per million characterisation of Blougat Spruit water chemistry

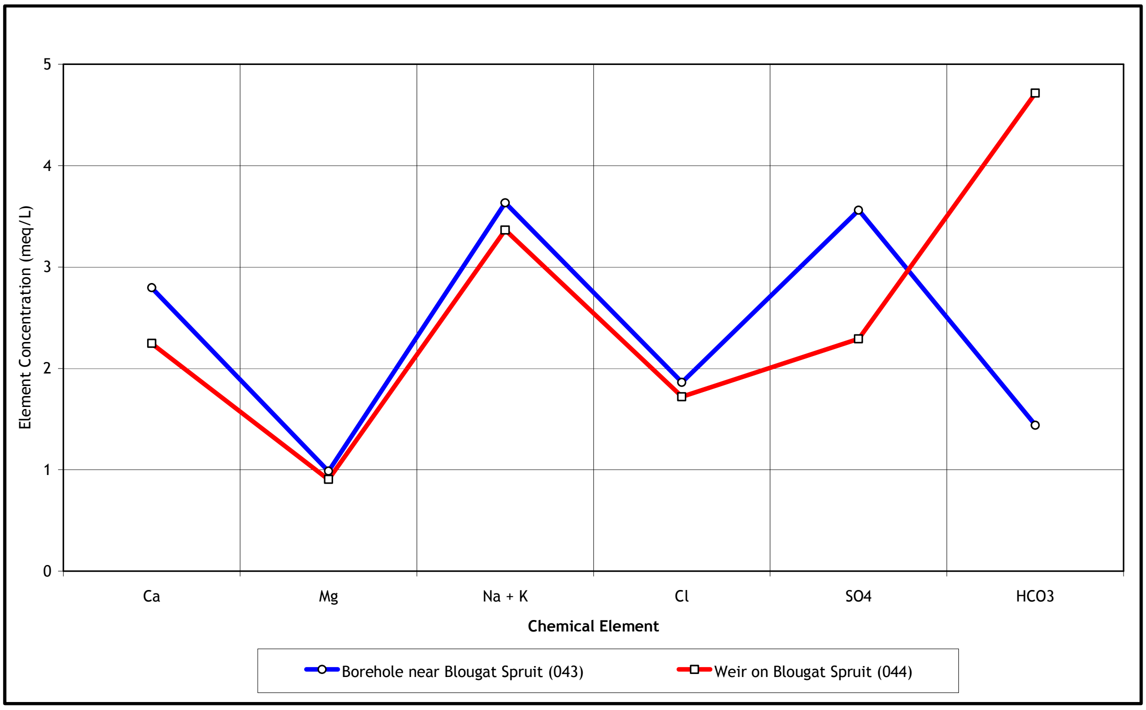


Figure 30. Schoeller diagram characterisation of Blougat Spruit water chemistry

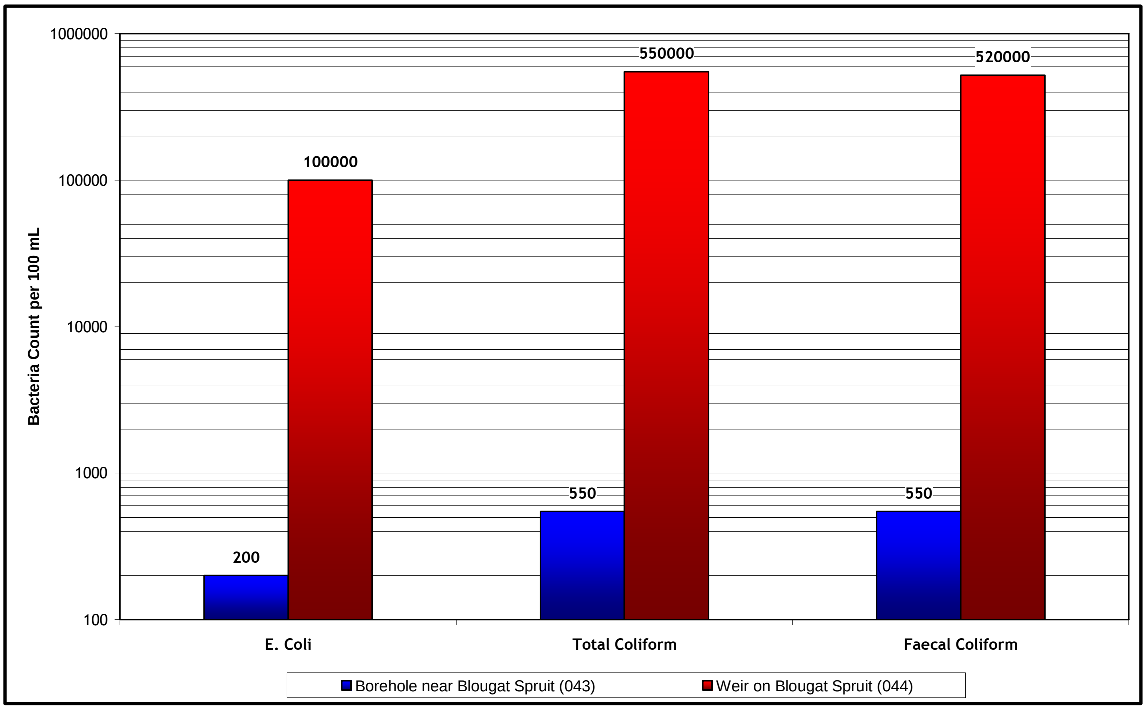


Figure 31. Bacteriological quality of Blougat Spruit water and adjacent groundwater

3.3.5.3 Riet Spruit

The Riet Spruit is an enigmatic drainage in the manifestation of its flow and no-flow segments. Upstream of Tarlton, the northwesterly draining stream is maintained by effluent discharge from the Randfontein WWTW. This flow is captured in a number of farm dams, the last of which is the Le Grange Dam immediately south of Tarlton.

In the vicinity of the N14/R24 junction at Tarlton, the Riet Spruit makes a 90° turn to the east and, more significantly, is virtually dry. From here, and extending all the way past the confluence with the Tweelopie Spruit down to the confluence with the Blougat Spruit in the Oaktree area, the Riet Spruit is dry. The contribution from the Tweelopie Spruit disappears below surface within a short distance of the confluence with the Riet Spruit. The section of the Riet Spruit between the Tweelopie Spruit and Blougat Spruit drainages is identified in this report as the Lower Riet Spruit (see Figure 15).

In light of the above, the quality of riverwater in the Riet Spruit only has relevance in its uppermost and lowermost reaches, i.e. upstream of Tarlton and downstream of the Oaktree area, respectively. Upstream of Tarlton, it is reasonable to expect that riverwater quality will be determined primarily by the quality of the treated effluent discharged from the Randfontein WWTW. Downstream of the Oaktree area, riverwater quality is likely to be determined by, amongst other sources, the treated effluent discharged from the Percy Stewart WWTW. Under circumstances where this study did not collect surface water samples that might illustrate these suppositions, information contained in the DWAF's NGDB/NGA and other repositories must be relied upon.

The difference in surface water chemistry associated with the samples collected as part of this study are illustrated in Figure 32. In the case of the Flip-se-Gat (site 041) and Tweelopie Spruit samples, the differences reflect those that distinguish dolomite groundwater and mine water, respectively. The Blougat Spruit water chemistry (site 044) represents an equally well-defined source that describes a third component of subregional water quality.

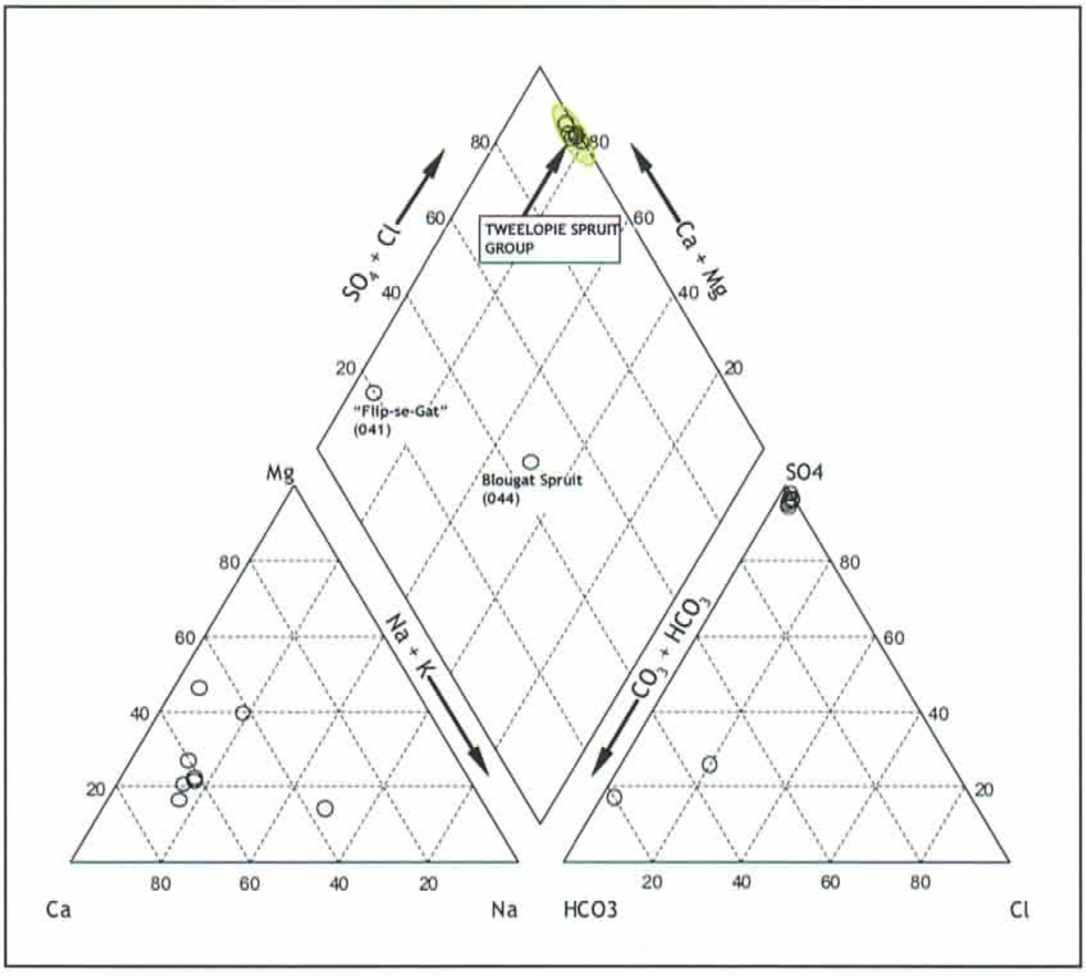


Figure 32. Piper diagram characterisation of surface water chemistry

3.3.6 Water toxicity

Previous water toxicity assessments in the area include SASS4 biomonitoring surveys (Du Toit, 2000) and similar SASS5 surveys which included toxicity assessments by Rand Water (Krige, 2005). Eight water samples collected in February 2007 were subjected to toxicity testing by the CSIR's Toxicity Testing Laboratory within the Water and Human Health Research Group. The sample localities are described in Table 3, and the full water toxicity evaluation report is presented in Annexure F.

Table 3. Description of sample localities sourced for water toxicity evaluation

Sample ID	Sampling date	Site description	Most probable origin
019	07 Feb.	Robinson Lake	Occasional mine process water repository
022	07 Feb.	Decanting mine shaft	Defunct underground mine workings
039	15 Feb.	Outlet of Hippo Dam in KGR	Harmony Gold Mine treatment plant effluent
040	15 Feb.	Outlet of Aviary Dam in KGR	Surface water in Tweelopie Spruit
041	15 Feb.	"Flip-se-Gat" stream	Dolomitic groundwater
044	20 Feb.	Weir on Blougat Spruit	Effluent discharge from the Percy Stewart WWTW
050	21 Feb.	Valley Spring	Valley slimes dam
051	21 Feb.	Battery Spring	Quartzitic groundwater

The results of direct tests (no sample dilution) on all samples are shown in Table 4. Samples 019, 022, 044 and 050 caused 100 % lethality after 24 hours. The optimum pH range for *Daphnia pulex* is 6.0 to 8.5. The pH values of samples 019, 022 and 050 (Table 4) were low and are suspected to have played a role in the observed lethality. Sample 044, the primary origin of which is effluent discharge from the Percy Stewart WWTW, contained 0.21 mg/L free chlorine. Free chlorine is usually toxic to *Daphnia p.* at this concentration. *Daphnia p.* were not affected by samples 039, 040, 041 and 051 (lethality value of <10 % indicates an absence of toxicity).

Table 4. Effect of water samples on *Daphnia pulex*

Sample ID	pH	% Lethality after time	
		24 hours	48 hours
019	2.1	100	100
022	3.7	100	100
039	7.3	0	0
040	7.3	0	0
041	7.9	0	0
044	7.6	100	100
050	4.1	100	100
051	6.2	0	5

Table 5 shows the results obtained when *Daphnia p.* were exposed to 10-fold dilutions (range finding tests) of the samples exhibiting low pH values (019, 022 and 050). Samples 019 and 022 caused 15 % and 100 % lethality, respectively, at the 1 % and 10 % concentration levels after 48 hours exposure. No lethality was observed at the 1 % and 10 % concentration levels of sample 050 during 24 h exposure. In all instances, except in the case of the 10 % concentration of sample 019 (pH = 3.4), the pH was very close to or within the required optimum pH range for *Daphnia p.*, suggesting that the observed effects were due to toxic chemicals present in the samples. Samples 019 and 022 turned yellow and dark orange, respectively, upon dilution with moderately hard water (increased pH), indicating the presence of dissolved iron in the samples.

Table 5. Effect of 10-fold dilutions of samples on *Daphnia pulex*

Sample ID	Concentration (%)	pH	% Lethality after time	
			24 h	48 h
019	10	3.4	100	100
	1	6.5	15	15
022	10	5.9	60	100
	1	6.5	15	15
050	10	7.2	0	not recorded
	1	7.6	0	not recorded

Definitive tests on serial dilutions were carried out on samples 019, 022, 044 and 050 to establish toxicity endpoints. A probit statistical method was applied to the toxicity data (lethality versus concentration) to calculate the LC_{10} (concentration causing 10 % lethality) and the LC_{50} (concentration causing 50 % lethality). In cases where the Probit method was not applicable (less than two effects between 0 and 100 % or an irregular distribution of data), the Spearman-Karber statistical programme was used. The results are presented in Table 6. Samples 019 and 022 exhibit the highest toxicity (low LC_{50} values), followed in order of magnitude by samples 044 and 050. The results obtained for 019 and 050, where lethality was observed, are also associated with low pH values. In these instances, pH would appear to be a significant contributing factor to the lethal effects observed.

Table 6. 48-h *Daphnia p.* LC_{10} and LC_{50} values for samples 019, 022, 044 and 050

Sample ID	Statistical Programme	LC_{10}		LC_{50}		95% Confidence limits	
		%	Dilution factor	%	Dilution factor	Lower limit	Upper limit
019	Spearman-Karber	2.5	40	3.3	30	3.0	3.6
022	Probit	1.3	77	2.3	43	1.8	2.8
044	Probit	28.7	3.5	43.5	2.3	36.6	51.6
050	Spearman-Karber	50.0	2	66.0	1.5	60.1	72.4

Note: Dilution factor denotes the number of times the water needs to be diluted in order to meet the respective lethality concentration

The toxicity evaluation produced the following conclusions.

- Samples 039 and 040 (surface water) and 041 and 051 (groundwater) were non-toxic.
- Samples 019, 022, 044 and 050 were toxic.
- pH played a major role in the lethalities exhibited by samples 019 (Robinson Lake) and 050 (Valley Spring).
- Sample 019 was highly toxic with an LC_{50} of 3.3 %.
- Compared to sample 019, the toxicity of sample 050 was low (LC_{50} = 66 %).
- The toxicity of sample 044, strongly influenced by sewage effluent, was slightly higher than that of sample 050 (LC_{50} = 43.5 %). The adverse activity was most probably due to free chlorine and toxic pollutants.
- Sample 022 (Black Reef Incline) exhibited the highest toxicity (LC_{50} = 2.3 %). *Daphnia p.* is sensitive to a range of heavy metals, and it is suspected that a combination of these pollutants in the mine water caused the adverse chemical activity.

The toxicity evaluation also produced the following recommendations.

- Only one toxicity test, the *Daphnia pulex* lethality test, was used in this study. This test was applied as a first tier screen to assess toxic potential. Since the sensitivities of aquatic organisms to toxic pollutants differ, it is recommended that a battery of toxicity tests is applied during future studies for a more complete picture of toxicity.

- The *Daphnia p.* test only responds to acute (short-term) toxicity. It is recommended that sub-lethal (long-term) tests, e.g. algal growth inhibition, *Daphnia p.* reproduction, etc. are included in future studies. Sub-lethal tests will be particularly useful for surface and groundwaters that did not show acute toxicity.
- Chronic effects such as mutagenicity, teratogenicity and estrogenicity should also be assessed.
- Toxic mine water also poses a health risk to mammals and humans. A range of tests for human health protection is available at the Toxicity Testing Laboratory, CSIR. It is recommended that some of these tests are also used in future studies.

4 CONCEPTUAL GROUNDWATER DYNAMICS

The extensive description of the groundwater environment presented in section 3 establishes the framework for arriving at an improved understanding of the physical and chemical dynamics that define the groundwater regime in the subregion. The physical dynamics describe the temporal potentiometric response and groundwater movement, whilst the chemical dynamics describe temporal and spatial changes in ambient groundwater quality as influenced by the quality of contributing surface water and other sources.

4.1 Physical Hydrogeology

4.1.1 Groundwater Level Response

Rison (2006) presents an analysis of long term groundwater rest level (hydrostatic) behaviour as recorded in several DWAF monitoring stations in the region. This indicates that groundwater rest levels in the Zwartkrans Compartment appear to have declined steadily since the mid-1980s. The reported magnitude of this decline ranges from some 2 m in the least effected sub-compartment (unnamed), to 5.4 m in the most effected sub-compartment B, with sub-compartment D which hosts the Sterkfontein Cave experiencing a decline of 2.75 m (Rison, 2006). These values have not been verified, although their derivation and accuracy is questioned on the basis that they are premised on average water levels calculated for each sub-compartment (Rison, 2006). By contrast, hydrostatic heads in the dolomitic outliers to the south have increased to the stage where free-flowing conditions were first manifested in boreholes and defunct mine shafts in 2002 and, more recently, in the “perennial” nature of the Hippo Dam and development of seeps and springs in the Krugersdorp Game Reserve (refer section 1).

A sharper focus on the hydrostatic response in the proximate portion of the Zwartkrans Compartment, viz. the portion immediately downstream (north) of the dolomite outlier and its locus of decant, is provided by the hydrographic records for DWAF monitoring stations 2627BA00091 (site 015), 2627BA00087 (site 033), 2627BA00084 (site 058) and 2627BA00090 (site 061). These are presented in Figures 33 and 34.

Figure 33 reveals a 100 m difference in potentiometric head between sites 015 and 033, leading Bredenkamp et al. (1986) to speculate on the presence of an east—west trending dyke structure that might account for such a head difference (see section 3.3). The scale-enhanced (relative water level data) hydrographs presented in Figure 34 show that site 015 experiences the greatest hydrostatic response, and site 061 the smallest response. The graphs also reveal the marked similarity of hydrostatic behaviour at sites 033 and 058.

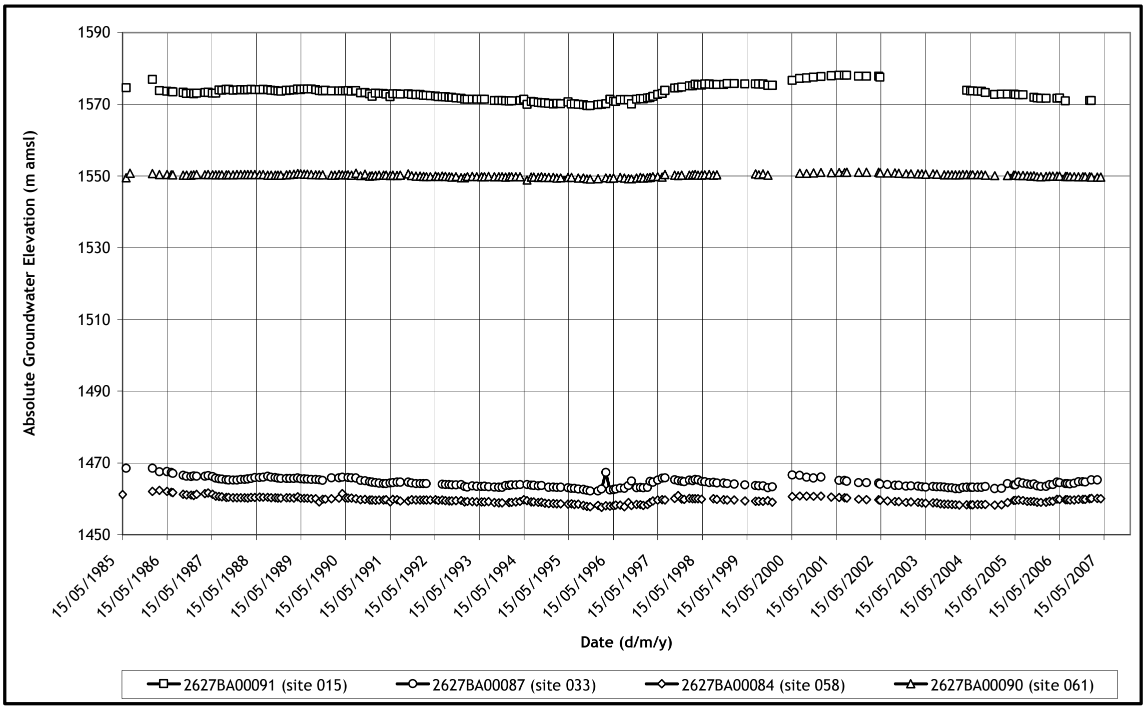


Figure 33. Hydrostatic behaviour in the proximate portion of the Zwartkrans Compartment

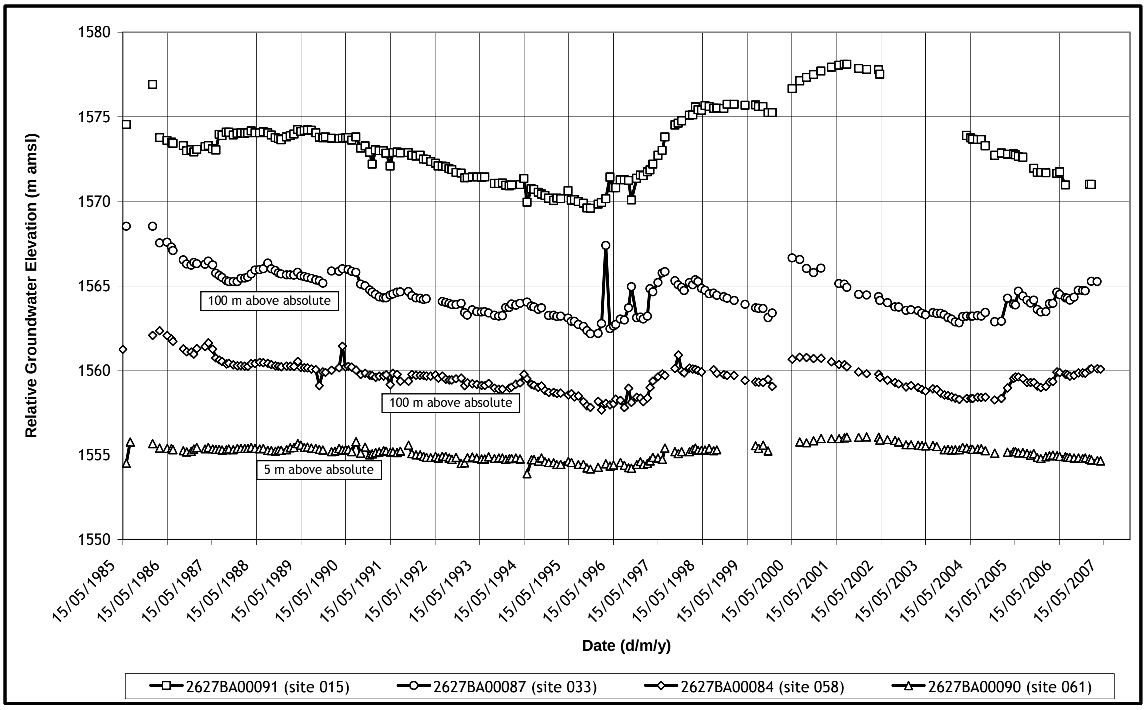


Figure 34. Scale-enhanced version of the hydrographs presented in Figure 33

The hydrostatic response patterns at stations 033 and 058 are correlated graphically with the monthly rainfall data for four rainfall stations in the region in Annexure C. Geosite 033, located close to the confluence of the Tweelopie Spruit and the Riet Spruit, exhibits the typical water level peak and recession curve that characterises runoff/recharge events. This effect is less pronounced at site 058 located some 1 700 m downstream and slightly further away from the Riet Spruit. These phenomena reflect both rapid recharge (including indirect recharge from streamflow), and a significant aquifer storativity able to dissipate such recharge.

Nevertheless, the natural groundwater level fluctuations at stations 033 and 058 do not exceed some 6.3 m. This is in contrast to the response at site 015, where a prolonged "positive" effect is evident in response to recharge from rainfall, and the cumulative natural groundwater level fluctuation is in the order of 8.5 m.

The observed response patterns to recharge observed at stations 033 and 058 appear to manifest themselves over a period of three to four years. This is similar to the period of "significant dependence" revealed by the correlation between rainfall and the discharge of Maloney's Eye (draining the Steenkoppies Compartment to the west) as reported by Fleisher (1979). Further, the observed magnitude of natural groundwater level fluctuations is similar to those reported by Hobbs (2004) for the dolomitic aquifer located south of Pretoria in quaternary basins A21A and A21B to the east.

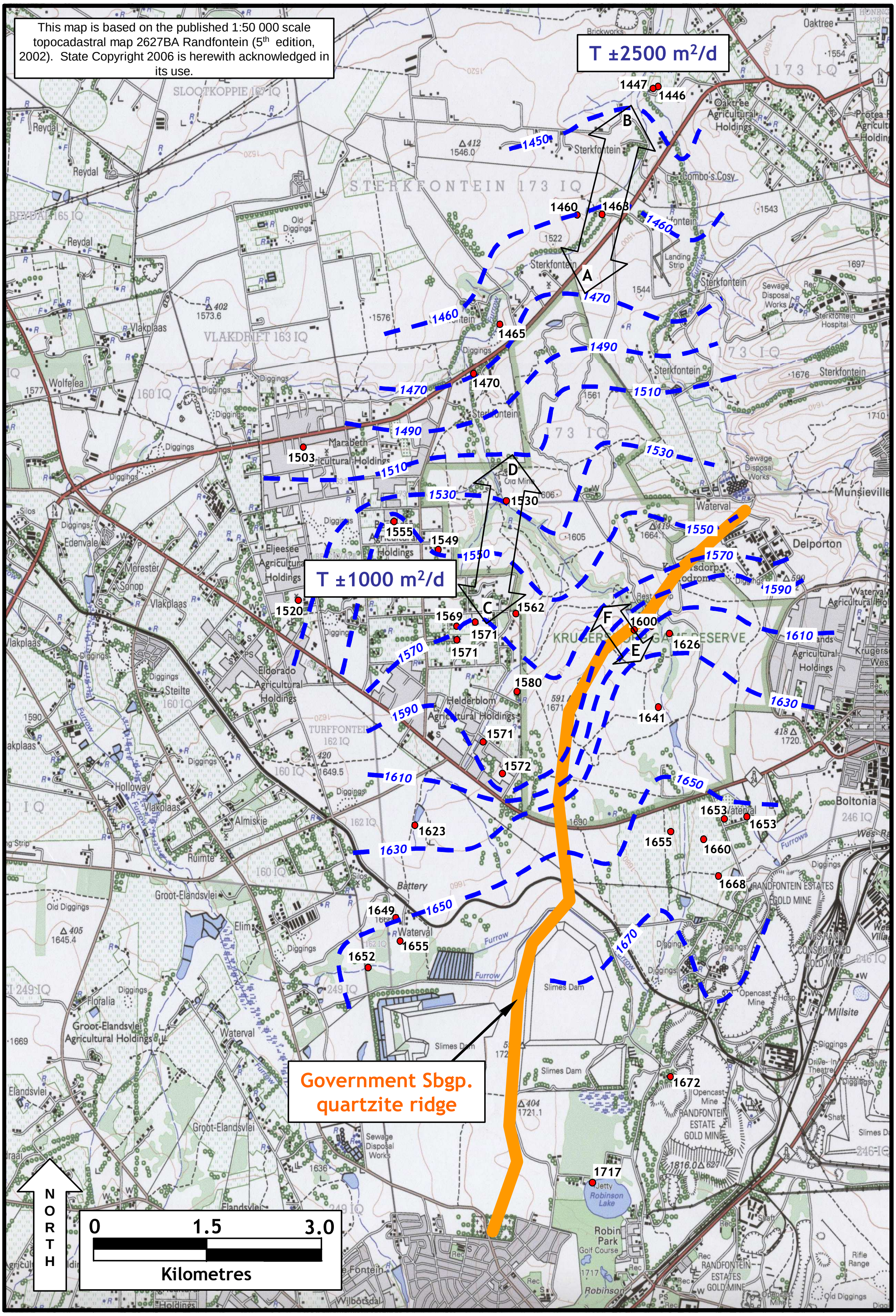
4.1.2 Groundwater Discharge

The discussion in section 3.2 of the groundwater dynamics in the study area focuses on the dolomite outlier and the proximate portion of the Zwartkrans Compartment to the north. For example, the groundwater level contours presented in Figure 9 do not extend northeastwards into the Oaktree area. The continuation of the groundwater contour pattern in this direction is shown in Figure 35.

The groundwater flow pattern shown in Figure 35 also provides the basis for developing a rudimentary semi-quantitative assessment of various groundwater discharge components. Such assessment provides an order-of-magnitude comparison of the groundwater dynamics in various portions of the study area. It is not intended to represent the actual groundwater discharges in the study area.

