Cradle of Humankind©
World Heritage Site

DEPARTMENT OF ECONOMIC DEVELOPMENT
GAUTENG PROVINCIAL GOVERNMENT, SOUTH AFRICA

PROJECT TITLE

ESTABLISHMENT OF A MONITORING SYSTEM FOR SURFACE WATER AND GROUNDWATER IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

SITUATION ASSESSMENT OF THE SURFACE WATER AND GROUNDWATER RESOURCE ENVIRONMENTS IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

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Unnumbered plate.
Panoramic view of the COH WHS 'core' area in the John Nash Nature Reserve showing the valley carved by the Grootvlei Spruit from upper left (south-east) to lower right (north-west) across the landscape.
(Photo: Phil Hobbs)

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Unnumbered plate.
View of DWA surface flow and water quality monitoring station A2H049 at the lower end of the Bloubank Spruit at Zwartkop showing hut housing automated stage gauging instrumentation at left, and vertical stage gauge plates in middle and right foreground for visual stage gauging observation.
(Photo: Phil Hobbs)

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Unnumbered plate.
Sampling position of subterranean lake water (ambient groundwater)
within the Sterkfontein Caves fossil site.
(Photo: Phil Hobbs)

Unnumbered plate.
Stream flow gauging at a weir on the Bloubank Spruit at Ekutheni Estate immediately downstream of the Kromdraai Spring. Flow on date of measurement (13/08/2010) ~547 L/s (~47.2 ML/d).
(Photo: Phil Hobbs)

CONDENSED ABSTRACT

A poor understanding of the surface and groundwater resources of the COH WHS has precipitated often alarmist reporting in the media regarding the negative impacts associated with various sources of poor quality water, most notably acid mine water decanting from the Western Basin, threatening the fossil sites and karst ecosystems in the COH WHS. A situation assessment of the water resources environment, commissioned by the Management Authority (MA), has better informed this situation. It also provides the basis for an integrated water resource monitoring programme that will support management efforts by the MA to protect the aquatic environment.

An evaluation of existing water quantity and quality monitoring programmes in the region shows a bias toward surface water resources in terms of both quantity and quality. Further, that existing monitoring programmes reflect a geographic focus directed at the south-western portion of the study area where concern exists for the impact associated with sources of poor quality water. The principal sources in this regard are mine water (both raw and treated) and treated municipal wastewater (sewage) effluent. The identification of an incongruency of geographic location for monitoring stations served by more than one organisation has been investigated, and definitive coordinates determined for acceptance and use by the relevant organisations. The absence of routine spring discharge measurements is recognized as the single most important deficiency in a water resource monitoring context.

The surface water environment comprises the nearly pristine Skeerpoort River and the impacted Bloubank Spruit system. These drain to Hartbeespoort Dam via the Magalies River and the Crocodile River, respectively. The Skeerpoort River, with a long-term median discharge of 8.9 Mm^3/a (24.3 ML/d), is fed by karst springs delivering >25.9 ML/d (~9.5 Mm^3/a) of excellent quality dolomitic groundwater. This contribution represents ~5% of the net capacity (~186 Mm^3) of Hartbeespoort Dam. The Bloubank Spruit system, with a long-term median discharge of 19.2 Mm^3/a (~10% of the net capacity of Hartbeespoort Dam), receives poor quality raw and treated mine water (≥10 ML/d) and treated municipal sewage effluent (13 ML/d) in its headwaters upstream of the karst environment. The balance of ≥29.6 ML/d (10.8 Mm^3/a) is contributed mainly by karst springs delivering 31.7 ML/d (11.6 Mm^3/a) of good quality dolomitic groundwater. The Crocodile River median long-term discharge of ~9.5 Mm^3/a of good quality surface water (measured above the confluence with the Bloubank Spruit) again represents ~5% of the net capacity of Hartbeespoort Dam. Expressed in terms of long-term annual total dissolved salt (TDS) load contributions, these drainages deliver in the order of 2350, 8560 and 2700 tons TDS respectively to Hartbeespoort Dam. The historical persistence of poor bacteriological quality as reflected in *E. coli* values associated with surface water in the Bloubank Spruit represents a significant threat to the 'fitness for use' of this resource, and the recent and current presence of mine water is cause for further concern.

The groundwater environment comprises ten dolomitic compartments, two of which are subdivided into subcompartments. Most of the compartments are drained by springs with quantified discharges and spring water qualities that include environmental isotope data. The aggregate discharge of eleven enumerated karst springs amounts to ~800 L/s (69.1 ML/d ≈ 25.2 Mm^3/a). This equates to ~14% of the net capacity of Hartbeespoort Dam, and reflects the very important contribution of mainly good to excellent "COH WHS dolomitic groundwater" to the water resources of the wider region. The very wet 2009-'10 and 2010-'11 summers precipitated an exceptional recharge of groundwater resources in the study area. A rise in groundwater rest levels by at least ~1 m (also observed in the Sterkfontein Caves water level) reflects this. Greater water level rises (by as much as ~5 m) are attributed to artificial and allogenic recharge associated with the infiltration of surface water contributed from extraneous sources including mining and municipal wastewater effluent. This infiltration has amounted to as much as ~32 ML/d in the case of mine water, and ~7 ML/d in the case of municipal wastewater effluent.

The symbiotic relationship between spring discharge, spring catchment area, spring water chemistry and rainfall recharge is demonstrated for most of the compartments. This has led to an improved understanding of groundwater flow patterns in the study area especially in regard to the dolomitic strata, and which provides a plausible conceptual hydrologic and hydrogeologic model of the water resources environment in the COH WHS that recognizes groundwater resource units (GRUs) as a key element.