Bredenkamp et. al. (1986) report transmissivity (T) values in the order of 1 000 and 2 500 m^2/d for the Smallholdings and Oaktree areas respectively (Figure 35). The hydraulic gradient in these areas is in the order of 0.024 (section A—B, Figure 35) and 0.008 (section C—D, Figure 35) respectively. The combination of these values yield similar unit discharge rates of 24 and 20 m^3/d, viz. 0.28 and 0.23 L/s per unit aquifer throughflow width of 1 m. The average unit discharge rate of 22 m^3/d (0.25 L/s/m) for the karst aquifer provides a reference value against which to assess the transmissivity of the quartzite ridge built from Black Reef Fm. and West Rand Sbgp. strata. The hydraulic gradient across this feature is in the order of 0.086 (section E—F, Figure 35). The quotient of 22 m^3/d and 0.086 returns a theoretical T-value of 255 m^2/d for the quartzitic strata. Although a T-value of this magnitude is quite plausible for geological structures such as fault and fracture zones, it is less plausible as a "bulk" value for these strata. For example, in regard to Table Mountain Group strata, Rosewarne (2002) suggests "……..… *that T values of a few hundred m^2/d are associated with productive fracture zones, while <10 m^2/d corresponds to matrix zones.*" Since the transmissive properties of especially the West Rand Gp. strata in the study area are poorly known, the result confirms the need to more substantively investigate this aspect.

The unit discharge rates reported above also provide a very coarse indication of groundwater discharge when calculated for specific flow path widths. For example, the average unit discharge rate of 22 m^3/d translates to a flow of 55 000 m^3/d (55 ML/d) across a flow path width of 2 500 m at the position of the Riet Spruit / Blougat Spruit confluence in the Oaktree area. It is uncertain to what extent this discharge includes the contribution of between 20 and 40 ML/d from the Percy Stewart WWTW via the influent Blougat Spruit.



This map is based on the published 1:50 000 scale topocadastral map 2627BA Randfontein (5th edition, 2002). State Copyright 2006 is herewith acknowledged in its use.

Figure 35. Subregional groundwater flow pattern

4.2 Chemical Hydrogeology

4.2.1 Introduction

The information presented in section 3.3 is synthesized in Figure 36. This diagram defines the framework within which the groundwater quality/chemistry dynamics in the study area are addressed.

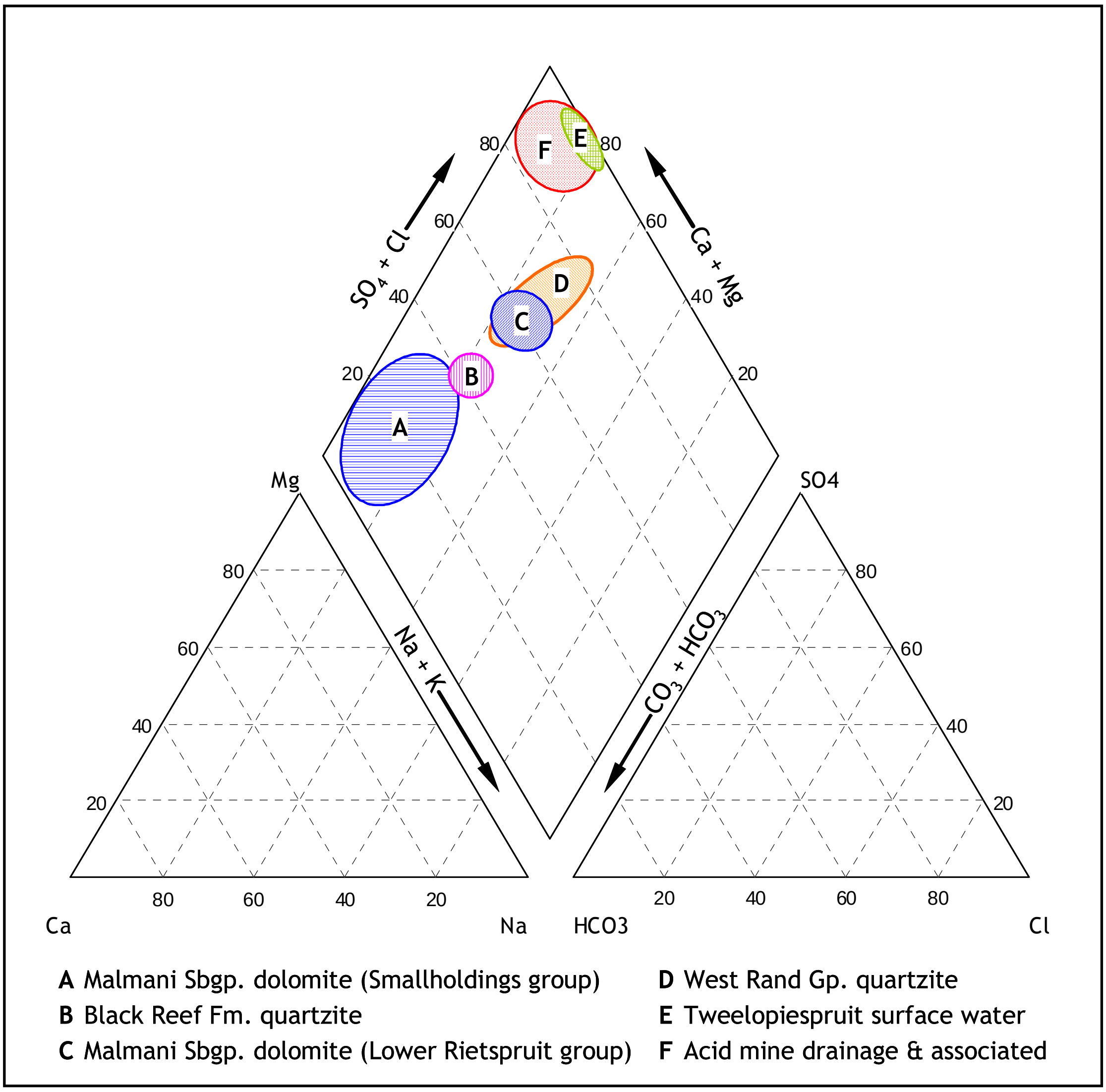


Figure 36. Synthesis of Piper diagram characterisation of water chemistry

4.2.2 Surface Water / Groundwater Interaction

The quality of surface water entering the middle and lower reaches of the Riet Spruit is mostly determined by the water quality leaving the Aviary Dam on the Tweelopie Spruit tributary in the KGR, and that discharged by the Blougat Spruit tributary, respectively. The difference in water quality between these two sources shown in Figure 32, is further defined in Figures 37 and 38. Also illustrated in these figures is the chemical characterisation of groundwater sourced from boreholes located close to the course of the Lower Riet Spruit between the two tributaries. It is evident from Table 7 that all of the groundwater samples are sourced from a depth that is well below that of the riverbed.

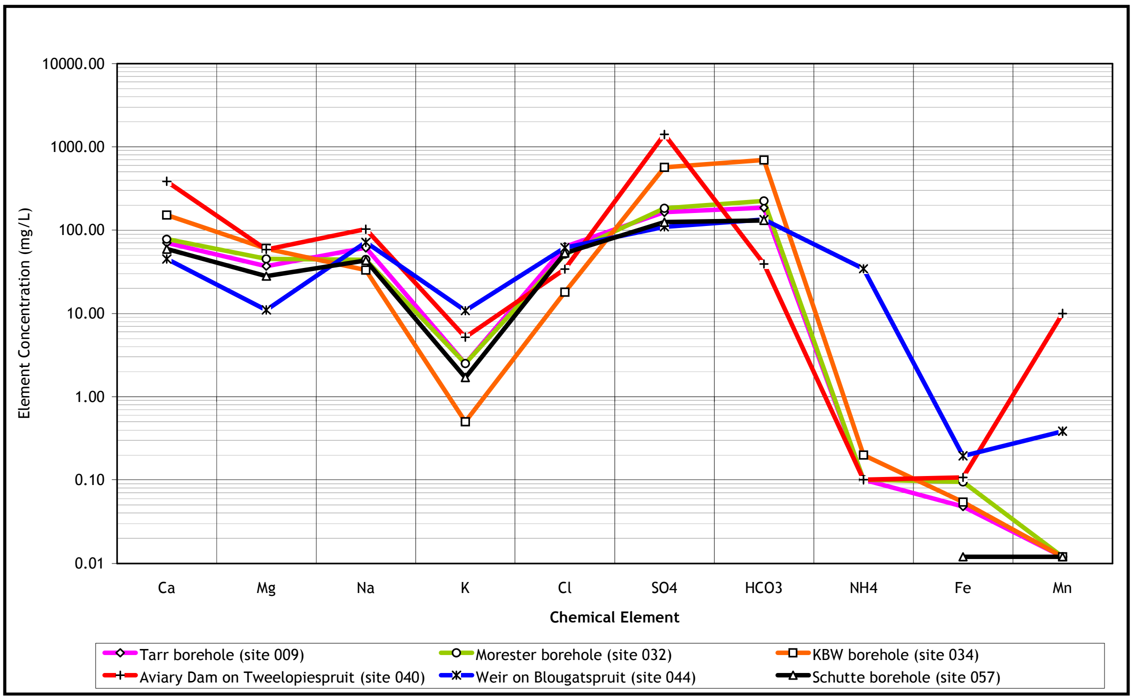


Figure 37. Parts per million characterisation of Lower Riet Spruit water chemistry

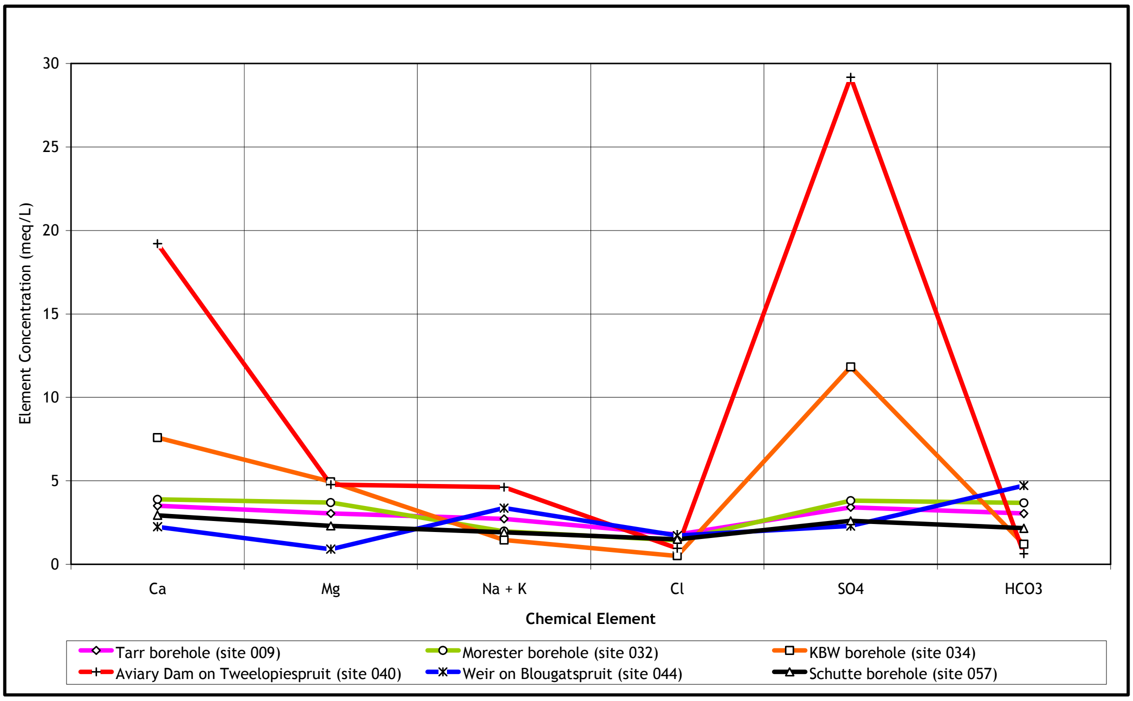


Figure 38. Schoeller diagram characterisation of Lower Riet Spruit water chemistry

Table 7. Groundwater rest level depth below riverbed along the Lower Riet Spruit

SITE No. (CSIR ID) along flow path	Upstream	⇨		Downstream
	034	032	057	009
WATER LEVEL DEPTH (m below riverbed)	30.0	21.0	12.0	18.0
WATER LEVEL ELEVATION (m amsl)	1470	1469	1463	1447

The Piper diagram presented in Figure 39 shows a schematic representation of the mixing that describes the development of Lower Riet Spruit groundwater quality (field "E" in Figure 39). The mixing derives from three end-members, viz. "pristine" dolomitic groundwater (field "A"), the grouping of groundwater influenced by acid mine drainage (field "B") and Tweelopie Spruit surface water (field "C"), and thirdly Blougat Spruit surface water as defined by Percy Stewart WWTW effluent discharge (field "D"). The slight displacement of the Lower Riet Spruit groundwater chemistry "E" away from the "A" – "B+C" axis suggests that the Percy Stewart WWTW contribution is subordinate to that of treated mine water effluent (and possibly also AMD) in the chemical evolution of Lower Riet Spruit groundwater. Further, this contribution is insufficient to significantly alter the roughly equal contribution of dolomitic groundwater and Tweelopie Spruit / AMD water in this evolvement.

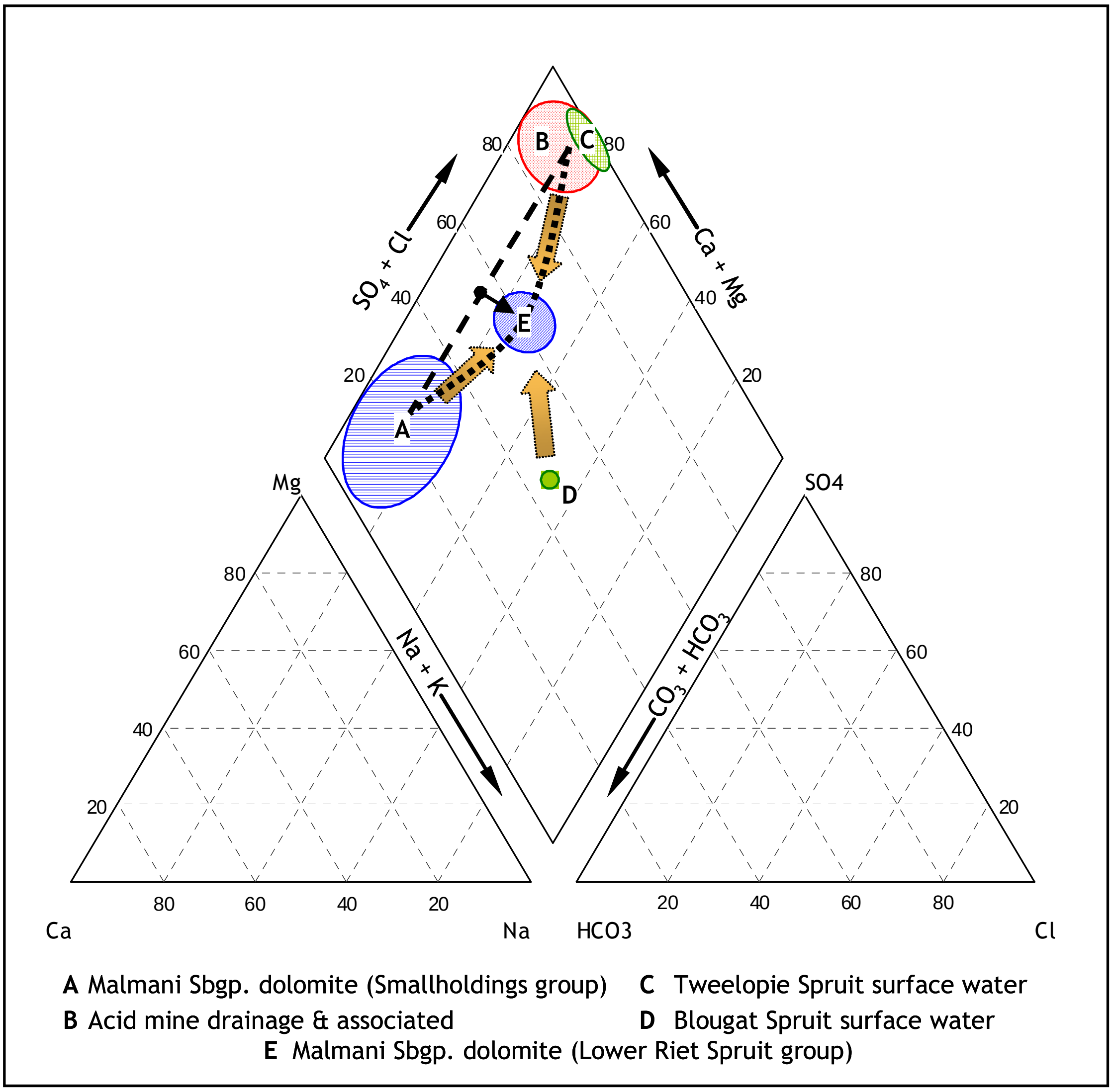


Figure 39. Piper diagram characterisation of Lower Riet Spruit groundwater chemistry development

The scatter plot of calcium and sulphate concentration presented in Figure 55 provides another perspective on the evolution of Lower Riet Spruit dolomitic groundwater. This perspective distinguishes between the Tweelopie Spruit surface water and the mine water sources in revealing the convergence from these two sources. The "attitude" of the two axes that define these vectors also suggest that the AMD (mine water) contribution is subordinate to that of the surface water.

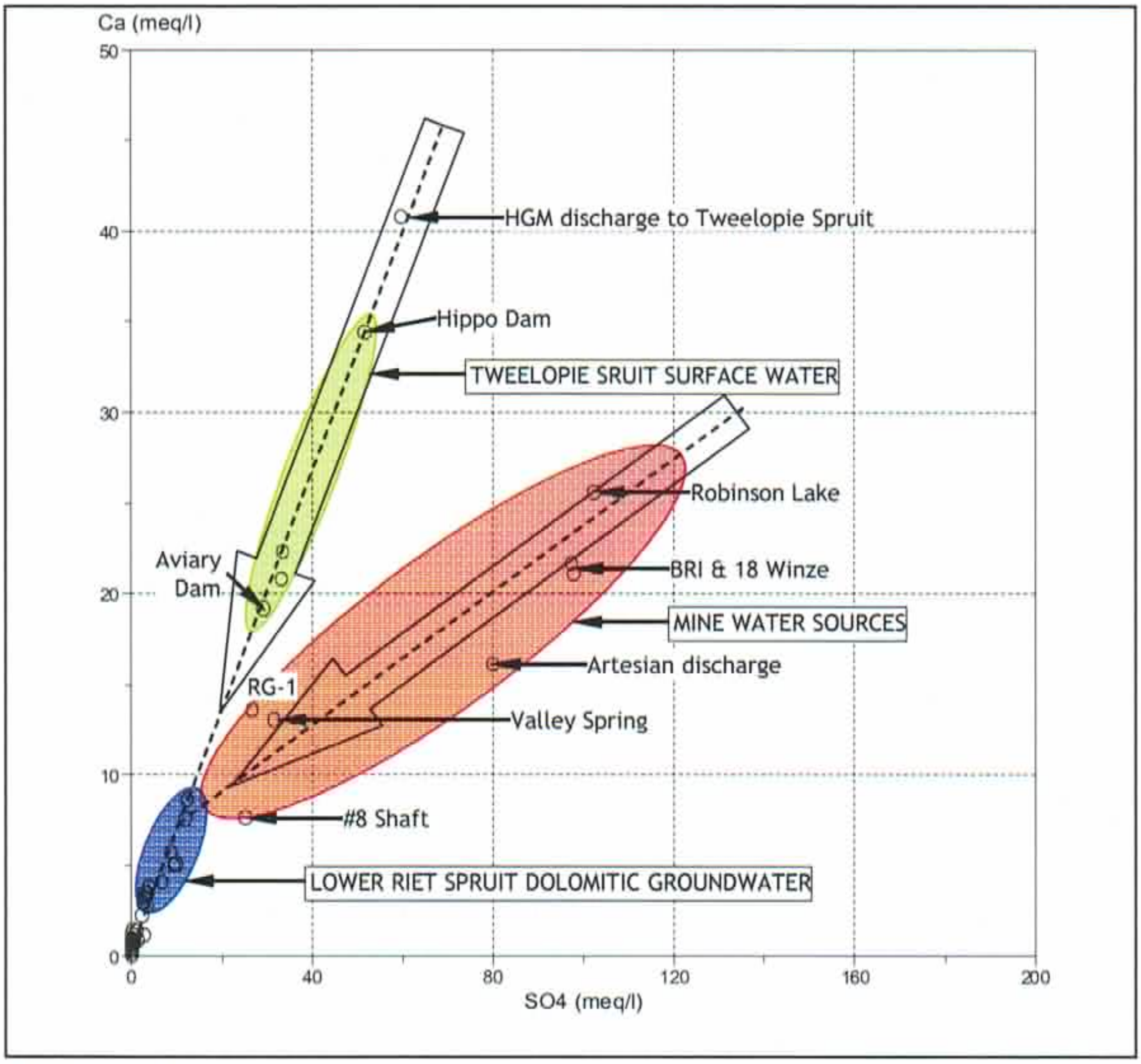


Figure 40. Scatter plot of calcium and sulphate concentration

4.2.3 Variations in Water Quality

An analysis of various water quality data sets reveals the variability associated with different water sources. The DWAFs NGDB/NGA provided the most comprehensive data set for this purpose, especially in regard to the Tweelopie Spruit water quality through the Krugersdorp Nature Reserve (KGR). The variability of surface water quality passing through the Hippo Dam near the southern (upstream) boundary is captured in Figures 41 and 42, and that exiting the KGR from its northern (downstream) boundary in Figures 43 and 44.

The variability illustrated in Figures 41 to 44 is better defined in Figures 45 and 46 for the Hippo Dam and the Aviary Dam, respectively. These figures confirm that SO_4 exhibits the greatest absolute variability of the major ions, followed by calcium. Despite the high variability of parameters such as SO_4, Ca and EC, Figures 41 to 44 indicate the gradual increase in element concentrations over the period of record. On the assumption that acid mine water decant is prevented (barring accidental spillages) from entering the Tweelopie Spruit, such increase must be attributed (amongst others) to a gradual increase in the volume of acid mine water entering this drainage via subsurface flow reporting to seepages and springs.

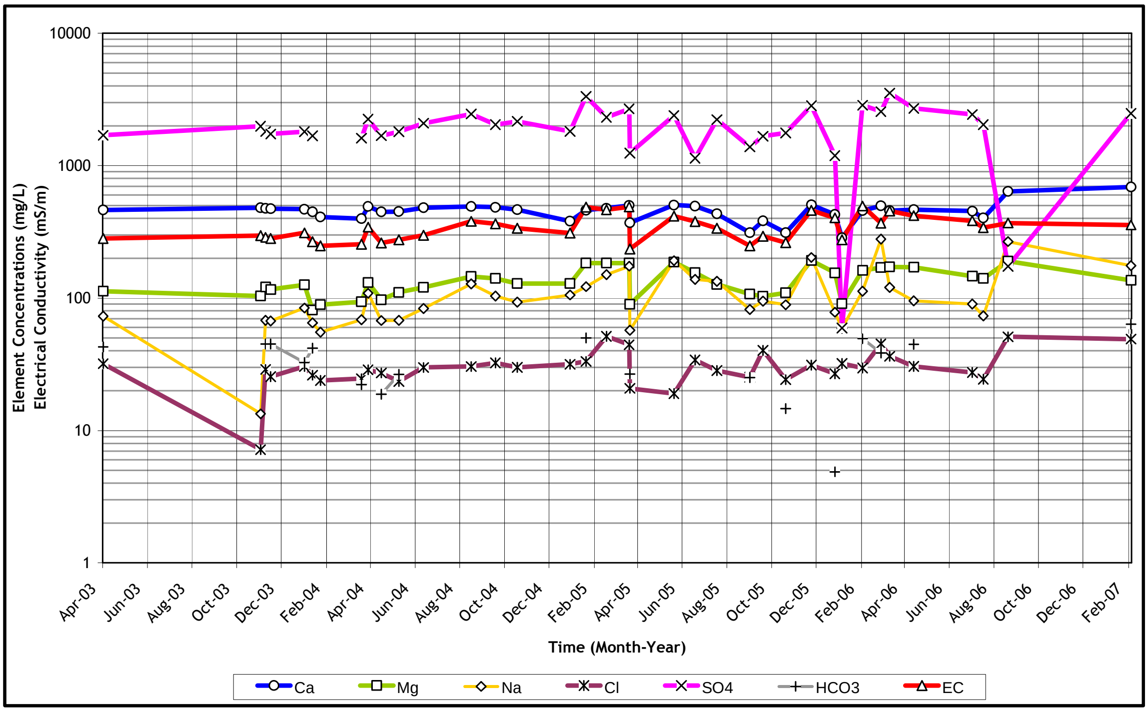


Figure 41. Parts per million variability in Tweelopie Spruit water at the Hippo Dam

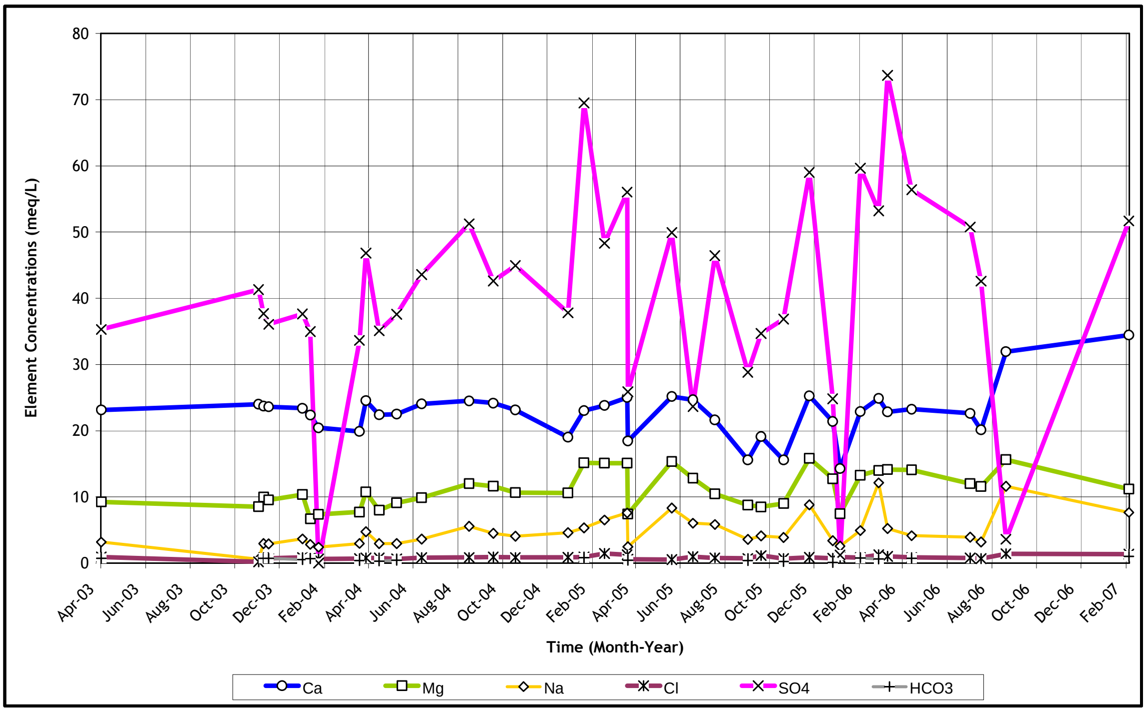


Figure 42. Equivalents per million variability in Tweelopie Spruit water at the Hippo Dam

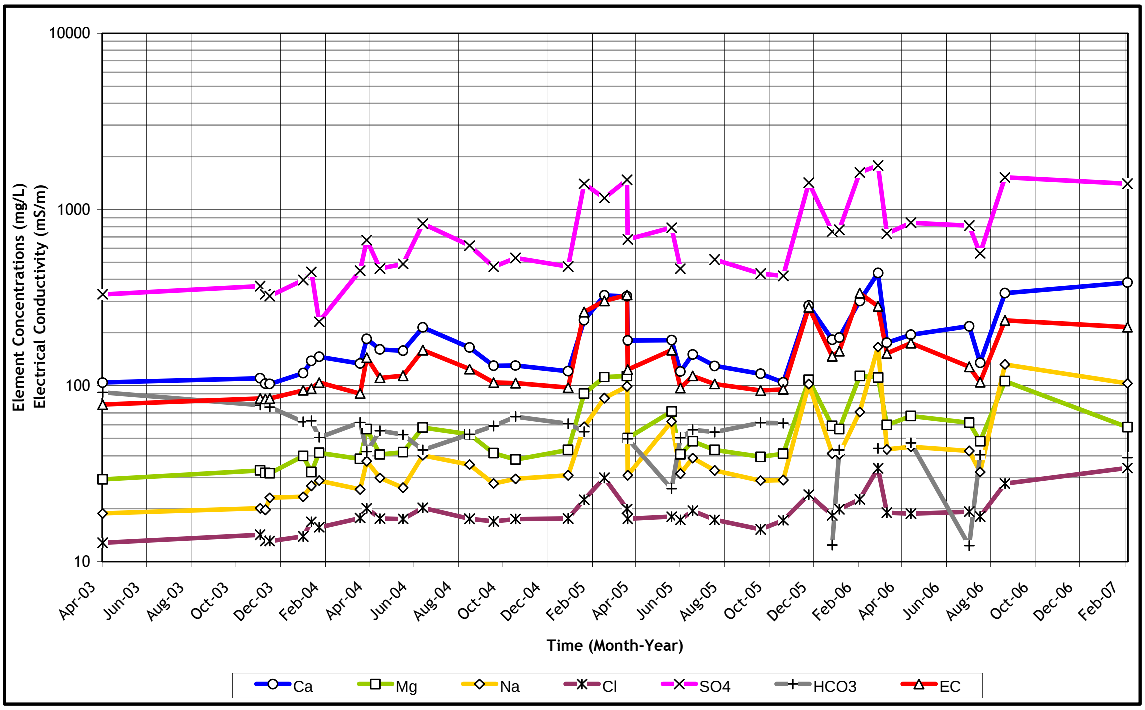


Figure 43. Parts per million variability in Tweelopie Spruit water at the Aviary Dam

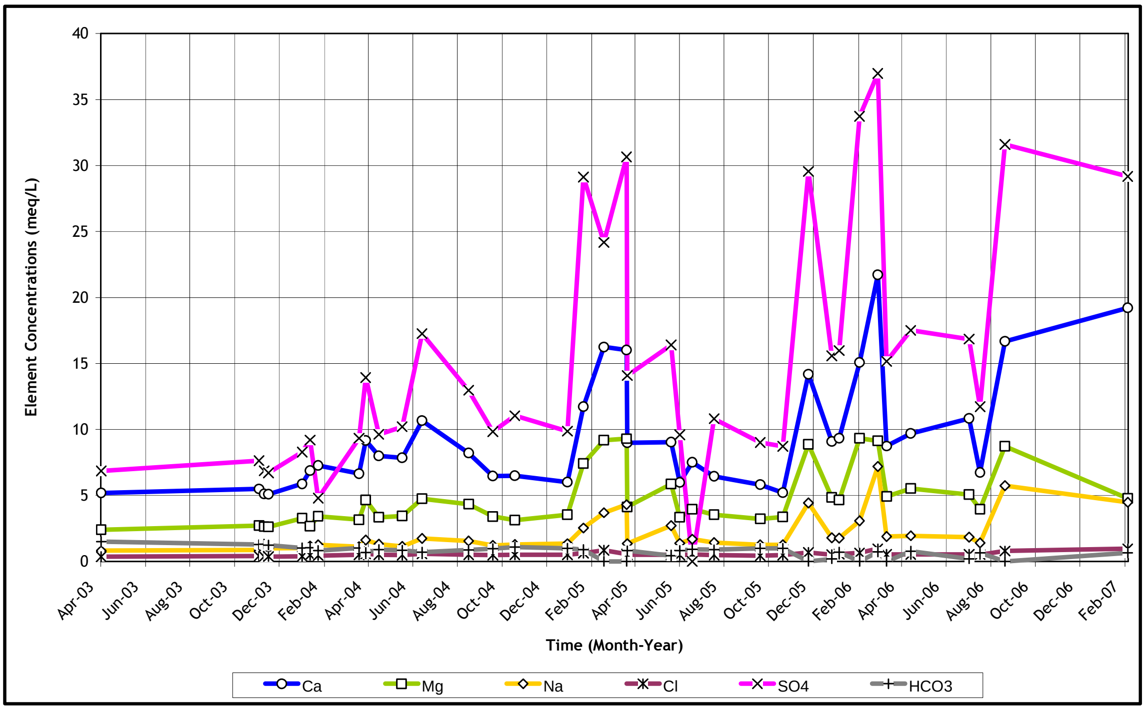


Figure 44. Equivalents per million variability in Tweelopie Spruit water at the Aviary Dam

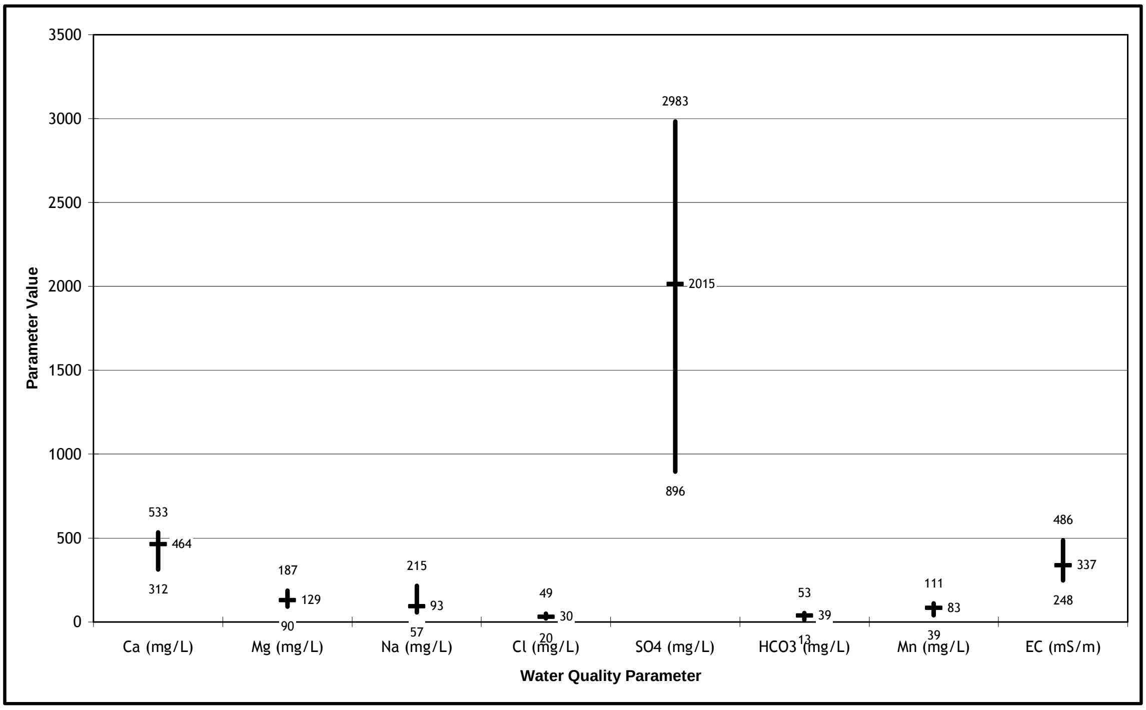


Figure 45. Variability (95%ile/median/5%ile) of Tweelopie Spruit water at the Hippo Dam

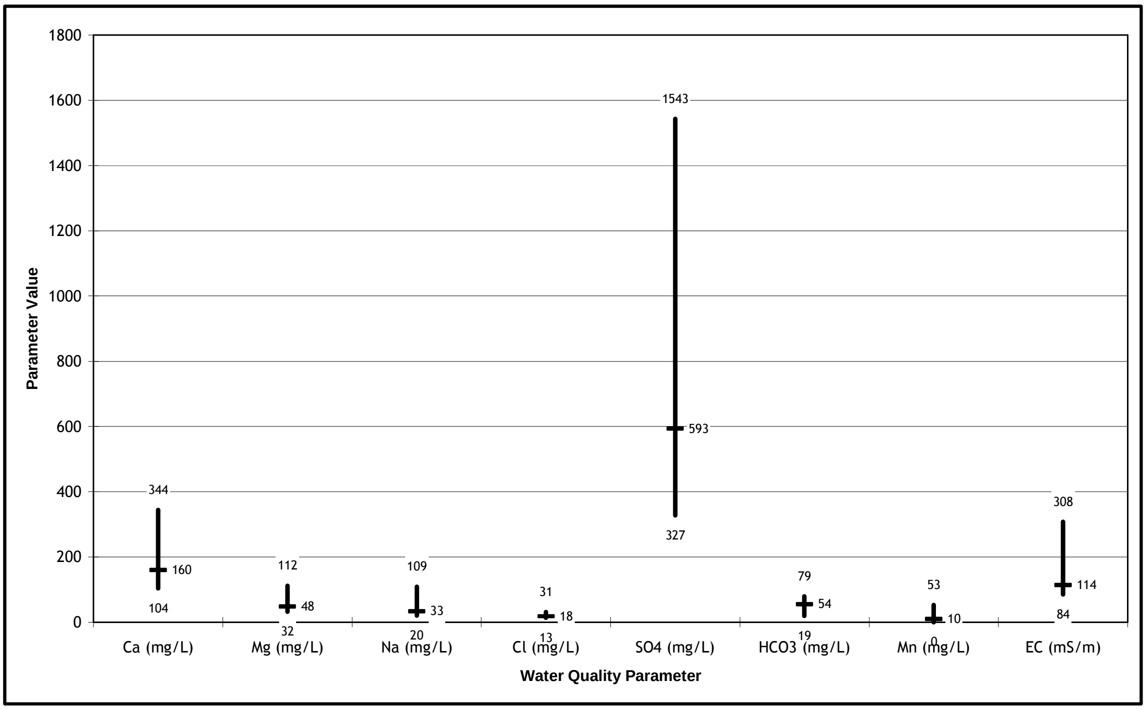


Figure 46. Variability (95%ile/median/5%ile) of Tweelopie Spruit water at the Aviary Dam

In contrast to the variability exhibited by Tweelopie Spruit water, the acid mine water (as for example produced by the Black Reef Incline) demonstrates a fairly constant chemical composition and much lesser variability. This is illustrated in Figures 47, 48, 49 and 50, and supports the previous observation (section 3.3.5) that surface water quality is subject to a much greater temporal variability than groundwater and, by association, also mine water.

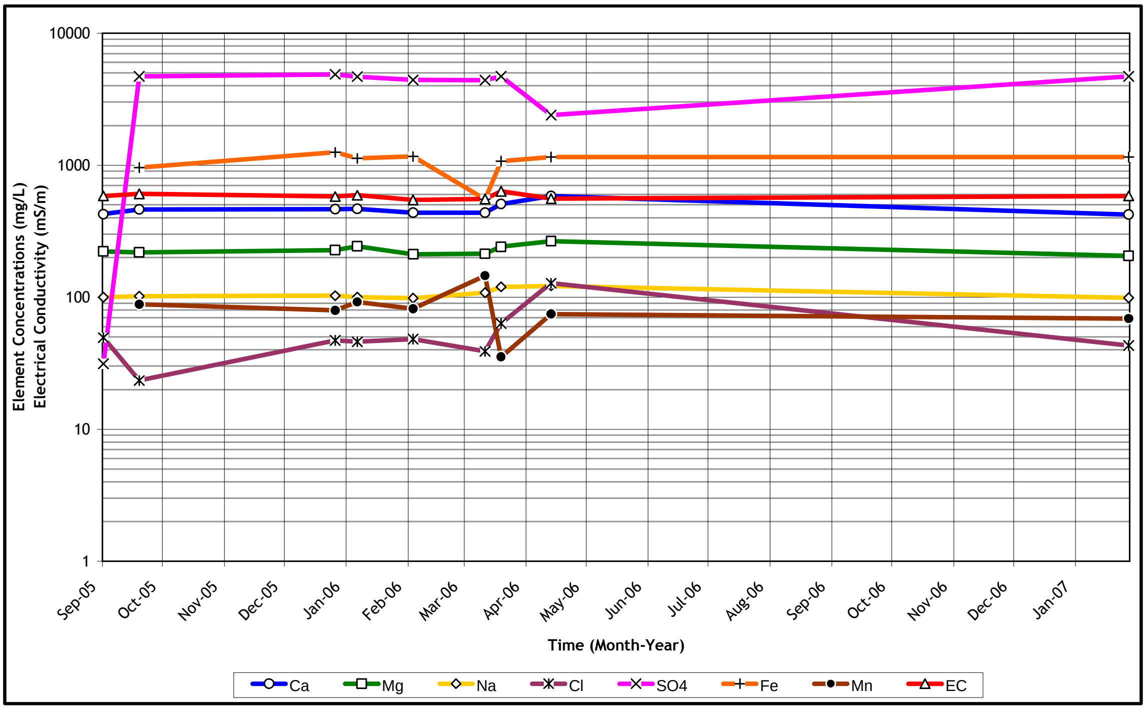


Figure 47. Parts per million variability in Black Reef Incline acid mine water

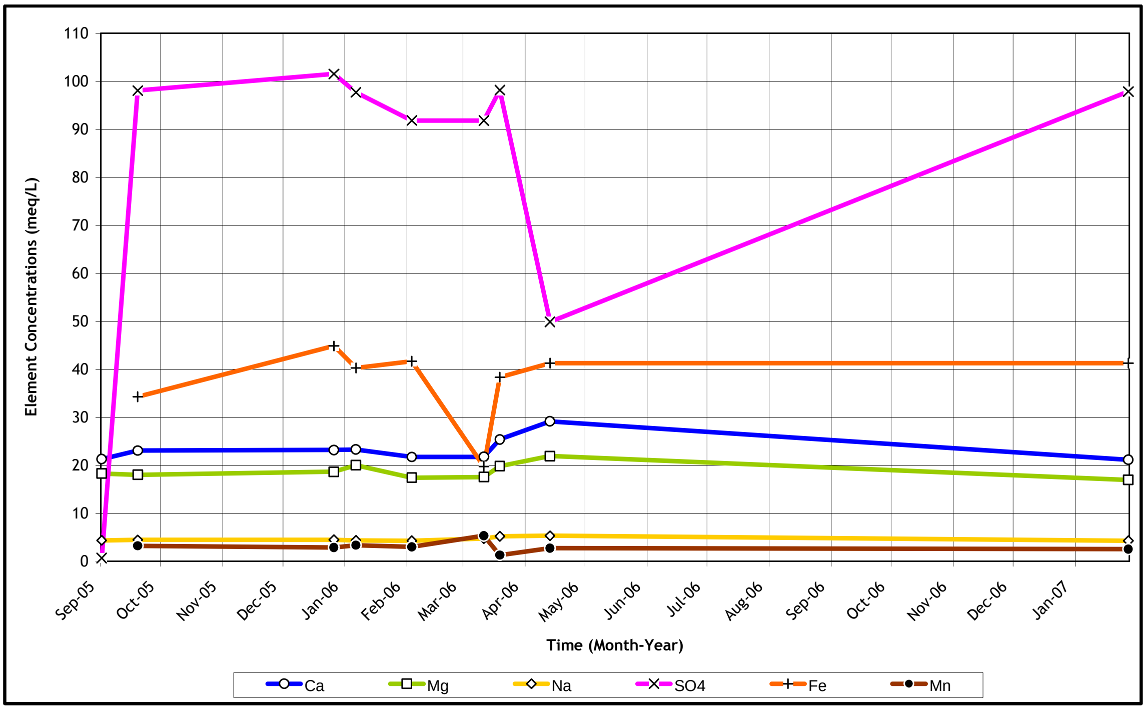


Figure 48. Equivalents per million variability in Black Reef Incline acid mine water

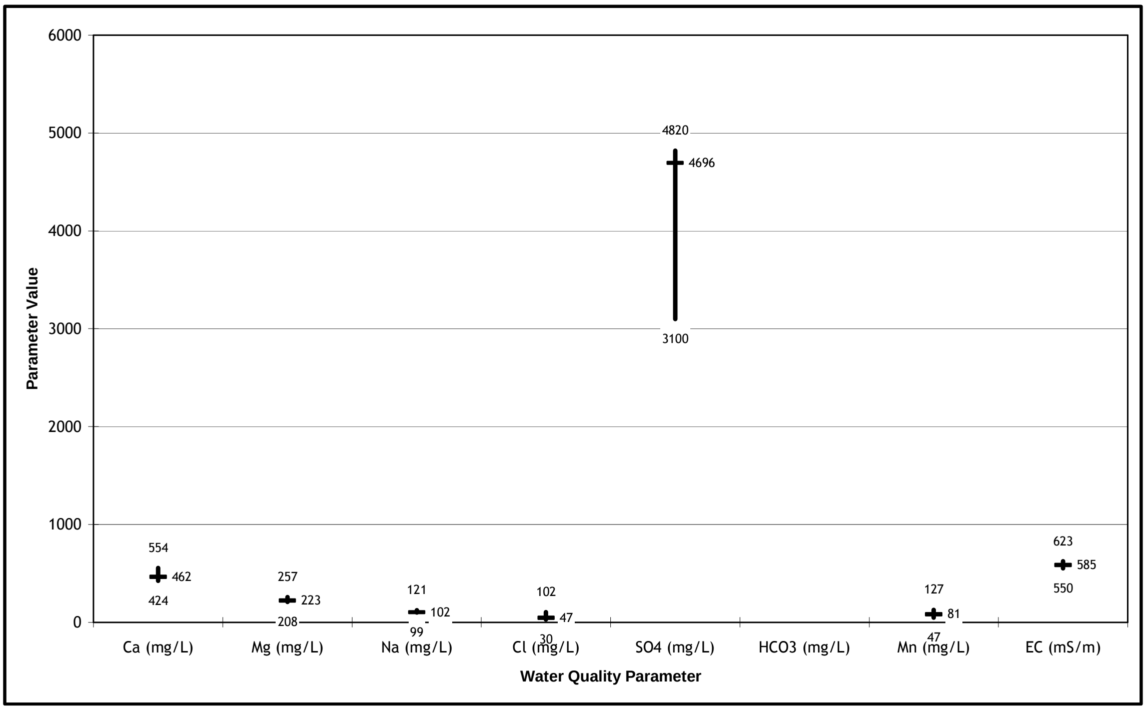


Figure 49. Variability (95%ile/median/5%ile) of Black Reef Incline acid mine water

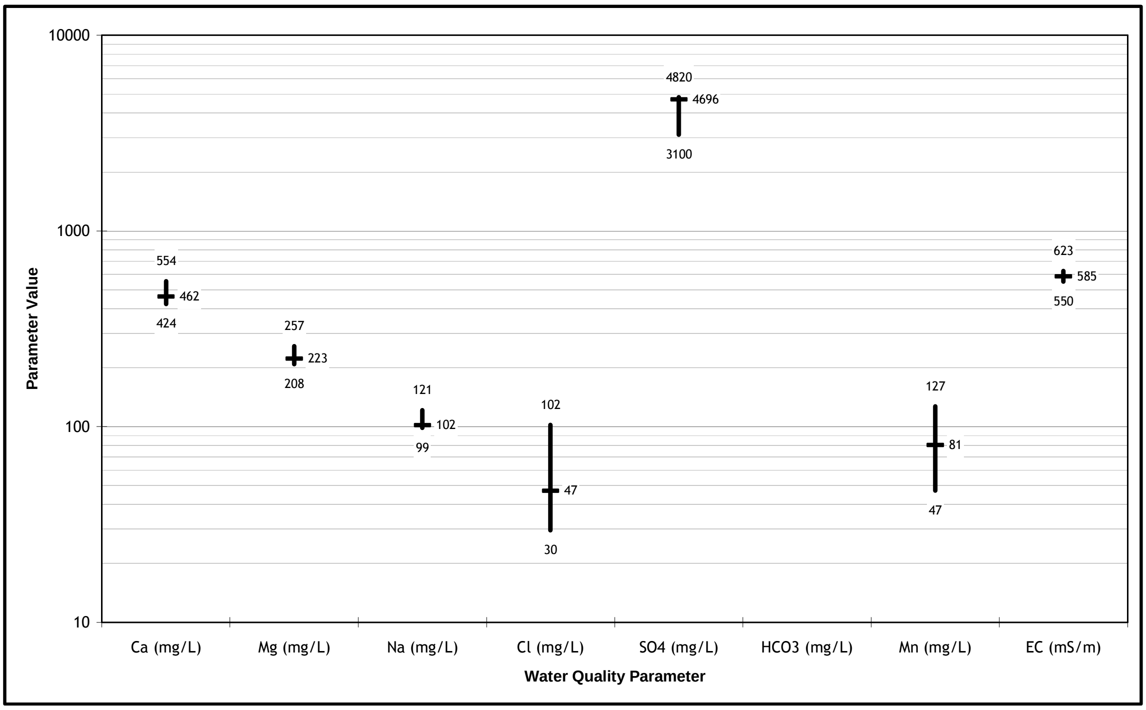


Figure 50. Semi-logarithmic version of Figure 49

4.2.4 Changes in Water Quality

Distinct changes in water quality over time are less readily discernible than mere variations as described in section 4.2.3. The regular sampling by DWAF of monitoring boreholes (e.g. site 033, already identified as DWAF site 2627BA00087 or A2N0584) in the Zwartkrans Compartment provides material to explore this phenomenon. Looking at the recent record, the outcome (Figure 51) is inconclusive in regard to this locality very near the confluence of the Tweelopie and the Riet Spruit (Figures 8, 12 and 15). It is necessary to look at the historical record (Figure 52) to see that the groundwater quality at this station appears to have improved since first sampled in 1985. Although sparse, historical data reflect more elevated EC, SO_4, Ca and Mg concentrations in July 1985 and September 1989 than has been recorded since September 2003.

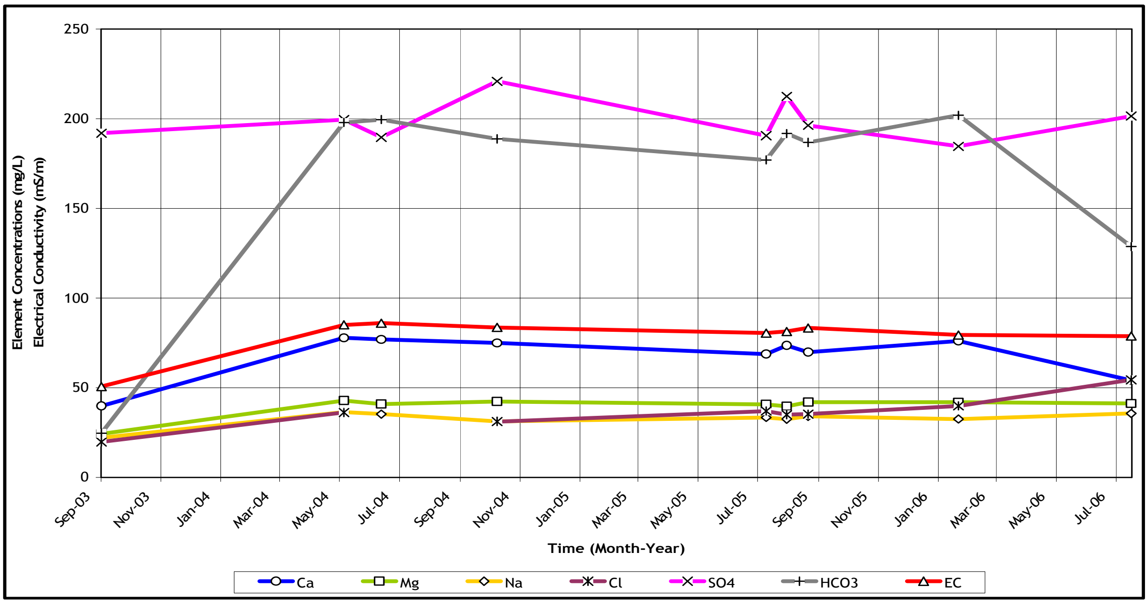


Figure 51. Recent temporal groundwater quality at site 033 (DWAF station A2N0584)

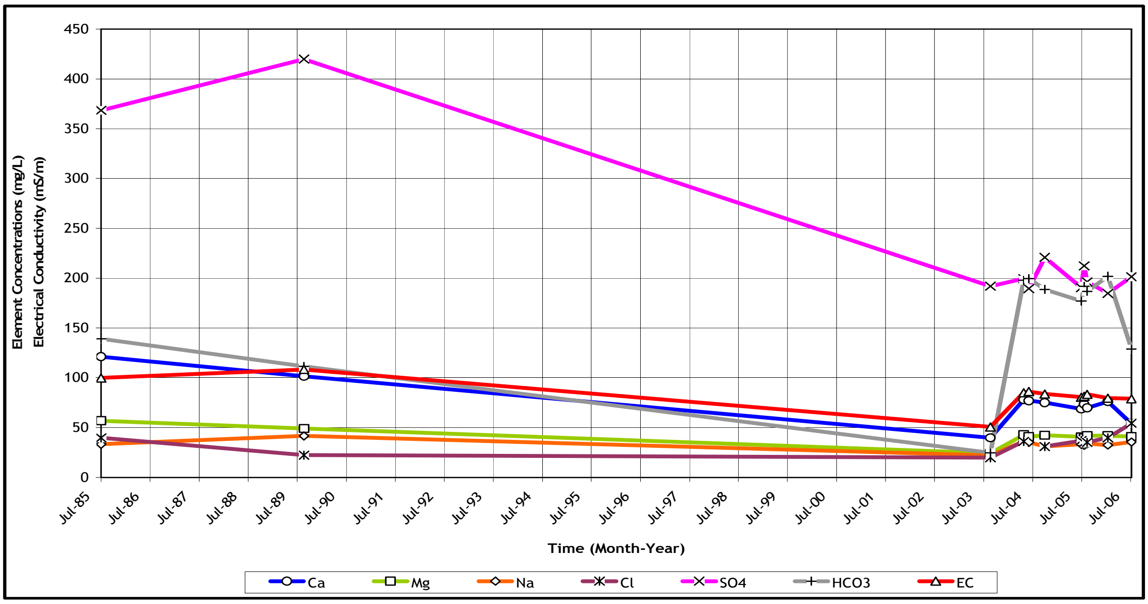


Figure 52. Historical temporal groundwater quality at site 033 (DWAF station A2N0584)

The early water quality record of station 033 (A2N0584) supports information contained in the KGR's Game Ranger's diary that Randfontein Estates Gold Mine discharged mine water into the Tweelopie Spruit in the course of mining operations (Du Toit, pers. comm., 2007).

The water quality associated with site 052, a borehole located on Plot 35 of the Helderblom A.H., sketches another picture. It is evident from Figures 53 and 54 that the water produced by this borehole has changed in regard to both its EC and its chemical composition. The increase in all major ion concentrations (except HCO_3) is reflected in a doubling of the electrical conductivity value from 13 to 25 mS/m between August 2000 and February 2007. More significantly, however, is the change from a Ca—HCO_3 (calcium bicarbonate) composition to a Mg—SO_4 (magnesium sulphate) composition, together with a decrease in pH value from 6.7 to 6.4, in the same time frame.

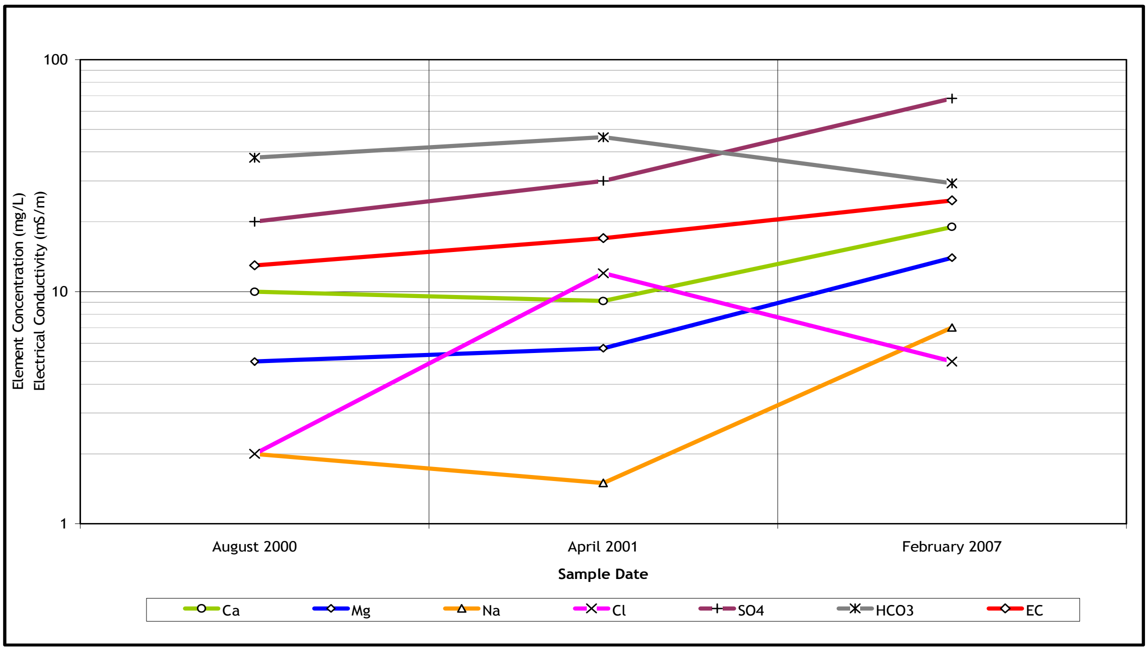


Figure 53. Change in groundwater quality at site 052, Helderblom A.H.

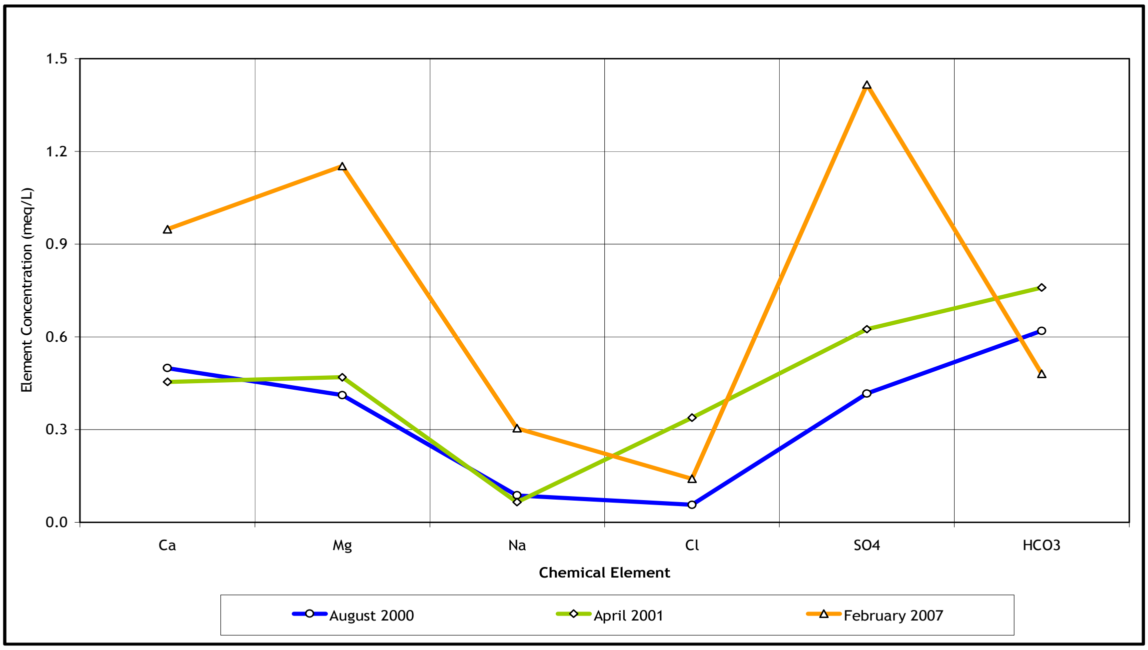


Figure 54. Change in groundwater composition at site 052, Helderblom A.H.

The change in groundwater quality at site 052 is illustrated in the Piper diagram characterisation of the groundwater chemistries in Figure 55. This diagram indicates the path followed by the groundwater chemistry from August 2000 to February 2007. It also places the transition in context with the typical compositions of dolomitic groundwater and that associated with acid mine water. The latter field includes the chemical composition of groundwater obtained in February 2007 from site 011 located some 400 m to the east of site 052, and closer to the outcrop of Government Sbgp. strata. The chemistry of the groundwater produced at site 011 is characterised by a comparatively low field pH value of 5.6 and EC of 37 mS/m. Whilst these circumstances do not necessarily indicate the influence of acid mine water at the two localities, the observations do raise concern for the long term threat posed by the migration of mine water in a northwesterly direction through the quartzitic strata from the decant area located to the southeast.