The improved understanding of the groundwater environment has informed an assessment of the relative risk to fossil sites from anthropogenic impacts on the water resources environment. A fossil site hydrovulnerablity assessment indicates that nine of the 14 fossil sites in the COH WHS reflect a **very low** or **low vulnerability** due to their location (a) in groundwater compartments that are hydrogeologically separated from those where the contaminated water impact is manifested, and (b) at substantial elevations above the ambient groundwater level. Only the Bolt's Farm site reflects a **very high vulnerability**. Although the Sterkfontein Caves site intersects the water table, it is assigned a **high vulnerability** on the basis that the observed long-term cave water quality record and recent hydrochemical data reflect a low impact to date. The Swartkrans, Minnaars and Plover's Lake sites reflect a **moderate vulnerability**. In conclusion, it is apparent that the majority of the fossil sites in the COH WHS are not under threat from either changes in surface water or groundwater levels and/or changes in surface water or groundwater chemistry (quality), whether these are due to mine water, treated sewage effluent or agricultural return water ingress. The more vulnerable sites are earmarked for short-, medium- and long-term monitoring.

Chemistry analyses of sediment collected at eight localities in the southern part of the study area established the chemical composition of streambed material in receiving drainages. The Tweelopie Spruit carries raw and/or treated mine water, and the Blougat Spruit treated municipal wastewater effluent. Both these drainages are tributaries of the Riet Spruit, itself a tributary of the Bloubank Spruit. A Tier 1 risk assessment of measured U and Ni concentrations identified the two most upstream localities, namely the Hippo Dam and the Lion Camp Dam on the Tweelopie Spruit in the Krugersdorp Game Reserve, as definitely posing a risk in regard to these metals. The next two localities downstream were identified as definitely posing a risk in regard to Ni only. Three different leach tests were carried out to determine the extractable (mobile) fraction of the total concentration of elements measured by XRF. None of the leach tests extracted a U concentration higher than the regulatory limit of 16 mg/kg proposed by the National Nuclear Regulator. A highest U concentration of ~5% of the total U concentration was extracted. A highest Ni concentration of ~12% was extracted from one sample, the extractable fraction of ~71 mg/kg exceeding the regulatory limit of 35 mg/kg proposed by the EU. The results suggest that a risk assessment based on extractable concentrations (as opposed to total concentrations) would return a greater number of lower risk quotient values. Although these circumstances mitigate the risk associated with the mobilization of sediment-bound trace/heavy metals, the cumulative mass/volume of sediment contained in the various impoundments cautions against minimization or downplaying of the associated risk.

The outcome of the risk and hazard mapping exercise indicates the greater hazard present in the south-western corner of the COH WHS in the Oaktree area, as well as the elevated hazard rating associated with the surface water drainages. Whereas the former is directly related to the intensity of agricultural activity, the latter is informed by the intrinsically close hydraulic relationship that exists between surface water and groundwater resources in a karst environment.

A petrographic study and laboratory kinetic leach tests of the impact of AMD on dolomite indicates that the likely effects of AMD ingress into the karst aquifer(s) of the COH WHS will be a rise in the pH of the influent mine water (as a result of the dissolution of dolomite) to a value comparable to that of the ambient karst groundwater. The rise in pH would result in the reduction of the solubility of some of the contaminant species in the mine water, significantly removing iron and aluminium from solution, partially removing manganese and not having a significant effect on the sodium or sulphate concentration. The metal precipitates, which would include gypsum, goethite and crystalline and amorphous (botryoidal) aluminium oxy-hydroxide species, are likely to form on the reactive surfaces of the dolomite, preventing further neutralisation reactions from taking place. Influent mine water would therefore tend to react at the point of first contact with the dolomite, resulting in both neutralisation of the mine water and the prevention of further neutralisation from taking place. Over time the mine water would migrate further and further into the karst aquifer, and the buffering capacity of the aquifer would reduce progressively. In conclusion, natural attenuation of AMD by allowing it to enter dolomitic aquifer systems is not regarded as an appropriate or sustainable management strategy.

The state of the environment assessment results for the 15 groundwater resource units (GRUs) shows that two of these are assigned a **'largely modified' class D** classification, and a further three a **'modified' class C** classification. The remainder are assigned either a **'slightly modified' class B/BC** or a **'natural'**

class AB classification. These circumstances reflect the good, and in some instances even excellent, state of the groundwater environment associated with 66% of the GRUs in the COH WHS. A closer inspection of the spatial representation of the 13 karst GRUs shows that 59% of the karst area supports a **'slightly modified' class B/BC** or better classification, and only 27% of this area a **'largely modified' class D** classification.

It is concluded that the platform built from historical data, and its integration with a wide range of rigorous and defensible newly-generated and interpreted hydrologic and hydrogeologic data and information, convincingly underpins the situation assessment of the surface water and groundwater environments in the COH WHS. This, in turn, has provided the means to objectively gauge the impact of varied and numerous threats to and on the water resources, and to develop a coordinated, appropriate and cost-effective water resources monitoring programme. It is equally evident, however, that the unprecedented abnormally high flow conditions experienced in the past two hydrological years in the Bloubank Spruit system is cause for grave concern under circumstances where much of this discharge has been due to abnormally high mine water decant driven by copious recharge associated with above average rainfall.

Unnumbered plate.
Dolomite pinnacle protruding from a recently formed doline following flooding by stormwater of a soil borrow-pit for road construction alongside Dolomite Road.
(Photo: Phil Hobbs)

Unnumbered plate.
View of the western sidewall of Sterkfontein Quarry showing the barricaded/gated portal to Alladin's Cave at centre right, the 3-4 m thick epikarst zone (above the sub-horizontal dotted line) and the gentle boudinage-like folding of the dolomitic strata exposed in the sidewall. (Photo: Phil Hobbs)

EXECUTIVE SUMMARY

INTRODUCTION

The fossil hominid sites of Sterkfontein, Swartkrans, Kromdraai and environs (the so-called Cradle of Humankind) were inscribed for protection of their cultural heritage in terms of the World Heritage Convention Act (Act No. 49, 1999) by UNESCO in 1999. The Management Authority (MA) of the Cradle of Humankind World Heritage Site (COH WHS) exercised its mandate to protect also the aquatic environment in the COH WHS by commissioning a study aimed at establishing a monitoring system for surface water and groundwater resources in its area of jurisdiction.

The implementation of an appropriate integrated hydrologic and hydrogeologic monitoring programme is considered crucial to the successful management of the water resources in the COH WHS area. An effective routine monitoring programme will be able to measure and demonstrate the success or failure of management efforts by the MA to protect the aquatic environment in the COH WHS. Such protection is not only required for the preservation of the karst features and their palaeo-anthropological treasures, but also for the water users who reside in the area and depend on local water resources (primarily groundwater) for their livelihood.

STATUS QUO OF WATER RESOURCE MONITORING

An assessment of current water resource monitoring activities in the study area indicates a bias toward surface water resources in terms of both quantity and quality. Further, that existing monitoring programmes reflect a geographic focus that is centered on the south-western portion of the study area where concern exists for the impact associated with sources of poor quality water. The principal sources in this regard are mine water (both raw and treated) and treated municipal wastewater (sewage) effluent.

An incongruency of geographic location for monitoring stations served by more than one organisation is identified. Such instances have been investigated, and definitive coordinates determined for acceptance and use by the relevant organisations. However, the complete absence of routine spring flow measurements is recognized as the single most important deficiency in a water resource monitoring context.

SURFACE WATER RESOURCES

Quantity

The Skeerpoort River system is in a nearly pristine condition. Its perennial nature is sustained by the combined discharge (>300 L/s ≈ 25.9 ML/d ≈ 9.5 Mm^3/a) of numerous mainly dolomitic springs located in the John Nash Nature Reserve. The flow gauging record for the Skeerpoort River indicates a long-term mean and median discharge of 11 and 8.9 Mm^3/a, respectively, into Hartbeespoort Dam via the Magalies River. The median value represents ~5% of the net capacity (186.4 Mm^3/a) of the dam.

The flow record for the Bloubank Spruit system indicates a long-term mean and median discharge of 22.9 and 19.2 Mm^3/a, respectively, into Hartbeespoort Dam via the Crocodile River. The median discharge represents ~10% of the net capacity of the dam. The Bloubank Spruit system has experienced above average discharges in its upper reaches via the Tweelopie Spruit and the lower Riet Spruit since the resumption of mine water decant in late-January 2010. The combined discharge of raw and treated mine water witnessed surface water losses of between 20 and 32 ML/d to the dolomitic aquifer in the lower Riet Spruit, equating to an infiltration rate of as much as ~90 L/s/km. Together with the discharge from the Percy Stewart Wastewater Treatment Works (WWTW) via the Blougat Spruit, these circumstances have resulted in an unprecedented volume and duration of surface water flow in the Bloubank Spruit system through the winter of 2010. The resulting impact will reflect in any future analysis of the Bloubank Spruit system discharge. The recent median discharge of ~13 ML/d (~4.7 Mm^3/a) of treated sewage effluent to the Blougat Spruit from the Percy Stewart WWTW equates to 24% of the long-term median annual discharge gauged at the end of the Bloubank Spruit System.

The Crocodile River flow gauging record immediately upstream of its confluence with the Bloubank Spruit indicates a long-term mean and median discharge of 12.3 and 9.5 Mm^3/a, respectively. The latter represents ~5% of the Hartbeespoort Dam net capacity. However, since only 15% of this catchment falls within the study area, this discharge is excluded from the aggregate long-term contribution of ~15% (28.1 Mm^3/a) delivered by the COH WHS to Hartbeespoort Dam.

Quality

The Skeerpoort River system continues to reflect a karst-dominated $CaMg\text{-}HCO_3$ water composition of excellent quality. Up until mid-2010, the impact of the poor quality associated with the recent abnormal combined discharge of treated and raw mine water in the upper reaches of the Bloubank Spruit system was mitigated by (a) the contribution of treated wastewater effluent discharged by the Percy Stewart WWTW and (b) the above average surface water runoff associated with the extremely wet 2009-'10 summer. Since mid-2010, the increase in salinity of Bloubank Spruit water from ~50 to >100 mS/m, together with a decrease in pH from 7.2 to 6.9 at the downstream boundary of the Zwartkrans Compartment, is considered to reflect an increasing contribution of mine water to the middle reaches of the Bloubank Spruit. This impact is less evident in the Zwartkrans Spring water, which as recently as August and December 2010 still reflected field salinity values of 77 and 74 mS/m, respectively.

The combination of long-term discharge and water chemistry records for the DWA gauging/sampling stations on the Skeerpoort River, the Bloubank Spruit and the Crocodile River allow for an assessment of the salt loads (based on TDS concentrations) associated with the respective drainages. This assessment indicates that the Skeerpoort River and upper Crocodile River deliver similar contributions of 2350 and 2706 t/a, compared to the 8560 t/a delivered by the Bloubank Spruit system. These values translate into contributions of 17%, 20% and 63%, respectively, of the total salt load of 13 616 t/a delivered by the drainages in the study area.