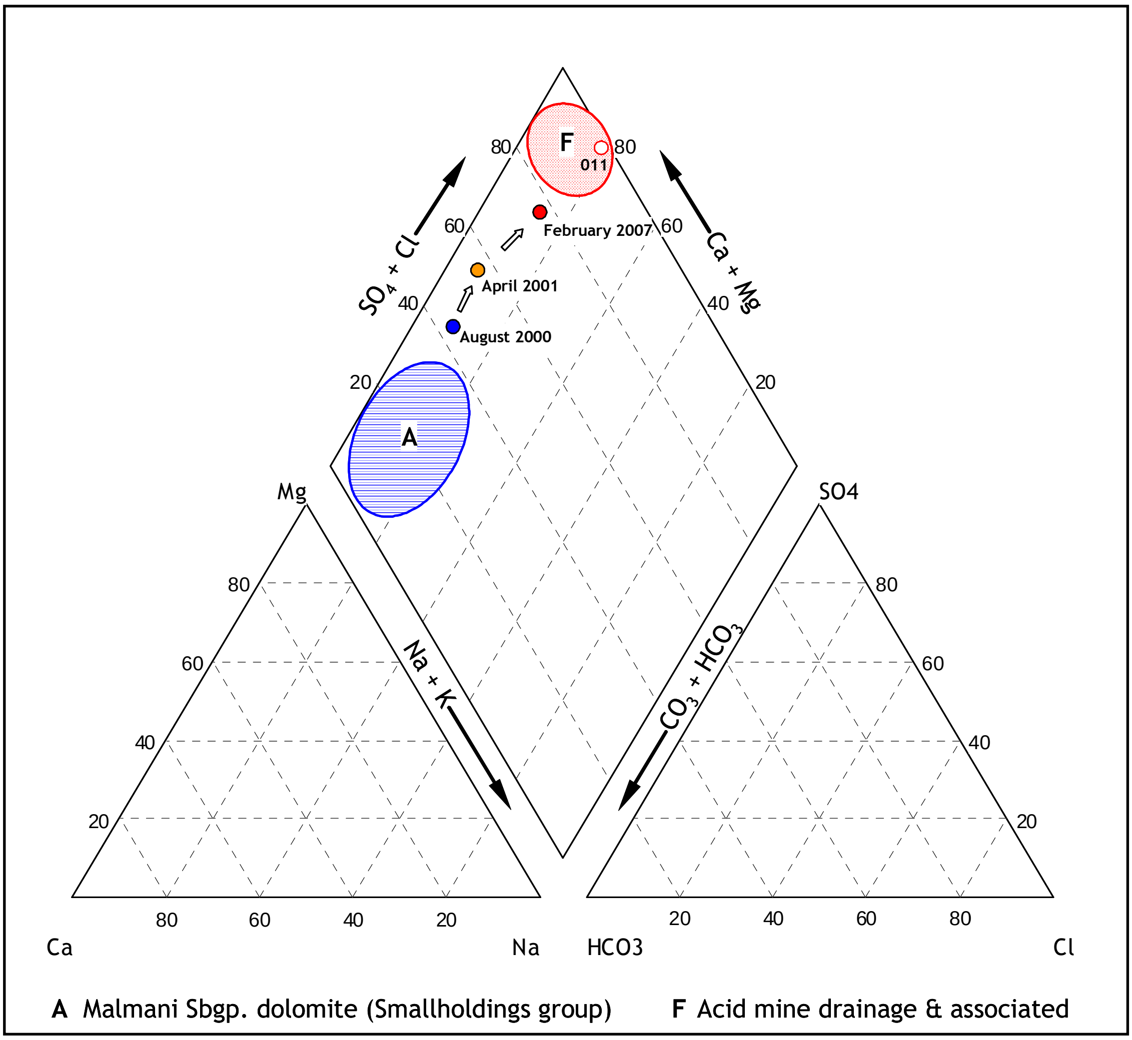


Figure 55. Piper diagram schematic of change in groundwater composition at site 052

4.2.5 Saturation Indices

The calculation of the calcite, dolomite, gypsum and goethite saturation indices (SI_{cal}, SI_{dol}, SI_{gyp} and SI_{goe} respectively) for each of the water samples subjected to chemical analysis, provides a measure of the extent to which each particular sample is in equilibrium with respect to these minerals. The SI values were calculated by the AquaChem for Windows 95/NT (Vers. 3.70) software programme using field pH values.

Expressed in logarithmic form, an SI value of zero denotes the equilibrium condition, a negative value denotes undersaturation and a positive value supersaturation. The results are presented in Annexure G. The SI_{cal} and SI_{dol} values are graphed in Figure 56, and demonstrate an excellent correlation as expected for dolomitic groundwater. The correlation coefficient value reflects the uniformity of the Ca to Mg ratio in the groundwater as shown in Figure 57. Since the Ca : Mg ratio approximates 1 : 1.1, the chemical composition of dolomite [$CaMg(CO_3)_2$] suggests that it contains half the calcium concentration of calcite [$Ca(CO_3)$]. This explains the slope constant of very nearly 2 in the regression equation that defines the SI_{dol} : SI_{cal} ratio, viz. $SI_{dol} = 1.9736\ SI_{cal} - 0.0703$, in Figure 56.

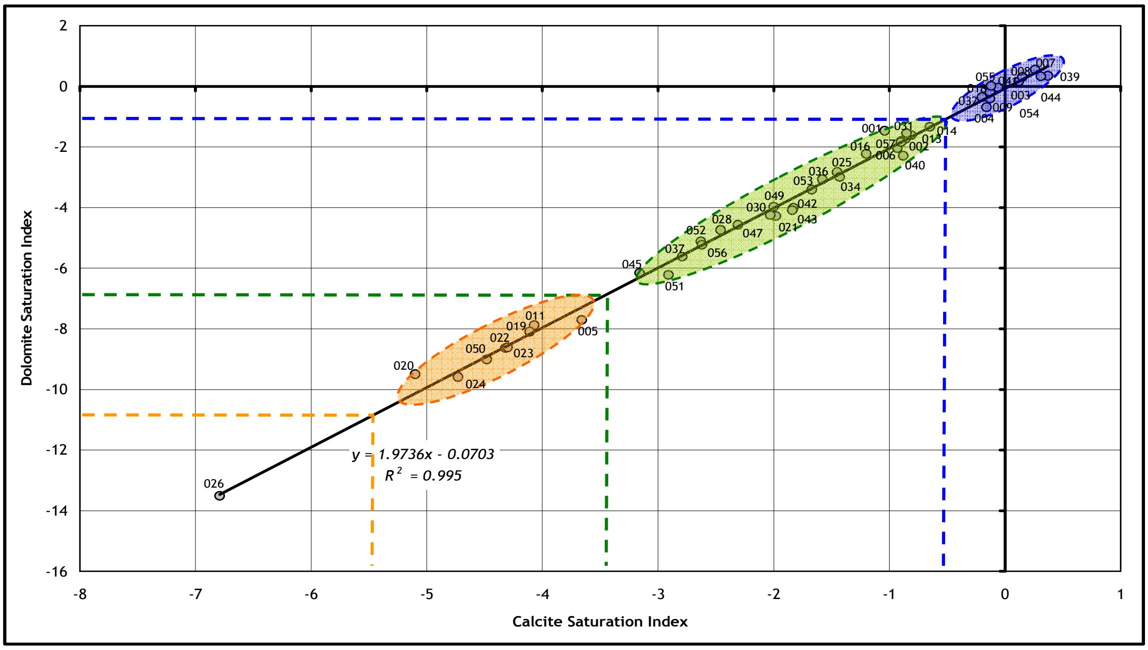


Figure 56. Correlation plot of calcite and dolomite saturation indices

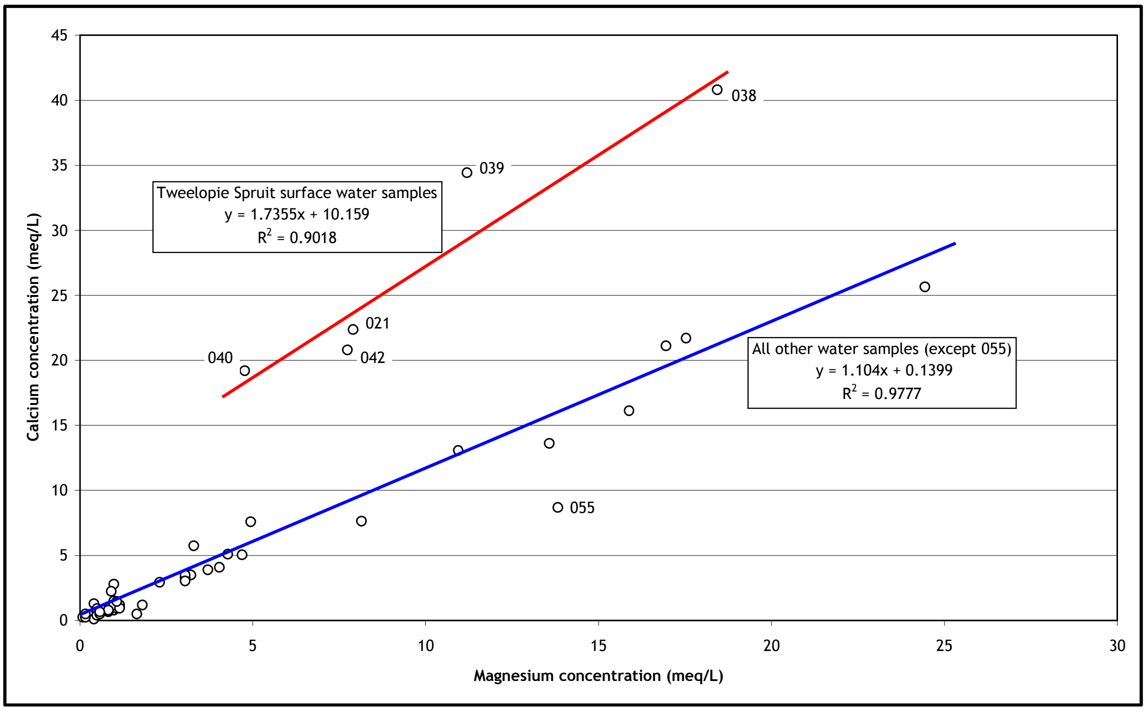


Figure 57. Scatter plot of calcium and magnesium concentrations

The correlation further suggests the subdivision of the data into three distinct "groups" (Figure 56). These are provisionally identified as the "equilibrium" group, the "moderately unsaturated" group and the "highly unsaturated" group. The "equilibrium" group encompasses samples that are either close to equilibrium or saturated with respect to both calcite and dolomite. The other groups encompass samples that are increasingly further removed from this state.

4.2.6 Anomalous Circumstances

The following anomalous circumstances in the vicinity of the BRI warrant mention. The HGM exploration borehole RG1 (site 025) located 375 m northeast of the BRI, produces acid mine water similar to that which decants from the BRI (Figure 58). This borehole is 36 m deep. In stark contrast, the HGM exploration boreholes RG2 located 320 m east of the BRI, and RG3 located 635 m northwest thereof, produce groundwater that indicates no contamination with mine water. Figure 58 reveals that the macro-element composition of the RG3 groundwater conforms to that of "pristine" dolomitic water in the region, while the composition of the RG2 groundwater is distinctly different from that obtained from any other source in the study area except, perhaps, that of surface water in the Blougat Spruit (see Figure 39).

Boreholes RG2 (site 024) and RG3 (site 028) are only 30 and 27 m deep, respectively. The anomalous circumstances associated with these boreholes are compounded by the ostensible changes in chemical composition between February 2006 and February 2007. These changes are shown in Figure 58.

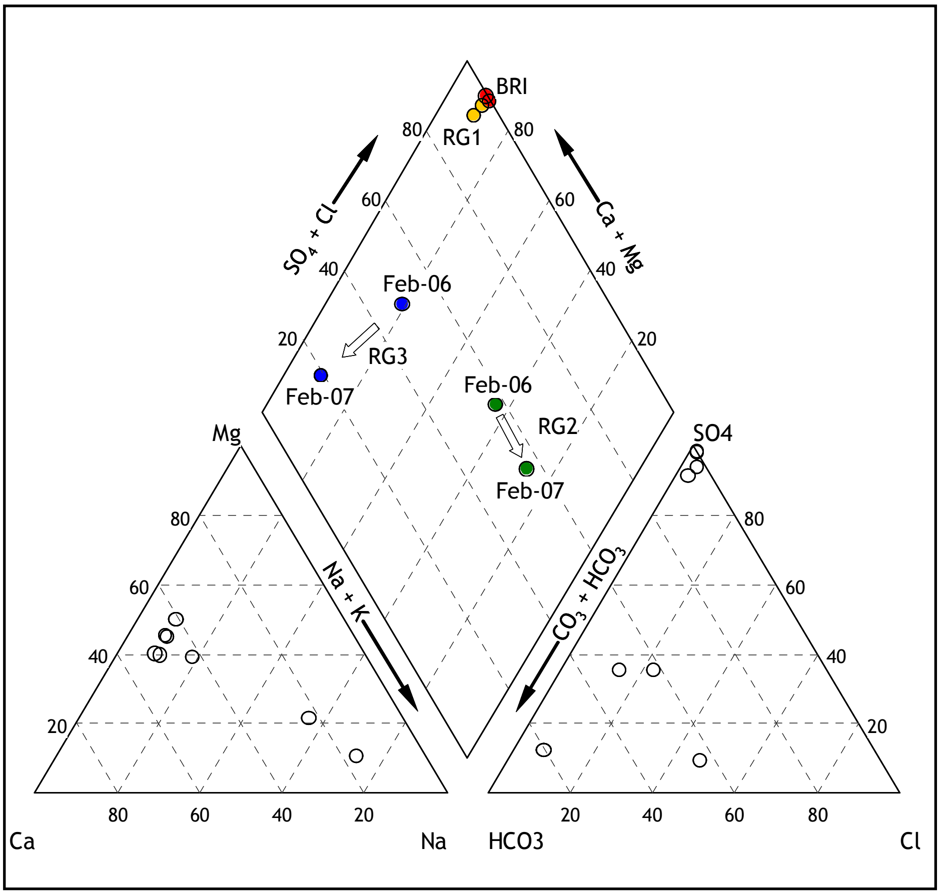


Figure 58. Piper diagram characterisation of changes in groundwater quality in the BRI environs

The paths that describe these changes are opposite to those which might be associated with a trend toward mine water quality. It is evident from section 3.2.2 (Figure 11) that all three boreholes target gravimetric "low" anomalies. The better quality groundwater sourced from borehole RG3 is readily explained on the basis of the separation of its gravimetric "low" anomaly from that which is common to boreholes RG1 and RG2 (Figure 11). The groundwater chemistry results for the latter two boreholes, however, suggest that the gravimetric "low" shared by these boreholes does not translate into hydraulic continuity. In fact, the path which describes the RG2 change in groundwater quality between February 2006 and February 2007 (Figure 58) indicates an as yet inexplicable extraneous influence, the origin and substance of which extends beyond the scope of this study to investigate. One possibility lies in the nature of sample acquisition itself, the February 2007 samples having been obtained by means of bailing, whereas the February 2006 samples were obtained during pumping of the boreholes (Van Biljon, pers. comm., 2007). Even so, the disparate chemical compositions of RG1 and RG2 groundwater remain apparent also in the February 2006 data.

5 DISCUSSION

The additional perspective on the groundwater environment provided by the hydrogeological assessment of acid mine drainage impacts in the West Rand Basin raises a concern for the veracity of the environmental critical level (ECL) that is proposed as a decant management measure. The ECL is defined as the lowest potentiometric head in the mine workings at which mine water will not daylight in the dolomite outlier. This elevation has been set at 1 636 m amsl (JFA, 2006), which corresponds to that of the Hippo Dam in the Krugersdorp Game Reserve. In essence, the concept entails lowering the water level in #8 Shaft, which currently stands at ≈1 672 m amsl, by 36 m. The ECL concept is illustrated in Figure 59.

It is foreseen that the potentiometric head in the flooded mining void can be lowered to the ECL elevation by abstracting mine water from #8 Shaft at the rate of 20 ML/d for a period of 32 months (JFA, 2006). The pumping rate is dictated mainly by the volume that can be treated at the treatment plant and otherwise disposed of, e.g. for use as process water by the Mogale Gold operation.

The feasibility of the ECL as a decant management measure rests on the premise that leakage through the Black Reef Formation and Government Subgroup strata in a northerly to northwesterly direction (see Figures 9 and 35) is insignificant. This necessarily presumes that the transmissive properties of these mainly quartzitic strata are poor. The information put forward in this report does not support this presumption under circumstances where the structural geology of the region is riddled with features, examples of which are provided in Figures 60 and 61, that are potentially conducive to the movement of groundwater along preferential flow paths. It must be considered that the geometry of the cave systems in the wider region is similarly dictated by these features (Jamison et al., 2004).

In light of the above, the difference in hydraulic head between the ECL in the outlier south of the BRFm. and the GSbgp. quartzites in the KGR, and the MSbgp. dolomite in the Zwartkrans Compartment to the north (e.g the Aviary spring at 1 530 m amsl), remains in the order of 100 m, equivalent to 10 bar or 1 000 kPa of pressure. These considerations suggest that the efficacy of the ECL as a decant management measure might need to be bolstered by drawing the potentiometric head in the mining void down even further in order to create a reverse hydraulic gradient to the south in the northern portion of the outlier. This would, however, have potentially negative impacts on the discharge of springs such as Spring 2 (site 030 in the Cemetery group), and the Poplar Spring (site 037).

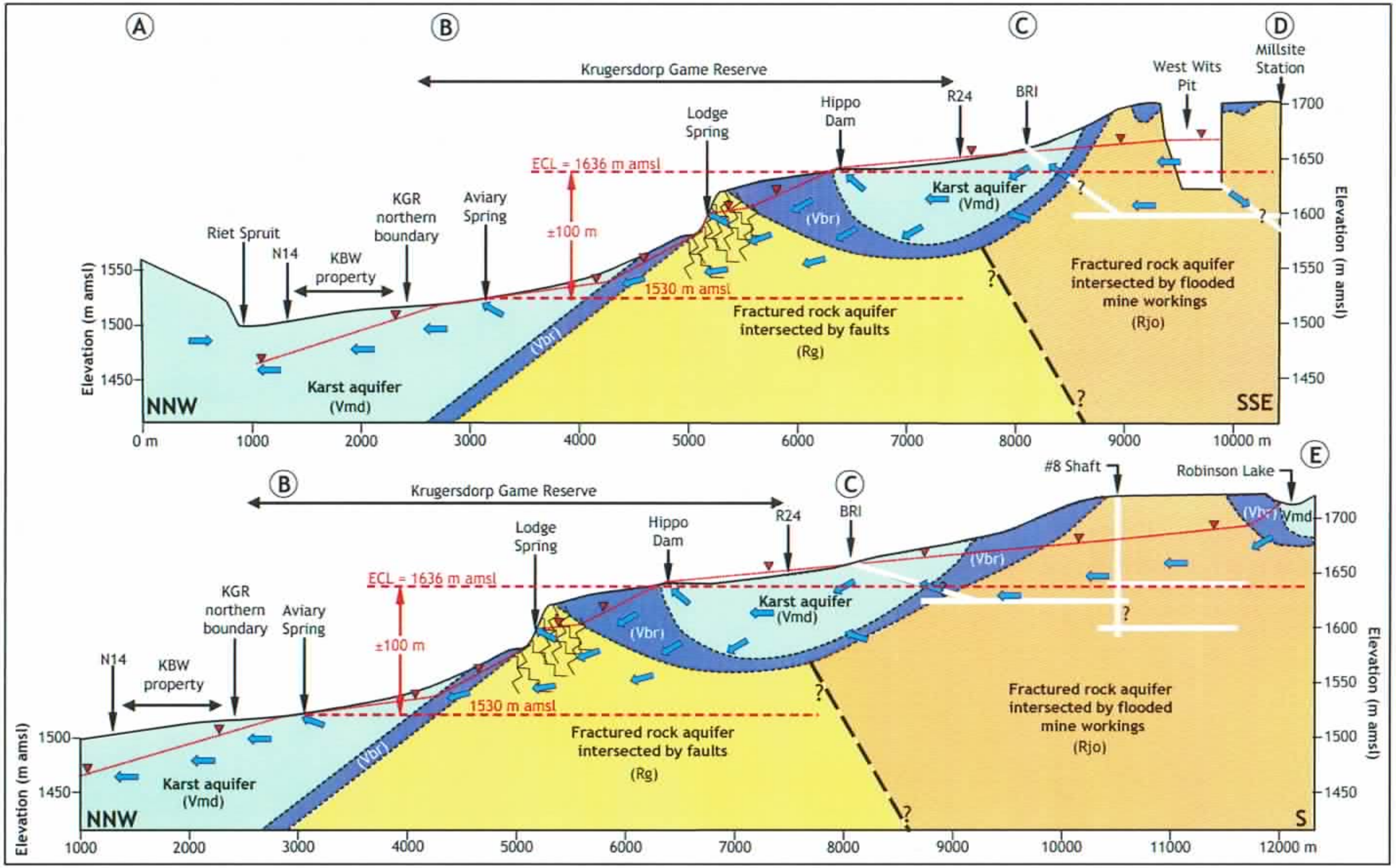


Figure 59. Hydrogeological context of the ECL concept in profile

Figure 60. View looking south, of steeply dipping and folded Government Subgroup quartzite in the KGR

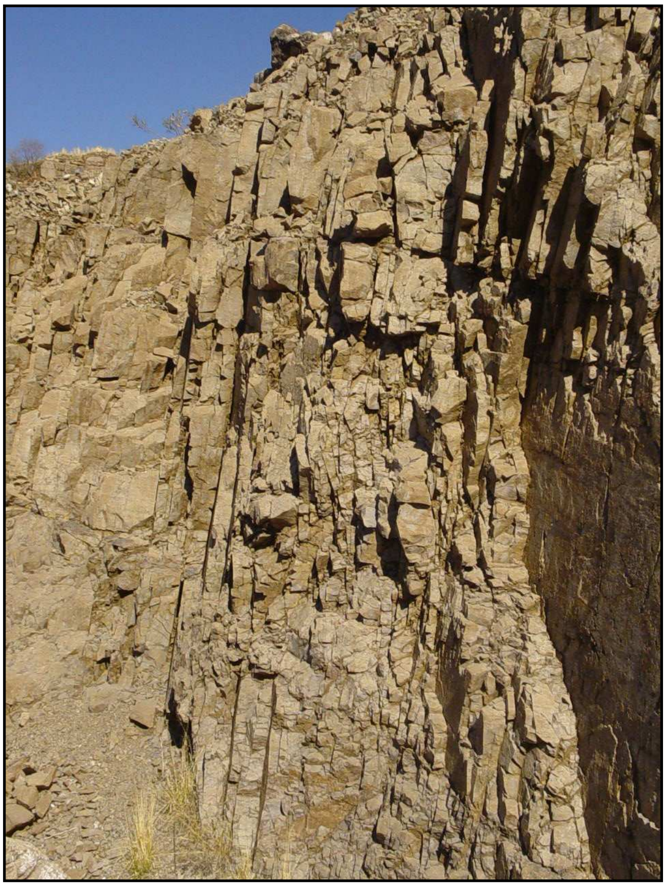


Figure 61. View looking south, of intensely fractured dolomite in north-south trending shear zone through the Zwartkrans Quarry near Oaktree

6 CONCLUSIONS

The review of hydrogeological assessments related to acid mine drainage in the West Rand Basin has generated a suite of data and information that not only augments the growing volume of such material, but also contributes materially to an improved understanding of the physical and chemical hydrogeology of the subregion. The following most salient conclusions are stated.

- An understanding of the groundwater environment in the subregion is obscured by the complex geology. This is manifested in the "popular" perception that the Government Subgroup strata form a comparatively low permeability "barrier" between the dolomitic outlier with its associated locus of mine water decant to the south, and the main dolomitic Zwartkrans Compartment to the north. This study has produced sufficient evidence to question the accuracy of such perception and, as its derivative, the Environmental Critical Level (ECL) as an absolute decant management solution.

- The threat to the quality of groundwater in especially the karst aquifer of the Zwartkrans Compartment derives from both acid mine drainage originating in the outlier and from effluent discharge originating at the Percy Stewart Waste Water Treatment Works. Whereas the former contributes elevated calcium, sulphate and heavy metal concentrations, the latter primarily contributes exceedingly high bacteriological concentrations to the karst environment.

- Although much effort and cost is expended by various organisations and parties in collecting hydrogeological data and information in the subregion, comparatively little of this data is subjected to scientific scrutiny and interrogation (either collectively or individually) with a view to further informing an understanding of the groundwater dynamic in the subregion.

7 RECOMMENDATIONS

The conclusions (section 6) precipitate the following recommendations.

- There is sufficient cause to investigate in detail the structural geology in the subregion insofar as it informs the physical groundwater environment. Such investigation should comprise a combination of complementary methods including structural geological mapping, an analysis of available remotely sensed geophysical information, and ground-based geophysical surveys. The latter must include at least the magnetic and electro-magnetic techniques. The Krugersdorp Game Reserve provides the ideal terrain in which to execute the field-based components of this recommendation.

- The evaluation of the structural geology and geophysical data sets must be followed by intrusive investigations comprising the sinking of percussion-drilled exploration boreholes that target clearly identified geological/hydrogeological features. These boreholes must be constructed to provide technically unequivocal hydrogeological test facilities (e.g. for test pumping, tracer testing, etc.) and vertically stratified groundwater quantity and quality monitoring stations.

- Under circumstances where the reticence of key role players to release important data sets impedes accurate judgement, it is imperative that such parties offer "proprietary" data sets up to objective independent scrutiny and application.

- There is an urgent need for all available existing data to be collated into a single data set that consolidates often duplicate sets (e.g. where sampling points common to a number of organisations/parties bear different identifiers), and that eliminates redundant monitoring stations.

8 ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the THRIP funding provided by Dr. Jannie Maree, and without which this project might never had materialised. Gratitude is also expressed toward the many landowners, both private and industrial, who granted access to their properties for the collection of raw data. In this regard, the good offices of Mr. Basie van der Walt of Harmony Gold Mining Company and Mr. Japie Mostert, Chief Game Ranger at the Krugersdorp Game Reserve, deserve special mention. The authors are also indebted to their colleague Dr. Pete Ashton, as well as Dr. Kai Witthüser (University of Pretoria), Prof. Dr. Frank Winde (North West University, Potchefstroom Campus), Mr. Ewald Erasmus (Consultant), and Dr. Nick Robins (British Geological Survey) for their thorough and mostly constructive review of this report.

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ANNEXURE A

Summary of field work scope, methodology and approach

The study documented in this report relies heavily on data and information sourced in the course of field work carried out mainly in February and March 2007. Field activities were directed at obtaining information that would inform both the hydrophysical and the hydrochemical aspects of the surface and groundwater environments in the study area. Access to all properties was at all times gained only following contact being made with the landowner and permission obtained.

HYDROPHYSICAL ASPECTS

These activities focussed primarily on sourcing depth to groundwater level data wherever possible from enumerated boreholes and mine shafts. The selection of such facilities sought to establish a representative distribution of water level measurements in the study area. In every instance where a measurement was possible, care was taken to ensure that the facility had been inactive for a sufficiently long period to establish a rest water level that was representative of the site and its surrounds. This extended to arranging with property owners that high-demand installations (e.g. those producing water for irrigation and industrial use) be "rested" overnight, and requiring of a researcher to take a rest water level measurement "at first light" in order to minimise disruption to the water use activity. The enumeration of springs and surface water sampling stations included an estimate of the discharge at the time of the visit. Such estimate was derived visually based on the experience of a researcher.

HYDROCHEMICAL ASPECTS

Activities in this regard focussed on the collection, preservation and custodianship of water samples prior to delivery to the analysing laboratory. Protocols and procedures in this regard were dictated by the specific analysis earmarked for each sample. The spectrum of analyses comprised:

- Inorganic analysis (pH, EC, Ca, Mg, Na, K, Cl, SO_4, Total alkalinity, NO_3, NH_4, F, PO_4 (total), ortho-PO_4, As, B, Fe, Mn, Zn, TOC)
  1 x 1500 mL plastic bottle for macro-element analysis
  1 x 350 mL plastic bottle re-filled with 14 mL of 10 % HNO_3 for trace metals analysis
- 66-element Inductively Coupled Plasma (ICP) scan
  1 x 500 mL plastic bottle
- Bacteriological analysis (Total coliform, faecal coliform and *E. coli.* bacteria)
  1 x 350 mL plastic bottle pre-sterilised by supply laboratory
- Radon analysis
  1 x 20 mL glass bottle pre-filled with scintillation oil solution
- Environmental isotope analysis
  1 x 500 mL plastic bottle
- Toxicity analysis (*Daphnia pulex* lethality)
  1 x 1000 mL plastic bottle

Samples for inorganic, ICP, bacteriological, isotope and toxicity analysis were transferred daily from ice brick and cooler box field storage facilities to refrigerated storage before weekly delivery to the analytical laboratory. Samples for bacteriological analysis were collected on the day before delivery to the laboratory. Samples for radon analysis were kept in the dark and delivered to the analytical laboratory on the day of collection.