The quality of surface water resources in the Bloubank Spruit system is further compromized by bacterial contamination and associated elevated nitrate and phosphate concentrations derived mainly from wastewater effluent. These circumstances also make it difficult to assess the agricultural impacts on the quality of surface water resources, since these are similarly associated with nutrient inputs represented by nitrate and phosphate contributions. A concern for the downstream environment (that includes the Hartbeespoort Dam) is the nutrient load delivered by the Bloubank Spruit and the upper Crocodile River catchments. The sampling stations on Bloubank Spruit system and the Crocodile River witnessed phosphate loads of 6.7 and 4.6 t/a, respectively, in the period mid-2007 to mid-2008. These drainages together therefore recently delivered 11.3 t/a of phosphate into the Hartbeespoort Dam catchment. By comparison, a cursory appraisal of relevant DWA data for the same period shows that the Jukskei and Hennops River catchments contributed median phosphate loads of 207 and 126 t/a, respectively. Contextually, the various loads represent 3% contributed by the study area (including the upper Crocodile River), 60% contributed by the Jukskei River, and 37% contributed by the Hennops River to the collective ~344 t/a phosphate recently entering Hartbeespoort Dam from these sources.

A further concern for the downstream environment is the impact of mine water, in particular the presence of trace/heavy metals and radionuclides, on the quality of water in the Bloubank Spruit. A surface water sample collected in May 2010 near the Sterkfontein Caves returned Fe and Mn values of 0.91 and 0.67 mg/L, respectively. A sample collected at Plover's Lake further downstream on the same day returned Fe and Mn values of 0.36 and 0.29 mg/L, respectively. Although both sets of values significantly exceed the long-term median values of 0.006 and 0.002 mg/L determined for these variables at the end of the Bloubank Spruit system, the significant differences between the 'upstream' and 'downstream' samples caution against a direct comparison with the long-term values. Whilst the observations may therefore be seen as reflecting the recent manifestation of a mine water impact on surface water quality in the lower reaches of the Bloubank Spruit system, the COH WHS monitoring programme will better inform this matter in time to come. Uranium concentrations in surface water nowhere exceeded the analytical detection limit of 0.001 mg/L for this variable.

Unsurprisingly, the persistence of poor bacteriological quality as reflected in *E. coli* values associated with surface water in the Bloubank Spruit continues to represent the current and singularly most significant threat to the 'fitness for use' of this resource. This situation can be traced back to the poor score achieved by the Percy Stewart WWTW in the 2009 "Green Drop Report", and in particular the non-compliance in regard to wastewater quality, which received a "G".

GROUNDWATER RESOURCES

Quantity

Springs are widely recognized as the most appropriate gauging, sampling and monitoring points in a karst environment. The study has enumerated eleven springs (excluding the seven located in the Krugersdorp Game Reserve) in the COH WHS study area. The total number of such features in the study area is probably an order of magnitude greater. Some of the features represent groups of springs (and seeps) located in close proximity to one another. Nine are associated with dolomite, the 'smallest' delivering ~2 L/s and the 'largest' ~307 L/s. The total yield of these sources amounts to ~800 L/s (69.1 ML/d ≈ 25.2 Mm^3/a). This equates to ~14% of the net capacity of Hartbeespoort Dam, and reflects the very important contribution of mainly good to excellent "COH WHS dolomitic groundwater" to the water resources of the wider region. None of the enumerated springs are subject to regular and routine discharge measurements. Individual 'once-off' measured discharge values for most of these features are reported for the first time in this study.

Groundwater quantity is further represented by groundwater level data and information. The study has generated 117 groundwater level measurements from as many sources (18 springs and 99 boreholes) in the study area. Each of these measurements has been translated into an absolute value representing a groundwater elevation above mean sea level. Together with the locations and elevations of the various springs, this information has led to an improved understanding of groundwater flow and movement in the study area especially in regard to the dolomitic strata. As a consequence, the study has redefined the physical hydrogeologic environment by recognising a degree of compartmentalization that contributes significantly to a more informed understanding of the karst groundwater environment. A total of ten dolomitic compartments, two of which comprise subcompartments, are identified in the study area. Most of the compartments are drained by springs.

The behaviour of groundwater levels associated with the karst aquifer is reflected in the long-term water level records for the 15 DWA monitoring boreholes in the study area. In most instances, the record period extends from 1985 to the present. An analysis of the data indicates a generally excellent agreement between the mean and median values. This reflects the large measure of constancy in this parameter. Further, there is little correlation between the depth to groundwater rest level and the magnitude of water level variation; relatively small variations (<3 m) being associated with both 'deep' (>60 mbs) and comparatively 'shallow' (<30 mbs) water levels. The data set revealed a maximum water level variation value of 12.2 m, with mean and median values of 6.7 m and 5.8 m, respectively.

The very wet 2009-'10 and 2010-'11 summers precipitated an exceptional recharge of groundwater resources in the study area. A rise in groundwater rest levels by at least ~1 m (also observed in the Sterkfontein Caves water level) testifies to these circumstances. Greater water level rises (by up to ~5 m) are attributed to artificial and allogenic recharge associated with the infiltration of surface water contributed from extraneous sources including mining and municipal wastewater effluent. This infiltration has amounted to as much as ~32 ML/d in the case of mine water, and ~7 ML/d in the case of municipal wastewater. It is concluded, therefore, that the aspect of groundwater quantity as represented by recent/current groundwater rest levels compared to historical levels, reflects a positive outlook.

Quality

Groundwater quality in the study area is defined on the basis of chemical analyses carried out on water samples obtained from 51 sources (7 springs and 44 boreholes). The analytical suite included inorganic, organic and bacteriological variables, heavy/trace metals and environmental isotopes as well as pesticide residue analyses employed selectively. In addition, numerous measurements of field parameters (pH, EC, Eh and temperature) have been carried out on an ad hoc basis at a number of springs.

As might be expected, the chemistry of groundwater in the study area reflects the greatest spatial variation depending on the position in the physical hydrogeologic environment. For instance, the subcompartments receiving water of compromized quality in terms of (a) either trace/heavy metals and elevated salt loads associated with mine water, and/or (b) elevated bacterial and nutrient loads associated with municipal wastewater (both representing allogenic recharge), reflect the poorest groundwater quality. Despite its location in such a hydrogeologic setting, however, the water in the Sterkfontein Caves continues to reflect a salinity of ~60 mS/m as it did in June 2006, a year after the start of monitoring of this variable by the DWA. Compartments/subcompartments receiving only autogenic recharge remain largely unaffected in terms of groundwater chemistry (and quality).

SEDIMENT CHEMISTRY

Sediment samples were collected at eight localities in the southern portion of the study area in order to determine the chemical composition of streambed material at various positions along the Tweelopie Spruit, the Riet Spruit, the Blougat Spruit and the Bloubank Spruit. The 'once-off' sampling campaign took the form of a screening level reconnaissance survey precipitated by the comparatively sparse data of this nature for the drainages that receive either raw and/or treated mine water via the Tweelopie Spruit, and treated municipal wastewater effluent via the Blougat Spruit.

A Tier 1 risk assessment compared measured concentrations of U and Ni to a regulatory standard using values from the European Union (EU) and the National Nuclear Regulator (NNR), since South Africa does not yet have freshwater sediment guidelines or legislated limits for most contaminants in soil. The outcome identified the two most upstream localities, namely the Hippo Dam and the Lion Camp Dam on the Tweelopie Spruit in the KGR, as definitely posing a risk in regard to both U and Ni. The next two localities downstream were identified as definitely posing a risk in regard to Ni only.

Three different leach tests were carried out to determine the extractable (mobile) fraction of the total concentration of elements measured by XRF. None of the leach tests extracted a U concentration higher than the regulatory limit of 16 mg/kg proposed by the NNR. A highest U concentration of ~5% of the total U concentration was extracted. A highest Ni concentration of ~12% was extracted from one sample, the extractable fraction of ~71 mg/kg exceeding the regulatory limit of 35 mg/kg proposed by the EU. These results put those of the Tier 1 risk assessment into perspective, since it is probable that a Tier 1 risk assessment based on extractable concentrations (as opposed to total concentrations) would return a greater number of lower risk quotient values. Although these circumstances mitigate the risk associated with the mobilization/remobilization of sediment-bound trace/heavy metals, the cumulative mass/volume of sediment contained in the various impoundments cautions against minimization or downplaying of the associated risk.

ASSESSMENT OF MINE WATER IMPACT ON DOLOMITE

The dissolution of dolomitic strata (carbonate rocks) is a naturally occurring phenomenon. However, concern has been expressed for the geochemical interaction between acid mine water and the dolomitic strata that build the receiving karst aquifer in the study area. The two main hypotheses are (a) the possible dissolution of the dolomitic strata by low pH mine water leading to a greater potential risk of increased subsurface instability and land subsidence, and (b) the precipitation of oxyhydroxides on the surface of the dolomite within fractures and karst features to armour the strata and inhibit any further dissolution. In order to further inform the topic, studies were carried out by the Council for Geoscience that entailed a comparative petrographic study of thin sections of dolomite before and after exposure to acid mine water, as well as laboratory kinetic (column leach) tests wherein acid mine water was passed through columns of dolomite.

The results indicate that the likely effects of AMD ingress into the karst aquifer(s) of the COH WHS will be a rise in the pH of the influent mine water (as a result of the dissolution of dolomite) to a value comparable to that of the ambient karst groundwater. The rise in pH would result in the reduction of the solubility of some of the contaminant species in the mine water, significantly removing iron and aluminium from solution, partially removing manganese and not having a significant effect on the sodium or sulphate concentration. The metal precipitates, which would include gypsum, goethite and crystalline and amorphous (botryoidal) aluminium oxy-hydroxide species, are likely to form on the reactive surfaces of the dolomite, preventing further neutralisation reactions from taking place. Influent mine water would therefore tend to react at the point of first contact with the dolomite, resulting in both neutralisation of the mine water and the prevention of further neutralisation from taking place. Over time the mine water would migrate further and further into the karst aquifer, and the buffering capacity of the aquifer would reduce progressively. In conclusion, natural attenuation of AMD by allowing it to enter dolomitic aquifer systems is not regarded as an appropriate or sustainable management strategy.

RESOURCE QUALITY OBJECTIVES

The inclusion of the resource quality objectives (RQO) aspect of a groundwater resource directed measures (GRDM) assessment significantly enhances the impact of the study. The compartments (and subcompartments) identified in the study area represent appropriate groundwater resource units (GRUs) on which to base and implement meaningful groundwater management measures.

Quantity

The statistical assessment of long-term groundwater rest level response patterns provides a means to quantify the setting of RQOs for groundwater quantity in that portion of the study area where such data are available. The proposed RQOs recognize ‘permissible’ changes in groundwater rest level that vary across a compartment. Although the proposed RQOs do not find a priori support in the DWA library of existing RQOs in this regard, they are nevertheless put forward for consideration as advancing the knowledge-base in regard to this GRDM component.

Long-term groundwater level monitoring data are only available for the Zwartkrans Compartment. The proposed RQOs for this compartment are quantified as follows:

- a change in groundwater rest level of $\leq$6.1 m in the upper reaches represented by the Vlakdrift Subcompartment;
- a value of $\leq$3.6 m for the middle reaches represented by the Sterkfontein Subcompartment; and
- a value of $\leq$2.3 m for the lower reaches represented by the Zwartkrans Subcompartment.