ANNEXURE B

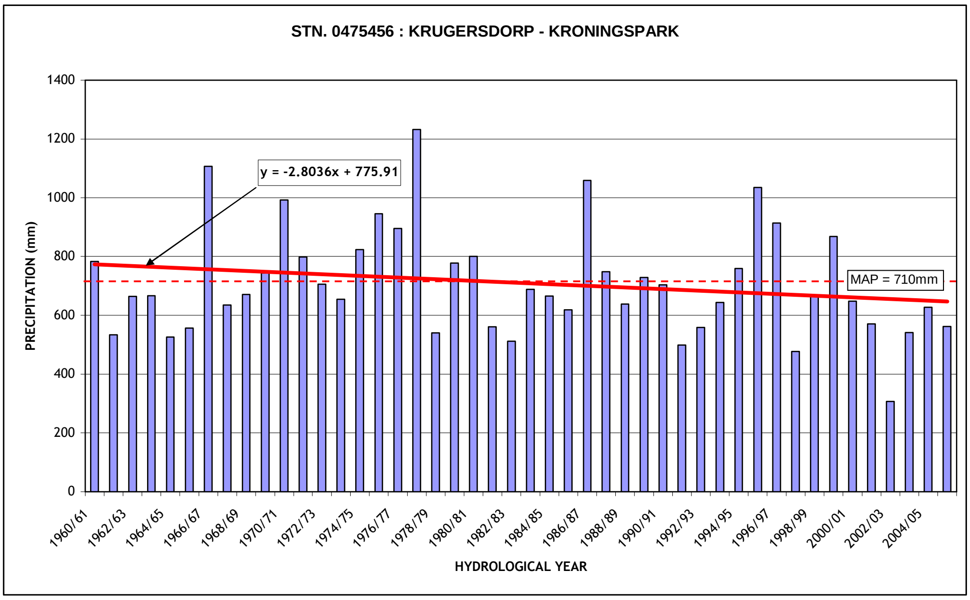
Regional long term annual precipitation information

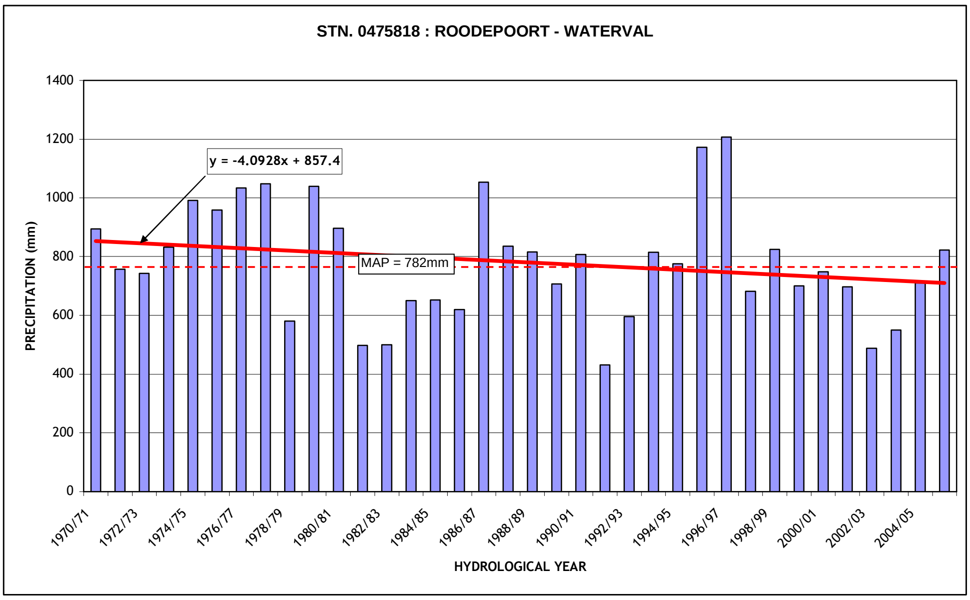
Station No.[(1)]	Station Name	Coordinates		Elevation (m amsl)	Opening Date	MAP[(2)] (mm)	Hydrological Year[(3)]
		Lat.	Long.				
0475338	Randfontein	26° 7.8’	27° 42.0’	1710	Dec 1954	657	1955/56
0475456	Krugersdorp Kroningspark	26° 6.0’	27° 46.2’	1699	Jul 1903	710	1960/61
0475818	Roodepoort Waterval	26° 7.8’	27° 58.2’	1580	Jun 1970	782	1970/71
0512082	Hekpoort Nooitgedacht	25° 52.2’	27° 33.0’	1463	Jan 1972	780	1972/73
0512090	Magaliesburg - Pol	26° 0.0’	27° 33.0’	1480	Jan 1969	634	1969/70

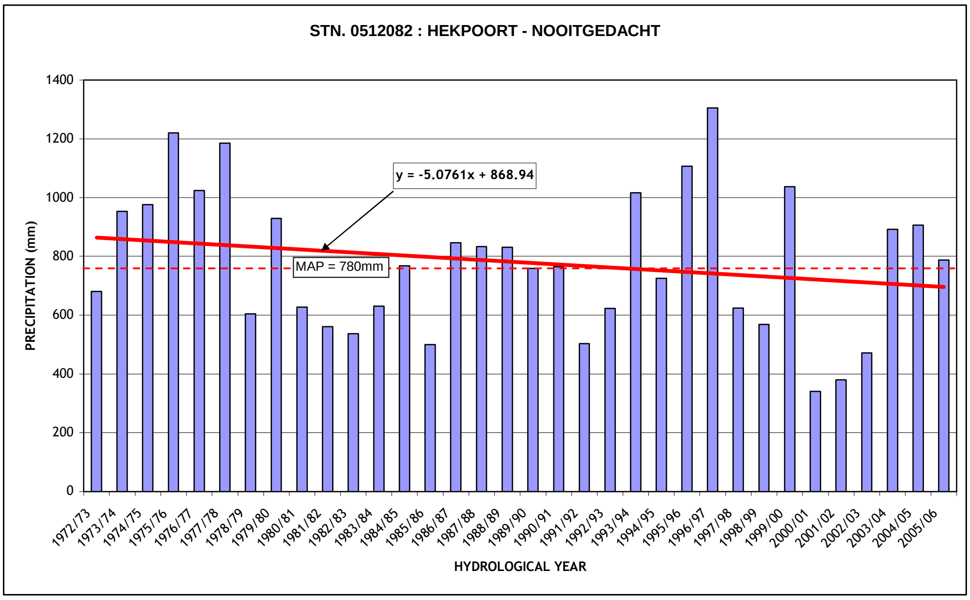
(1) See Figure 2 for station localities

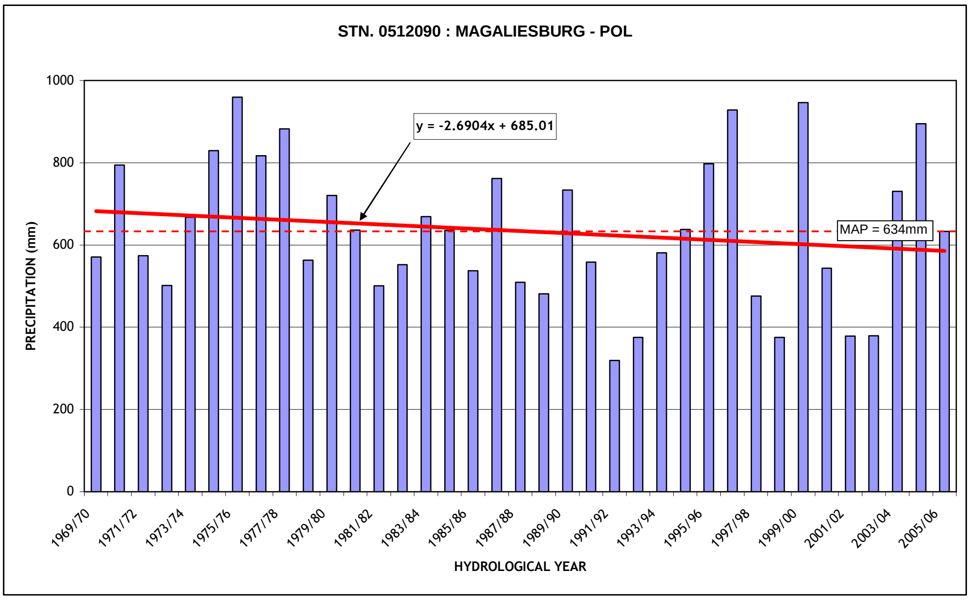
(2) Mean annual precipitation per hydrological year

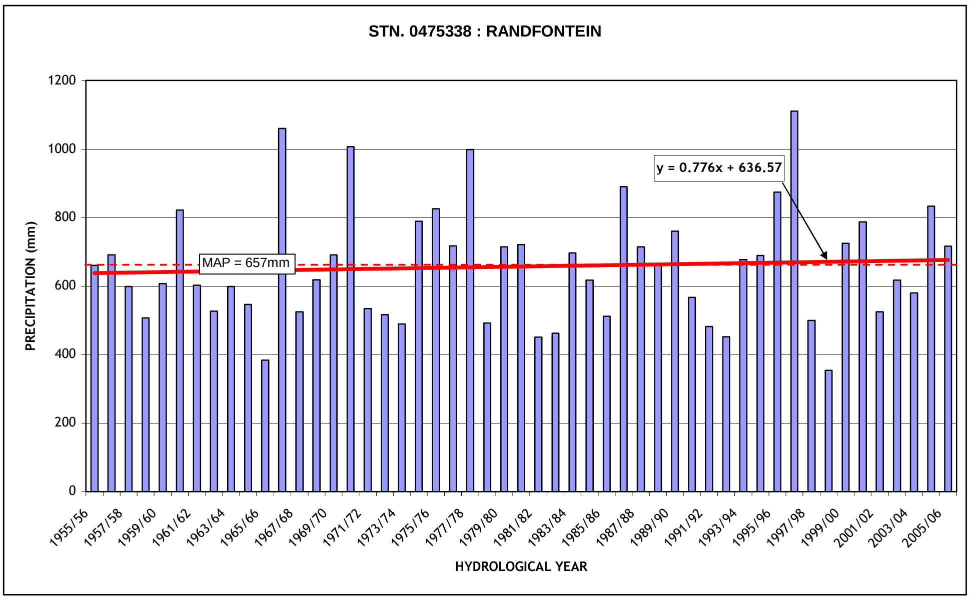
(3) First hydrological year of analysis period and graph/histogram


STN. 0475456 : KRUGERSDORP - KRONINGSPARK
y = -2.8036x + 775.91
MAP = 710mm
PRECIPITATION (mm)
0
200
400
600
800
1000
1200
1400
HYDROLOGICAL YEAR
1960/61
1962/63
1964/65
1966/67
1968/69
1970/71
1972/73
1974/75
1976/77
1978/79
1980/81
1982/83
1984/85
1986/87
1988/89
1990/91
1992/93
1994/95
1996/97
1998/99
2000/01
2002/03
2004/05


STN. 0475818 : ROODEPOORT - WATERVAL
y = -4.0928x + 857.4
MAP = 782mm
PRECIPITATION (mm)
0
200
400
600
800
1000
1200
1400
HYDROLOGICAL YEAR
1970/71
1972/73
1974/75
1976/77
1978/79
1980/81
1982/83
1984/85
1986/87
1988/89
1990/91
1992/93
1994/95
1996/97
1998/99
2000/01
2002/03
2004/05

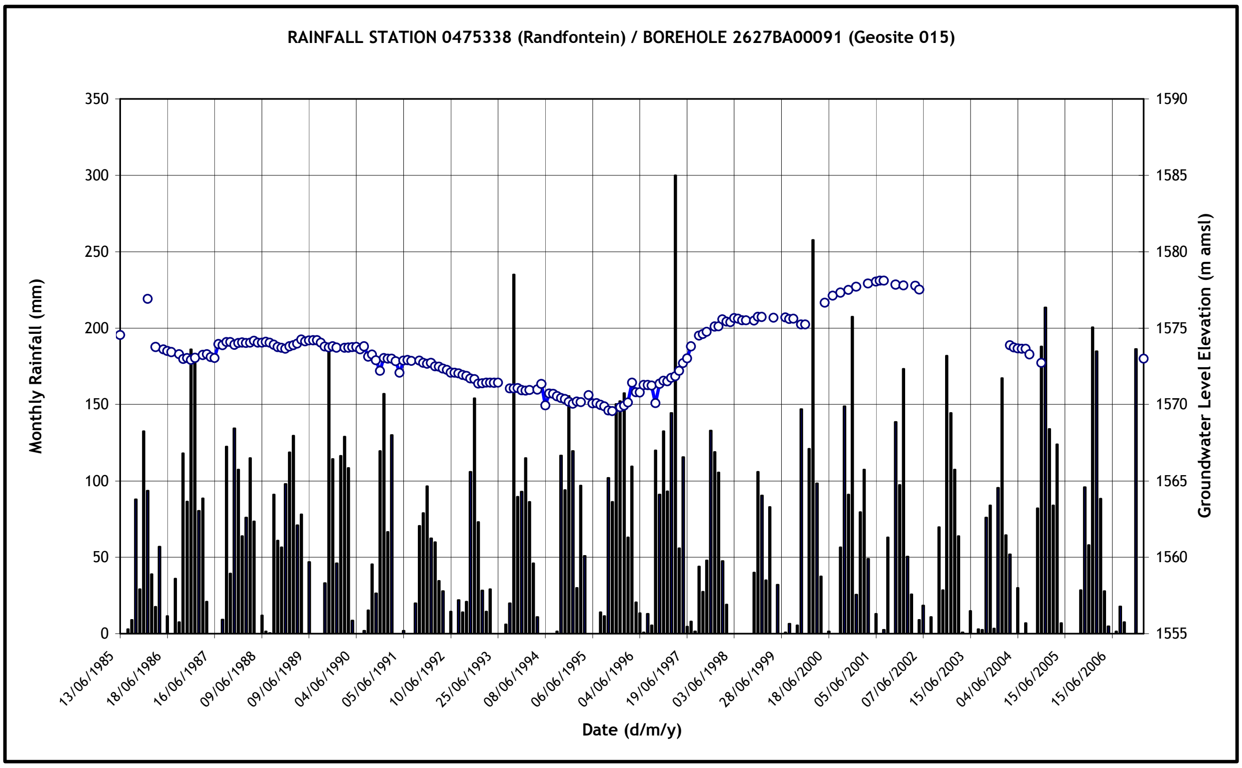

STN. 0512082 : HEKPOORT - NOOITGEDACHT
y = -5.0761x + 868.94
MAP = 780mm
PRECIPITATION (mm)
0
200
400
600
800
1000
1200
1400
HYDROLOGICAL YEAR
1972/73
1973/74
1974/75
1975/76
1976/77
1977/78
1978/79
1979/80
1980/81
1981/82
1982/83
1983/84
1984/85
1985/86
1986/87
1987/88
1988/89
1989/90
1990/91
1991/92
1992/93
1993/94
1994/95
1995/96
1996/97
1997/98
1998/99
1999/00
2000/01
2001/02
2002/03
2003/04
2004/05
2005/06

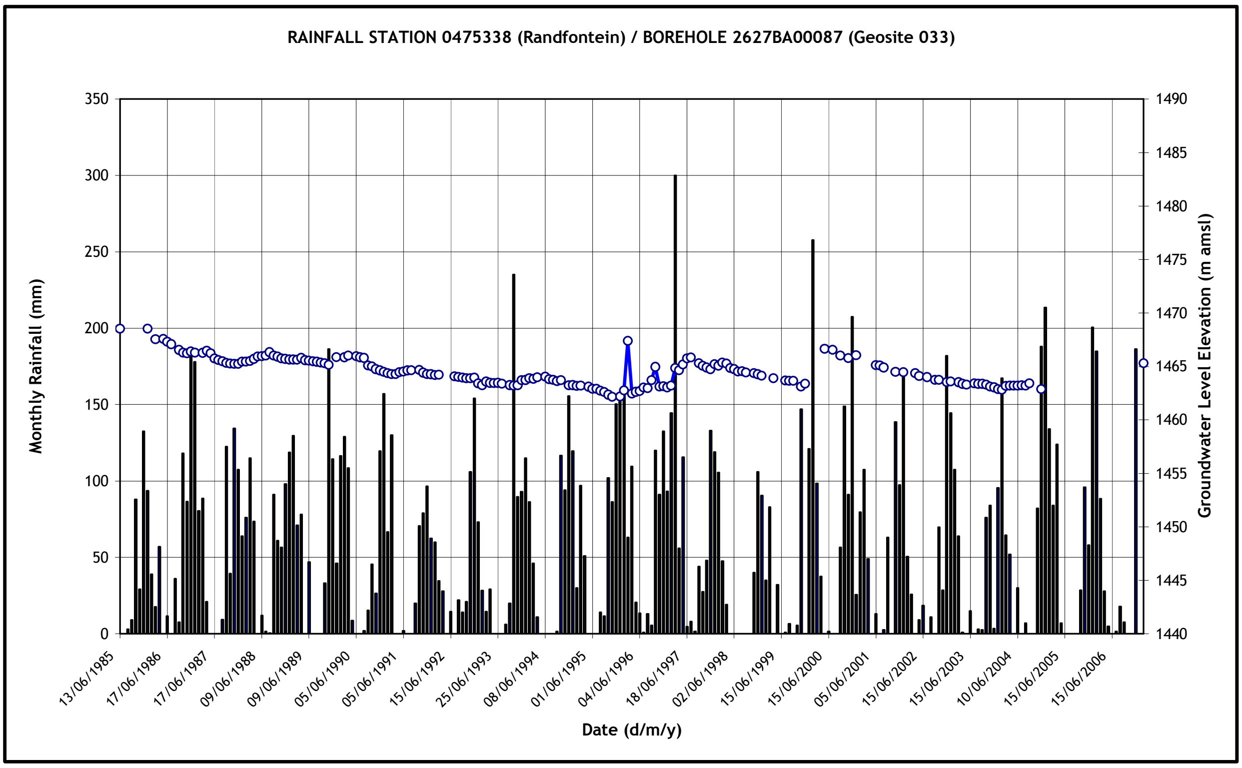

STN. 0512090 : MAGALIESBURG - POL
PRECIPITATION (mm)
HYDROLOGICAL YEAR
y = -2.6904x + 685.01
MAP = 634mm
0
200
400
600
800
1000
1969/70
1971/72
1973/74
1975/76
1977/78
1979/80
1981/82
1983/84
1985/86
1987/88
1989/90
1991/92
1993/94
1995/96
1997/98
1999/00
2001/02
2003/04
2005/06

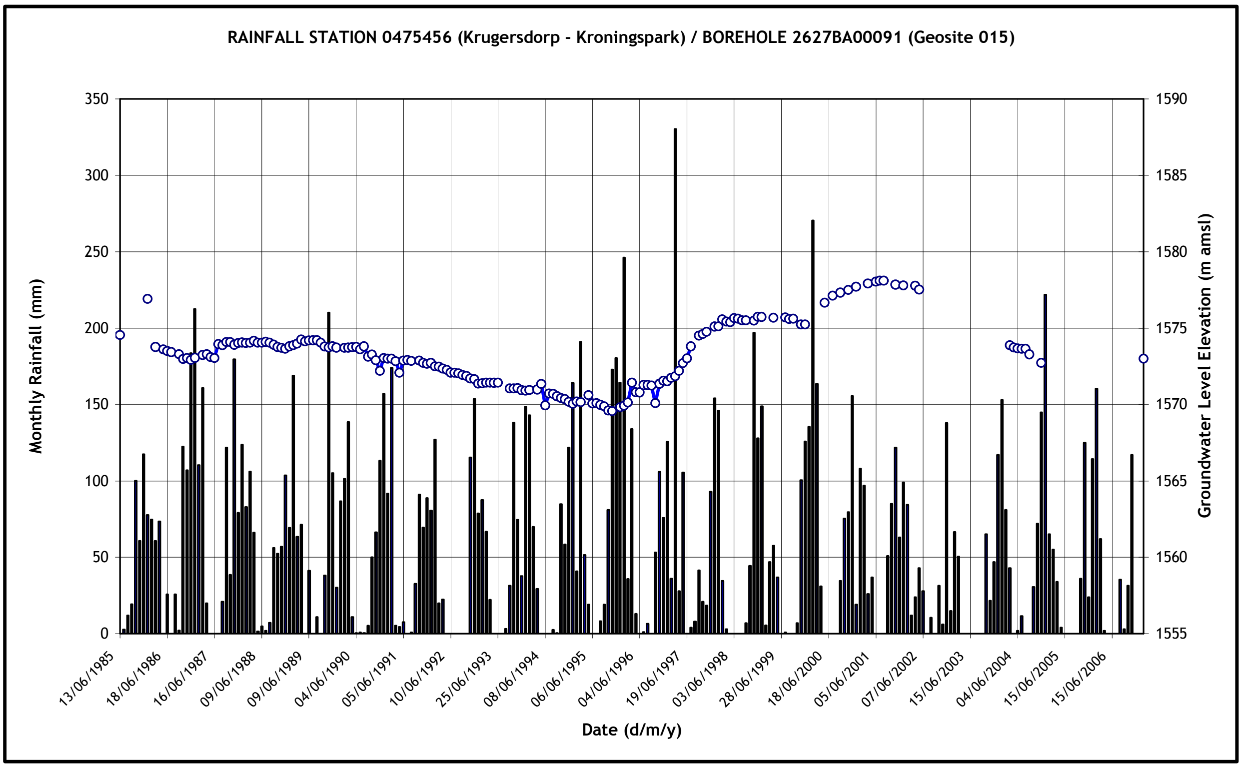

STN. 0475338 : RANDFONTEIN
PRECIPITATION (mm)
HYDROLOGICAL YEAR
y = 0.776x + 636.57
MAP = 657mm
0
200
400
600
800
1000
1200
1955/56
1957/58
1959/60
1961/62
1963/64
1965/66
1967/68
1969/70
1971/72
1973/74
1975/76
1977/78
1979/80
1981/82
1983/84
1985/86
1987/88
1989/90
1991/92
1993/94
1995/96
1997/98
1999/00
2001/02
2003/04
2005/06

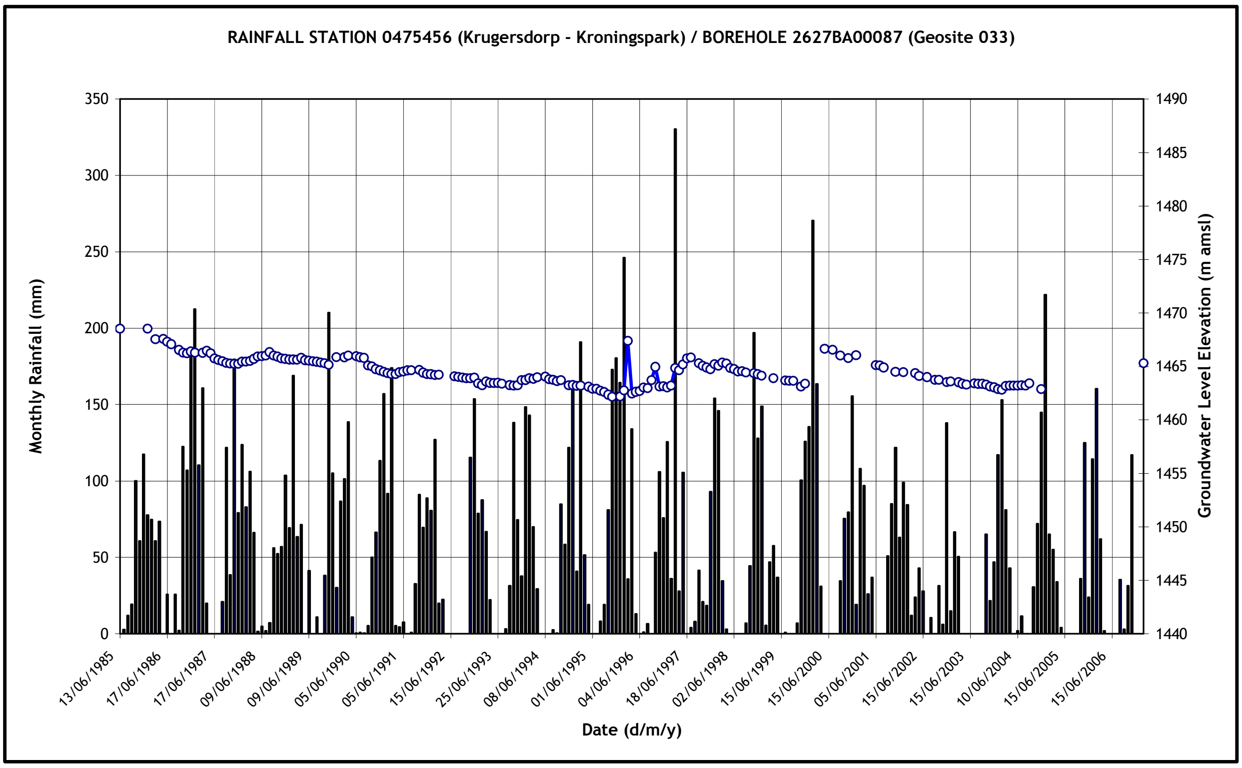
ANNEXURE C

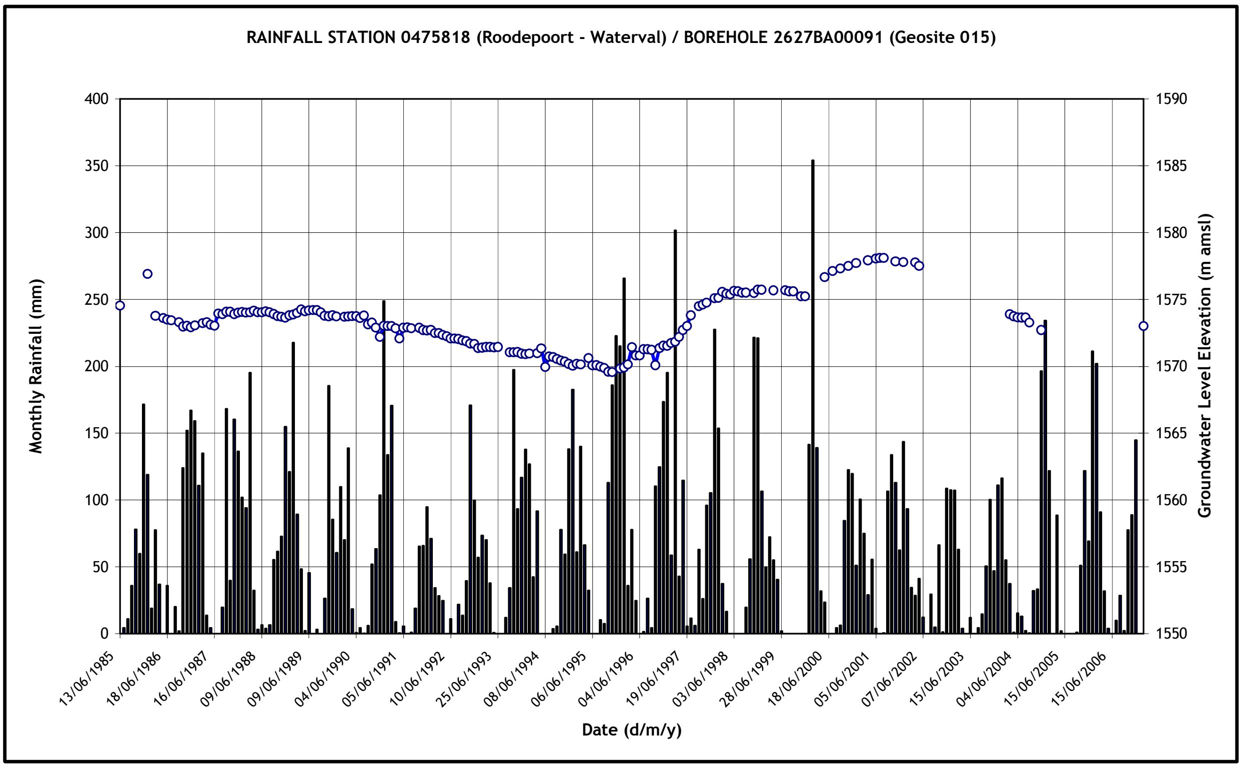
Hydrostatic response patterns versus rainfall

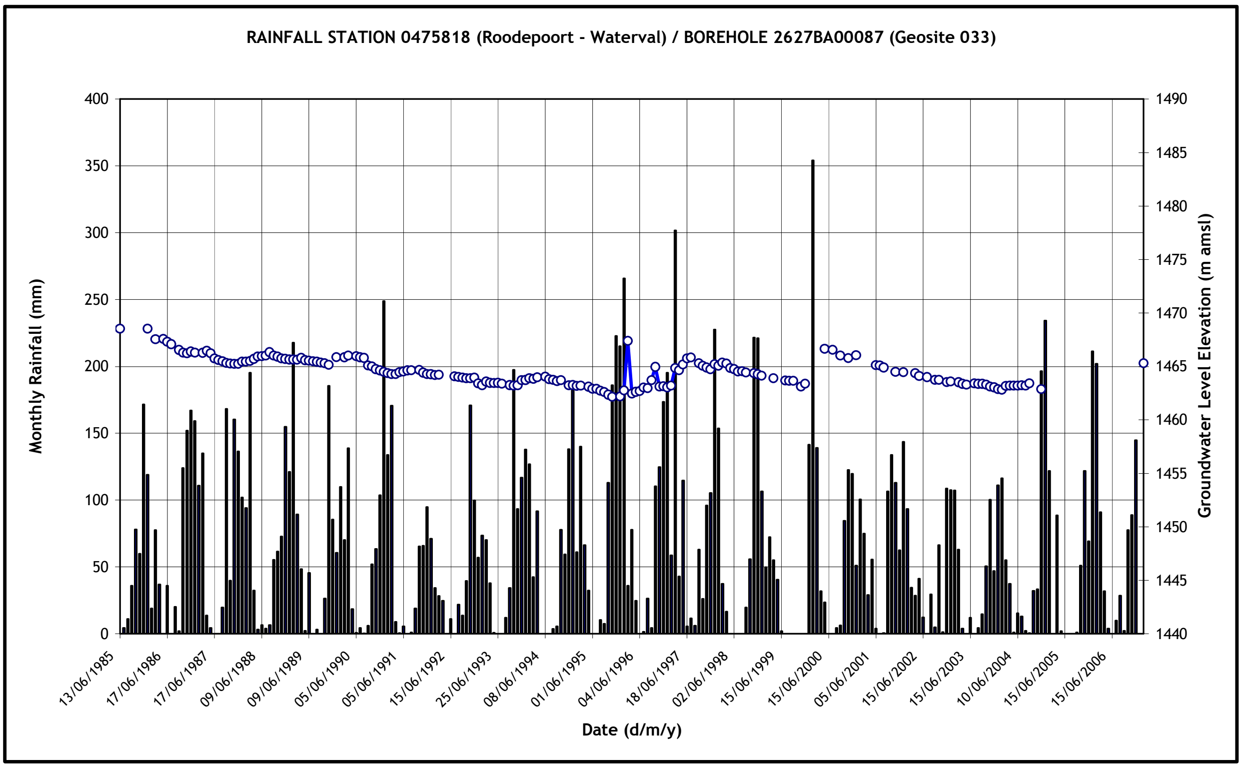

RAINFALL STATION 0475338 (Randfontein) / BOREHOLE 2627BA00091 (Geosite 015)
Monthly Rainfall (mm)
0
50
100
150
200
250
300
350
Groundwater Level Elevation (m amsl)
1555
1560
1565
1570
1575
1580
1585
1590
13/06/1985
18/06/1986
16/06/1987
09/06/1988
09/06/1989
04/06/1990
05/06/1991
10/06/1992
25/06/1993
08/06/1994
06/06/1995
04/06/1996
19/06/1997
03/06/1998
28/06/1999
18/06/2000
05/06/2001
07/06/2002
15/06/2003
04/06/2004
15/06/2005
15/06/2006
Date (d/m/y)