Quality

The setting of RQOs in regard to groundwater chemistry (quality) is a comparatively simpler task given the relationship of analytical groundwater chemistry data with the discharge(s) of associated groundwater compartments, especially where these are coupled with spring water chemistries. The springs draining the largely pristine Danielsrust, Tweefontein, Uitkomst and Diepkloof compartments do not reflect anthropogenic impacts on the chemistry (quality) of the groundwater discharged from these GRUs, compared to the chemistry of groundwater produced by the Zwartkrans Spring. The latter drains the most severely compromized hydrogeologic system in terms of groundwater quality in the study area, with groundwater analyses typically exhibiting electrical conductivity values of >100 mS/m, SO_4 concentrations of >150 mg/L, and Cl concentrations of >50 mg/L.

STATE OF THE ENVIRONMENT ASSESSMENT

Surface Water

The National Freshwater Ecosystem Priority Areas (NFEPA) project provides a recent perspective on the ‘state’ (condition) of rivers also in the study area. This project assigns a **‘natural’ class AB** condition to the Skeerpoort River, and a **‘largely modified’ class D** condition to the Bloubank Spruit system and the Crocodile River upstream of its confluence with the Klein Jukskei River. Downstream of this confluence, into and beyond Hartbeespoort Dam, the Crocodile River is assigned a **'modified' class C** condition.

SASS assessments were carried out at different positions in the Tweelopie Spruit in 2000 and 2005. The results clearly revealed the measure of aquatic habitat degradation that occurred in this drainage in the period between assessments. The Rand Water toxicity testing results (using *Daphnia pulex* and *Poecilia reticulate*) similarly revealed the toxicity of especially the raw mine water. Toxicity testing (using *Daphnia pulex*) carried out by the CSIR on eight water samples collected from various sources in the locus of mine water decant in early-2007 similarly indicated a high toxicity associated with raw mine water. Further, that low pH values would appear to be a significant contributing factor to the lethal effects observed.

The value of both SASS-type and toxicity assessment exercises in gauging the 'health' of aquatic ecosystems and water as a measure of the state of the environment in the COH WHS area has been under-utilized in the past. It is recommended that such assessments and tests be carried out regularly at selected sites in accordance with the necessary guidelines and protocols in order to generate temporally comparative data. The Skeerpoort River in the John Nash Nature Reserve represents a natural river system that can provide a benchmark against which to gauge the measure of deterioration established for other 'karst-driven' drainages in the study area.

Groundwater

The state of the environment assessment results for the various groundwater resource units (GRUs) are summarized in the following table. This shows that two of the 15 GRUs are assigned a **'largely modified' class D** classification, and a further three a **'modified' class C** classification. The remainder are assigned either a **'slightly modified' class B/BC** or a **'natural' class AB** classification. These circumstances reflect the good, and in some instances even excellent, state of the groundwater environment associated with 66% of the GRUs in the study area. A closer inspection of the spatial representation of the karst GRUs according to their SoE classification shows that 59% of the karst area supports a **'slightly modified' class B/BC** or better classification. Further, that only 27% of this area supports a **'largely modified' class D** classification.

Compartment	Subcompartment	GRU	DWA GMU #	SoE	Description	Type
Zwartkrans	Vlakdrift	1a	A21D-01	C	Modified	Karst
	Sterkfontein	1b	A21D-02	D	Largely modified	Karst
	Zwartkrans	1c	A21D-03	D	Largely modified	Karst
Krombank	Kromdraai	2a	A21D-04	B	Slightly modified	Karst
	Bloubank	2b		C	Modified	Karst
Danielsrust		3		B	Slightly modified	Karst
Uitkomst		4	A21G-01	AB	Natural	Karst
Tweefontein		5		AB	Natural	Karst
Rietfontein		6		B	Slightly modified	Karst
Diepkloof		7	A21G-02	AB	Natural	Karst
Motsetse		8		AB	Natural	Karst
Rhenosterspruit		9	A21H-02	BC	Slightly modified	Karst
Broederstroom		10		BC	Slightly modified	Karst
Pretoria Group strata		11	Not assigned	B	Slightly modified	Non-karst
Witwatersrand Supergroup & older strata		12	Various	C	Modified	Non-karst

GROUNDWATER RESOURCE RISK ASSESSMENT

A 2008 aquifer vulnerability study of the COH WHS generated the first assessment of this kind for a karst aquifer in South Africa. A subsequent refinement of the algorithm has incorporated the concepts of hazard (recognized as activities and land use practices that pose a threat to groundwater resources) and risk (determined from a synthesis of the information provided by hazard and vulnerability maps). The application of hazard and risk mapping procedures in the COH WHS expanded on the 2008 aquifer vulnerability study to produce a more realistic risk management tool for this sensitive environment.

The outcome of the hazard mapping exercise indicates the greater hazard present in the south-western corner of the COH WHS in the Oaktree area, as well as the elevated hazard rating associated with the surface water drainages. Whereas the former is directly related to the intensity of agricultural activity mainly in the form of cut flower production for the export market, the latter is informed by the intrinsically close hydraulic relationship that exists between surface water and groundwater resources in a karst environment. The risk map developed by combining the aquifer vulnerability map and the hazard map, clearly reveals the elevated risk associated with the roads running through the area.

The proliferation of 'illegal' refuse disposal sites associated with both informal and formal low-cost residential areas is further cause for concern. This is especially relevant in instances where the disposal sites occupy positions close to or even within surface drainages that traverse dolomite. The provision of suitably adequate refuse/waste removal facilities for the low-cost and/or informal residential areas that have been developed on dolomitic ground in the COH WHS and surrounds, is no less important than the provision of water and sanitation facilities to these communities. This represents an opportunity for integrated land use development between local and district municipal authorities.

FOSSIL SITE HYDROVULNERABILITY ASSESSMENT

As far as can be established, the COH WHS is the only protected karst landscape in the world that is ostensibly threatened by acid mine drainage (AMD). The perceived threat of AMD to the area has generated wide and considerable concern for the preservation of the UNESCO-inscribed fossil sites. Against this background, the fossil site hydrovulnerability assessment represents a first attempt to evaluate the threat on the basis of a better understanding of the physical and chemical hydrologic and hydrogeologic frameworks that describe the receiving aquatic environment as both a pathway for and receptor of AMD. The assessment indicates that concern is justified in only a few instances.

It is concluded that nine of the 14 fossil sites in the COH WHS exhibit a **very low** or **low vulnerability**. This is attributed to their location (a) in groundwater compartments that are hydrogeologically separate from those where the contaminated water impact is manifested, and (b) at substantial elevations above the ambient groundwater level. Only the Bolt's Farm site exhibits a **very high vulnerability**. This is due to its position immediately down-gradient of the two main sources of poor quality surface water, namely mine water via the Riet Spruit and treated municipal wastewater via the Blougat Spruit. This is compounded by the fact that (a) both these drainages lose water to the karst aquifer, and (b) at least one cave system in this area is known to intersect the water table. The Sterkfontein site is assigned a **high vulnerability**. The fact that this cave system intersects the water table is mitigated by the observed long-term cave water quality record and other hydrochemical data. These reflect circumstances where the cave water does not exhibit the measure of impact observed in the Zwartkrans Subcompartment as is recorded for the Zwartkrans Spring. The Swartkrans, Minnaars and Plover's Lake sites exhibit a **moderate vulnerability**. This is mainly due to a relatively shallow (5 to 25 m below surface) water table. In conclusion, therefore, it is apparent that the majority of the fossil sites in the COH WHS are not under threat from either changes in surface water or groundwater levels and/or changes in surface water or groundwater chemistry (quality), whether due to mine water or treated sewage effluent ingress, or from agriculture. The sites that are the most vulnerable have been earmarked for specific short-, medium- and long-term monitoring.

CONCLUSIONS

The understanding of the surface water and groundwater environments in the COH WHS area, also in regard to the inter-relationship between these resources, is considerably expanded by the current study. This understanding extends as much to the water chemistry aspect as it does to the water quantity aspect. The platform built from historical data, and its integration with a wide range of rigorous and defensible newly-generated and interpreted hydrologic and hydrogeologic data and information, convincingly underpins the situation assessment of the surface water and groundwater environments. This, in turn, has provided the means to objectively gauge the impact of varied and numerous threats on the water resources in the study area, and to develop a coordinated, appropriate and cost-effective water resources monitoring programme. Outcomes of the study that are considered especially significant are summarized as follows.

- The quantification of surface water flow losses, especially those dominated by a mine water character in the lower Riet Spruit valley.
- The quantification of spring discharges.
- The definition of compartments/subcompartments and corresponding groundwater resource units associated mainly with the karst formations in the study area.
- The evaluation of the geochemical interaction between acidic mine water and the dolomitic strata that form the receiving karst aquifer in the study area.
- The screening study of sediment chemistry.
- The development of semi-quantitative resource quality objectives (RQOs) to inform groundwater resource directed measures for the karst portions of the study area.
- The derivation of a fossil site risk assessment that informs the vulnerability of each recognized fossil site and associated cave system in the context of its hydrogeologic setting.

A cause for grave concern is the unprecedented abnormally high flow conditions experienced in the past two hydrological years in the Bloubank Spruit system, since this discharge is due to abnormally high mine water decant driven by copious recharge associated with above average rainfall.

RECOMMENDATIONS

The study has identified various concerns that give rise to the following general recommendations. Recommendations that address aspects specific to the water resources and ancilliary aspects such as sediment chemistry, fossil site hydrovulnerability and cave ecosystem integrity have been put forward in the body of the report. They have not been repeated here.

- The advisability of carrying out a gravimetric survey in the lower Riet Spruit valley extending from the confluence of the Tweelopie Spruit and the Riet Spruit down to the confluence of the Blougat Spruit and the Riet Spruit. The results of such a survey will indicate the measure of karst dissolution present in this important E-W corridor that hosts the N14 national road.
- The advisability of extending the hydrovulnerability assessment to other cave systems in the study area.
- The establishment of a monitoring committee comprising a core of key stakeholder groupings, e.g. national, provincial and local government, environment and tourism, agriculture.
- The hosting (by the Management Authority) of a workshop or seminar to communicate the outcomes of the study to as wide an audience of stakeholders and interested and affected parties as are interested.
- The expansion of the mine water treatment capacity in the headwaters of the Tweelopie Spruit to accommodate a decant volume of 40 ML/d, representing a 3-fold increase in the current treatment capacity.
- The establishment of additional mine water treatment facilities in the headwaters of the Tweelopie Spruit to further ‘polish’ the treated mine water that is generated by the expanded mine water treatment capacity and released into the environment.