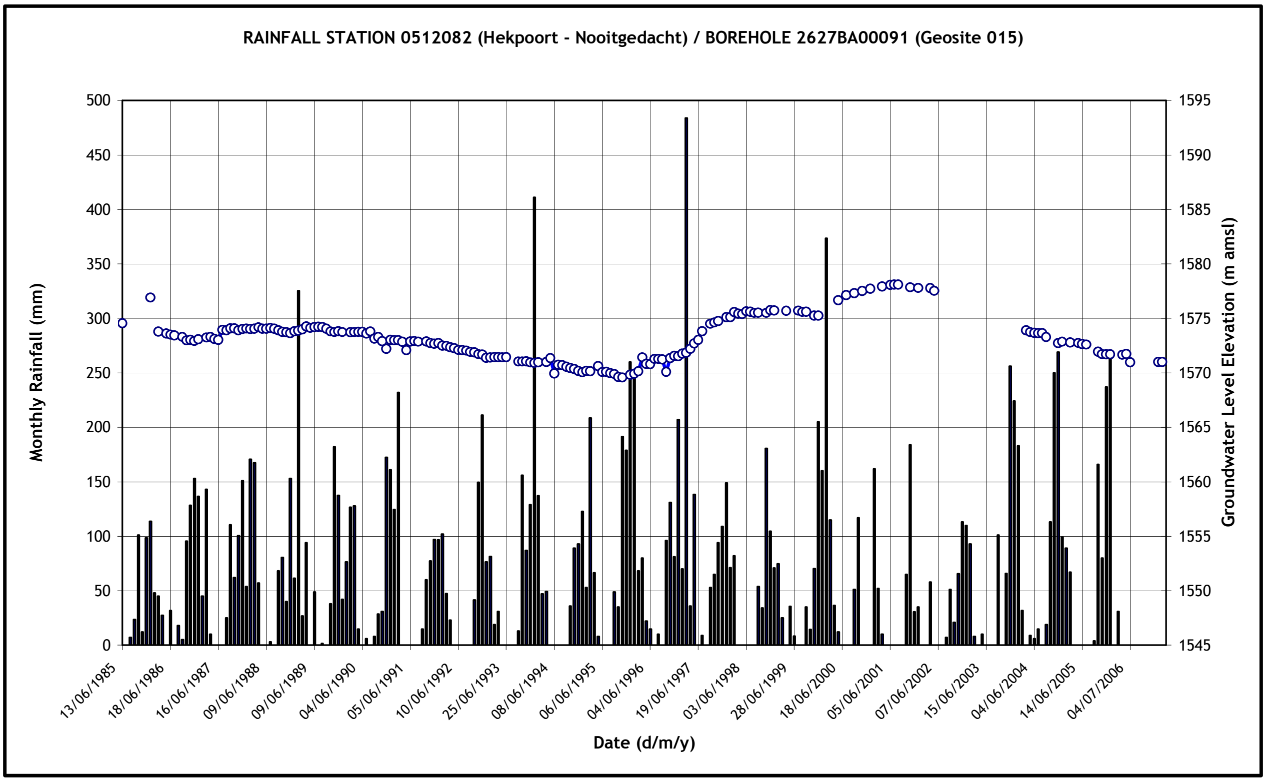

RAINFALL STATION 0475338 (Randfontein) / BOREHOLE 2627BA00087 (Geosite 033)
Monthly Rainfall (mm)
0
50
100
150
200
250
300
350
Groundwater Level Elevation (m amsl)
1440
1445
1450
1455
1460
1465
1470
1475
1480
1485
1490
13/06/1985
17/06/1986
17/06/1987
09/06/1988
09/06/1989
05/06/1990
05/06/1991
15/06/1992
25/06/1993
08/06/1994
01/06/1995
04/06/1996
18/06/1997
02/06/1998
15/06/1999
15/06/2000
05/06/2001
15/06/2002
15/06/2003
10/06/2004
15/06/2005
15/06/2006
Date (d/m/y)


RAINFALL STATION 0475456 (Krugersdorp - Kroningspark) / BOREHOLE 2627BA00091 (Geosite 015)

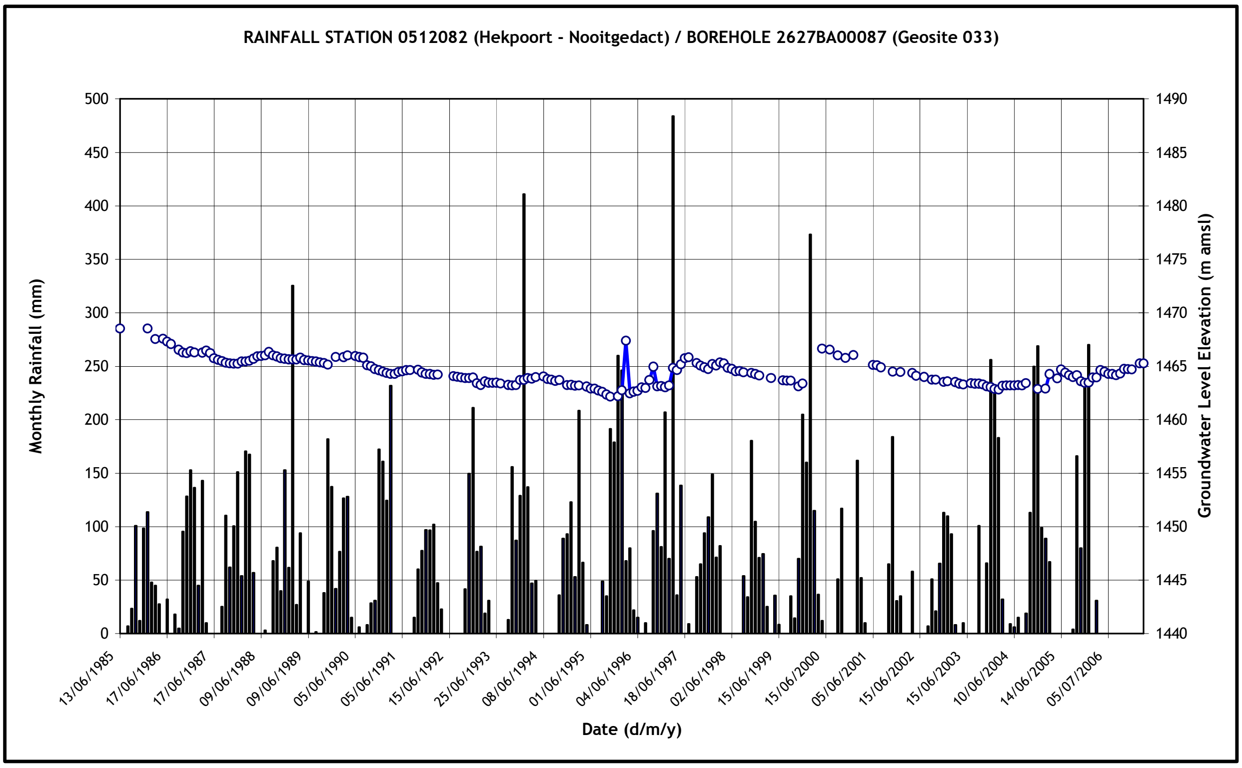

RAINFALL STATION 0475456 (Krugersdorp - Kroningspark) / BOREHOLE 2627BA00087 (Geosite 033)


RAINFALL STATION 0475818 (Roodepoort - Waterval) / BOREHOLE 2627BA00091 (Geosite 015)

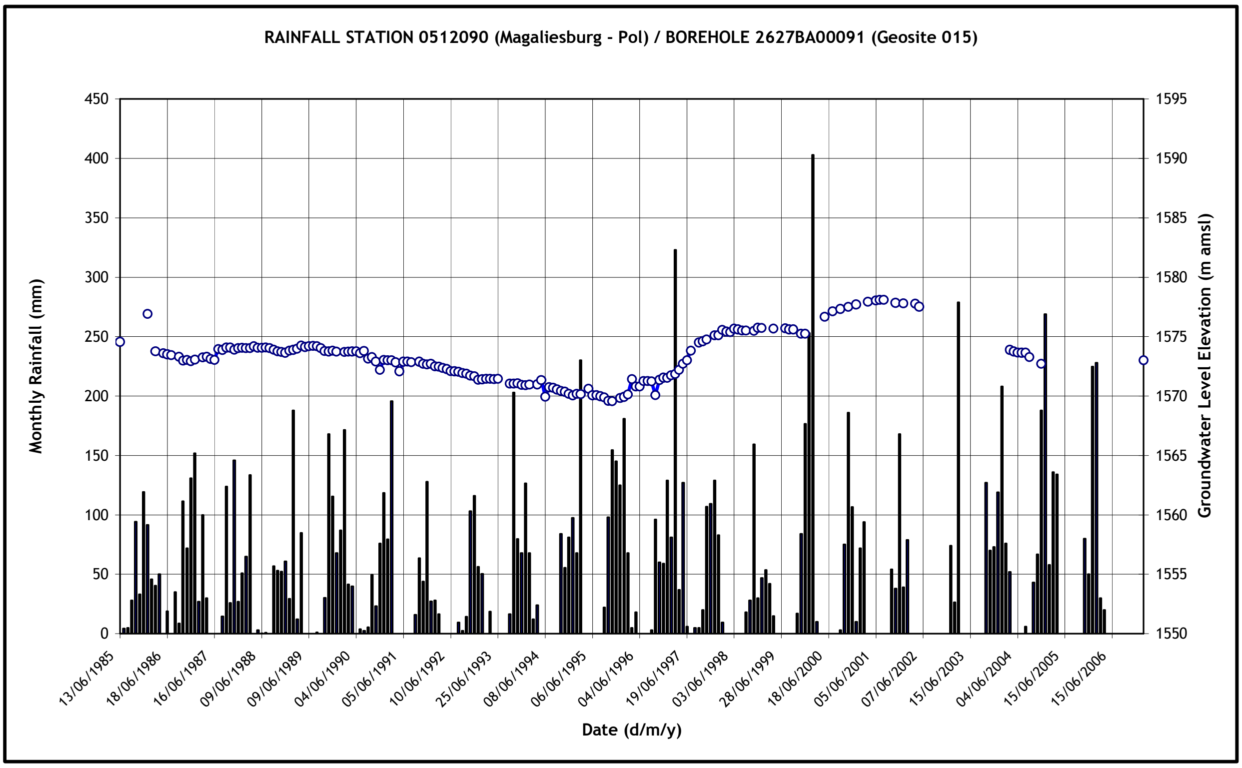

RAINFALL STATION 0475818 (Roodepoort - Waterval) / BOREHOLE 2627BA00087 (Geosite 033)

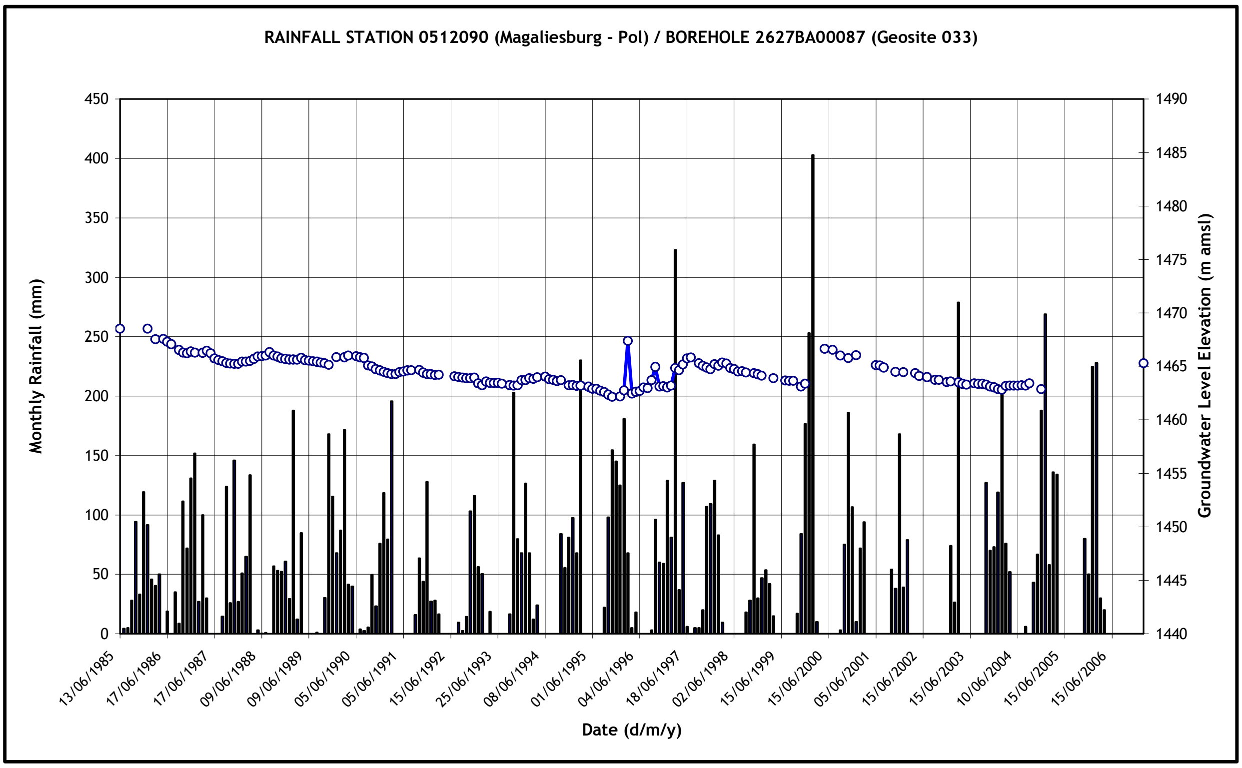


RAINFALL STATION 0512082 (Hekpoort - Nooitgedacht) / BOREHOLE 2627BA00091 (Geosite 015)



RAINFALL STATION 0512082 (Hekpoort - Nooitgedact) / BOREHOLE 2627BA00087 (Geosite 033)


RAINFALL STATION 0512090 (Magaliesburg - Pol) / BOREHOLE 2627BA00091 (Geosite 015)


RAINFALL STATION 0512090 (Magaliesburg - Pol) / BOREHOLE 2627BA00087 (Geosite 033)

ANNEXURE D

Summary of geosite hydrophysical data and information

Identifier Information		Position Information									Groundwater Level Information			
Station No.	Alternate No. or Name and Description	Datum = WGS 84						LO (27)			Water Rest Level Depth	Stick-up Height	Date	Groundwater Elevation
		Latitude			Longitude			Y	X	Z				
		d	m	s.s	d	m	s.s	(m)	(m)	(m amsl)	(m bd)	(m agl)	(d/m/y)	(m amsl)
1	Water supply borehole - Discover Lodge	26	5	17.3	27	42	6.0	-70198	2886788	1593	30.96	0.27	31/01/2007	1562
2	Water supply borehole A - J. van Niekerk	26	5	27.2	27	41	40.6	-69490	2887089	1617	46.22	0.20	31/01/2007	1571
3	Water supply borehole B - J. van Niekerk	26	5	23.2	27	41	38.5	-69433	2886966	1613	44.20	0.18	31/01/2007	1569
4	Water supply borehole - W. van Niekerk	26	5	49.8	27	41	52.8	-69826	2887787	1601	60.00	0.18	31/01/2007	1541
5	Water supply borehole - A. Crawford	26	5	47.4	27	42	6.4	-70204	2887715	1607	26.85	0.16	08/02/2007	1580
6	Water supply borehole - A. van Vuuren	26	5	29.4	27	41	54.1	-69865	2887159	1612	n.m.	0.00	31/01/2007	n.m.
7	Water supply borehole - R. Tarr	26	2	4.8	27	43	7.9	-71951	2880873	1472	24.72	0.55	01/02/2007	1447
8	Water supply borehole - R. Tarr	26	1	57.2	27	43	15.7	-72169	2880641	1475	28.42	0.22	13/02/2007	1446
9	Water supply borehole - R. Tarr	26	2	6.5	27	43	4.6	-71859	2880925	1468	*21.00*	0.11	*circa* 2002	1447
10	Harmony Gold Mine #8 Shaft	26	8	7.6	27	43	12.2	-72009	2892040	1714	41.46	0.24	01/02/2007	1672
11	Water supply borehole - B. van Vuuren	26	6	13.8	27	42	0.4	-70033	2888526	1625	53.09	0.00	01/02/2007	1572
12	Standby water supply borehole - Rosendal Farms	26	4	41.1	27	40	11.0	-67008	2885657	1576	73.03	0.37	01/02/2007	1503
13	Secondary water supply borehole - Rosendal Farms	26	4	51.3	27	40	11.2	-67012	2885971	1579	76.26	0.23	01/02/2007	1503
14	Main water supply borehole - Rosendal Farms	26	4	42.3	27	40	10.3	-66988	2885694	1576	n.m.	n.m.	01/02/2007	n.m.
15	DWAF monitoring borehole (A2N0582 / 2627BA00091 / G36338)	26	5	20.9	27	41	46.8	-69664	2886896	1613	42.00	0.28	01/02/2007	1571
16	Water supply borehole - D. Jacobs	26	5	36.6	27	41	28.8	-69161	2887377	1618	n.m.	0.25	06/02/2007	n.m.
17	Stand-by water supply borehole - C. Eksteen	26	5	11.9	27	40	29.7	-67522	2886608	1597	76.65	0.10	06/02/2007	1520
18	Water supply borehole - C. Eksteen	26	5	9.3	27	40	27.9	-67473	2886528	1593	n.m.	0.00	06/02/2007	n.m.
19	Robinson Lake	26	8	45.7	27	42	38.6	-71069	2893207	1717	0.00	0.00	06/02/2007	1717
20	"Lodge" spring rising in GSbgp. quartzite (opposite Ngonyama Lodge in KGR)	26	5	25.6	27	42	58.5	-71655	2887052	1600	0.00	0.00	06/02/2007	1600
21	Waterfall immediately south of Ngonyama Lodge	26	5	22.1	27	43	5.2	-71842	2886945	1590	0.00	0.00	06/02/2007	1590
22	Harmony Gold Mine Black Reef Incline	26	6	54.8	27	43	23.0	-72321	2889801	1662	0.00	0.00	07/02/2007	1662
23	Harmony Gold Mine 18 Winze	26	6	54.5	27	43	29.6	-72505	2889793	1672	-1.35	0.00	07/02/2007	1673
24	Harmony Gold exploration borehole RG-2	26	6	55.4	27	43	34.6	-72643	2889821	1678	9.61	0.70	07/02/2007	1668
25	Harmony Gold exploration borehole RG-1	26	6	43.8	27	43	28.9	-72487	2889463	1667	6.02	0.70	07/02/2007	1660
26	Artesian discharge located between HGMs BH-1 and BH-2	26	6	44.1	27	43	21.9	-72292	2889471	1659	0.00	0.00	07/02/2007	1659
27	Harmony Gold scavenger borehole BH-2	26	6	40.2	27	43	21.3	-72276	2889351	1658	0.00	0.00	07/02/2007	1658
28	Harmony Gold exploration borehole RG-3	26	6	35.7	27	43	14.4	-72085	2889212	1663	7.19	0.57	07/02/2007	1655
29	Council for Geoscience borehole @ Hippo Dam in KGR	26	5	59.6	27	43	11.6	-72014	2888100	1646	n.m.	0.49	07/02/2007	n.m.
30	Spring 2 of "Cemetery" group on left bank downstream of Hippo Dam	26	5	53.1	27	43	8.1	-71918	2887900	1641	0.00	0.00	07/02/2007	1641
31	Water supply borehole - D. Lindeque	26	4	16.3	27	40	31.3	-67576	2884897	1565	61.61	0.10	08/02/2007	1503
32	Water supply borehole - Môrester Camp	26	3	25.4	27	42	6.6	-70233	2883345	1505	*36.40*	0.00	10/12/2006	1469
33	DWAF monitoring borehole (A2N0584 / 2627BA00087 / G36334)	26	3	30.4	27	41	58.8	-70015	2883497	1491	25.71	0.23	08/02/2007	1465
34	Water supply borehole - Krugersdorp Brick Works	26	3	48.0	27	41	48.2	-69718	2884037	1505	35.10	0.36	13/02/2007	1470
35	Water supply borehole - M. Fourie	26	4	46.0	27	41	30.1	-69205	2885820	1593	43.95	0.30	08/02/2007	1549
36	Water supply borehole - Country Supermarket	26	6	3.8	27	41	17.9	-68854	2888212	1624	n.m.	0.20	08/02/2007	n.m.
37	"Poplar" spring in "Poplar" grove on minor MSbgp. dolomite outlier in KGR	26	5	27.3	27	43	12.4	-72041	2887106	1626	0.00	0.00	08/02/2007	1626
38	"End-of-pipe" from Harmony Gold treatment plant upstream of KGR	26	6	27.0	27	43	20.3	-72251	2888945	1652	0.00	0.00	15/02/2007	1652
39	Outlet of Hippo Dam in KGR	26	5	57.1	27	43	15.9	-72134	2888024	1645	0.00	0.00	15/02/2007	1645
40	Outlet of Aviary Dam in KGR	26	4	26.5	27	41	54.7	-69892	2885223	1518	0.00	0.00	15/02/2007	1518
41	"Flip-se-Gat" stream immediately above confuence with Tweelopiespruit in KGR	26	4	36.9	27	41	57.4	-96648	2885714	1527	0.00	0.00	15/02/2007	1527
42	Tweelopiespruit above confluence with Lion Camp drainage in KGR	26	5	3.0	27	42	29.5	-70853	2886352	1544	0.00	0.00	15/02/2007	1544
43	Water supply borehole - P. Travers	26	3	11.9	27	43	27.6	-72487	2882941	1491	n.m.	0.10	21/02/2007	n.m.
44	Weir on Blougatspruit downstream of Percy Stewart WWTW	26	3	18.4	27	43	23.6	-72375	2883141	1485	0.00	0.00	21/02/2007	1485
45	Water supply borehole - J. Wentzel	26	3	29.4	27	43	21.2	-72306	2883479	1503	n.m.	0.25	21/02/2007	n.m.
46	Standby water supply borehole - J. Wentzel	26	3	24.8	27	43	23.6	-72374	2883338	1491	n.m.	0.64	21/02/2007	n.m.
47	Water supply borehole - P. Esterhuizen	26	7	8.6	27	41	13.3	-68715	2890206	1663	13.75	0.05	21/02/2007	1649
48	Standby water supply borehole - P. Esterhuizen	26	7	18.5	27	41	15.0	-68761	2890511	1658	2.32	0.33	21/02/2007	1655
49	Water supply borehole - P. Esterhuizen	26	7	18.9	27	41	15.0	-68761	2890523	1658	1.94	0.00	21/02/2007	1656
50	"Valley" spring located north of Valley slimes dam	26	7	26.7	27	40	59.8	-68337	2890761	1652	0.00	0.00	21/02/2007	1652
51	"Battery" spring located in valley north of Battery Railway Station	26	6	33.3	27	41	20.7	-68927	2889121	1623	0.00	0.00	21/02/2007	1623
52	Water supply borehole - L. Fourie	26	6	4.3	27	41	50.7	-69765	2888233	1611	39.54	0.32	21/02/2007	1571
53	Water supply borehole - A. Jacobs	26	6	33.4	27	43	36.3	-72694	2889144	1669	0.00	15.23	21/02/2007	1654
54	Water supply borehole - P. van der Westhuizen	26	2	4.3	27	43	29.9	-72563	2880861	1486	n.m.	n.m.	21/02/2007	n.m.
55	"Aviary" spring upstream of "Flip-se-Gat" confluence (2627BA00271)	26	4	39.1	27	42	3.3	-70129	2885612	1530	0.00	0.00	08/03/2007	1530
56	Water supply borehole - A. Jacobs	26	6	34.4	27	43	44.5	-72922	2889176	1673	18.50	0.21	08/03/2007	1654
57	Water supply borehole - P. Schutte	26	2	51.2	27	42	44.4	-71290	2882298	1475	12.32	0.18	08/03/2007	1463
58	DWAF monitoring borehole (A2N0586 / 2627BA00084 / G36331)	26	2	51.4	27	42	32.5	-70959	2882302	1487	26.96	0.26	08/03/2007	1460
59	Harmony Gold Mine 17 Winze	26	7	17.4	27	43	16.9	-72148	2890495	1669	0.00	0.00	14/03/2007	1669
60	Mogale Gold 9E Shaft	26	7	34.8	27	43	27.4	-72436	2891033	1705	0.00	0.00	14/03/2007	1705
61	DWAF monitoring borehole (A2N0583 / 2627BA00090 / G36337)	*26*	*4*	*45.3*	*27*	*41*	*10.7*	*-68666*	*2885795*	*1615*	n.m.	?.??	—	n.m.

Note: Italicized and underlined entries not measured by this study

ANNEXURE E.1

Field hydrochemical data and information

Station No.	Identifier Information	CSIR Field Quality Measurements				
	Alternate No. or Name and Description	Sample date dd/mm/yyyy	Temp. °C	pH	EC(jc) mS/m	EC(ph) mS/m
1	Water supply borehole - Discover Lodge	31/01/2007	22.1	7.35	21	n.m.
2	Water supply borehole A - J. van Niekerk	31/01/2007	21.4	7.30	18	n.m.
3	Water supply borehole B - J. van Niekerk	31/01/2007	22.9	7.90	32	n.m.
4	Water supply borehole - W. van Niekerk	31/01/2007	23.7	7.86	16	n.m.
5	Water supply borehole - A. Crawford	31/01/2007	22.4	5.98	6	n.m.
6	Water supply borehole - A. van Vuuren	31/01/2007	21.3	7.36	14	n.m.
7	Water supply borehole - R. Tarr	01/02/2007	20.0	7.76	92	90
8	Water supply borehole - R. Tarr	01/02/2007	19.1	7.70	89	87
9	Water supply borehole - R. Tarr	01/02/2007	20.0	7.52	91	89
10	Harmony Gold Mine #8 Shaft	06/02/2007	25.4	1.06	217	220
11	Water supply borehole - B. van Vuuren	01/02/2007	20.9	5.57	43	47
12	Standby water supply borehole - Rosendal Farms	01/02/2007	n.m.	n.m.	n.m.	n.m.
13	Secondary water supply borehole - Rosendal Farms	01/02/2007	21.6	7.48	13	16
14	Main water supply borehole - Rosendal Farms	01/02/2007	21.7	7.80	11	13
15	DWAF monitoring borehole (A2N0582 / 2627BA00091 / G36338)	06/02/2007	n.m.	n.m.	n.m.	n.m.
16	Water supply borehole - D. Jacobs	06/02/2007	21.1	7.20	17	20
17	Stand-by water supply borehole - C. Eksteen	06/02/2007	n.m.	n.m.	n.m.	n.m.
18	Water supply borehole - C. Eksteen	06/02/2007	23.4	8.27	13	14
19	Robinson Lake	06/02/2007	29.3	2.73	712	619
20	"Lodge" spring rising in GSbgp. quartzite (opposite Ngonyama Lodge in KGR)	06/02/2007	21.2	5.46	6	9
21	Waterfall immediately south of Ngonyama Lodge	06/02/2007	26.5	6.20	277	273
22	Harmony Gold Mine Black Reef Incline	07/02/2007	23.2	4.03	558	555
23	Harmony Gold Mine 18 Winze	07/02/2007	22.3	4.22	570	530
24	Harmony Gold exploration borehole RG-2	15/02/2007	19.1	4.79	16	18
25	Harmony Gold exploration borehole RG-1	15/02/2007	20.5	6.39	223	215
26	Artesian discharge located between HGMs BH-1 and BH-2	07/02/2007	21.8	2.64	502	484
27	Harmony Gold scavenger borehole BH-2	07/02/2007	n.m.	n.m.	n.m.	n.m.
28	Harmony Gold exploration borehole RG-3	15/02/2007	21.5	6.34	4	12
29	Council for Geoscience borehole @ Hippo Dam in KGR	07/02/2007	n.m.	n.m.	n.m.	n.m.
30	Spring 2 of "cemetery" group on left bank downstream of Hippo Dam	07/02/2007	18.7	6.07	93	91
31	Water supply borehole - D. Lindeque	08/02/2007	22.9	7.23	22	22
32	Water supply borehole - Môrester Camp	08/02/2007	19.5	7.19	93	91
33	DWAF monitoring borehole (A2N0584 / 2627BA00087 / G36334)	19/07/2006	n.m.	*8.5*	*79*	n.m.
34	Water supply borehole - Krugersdorp Brick Works	08/02/2007	19.3	6.26	125	120
35	Water supply borehole - M. Fourie	08/02/2007	20.8	7.21	25	26
36	Water supply borehole - Country Supermarket	08/02/2007	20.8	6.82	17	17
37	"Poplar" spring in poplar grove on minor MSbgp. dolomite outlier in KGR	08/02/2007	18.7	5.61	100	96
38	End-of-pipe from Harmony Gold treatment plant upstream of KGR	15/02/2007	24.5	8.50	408	400
39	Outlet of Hippo Dam in KGR	15/02/2007	24.3	7.69	370	358
40	Outlet of Aviary Dam in KGR	15/02/2007	20.6	6.82	224	221
41	"Flip-se-Gat" stream immediately above confuence with Tweelopiespruit in KGR	15/02/2007	21.4	7.94	21	23
42	Tweelopiespruit above confluence with Lion Camp drainage in KGR	15/02/2007	21.7	6.44	262	243
43	Water supply borehole - P. Travers	20/02/2007	18.8	6.07	80	84
44	Weir on Blougatspruit downstream of Percy Stewart WWTW	20/02/2007	22.7	7.76	97	92
45	Water supply borehole - J. Wentzel	20/02/2007	23	5.83	14	17
46	Standby water supply borehole - J. Wentzel	20/02/2007	n.m.	n.m.	n.m.	n.m.
47	Water supply borehole - P. Esterhuizen	20/02/2007	19.9	5.96	98	99
48	Standby water supply borehole - P. Esterhuizen	02/02/2007	n.m.	n.m.	n.m.	n.m.
49	Water supply borehole - P. Esterhuizen	20/02/2007	19.7	6.40	115	115
50	"Valley" spring located north of Valley slimes dam	21/02/2007	16.8	3.62	278	n.m.
51	"Battery" spring located in valley north of Battery Railway Station	21/02/2007	20.9	5.95	7	n.m.
52	Water supply borehole - L. Fourie	21/02/2007	20.4	6.10	19	n.m.
53	Water supply borehole - A. Jacobs	08/03/2007	19.8	6.53	31	n.m.
54	Water supply borehole - P. van der Westhuizen	21/02/2007	20.6	7.42	80	n.m.
55	"Aviary" spring upstream of "Flip-se-Gat" confluence (2627BA00271)	08/03/2007	18.2	7.31	139	n.m.
56	Water supply borehole - A. Jacobs	08/03/2007	19.3	6.12	15	n.m.
57	Water supply borehole - P. Schutte	08/03/2007	20.4	6.78	73	n.m.
58	DWAF monitoring borehole (A2N0586 / 2627BA00084 / G36331)	08/03/2007	n.m.	n.m.	n.m.	n.m.
59	Harmony Gold Mine 17 Winze	—	n.m.	n.m.	n.m.	n.m.
60	Mogale Gold 9E Shaft	–	n.m.	n.m.	n.m.	n.m.
61	DWAF monitoring borehole A2N0583 / 2627BA00090 / G36337	–	n.m.	n.m.	n.m.	n.m.
Notes	1. Italicized and underlined values not measured by this study 2. EC(jc) denotes salinity according to J Cobbing's meter 3. EC(ph) denotes salinity according to P Hobbs's meter 4. n.m. denotes not measured					

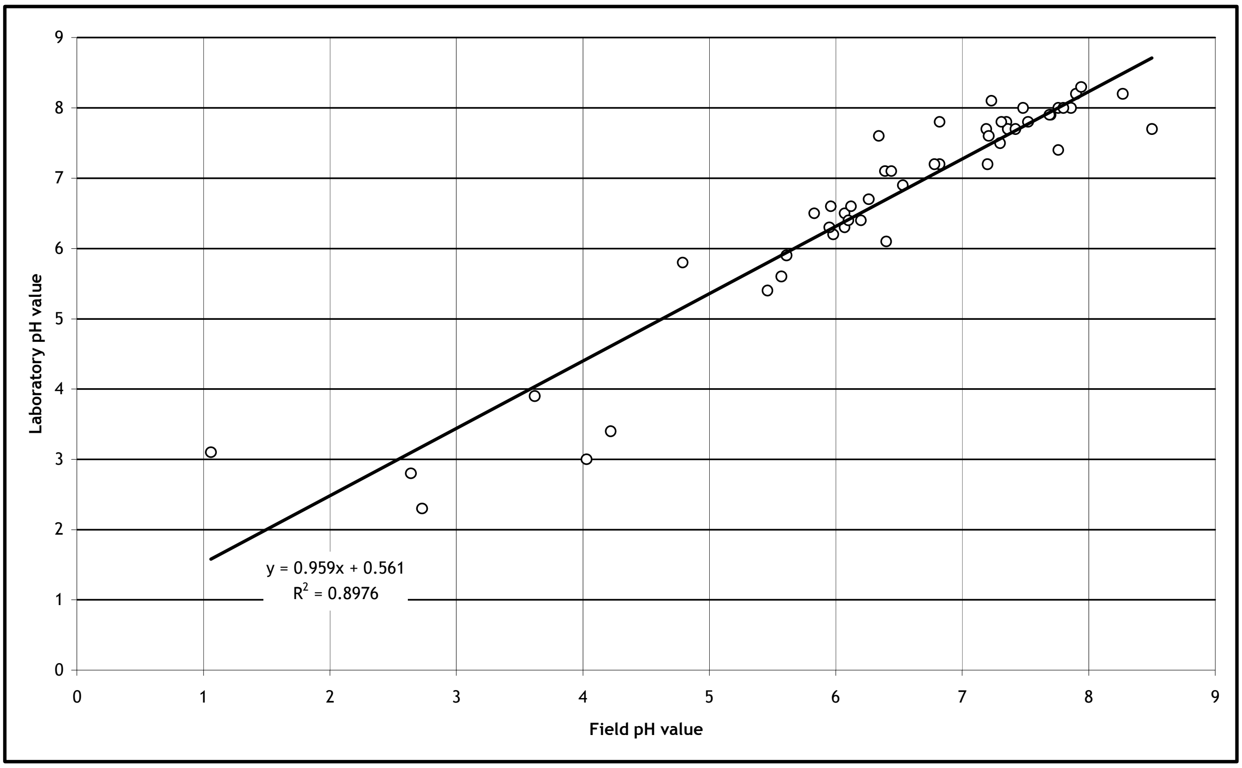
ANNEXURE E.2

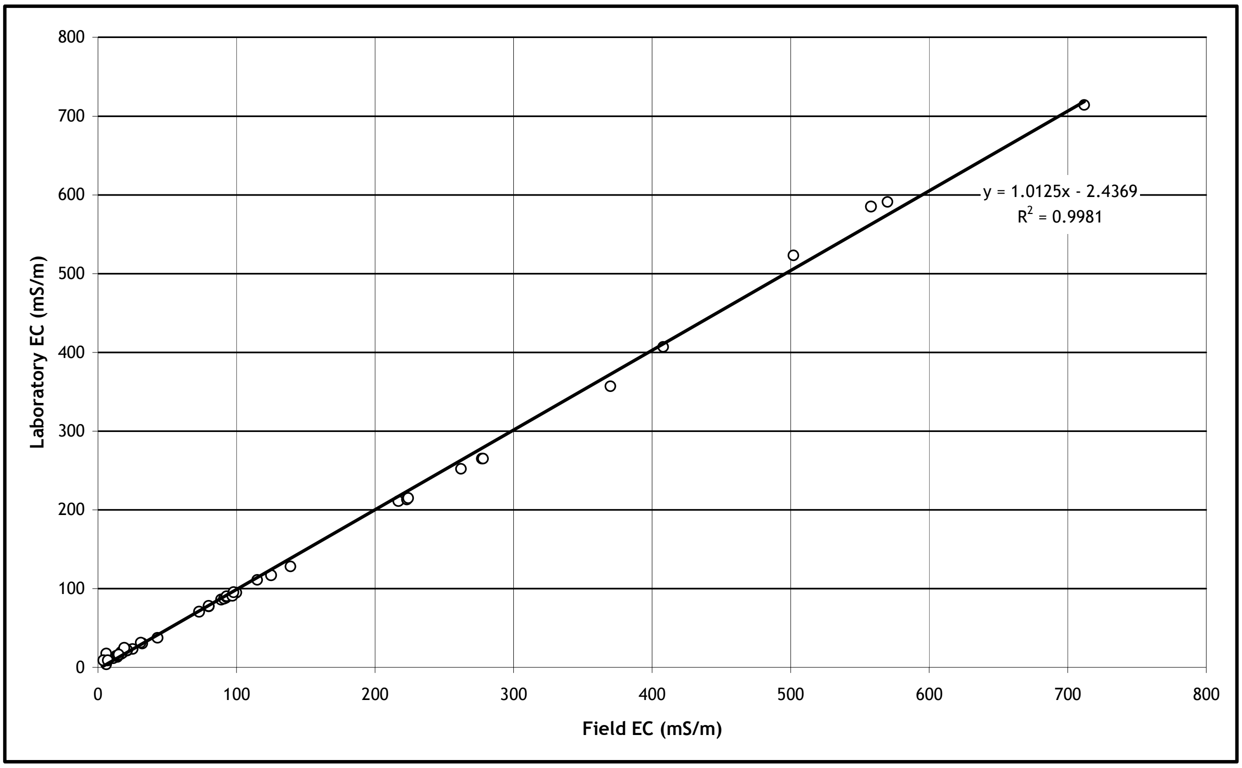
Laboratory hydrochemical data and information

Station No.	Laboratory Chemical Analysis Results																			
	pH	EC	Ca	Mg	Na	K	Cl	SO4	T. Alk.	NO3	NH4	F	Tot. PO4	Ortho-PO4	As	B	Fe	Mn	Zn	TOC
		mS/m	mg/L Ca	mg/L Mg	mg/L Na	mg/L K	mg/L Cl	mg/L SO4	mg/L CaCO3	mg/L N	mg/L N	mg/L F	mg/L P	mg/L P	mg/L As	mg/L B	mg/L Fe	mg/L Mn	mg/L Zn	mg/L C
1	7.8	21.2	10.0	20.0	2.0	*0.5*	*2.5*	*2.5*	88.0	1.7	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.413	0.057	0.432	1.3
2	7.5	18.5	21.0	10.0	3.0	*0.5*	*2.5*	5.0	72.0	1.9	*0.1*	*0.1*	*0.1*	*0.1*	0.007	0.090	0.051	*0.012*	0.027	2.2
3	8.2	30.4	30.0	12.0	18.0	*0.5*	6.0	19.0	128.0	*0.1*	*0.1*	0.7	*0.1*	*0.1*	*0.001*	*0.005*	0.052	0.048	*0.012*	3.8
4	8.0	17.3	26.0	5.0	5.0	*0.5*	*2.5*	*2.5*	76.0	*0.1*	*0.1*	0.2	*0.1*	*0.1*	*0.001*	*0.005*	0.123	0.202	0.027	1.3
5	6.2	3.8	5.0	*1.0*	2.0	*0.5*	*2.5*	*2.5*	8.0	0.4	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.465	0.031	*0.012*	*0.5*
6	7.7	13.2	18.0	6.0	2.0	*0.5*	*2.5*	*2.5*	60.0	0.6	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.056	*0.012*	*0.012*	1.3
7	8.0	87.7	70.0	39.0	56.0	2.4	68.0	140.0	152.0	14.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.064	*0.012*	*0.012*	3.8
8	7.9	86.0	66.0	37.0	59.0	2.7	66.0	136.0	144.0	14.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.020	0.041	*0.012*	*0.012*	3.6
9	7.8	87.0	70.0	37.0	61.0	2.5	63.0	164.0	152.0	11.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.048	*0.012*	*0.012*	2.8
10	3.1	211.0	153.0	99.0	48.0	6.2	27.0	1211.0	*2.5*	0.3	1.1	*0.1*	*0.1*	*0.1*	*0.001*	0.015	82.000	51.000	3.070	*0.5*
11	5.6	37.4	24.0	22.0	13.0	*0.5*	7.0	132.0	*2.5*	4.8	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.516	1.100	*0.012*	*0.5*
12	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
13	8.0	14.2	16.0	8.0	2.0	*0.5*	*2.5*	*2.5*	68.0	0.7	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.070	*0.012*	*0.012*	1.0
14	8.0	11.5	13.0	6.0	3.0	*0.5*	*2.5*	*2.5*	56.0	0.8	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.073	*0.012*	*0.012*	*0.5*
15	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
16	7.2	19.8	16.0	12.0	3.0	*0.5*	*2.5*	23.0	56.0	2.2	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.066	*0.012*	*0.012*	*0.5*
17	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
18	8.2	14.3	13.0	10.0	3.0	*0.5*	*2.5*	*2.5*	64.0	1.0	0.2	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	0.132	*0.012*	*0.012*	*0.5*
19	2.3	714.0	514.0	297.0	262.0	1.2	66.0	4918.0	*2.5*	0.2	8.9	*0.1*	4.0	*0.1*	*0.001*	1.120	230.000	145.000	9.000	1.2
20	5.4	17.7	2.0	5.0	5.0	*0.5*	5.0	*2.5*	*2.5*	5.9	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.020	0.052	*0.012*	*0.012*	*0.5*
21	6.4	265.0	448.0	96.0	139.0	7.2	33.0	1616.0	8.0	1.8	*0.1*	0.6	*0.1*	*0.1*	*0.001*	0.090	0.087	20.000	0.036	1.3
22	3.0	585.0	423.0	206.0	99.0	12.0	43.0	4700.0	*2.5*	*0.1*	5.0	0.2	*0.1*	*0.1*	0.159	1.850	1153.000	69.000	1.300	6.1
23	3.4	591.0	435.0	213.0	98.0	12.0	46.0	4673.0	*2.5*	0.2	4.9	0.2	*0.1*	*0.1*	0.214	1.800	1306.000	47.000	1.000	6.1
24	5.8	16.5	5.0	2.0	25.0	*0.5*	9.0	*2.5*	12.0	13.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.100	0.109	0.029	*0.012*	*0.025*
25	7.1	213.0	273.0	165.0	62.0	22.0	34.0	1286.0	32.0	1.0	1.4	*0.1*	*0.1*	*0.1*	*0.001*	0.100	4.920	41.000	*0.012*	1.0
26	2.8	523.0	323.0	193.0	88.0	11.3	45.0	3847.0	*2.5*	*0.1*	4.3	*0.1*	*0.1*	*0.1*	*0.001*	1.840	190.000	477.000	6.410	2.6
27	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
28	7.6	8.9	8.0	6.0	2.0	*0.5*	*2.5*	6.0	40.0	0.6	0.2	0.2	*0.1*	*0.1*	*0.001*	0.140	0.172	0.052	*0.012*	*0.025*
29	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
30	6.3	89.1	115.0	40.0	24.0	1.3	14.0	417.0	28.0	3.1	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.030	0.076	*0.012*	*0.012*	*0.5*
31	8.1	22.3	19.0	13.0	4.0	*0.5*	*2.5*	*2.5*	92.0	1.3	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.010	0.073	*0.012*	*0.012*	1.3
32	7.7	90.4	78.0	45.0	44.0	2.5	51.0	183.0	184.0	10.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.050	0.094	*0.012*	*0.012*	3.6
33	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
34	6.7	117.0	152.0	60.0	33.0	*0.5*	18.0	568.0	60.0	0.8	0.2	*0.1*	*0.1*	*0.1*	*0.001*	0.040	0.054	*0.012*	*0.012*	*0.5*
35	7.6	23.4	24.0	12.0	4.0	*0.5*	*2.5*	32.0	76.0	3.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	*0.012*	*0.012*	*0.012*	1.1
36	7.2	17.4	16.0	10.0	4.0	*0.5*	*2.5*	22.0	56.0	1.6	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.020	0.031	*0.012*	*0.012*	*0.5*
37	5.9	94.9	102.0	52.0	29.0	1.7	13.0	470.0	16.0	1.6	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.030	0.035	0.026	*0.012*	*0.5*
38	7.7	407.0	818.0	224.0	195.0	11.1	49.0	2873.0	36.0	0.9	2.6	0.2	*0.1*	*0.1*	*0.001*	0.200	47.000	38.000	0.196	3.0
39	7.9	357.0	690.0	136.0	176.0	11.0	49.0	2483.0	52.0	1.0	0.4	1.0	*0.1*	*0.1*	*0.001*	0.170	0.448	17.000	*0.012*	3.9
40	7.8	215.0	385.0	58.0	103.0	5.2	34.0	1401.0	32.0	1.6	*0.1*	0.4	*0.1*	*0.1*	*0.001*	0.100	0.107	10.000	0.030	1.6
41	8.3	21.8	24.0	14.0	3.0	*0.5*	*2.5*	21.0	100.0	2.6	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.120	0.099	0.088	*0.012*	1.0
42	7.1	252.0	417.0	94.0	126.0	6.9	39.0	1601.0	8.0	1.9	0.2	0.6	*0.1*	*0.1*	0.005	0.120	0.126	15.000	0.035	1.0
43	6.5	77.4	56.0	12.0	77.0	11.1	66.0	171.0	72.0	11.0	1.2	*0.1*	*0.1*	*0.1*	*0.001*	0.140	*0.012*	0.059	*0.012*	2.6
44	7.4	91.0	45.0	11.0	71.0	10.8	61.0	110.0	236.0	*0.1*	34.2	*0.1*	2.6	2.2	*0.001*	0.350	0.195	0.386	*0.012*	*0.5*
45	6.5	15.0	10.0	7.0	10.0	*0.5*	17.0	12.0	20.0	4.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.460	*0.012*	*0.012*	0.529	*0.5*
46	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
47	6.6	95.4	82.0	49.0	51.0	3.0	66.0	326.0	24.0	9.8	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	*0.012*	0.044	*0.012*	*0.5*
48	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
49	6.1	111.0	101.0	57.0	60.0	3.6	70.0	447.0	16.0	6.5	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	*0.012*	0.035	*0.012*	*0.5*
50	3.9	265.0	262.0	133.0	111.0	7.8	98.0	1516.0	*2.5*	4.1	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.030	0.103	100.000	0.433	*0.5*
51	6.3	8.9	10.0	2.0	4.0	*0.5*	12.0	*2.5*	28.0	1.8	2.3	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	*0.012*	0.029	*0.012*	*0.5*
52	6.4	24.7	19.0	14.0	7.0	*0.5*	5.0	68.0	24.0	3.5	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	*0.005*	*0.012*	*0.012*	0.081	*0.5*
53	6.9	31.5	29.0	13.0	12.0	*0.5*	19.0	59.0	56.0	2.3	n.a.	*0.1*	n.a.	n.a.	n.a.	*0.050*	*0.012*	*0.012*	n.a.	n.a.
54	7.7	78.0	61.0	37.0	47.0	2.4	63.0	117.0	144.0	11.0	*0.1*	*0.1*	*0.1*	*0.1*	*0.001*	0.030	*0.012*	*0.012*	*0.012*	1.8
55	7.8	128.0	174.0	168.0	42.0	1.4	22.0	594.0	108.0	0.7	n.a.	*0.1*	n.a.	n.a.	n.a.	*0.050*	*0.012*	*0.012*	n.a.	n.a.
56	6.6	16.0	13.0	7.0	8.0	*0.5*	16.0	16.0	32.0	1.3	n.a.	*0.1*	n.a.	n.a.	n.a.	*0.05*	*0.012*	*0.012*	n.a.	n.a.
57	7.2	70.8	59.0	28.0	43.0	1.7	53.0	125.0	108.0	11.0	n.a.	*0.1*	n.a.	n.a.	n.a.	*0.05*	*0.012*	*0.012*	n.a.	n.a.
58	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
59	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
60	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
61	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Notes	1. Italicized values denote detection limit 2. n.s. denotes not sampled 3. n.a. denotes not analysed																			

ANNEXURE E.3

Correlation of field and laboratory pH and EC results





ANNEXURE F

Water toxicity evaluation report

our future through science

TOXICITY EVALUATION OF SELECTED SURFACE AND MINE WATER FROM THE WEST RAND MINING BASIN, KRUGERSDORP

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Prepared by:	Ms L Slabbert
Date:	25 April 2007
Place:	PRETORIA

1 BACKGROUND

1.1 Scope of work

The Groundwater Science Research Group in the Water Resources Competence Area of the CSIRs NRE requested the Water and Human Health Research Group of the same Competence Area to conduct a toxicity study on selected surface and mine water from the West Rand Mining Basin, Krugersdorp. The specific objectives of the study were:

- To establish if the waters were toxic; and
- If toxic, to establish the extent of toxicity.

1.2 Toxicity testing as a water quality management tool

Substance-specific methods are traditionally applied to monitor and control water pollution. However, experience has shown that this approach is not able to fully assess the hazard posed by complex pollution problems. To protect the ecological integrity of aquatic ecosystems and human health, a more comprehensive approach is necessary, one that focuses on the potential effects of chemical substances, rather than on the substances themselves.

The National Water Act, promulgated in 1998, laid down measures intended to ensure the comprehensive protection of all water resources, the prevention of pollution, and remediation of effects of pollution. A crucial implication of the Act is an effect-based approach to resource management. This approach is apparent in both the source-directed controls and resource-directed measures. Effects are typically assessed by means of biological toxicity tests. The effect-based approach is flexible and can include a variety of toxicity tests. In 2003 the Department of Water Affairs and Forestry (DWAF) adopted the Direct Estimation of Ecological Effect Potential (DEEEP) approach to manage complex waste water discharges (DWAF, 2003). Several short- and long-term aquatic toxicity tests, as well as a mutagenicity test for human health protection, were selected for use (Slabbert, 2004). More recently, a number of toxicity tests were also included into DWAF's National Toxicity Monitoring Programme (NTMP), which is aimed at status and trends monitoring (Slabbert, 2005).

Toxicity is the characteristic or inherent potential of a chemical or a group of chemicals to cause adverse effects in living organisms. Adverse effects include lethality or those effects limiting an organism's ability to survive in nature (Slabbert *et al.,* 1998a). Such effects could be acute or chronic. A toxicity test is a technique that determines, under defined conditions, the effect of chemical pollutants in water on a group of living organisms, cellular systems (e.g. mammalian cells) or sub-cellular structures (e.g. enzymes). The test is applied directly (screening test), without dilution, to resource water to determine the proportions of organisms or biological material affected (e.g. percentage lethality or growth inhibition). A definitive test (testing serial dilutions) is carried out on waste water discharges to estimate the concentration of the waste water at which a specified percentage of organisms or biological material exhibit a certain response. This concentration is referred to as the toxicity endpoint, and becomes the quantified measure of the waste water concentration that would cause an instream impact if exceeded for a particular period of time. Typical toxicity endpoints include the LC_{50} (concentration at which 50 % of the test organisms are killed), EC_{50} (concentration causing 50 % effect, e.g. growth inhibition), LC_{10} (concentration at which 10 % of the test organisms are killed - also known as the minimum effect concentration), EC_{20} (concentration causing 20 % effect – minimum effect concentration), NOEC (No Observed Effect Concentration - highest discharge concentration at which no unacceptable effect will occur even at continuous exposure), and LOEC (Lowest Observed Effect Concentration - lowest discharge concentration at which an unacceptable effect will occur (Slabbert *et al.,* 1998b).

Toxicity units, e.g. TU_a (acute) and TU_c (chronic) are often used as a mechanism for quantifying instream toxicity. The number of toxic units in a wastewater discharge is defined as follows: TU_a = 100 divided by LC_{50}, and TU_c = 100 divided by NOEC, where 100 = the waste water discharge toxicity expressed as percentage (100 %) and both the LC_{50} and NOEC are calculated as a percentage dilution of the waste water discharge.

Various criteria are used to regulate waste water discharges (Slabbert *et al.,* 1998b). The US EPA's recommended criteria for waste water discharges are as follows: in order to protect aquatic life against chronic effects, the ambient (instream) toxicity should not exceed 1.0 TU_c to the most sensitive of at least three different test species. For the protection against acute effects, the ambient toxicity should not exceed 0.3 of the TU_a to the most sensitive of at least three different test species. Canada's regulation requires 'no acute toxicity' (using their standard fish test) at the point of discharge (end-of-pipe). Germany allows some degree of acute toxicity in the 100 % discharge, but toxicity is prohibited at the 50 % concentration (fish and *Daphnia* tests). Ireland requires a factor of at least 20 dilutions in the immediate vicinity of a discharge for each toxic unit discharged. Toxicity criteria still need to be set for discharge management in South Africa. Because the flow in most of our rivers is dependent on rainfall, and the country is prone to serious droughts, criteria might not be based on dilution as used in the USA. It is more likely that a conservative approach such as implemented by Canada, stating no acute toxicity or even no chronic toxicity at the end-of-pipe, could be followed. Treatment to remove the toxicants is an important part of the latter approach.

1.3 Toxicity tests

An extensive number and variety of aquatic toxicity tests are available (Slabbert and Murray, 2007), and new developments are regularly published. However, only a few of them have been successfully standardized. Countries like the USA, Canada, Germany and France have their own standard methods. These closely resemble the standard methods of organisations such as the International Organization for Standardization (ISO), the Organization for Economic Cooperation and Development (OECD) and the American Society for Testing Materials (ASTM). Most of the regulations addressing discharges and receiving waters include fish, water flea and algal tests, representing freshwater vertebrates, invertebrates and plants (Slabbert *et al.*, 1998a,b).

The South African DEEEP methodology includes fish (*Poecilia reticulata*) and water flea (*Daphnia pulex*) lethality tests, and algal (*Selenastrum capricornutum* Printz) growth inhibition tests (microplate assay and flask test) to establish short-term toxicity (Slabbert, 2004). A *Daphnia* reproduction test is used for long-term toxicity. Mutagenicity is assessed by means of the Ames *Salmonella* plate incorporation assay. The following long-term toxicity tests were recommended for status and trends monitoring (NTMP): Zebrafish (*Danio rerio*) embryo and larval development test, *Daphnia* reproduction test, algal microplate test and recombinant yeast (*Saccharomyces cerevisiae*) estrogen screen.

There is no single toxicity test that meets all the monitoring requirements. The best results are, therefore, obtained when tests are applied in battery form (simultaneous testing). However, single tests are often used for initial screening to establish the toxic potential of discharges and receiving waters. A single test is later followed by toxicity tests of increasing complexity to obtain more detailed effect information. Tests used for initial screening are usually simple and inexpensive and mainly measure short-term toxicity. The *Daphnia* lethality test is known as the workhorse of biotoxicology because of its world-wide use in research and applied studies, its simplicity, and its high sensitivity to a wide range of organic and inorganic toxicants. This test is, therefore, often used for initial screening purposes.

The acute toxicities of selected metal ions to *D. pulex* are presented in Table 1 (Elnabarawy *et al.*, 1986). Table 2 shows the sensitivity of the *Daphnia* test to a number of waste waters, while the response of the test to surface and groundwaters is shown in Table 3 (Slabbert *et al.*, 1998a,b).

Table 1. Acute toxicities of selected metal ions to *Daphnia pulex*

Test chemical	48 h LC_{50} (µg/L)	95% confidence limits (µg/L)
Silver	1.9	1.7 - 2.3
Lead	2 003	1 878 - 2 191
Chromium-6	122	105 - 147
Cadmium	319	288 - 362
Copper	31	30 - 34
Arsenic-3	2 366	2 020 - 2 943
Mercury	3.8	3.3 - 4.5

Table 2. Sensitivity of *Daphnia pulex* to different waste waters

Wastewater	48 h LC_{50} (%)
Treated sewage effluent discharged into the Hennops River	>100
Paper mill effluent discharged into the Cowles Dam, Springs	>100
Copper mine return water dam waste water discharged into a river in peak rainy season	23 - >100
Vanadium mine return water dam waste water not discharged into the environment	0.5 - 14
Metal plating waste water discharged into a sewer system	0.10 - 1.08

Table 3. Sensitivity of *Daphnia pulex* to different surface and groundwaters

Water	% Lethality after 48 h exposure
Hennops River	0
Moreleta Spruit	0
Jukskei River	0
Rietvlei Dam	0
Roodeplaat Dam	0
Hartebeespoort Dam	0
CSIR borehole	0
Borehole on ISCOR premises in western Pretoria	100
Borehole on SPCA grounds in Silverton	25

2 SAMPLE INFORMATION

The information on the water samples submitted for the toxicity evaluation is shown in Table 4. The sample localities are shown in Figure 1, and visuals of each presented in Appendix A.

Sampling was carried out by Jude Cobbing following standard operating procedures. Chemically clean 500 mL plastic bottles were used. Bottles were filled to the brim to eliminate air and were well sealed to avoid leaking. Samples were kept in a cooler box after collection and delivered to the test laboratory within 24 h.

Table 4. Information(1) on water samples submitted for toxicity testing

Sample ID	Sampling date	Site description	Most probable origin
019	07/02/2007	Robinson Lake	Occasional mine process water repository
022	07/02/2007	Decanting mine shaft	Defunct underground mine workings
039	15/02/2007	Outlet of Hippo Dam in KGR	Harmony Gold Mine treatment plant effluent
040	15/02/2007	Outlet of Aviary Dam in KGR	Surface water in Tweelopiespruit
041	15/02/2007	"Flip-se-Gat" stream	Dolomitic groundwater
044	20/02/2007	Weir on Blougatspruit	Effluent discharge from the Percy Stewart WWTW
050	21/02/2007	Valley Spring	Valley slimes dam
051	21/02/2007	Battery Spring	Quartzitic groundwater

(1) Information provided by Phil Hobbs

Figure 1. Sampling station locality map (provided by Phil Hobbs)

3 TOXICITY TEST

Toxicity was established by means of the *D. pulex* lethality test (Slabbert, 2004). *Daphnia* 24 h or less in age were used. To obtain the necessary number of young for a test, adult females bearing embryos in their brood pouches were removed from stock cultures on the previous day and placed in beakers containing moderately hard water (Table 5) and food suspension. The test *Daphnia* were transferred to a small intermediary holding beaker, and from there to the test beakers. Test conditions are summarised in Table 6. Lethality was recorded after 24 and 48 h exposure. Lethality ≥10 % is an indication of toxic activity.

Table 5. Moderately hard water(1)

KCl	$MgSO_4$	$NaHCO_3$	$CaSO_4.2H_20$	pH(2)	Dissolved O_2	Hardness	Alkalinity
mg/L					mg/L	mg/L $CaCO_3$	
4	60	96	60	7.4 – 7.8	≥6.8	80 - 100	60 – 70

(1) Prepared with Milli-Q® (2) Approximate equilibrium pH after aeration

Table 6. Summary of test conditions for the *Daphnia pulex* lethality test

Test type	Static
Water temperature	20±2°C
Light quality	Ambient laboratory illumination
Photoperiod	Approximately 14 h light
Oxygen concentration	As obtained
pH	As obtained
Feeding	None
Size of test container	50 mL
Volume of test sample	25 mL
Number of organisms/container	5
Number of replicate containers	4
Total number of organisms/test	20
Control and dilution water	Moderately hard water
Test duration	48 h

4 RESULTS AND DISCUSSION

The results of direct tests (no sample dilution) on water samples are shown in Table 7. Samples 019, 022, 044 and 050 caused 100 % lethality after 24 h. The optimum pH range for *D. pulex* is 6.0 to 8.5. The pH of samples 019, 022 and 050 (Table 7) were low and are suspected to have played a role in the observed lethality. Sample 044, the primary origin of which is effluent discharge from the Percy Stewart WWTW, contained 0.21 mg/L free chlorine. Free chlorine is usually toxic to *Daphnia* at this concentration (Slabbert, 2004). *Daphnia* were not affected by samples 039, 040, 041 and 051 (lethality value of <10 % indicates an absence of toxicity).

Table 7. Effect of water samples on *Daphnia pulex*

Sample ID	pH	% Lethality after time	
		24 h	48 h
019	2.1	100	100
022	3.7	100	100
039	7.3	0	0
040	7.3	0	0
041	7.9	0	0
044	7.6	100	100
050	4.1	100	100
051	6.2	0	5

Table 8 shows the results obtained when *Daphnia* were exposed to 10-fold dilutions (range finding tests) of the samples exhibiting low pH values (019, 022 and 050). Samples 019 and 022 caused 15 % and 100 % lethality, respectively, at the 1 % and 10 % concentration levels after 48 h exposure. No lethality was observed at the 1 % and 10 % concentration levels of sample 050 during 24 h exposure. [The results for this sample were not recorded after 48 h exposure]. In all instances, except in the case of the 10 % concentration of sample 019 (pH = 3.4), the pH was very close to or within the required optimum pH range for *Daphnia*, suggesting that the observed effects were due to toxic chemicals present in the samples.

Samples 019 and 022 turned yellow and dark orange, respectively, upon dilution with moderately hard water (increased pH).

Table 8. Effect of 10-fold dilutions of samples on *Daphnia pulex*

Sample ID	Concentration (%)	pH	% Lethality after time	
			24 h	48 h
019	10	3.4	100	100
	1	6.5	15	15
022	10	5.9	60	100
	1	6.5	15	15
050	10	7.2	0	not recorded
	1	7.6	0	not recorded

Definitive tests on serial dilutions were carried out on samples 019, 022, 044 and 050 to establish toxicity endpoints (extent of toxicity). A probit statistical method was applied to the toxicity data (lethality versus concentration) to calculate the LC_{10} (concentration causing 10 % lethality) and the LC_{50} (concentration causing 50 % lethality). In cases where the probit method was not applicable (less than two effects between 0 and 100 % or an irregular distribution of data), the Spearman-Karber statistical programme was used. The results are presented in Table 9.

Samples 019 and 022 exhibit the highest toxicity (low LC_{50}s), followed in order of magnitude by samples of 044 and 050.

Table 9. 48-h *Daphnia* LC_{10}s and LC_{50}s (%) for samples 019, 022, 044 and 050

Sample	Statistical programme	LC_{10}	LC_{50}	95% Confidence limits	
				Lower limit	Upper limit
019	Spearman-Karber	2.5	3.3	3.0	3.6
022	Probit	1.3	2.3	1.8	2.8
044	Probit	28.7	43.5	36.6	51.6
050	Spearman-Karber	50.0	66.0	60.1	72.4

The oxygen concentrations of all the test solutions were within the required limits for aquatic organisms (>40 % of saturation) (see Appendix B). The pH of samples 022 and 044 (see Appendix B) were also within the required limits. The results obtained for 019 and 050 indicated that pH was low where lethality was observed. It therefore appears that, in these instances, pH was a significant contributing factor to the lethal effects observed.

5 CONCLUSIONS

- The surface water (039 and 040) and groundwater samples (041 and 051) did not exhibit toxicity. The findings are similar to some of the results obtained during previous studies on surface and groundwaters in the Gauteng area (Table 3).
- Samples 019, 022, 044 and 050 were toxic.
- pH played a major role in the lethalities exhibited by samples 019 (Robinson Lake) and 050 (Valley Spring, possibly contaminated by slimes dam effluent).
- Sample 019 was highly toxic with an LC_{50} of 3.3 %. The toxicity is in agreement with results obtained for vanadium mine return water dam waste water that is not discharged into the environment, but more toxic than the copper mine return water dam waste water discharged into receiving water during the rainy season (Table 2).
- Compared to sample 019, the toxicity of sample 050 was low (LC_{50}: 66 %). The toxicity was, however, greater than the toxicity exhibited by some treated sewage and paper mill effluents (Table 2).
- The toxicity of sample 044, strongly influenced by sewage effluent, was slightly higher than that of sample 050 (LC_{50}: 43.5 %). The adverse activity was most probably due to free chlorine and toxic pollutants. The toxicity of this sample was greater than the results obtained for sewage effluent discharged into the Hennops River south of Pretoria (Table 2).
- Sample 022 (decanting mine shaft) exhibited the highest toxicity (LC_{50}: 2.3 %). The result is in agreement with the toxicity obtained for vanadium mine return water dam waste water that is not discharged into the environment (Table 2). Table 1 shows that *Daphnia* is sensitive to a range of heavy metals. It is suspected that a combination of these pollutants in the mine water caused the adverse chemical activity.

6 RECOMMENDATIONS

- Only one toxicity test, namely the *Daphnia pulex* lethality test, was used in this study. This test was applied as a first tier screen to assess toxic potential. Since the sensitivities of aquatic organisms to toxic pollutants differ, it is recommended that a battery of toxicity tests is applied during future studies for a more complete picture of toxicity.
- The *Daphnia* test only responds to acute (short-term) toxicity. It is recommended that sub-lethal (long-term) tests, e.g. algal growth inhibition, *Daphnia* reproduction, etc. are included in future studies. Sub-lethal tests will be particularly useful for surface and groundwaters that did not show acute toxicity.
- Chronic effects such as mutagenicity, teratogenicity and estrogenicity should also be assessed.
- Toxic mine water also poses a health risk to mammals and humans. A range of tests for human health protection is available at the Toxicity Testing Laboratory, CSIR. It is recommended that some of these tests are also used in future studies.

7 REFERENCES

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APPENDIX A — VISUALS(1) OF SAMPLE LOCALITIES

Sample locality 019

Sample locality 022

Sample locality 039

Sample locality 040

Sample locality 041

Sample locality 044

Sample locality 050

Sample locality 051

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(1) Provided by Phil Hobbs.

APPENDIX B – EFFECT OF SERIAL DILUTIONS OF SAMPLES ON *DAPHNIA PULEX*

Sample ID	Concentration (%)	pH	Oxygen concentration (mg/L)	% Lethality after time	
				24 h	48 h
019	10	3.5	7.0	100	100
	5	4.9	7.3	100	100
	2.5	6.1	7.4	5	10
	1.25	6.5	7.0	0	5
	0.625	6.9	7.2	0	0
022	10	6.3	7.6	60	100
	5	6.5	7.3	55	100
	2.5	6.7	7.6	0	45
	1.25	7.0	7.7	0	20
	0.625	7.3	7.2	0	0
044	100	7.9	8.5	100	100
	50	8.3	7.4	0	65
	25	8.3	8.2	0	5
	12.5	8.2	8.4	0	0
	6.25	8.2	7.2	0	0
050	100	4.1	7.6	100	100
	50	7.5	7.4	5	10
	25	7.8	7.6	0	0
	12.5	8.0	8.0	0	0
	6.25	8.2	7.8	0	0
	3.13	8.2	8.0	0	0

Control lethality	<10%
Control pH	7.5 – 7.8
Control oxygen concentration	6.8 – 8.2

ANNEXURE G

Calcite, dolomite, gypsum & goethite saturation index values

Station No.	Calcite SI [$CaCO_3$]	Dolomite SI [$CaMg(CO_3)_2$]	Gypsum SI [$CaSO_4.2H_2O$]	Goethite SI [$FeO(OH)$]
001	−1.04	−1.47	−3.88	8.24
002	−0.86	−1.74	−3.24	7.28
003	0.12	0.16	−2.57	7.58
004	−0.16	−0.69	−3.44	7.90
005	−3.66	−7.71	−4.02	4.72
006	−0.93	−2.04	−3.57	7.42
007	0.26	0.55	−1.54	7.80
008	0.15	0.31	−1.56	7.63
009	−0.13	−0.41	−1.44	7.67
010	Non-convergence	Non-convergence	Non-convergence	Non-convergence
011	−4.07	−7.88	−1.88	3.38
013	−0.81	−1.61	−3.63	7.63
014	−0.65	−1.34	−3.70	7.79
016	−1.20	−2.23	−2.70	7.22
018	−0.13	−0.04	−3.73	7.95
019	−4.11	−8.09	−0.35	−3.23
020	−5.10	−9.50	−4.44	2.18
021	−1.98	−4.28	−0.14	4.33
022	−4.32	−8.64	−0.03	1.70
023	−4.30	−8.61	−0.02	2.31
024	−4.73	−9.59	−4.07	0.42
025	−1.45	−2.83	−0.39	6.55
026	−6.79	−13.51	−2.16	−5.30
028	−2.46	−4.74	−3.51	5.30
030	−2.03	−4.25	−0.93	3.88
031	−0.85	−1.55	−3.60	7.29
032	−0.20	−0.36	−1.40	7.21
034	−1.43	−2.99	−0.76	4.26
035	−0.90	−1.82	−2.41	6.48
036	−1.58	−3.07	−2.71	5.91
037	−2.79	−5.62	−0.95	2.15
038	Non-convergence	Non-convergence	0.19	10.38
039	0.37	−0.35	0.10	8.37
040	−0.88	−2.29	−0.20	6.15
041	−0.06	−0.04	−2.60	7.95
042	−1.83	−4.01	−0.15	5.10
043	−1.84	−4.09	−1.49	3.12
044	0.31	0.33	−1.78	8.13
045	−3.16	−6.16	−3.13	2.65
047	−2.31	−4.57	−1.16	2.79
049	−2.00	−3.97	−0.99	4.08
050	−4.48	−9.01	−0.36	3.55
051	−2.91	−6.22	−3.77	2.97
052	−2.63	−5.11	−2.20	3.35
053	−1.67	−3.41	−2.10	4.60
054	−0.13	−0.19	−1.65	6.78
055	−0.12	0.01	−0.79	6.56
056	−2.62	−5.23	−2.91	3.42
057	−0.90	−1.84	−1.61	5.27

ANNEXURE H

Reviewer's comments and author's response

As indicated on page (ii) of this document, the report was submitted to three peers for review. One of these, Prof. Dr. Winde, sought permission to include his colleagues. This explains the contribution by Mr. Ewald Erasmus as part of the response received from Dr. Winde. The following discussion presents a synthesis of the comments provided by the respective reviewers. It follows the order in which comments were received from reviewers. The author's response is presented as <u>underlined text</u>.

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1. DR. KAI WITTHüSER (Department of Geology, University of Pretoria)

Dr. Witthüser's exhaustive comments were received on 12 July 2007 in the form of margin notes on a hard copy of the draft report. The comments were discussed during an interview between the Principal Author and the Reviewer. They are condensed as follows.

a) Advise that regional trend in rainfall be supported by a statistical analysis such as linear regression or time series analysis.
<u>Advice followed through application of linear regression as shown in Annexure B.</u>

b) Suggest rainfall station positions be shown on Figure 2.
<u>Suggestion implemented.</u>

c) Advise use of legends in figures, alternatively mutual cross-referencing of legends (e.g. Table 1 and Figure 3).
<u>Advice implemented.</u>

d) Advise against use of the term "salinity" when referring to electrical conductivity; suggest the term "mineralization" instead.
<u>Suggestion implemented, although authors of the opinion that the term "salinity" is recognised as describing the measure of total dissolved salts concentration in water.</u>

e) Poor legibility of selective text on certain figures, e.g. text box in top left corner of Figure 8.
<u>Quality of figure-based text improved.</u>

f) Advise against use of the term "vector" in regard to groundwater flow, since this implies both direction and magnitude; suggest the term "direction" instead.
<u>Advice implemented.</u>

g) Caution against depiction of groundwater flow direction indicators (arrows in Figure 9) as intersecting lithological boundaries.
<u>Caution heeded and necessary changes made.</u>

h) Advise conversion of unnumbered tabulated information to formal numbered table.
Advice not implemented on the basis that the information is illuminating rather than being crucial to the assessment.

i) Advise use of the term "Piper plot" instead of "trilinear" in relevant figure titles, since "trilinear" refers only to the triangular fields and not the central diamond field in these figures.
Advice implemented by changing "trilinear" to "Piper diagram".

j) Advise removal of "dissolution & mixing vector" in Figure 14.
Advice implemented, although authors remain of the opinion that this generic interpretation by Johnson (1975) might account in some part for the observed difference in dolomitic groundwater quality between stations 002 and 003.

k) Object to title of Figure 16 "Variation in Malmani Sbgp. water chemistry with depth" on the basis that the graph does not represent a depth profile.
Title modified to read "Difference in dolomite water chemistry between adjacent boreholes of different depth"

l) Object to exclusion of site 047 from Figure 17.
Site 047 included in Figure 17.

m) Object to use of both mg/L and meq/L reporting format in Schoeller-type graphs, e.g. Figures 20 and 21, on the basis that they portray the same information; prefer meq/L format.
Objection noted but not addressed, since authors are of the opinion that each graph serves a particular and different purpose. The mg/L format accommodates those readers who prefer to see the actual individual element salt concentrations present in water. This may include the layperson to whom the meq/L format might be meaningless. For the edification of these readers, the meq/L format provides a direct comparison between individual element/ion concentrations.

n) Advise that the ion balance of samples 022, 023 and 026 in Figure 21 is heavily skewed toward the anions (dominated by SO_4) due to the absence of iron from these plots.
Iron and manganese included in Figure 21.

o) Advise use of the term "Schoeller plot" instead of "Equivalents per million" in relevant figure titles.
Advice implemented by changing "Equivalents per million " to "Schoeller diagram".

p) Advise use of the term "indicator" instead of "fingerprint" or "signature" when referring to similar chemical properties of water from different sources.
Advice implemented.

q) Advise against use of the term "artesian" when referring to decanting mine structures; suggest the term "free-flowing" instead.
Suggestion implemented.

r) Advise against use of the term "response" in the titles of Figures 33 and 34, since this implies a prior event.
Advice implemented by replacing "response" with "behaviour".

s) Suggest elimination of Figure 33, since this is duplicated in Figure 34.
Suggestion rejected, since Figure 33 shows true absolute groundwater elevation data that draws attention to the substantial differences in this parameter that are manifested in the study area, and especially so in this instance where all four stations are located in the Zwartkrans Compartment. Figure 34 with its adjusted vertical scale allows an improved resolution and hence better comparison of the hydrographs.

t) Caution against calculation of transmissivity (T) values based on interpolated gradients and literature values for T.
Caution recognised, but authors of the opinion that this discussion helps illustrate the hydrodynamic complexities of the study area. Caution addressed by prefacing this discussion with the following paragraph: "The groundwater flow pattern shown in Figure 35 also provides the basis for developing a rudimentary semi-quantitative assessment of various groundwater discharge components. Such assessment provides an order-of-magnitude comparison of the groundwater dynamics in various portions of the study area. It is not intended to represent the actual groundwater discharges in the study area."

u) Caution that title of section 4.2.3 (Variations in Water Quality) not different from title of section 4.2.4 (Changes in Water Quality).
Authors disagree; section 4.2.3 discusses variability in water quality over time where the chemical character of the water remains essentially the same, whereas section 4.2.4 discusses observed changes in chemical composition over time.

v) Suggest inclusion of the cation and anion plotting positions in the respective ternary diagrams in Figure 36.
Suggestion not implemented, since authors of the opinion that the figure represents a synthesis of Figures 14, 19, 22 and 32 where these data are displayed, and their inclusion in Figure 36 is therefore not a crucial enhancement of this figure.

w) Advise use of percentile and median values rather than minimum, mean and maximum values in Figures 45, 46, 49 and 50.
Advice implemented.

x) Note figure numbering discrepancy in text *circa* Figure 40 onwards.
Figure numbering corrected.

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2. **DR. PETER ASHTON** (Principal Scientist and CSIR Fellow, CSIR–NRE, Pretoria)

Dr. Ashton's comments were received on 22 July 2007 in the form of margin notes on a hard copy of the draft report. These are condensed as follows.

a) Caution against the use of terms such as "largely" on the basis that "…… *it serves no useful purpose*."
The use of such terminology has been limited to only where directly applicable.

b) Advise that references should first be listed in chronological order (where the first author is the same), and then in alphabetical order.
Advice implemented.

c) Poor legibility of selective text on certain figures, e.g. text box in top left corner of Figure 8.
Refer K. Witthüser comment (d) and response.

d) Advise use the apostrophe ’s when denoting the possessive form of acronyms, e.g. CSIR’s as opposed to CSIRs
Advice implemented.

e) Advise that references should first be listed in chronological order (where the first author is the same), and then in alphabetical order.
Advice implemented.

f) Identification of an error in figure numbering in the text from Figure 39 onwards.
Refer response to K. Witthüser comment (x).

g) Advise change of wording in section 6 (Conclusions) in regard to “obfuscated” and “veracity”.
“Obfuscated” replaced with “obscured”, and “veracity” replaced with “accuracy”. These changes carried through to the Executive Summary.

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3. PROF. DR. FRANK WINDE (North West University, Potchefstroom Campus)

Dr. Winde’s comments, together with those of Mr. Ewald Erasmus, were received via email on 30 July 2007. This allows the comments to be replicated verbatim, rather than as understood and condensed by the Principal Author. The comments are replicated in two parts to clearly distinguish between the two contributions, viz. section 3.1 for Dr. Winde and section 3.2 for Mr. Erasmus.

3.1 Comments provided by Dr. Winde

Hi Phil,

Owing to time constraints I am not able to provide you with a comprehensive review on your report and confine myself to a few remarks of more general nature.

- The report lacks a clear statement regarding the research question(s) and objectives and completely omits a methodology chapter in which all employed scientific methods are described (e.g. interpretation of secondary data, sampling of boreholes, field measurements, lab analyses, statistical evaluation of data ect.) and associated error margins are discussed.

The authors contend that this study and report does not constitute a thesis or in-depth scientific research contribution on the subject matter, and that the necessary and appropriate layout for a consulting-type report has been followed.

- Also missing is any reference to the general design and approach of your research i.e. explaining and justifying why you did what you did. E.g. (I make up an example):

1. Analysing secondary data to characterise hydrogeology, …

2. Use own measurements of water levels, field observations, … to assess possibility of hydraulic link through perceived ‘barrier’

3. Compare water quality up- and downstream of barrier to support/ dismiss above hypothesis of leaking through quartzite barrier

It also appears that two of the three most important conclusions you included in the Executive Summary have little or nothing to do what you actually did and investigated. That also applies to some extent to the subsequently listed recommendations.

See response to previous comment.

Minor observations:

- A large part of the report consist of secondary data which are often replicated but not newly interpreted or condensed. Here mere mentioning of the appropriate reference would suffice. Often the border between secondary and primary data is blurred or obscure.

The authors disagree that the secondary data are not newly interpreted on the basis that no previous interpretation exists. It is our opinion that the secondary data presented and employed in the report is now not only consolidated with the primary data but is also presented holistically for the first time, without necessarily being subjected to rigorous scientific interpretation, whether new or not.

- The introduction gives large room to the different estimates of the decant volume which is neither the focus of the report nor does it add value to understand your line of argument any better, but does not explain what you set out to investigate and how you want to do it.

The authors disagree that "…… *large room* ….." is afforded this aspect, and are of the opinion that this background information serves to highlight the potential threat to the receiving environment.

- The report contains a large amount of redundant information where identical data sets are either displayed using different units (e.g. mequ/l vs mg/l) or where large parts of the displayed data are not explained or interpreted (piper diagrams)

Refer K. Witthüser comment (m) and response.

- Most of the maps do not have a legend explaining symbols or colour codes used – this reduces there value markedly.

Refer K. Witthüser comment (c) and response.

The list of references provided also suggests some room for improvement regarding completeness and relevance to put it mildly.

See response to first comment.

Below please find the comments of Ewald provided on my request.

Based on his opinion and my observations I would suggest to address some of the concerns before attempting wider distribution of the report.

Kind regards,

Frank

(Potchefstroom, 27.07.2007)

3.2 Comments provided by Mr. Erasmus

Frank

Just some main comments

Assumptions (mine)

- The authors took 49 odd water samples, analised them & attempted to interpret them
- Some (minimal) litterature elements were evalutated
- The report should thus only cover the above

However the report covers many other geohydrological aspects based on scant data from other sources, not properly evaluated. This should either be properly done along the requirements of a scientific study or not addressed at all. The basic assumption is thus that these elements should not be covered in the report given the display of lack of understanding by the author of these items in the report.

The authors dispute the "assumption" that only their "attempted" interpretation of "49 odd water samples" should be covered in the report. Amongst others, the study also yielded 54 groundwater levels reduced to absolute elevations and used to compile the first potentiometric map of the study area. The comment regarding the "……. *lack of understanding by the author* ……." is accepted as a personal opinion not warranting a response.

Main Comments

1. On Information in report

a. Outlay not user -friendly - exec summary used to cover some of the basic premises (what when why etc.). Problem statement also hidden in this section

Unconstructive opinion of Reviewer not warranting a response. See also comment 2f and author's response.

b. Assuming the "recommendations" covers the problem statement then this does not cover the actual research done

The authors are of the opinion that the recommendations present a pro-active approach toward advancing the common knowledge base that will inform the successful management of AMD concerns in the subregion. No further response considered necessary.

c. Figures can be halved - the Schoeller type graphic displays were repeated as Meq/l & mg/l - serves exactly the same purpose (actually displays a lack of understanding of the author of there use)

Refer response to K. Witthüser comment (m). The comment regarding the "……. *lack of understanding by the author* ……." is again accepted as a personal opinion not warranting a response.

d. The whole article including the recommendations were based on one point (geosite 20, spring, EC ~10) namely the groundwater flow pattern through the Government Sgp quartzites as indicated in the hydrostatic contour map. However, no attempt was made to evaluate the waterchemistry of this point with adjacent monitoring points (EC~ 100) - purely based on EC values there cannot be a flow through this "barrier' although the element ratio's (Piper plots) could either reflect a through flow or the influence of the uphill tailings dams. Similarly, no attempt was made to fingerprint the groundwater on both sides of this divide and to evaluate the respective possible connectivity or lack there-off.

The authors are of the opinion that this comment reflects a poor understanding of the hydrogeological and hydrochemical complexities revealed by the study, and contend that the issues raised are clearly addressed in the report. No further response considered necessary.

e. The Geology of the area forms half of the conclusion argument (leaking barrier). No attempt was made to properly describe the geological barriers, or the reasons why they are not barriers – i.e. the nature of the various fault / fracture sets, etc. despite a wealth of readily available info in the literature Similarly what the author included on dolomite geohydrological properties displays a lack of understanding of dolomite geohydrology (whether true or not). Of note is the lack of understanding of the nature of the outlier material, as was well described for the West Wits pit (in essence predominantly Wad).

The authors dispute the availability of "……. *a wealth of readily available info* ……..” in regard to "……. *the nature of the various fault / fracture sets* …….” especially in a hydrogeological context, e.g. their transmissive properties. This limitation prompts the first two recommendations made.

Regarding the comment comparing the "outlier material" to that which "….. *was well described for the West Wits pit* ……..", the authors do not dispute that the Black Reef Formation shown on the published geological map 2626 West Rand (1986) at scale 1:250 000 as occurring at this location, comprised a fair proportion of wad (manganese hydroxide). It is the author's opinion, however, that extrapolation of these circumstances to both the outliers is irresponsible and untenable, as indeed is a comment such as this without a reference.

f. The twofold subdivision of the geohydrological regime in dolomitic and non dolomitic (although split per main subgp) is over simplistic. Especially the latter varies dramatically with depth below surface.

Whilst the subdivision referred to by the Reviewer might indeed be over-simplistic, the authors contend that it represents an acceptable and scientifically justifiable distinction within the context of the study. The dramatic variation ascribed by the Reviewer to the "non dolomitic" regime is possibly over-shadowed ten-fold by the variation in both lateral and vertical heterogeneity in the karst environment as, indeed, is alluded to in section 3.1.

g. The geological sections are clear but "sweeping statements' are displayed in them without proof - groundwater connectivity.

The authors appreciate the comment regarding the clarity of the cross-sections, both geological and hydrogeological, and recognise the tenuous nature of especially the latter in the figure titles which commence with the word "Conceptual ………".

h. The article is about AMD. However, the author did not display an in depth knowledge (in fact any understanding at all) of the various other sources of "AMD" – tailings dams / return water dams, storage dams etc. The remark on the Robinson lake storing occasionally mine effluent is besides being wrong also contrasting with the chemical signature of the water. The fingerprinting remark of the various types of AMD (d above) also applies to these sources and resulted in seriously flawing the "lack of a barrier" argument.

Apart from its blatantly insulting tone, the authors refute this comment on the basis that due attention was afforded the Valley slimes dam and its impact on the Valley spring, insofar as the available data permitted an assessment of the impacts associated with "other" sources of AMD.

The use of Robinson Lake as a temporary process water storage facility by Harmony Gold Mine was acknowledged by Mr. Rex Zorab at the 3rd Western Basin Decant Special Technical Meeting held on 28 February 2007 at the Harmony Office Park in Randfontein.

i. Information loosely quoted like storativity / transmissivity, rainfall data was not used to build up a geohyrological picture of the area. It should thus either not be included at all or systematically being incorporated. In particular to compare the cape sandstones with the Wits Qzts iro transmissivity is ludicrous

The authors attribute this comment to a lack of appreciation by the Reviewer for the similar morphologic and tectonic fabric of the Table Mountain Group quartzite, in particular that of the Peninsula Formation, and the similar strata exposed in the Krugersdorp Game Reserve (see Figure 60). Comment rejected.

j. The evaluation of the water chemistry data, although much space was used on it, is not convincing. It gives the impression that the author punched it into a water chem. program and used as many features as possible to produce prints rather than attempting to really fingerprint the groundwater - surface water dynamics. A simple sulphate contoured plume plan (besides the other elements) would go a long way in presenting the real picture. Element ratio fingerprinting besides the Piper plots?

The unconvincing "……. *evaluation of the water chemistry data, ……*" is again the opinion of the Reviewer, although this time some constructive comment is provided in regard to producing, amongst others, "*A simple sulphate contoured plume ………..*". The authors are of the opinion that the distribution of groundwater quality sampling points in the study area does not allow the construction of a sulphate contour map or, for that matter, any other element contour map that will stand up to rigorous scrutiny.

k. Snide remarks does not have a place in a publication

Without a specific reference, authors do not understand the context of this remark and are therefore unable to respond.

2. On Information not in report

a. Key info from readily available literature - geology, ground & surface water data,

The authors are of the opinion that the amount of "outside" information sourced and reported is commensurate with the scope, context, aims, objectives and budget of the study.

b. Use of own data to generate for example plume contour plans

Refer response to comment (j) above.

c. Pending on the authors intention with the report (see my assumption above) either many standard geohydrological elements (see section above) if to be a comprehensive literature summary study. For example - references were made to the Zwartkrans compartment & sub-compartmentalization there-off without any plans to indicate the spatial connection with the study area including zones of potential impact..

Apart from the incoherency apparent in the first part of this comment, the authors reject the example held up by the Reviewer on the basis that (a) the extent of sub-compartmentalisation of the Zwartkrans Compartment remains, in their opinion, unproven, and (b) the restricted extent of the study area and limited budget did not allow for this aspect to be addressed with any degree of rigour.

d. More site plans would make the report easier to read & evaluate

The authors might agree with this comment if the Reviewer was more specific.

e. The conclusion & recommendations does not cover anything dealt with in the study - irrelevant.

The authors reject such a sweeping unsubstantiated comment, and again regard it as an opinion to which the Reviewer is entitled.

f. Whole report format is irregular

Since this comment is not elaborated on or explained by the Reviewer, the authors are unable to respond beyond expressing their intrigue by such opinion.

Conclusion:

Possibly motivated by sensationalizing a possible pollution threat, the author base their conclusions on insufficient own generated data, incomplete interrogation of own and secondary data as derived from a rather limited literature review displaying little or no experience in interpreting mining related pollution data.

The authors reject this conclusion on the basis that the Reviewer has clearly demonstrated a biased and jaundiced demeanor toward the report that casts the objectivity of his review in serious doubt.

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A HYDROGEOLOGICAL ASSESSMENT OF ACID MINE DRAINAGE IMPACTS IN THE WEST RAND BASIN, GAUTENG PROVINCE
Technical Report CSIR/NRE/WR/ER/2007/0097/C

Peer Review Statement by Dr N S Robins,
British Geological Survey, Wallingford, OX10 8BB, UK

This is an important report which gathers together the available but sparse data which describe the generation and discharge of acid mine water in the West Rand Basin to the west of Krugersdorp. The report describes a situation which with foresight and planning both by the mining operator and the regulatory authorities should have been predicted so that ameliorating measures could be designed and implemented. The consequence is discharge of acid mine water into a surface catchment and the likely throughflow of mine water down the hydraulic gradient to emerge at some lower elevation via the quartzites. This could seriously impact habitat and amenity in a game park and might even impact karstic amenity towards Sterkfontein Caves.

The surprise revealed in the report is the lack of data that the authors have been able to access, and this includes the precise geological framework for the area. This reflects a serious lack of investment in investigation and monitoring before, during and subsequent to the extraction phases in the Black Reef, an issue which highlights a number of lessons which the South African mining industry and its regulators should take on board. The consequence of the data scarcity includes formation constants for specific lithologies i.e. including diffusivity, depths of weathering, connectivity between formations and calculations of rainfall recharge to the country rock. It is, however, feasible to develop a conceptual model – which may be non-unique and include a variety of options - for the overall system controlling the generation, transport and dispersal of the mine water. In addition, the mine water chemistry and concentration may allow estimates to be made on the half-life concentrations of the mine water by analogy to historical data from other sites. Data are as yet insufficient for any attempt at numerical modelling, although additional data may not yet have been released by other stakeholders.

The authors develop their conceptual flow model using all the available evidence including groundwater and mine water chemistry. The synthesis of the chemistry data in a piper diagram shows the relationships and possible mixing between water types and is successfully used to illustrate groundwater provenance. Use of Schoeller diagrams, although a convenient graphic providing the y-axis scales are consistent, does not greatly add to the analysis.

The discussion section cites a pump and treat proposal presented by JFA (2006) whereby a yield of over 200 l s^{-1} would produce a dynamic water level at an elevation as the Hippo Dam in the Krugersdorp Game Park in 32 months. This suggests that a numerical model has been made for the partially karst system and that a whole raft of data may exist but which has not been released to the authors of the present report. If these data do not exist, and the system has not been numerically modelled and validated against actual data, then the cited prognosis may be in serious error. It would be useful to know the historical mine dewatering rates.

The Hobbs and Cobbing report is a solid document that brings together all the available data for the hydraulic system and which identifies a number of uncertainties and a list of data needs. The recommendations and conclusions are sound and justified by the main body of the report. The authors are to be congratulated on achieving a high level of understanding of a complex system whilst realising that additional data acquisition will be the essence of complete understanding and of remediation planning.

Some of the diagrams are confused, e.g. the use of rectangular blocks of colour in the cross sections, and some would benefit from a key. Parts of the report are verbose and the text would benefit from condensing and editing so that its message is sharp and clear. Strands that are not used in the summation, such as the gravimetric map (Fig. 11), could be omitted.

This review received via e-mail on 19 October 2007. The authors acknowledge the comment regarding verbosity in portions of the report, and undertake to improve on the brevity of the text should the opportunity to update the report arise.