CONTENTS

TABLES

Page

FIGURES

Page

PLATES

Page

ANNEXURES

APPENDED SUPPLEMENTARY REPORTS (p. 275 onwards)

Unnumbered plate.
View of the 130 L/s Nash Spring in the John Nash Nature Reserve.
(Photo: Phil Hobbs)

SYMBOLS, ACRONYMS AND ABBREVIATIONS

~	approximately
≡	equivalent
≥	greater than or equal to
>	greater than
≤	less than or equal to
»	much greater than
±	plus-minus
δ	delta (notation)
Δ	change in
µg/g	microgram(s) per gram
%	per cent (parts per hundred)
‰	per mil (parts per thousand)
%ile	percentile
°C	degree(s) Centigrade
°E	degree(s) East (longitude)
°S	degree(s) South (latitude)
^{2}H	deuterium
^{3}H	tritium
^{18}O	oxygen-18
a_h	hydrological year
A.	Afrikaans
ABA	acid base accounting
A.H.	Agricultural Holdings
a.k.a.	also known as
Al	aluminium
AMD	acid mine drainage/decant/discharge
amsl	above mean sea level
ARC	Agricultural Research Council
As	arsenic
B	boron
Ba	barium
bc	below collar
BE	Built Environment (business unit of the CSIR)
bgl	below ground level
Bq/g	Becquerel(s) per gram
Bq/L	Becquerel(s) per litre
bs	below surface
BSR	bacterial sulphate reduction
C	concentration
c/100 mL	count(s) per 100 millilitres
ca.	*circa* (about)
Ca	calcium
Cd	cadmium
CDSM	Chief Directorate: Surveys & Mapping (in the Department of Land Affairs)
CGS	Council for Geoscience
Cl	chloride
cm	centimetre(s)
CN	cyanide
Co	cobalt
COD	chemical oxygen demand
COH WHS	Cradle of Humankind World Heritage Site
CoV	coefficient of variation
Cr	chromium
CROSA	Cave Research Organisation of South Africa

CSIR	Council for Scientific and Industrial Research
CTR	corrosion tendency ratio
Cu	copper
dd.ddddd	degrees latitude/longitude expressed to the 5th decimal
DEA	Department of Environmental Affairs (formerly Department of Environmental Affairs and Tourism; DEAT)
DLA	Department of Land Affairs
dm	decimetre
DMR	Department of Mineral Resources (formerly Department of Minerals and Energy; DME)
DMS	dissolved mineral salts
DO	dissolved oxygen
DPLG	Department of Development, Planning & Local Government
D:RQS	Directorate: Resource Quality Services (within DWA)
DWA	Department of Water Affairs (formerly Department of Water Affairs & Forestry; DWAF)
DWEA	Department of Water and Environmental Affairs
EB	electrical balance
EC	electrical conductivity
E. coli	*Escherichia coli* bacteria
EDC	endocrine disrupting chemical
Eh	redox potential
e.g.	*exempli gratia* (for example)
EI&S	ecological importance and sensitivity
EMF	environmental management framework
EMS	environmental management system
EoP	end-of-pipe
EPA	Environmental Protection Agency
ERWAT	East Rand Water Care Company
ESE	east-south-east
ET	evapotranspiration
EurepGAP	Euro-Retailer Produce Working Group Good Agricultural Practice
Fe	iron
FIB	faecal indicator bacteria
Fm.	Formation (geological term)
Ga	billion years
GC	gas chromatograph
GDACE	Gauteng Department of Agriculture, Conservation and the Environment
GDARD	Gauteng Department of Agriculture and Rural Development (formerly GDACE)
GIS	geographic information system
GMU	groundwater management unit
GNIP	global network of isotopes in precipitation
Gp.	Group (geological term)
GPS	global positioning system
GRDM	groundwater resource directed measures
GRU	groundwater resource unit
H	weighting value,
HCO_3	bicarbonate
ha	hectare(s)
HDS	high density sludge
H_i	hazard index
HPC	heterotrophic plate count (also known as total plate count)
I&AP	interested and affected party
IDP	integrated development plan
i.e.	*id est* (that is to say)
IMC	Inter-Ministerial Committee (on AMD)
iTLABS	iThemba LABS
IUCN	International Union for Conservation of Nature

JFA	Johan Fourie and Associates (Environmental Consultant)
JNNR	John Nash Nature Reserve
K	potassium
Ka	thousand years
kg/m^3	kilogram(s) per cubic metre
KGR	Krugersdorp Game Reserve
km^2	square kilometre
LC_x	concentration causing x% lethality
L/kg/d	litre(s) per kilogram per day
LMDC	Leadership and Management Development Centre (Nedbank's Olwazini Estate)
L/s	litre(s) per second
L/s/km	litre(s) per second per kilometre
m	metre(s)
m^2/d	square metre(s) per day
$m^3/km^2/a$	cubic metre(s) per square kilometre per annum ≡ mm/Ka
m^3/s	cubic metre(s) per second (or cumec)
MA	Management Authority
Ma	million years
MAP	mean annual precipitation
MAPE	mean annual potential evaporation
MAR	mean annual runoff
MAT	mean annual temperature
max.	maximum
MCLM	Mogale City Local Municipality
MDB	Municipal Demarcation Board
MEC	Member of the Executive Council
med.	median
MG	Mogale Gold (operating in conjunction with Mintails SA)
Mg	magnesium
mg/kg	milligram(s) per kilogram
mg/L	milligram(s) per litre
mg/s	milligram(s) per second [1 mg/s ≡ 0.000084 t/d]
min.	minimum
mL	millilitre(s)
ML	megalitre(s)
ML/d	megalitre(s) per day
mm/a	millimetre(s) per annum
mm/Ka	millimetre(s) per thousand years
mm/yyyy	month/year (e.g. 01/2010)
Mm^3/a	million cubic metre(s) per annum
Mm^3/m	million cubic metre(s) per month
Mn	manganese
MNR	Motsetse Nature Reserve
Mo	molybdenum
MP	management plan
mS/m	milliSiemens per metre
MSM	monitoring system manual
mV	milliVolt(s)
n	count (of sample population)
n.a.	not analysed
Na	sodium
NAEHMP	National Aquatic Ecosystem Health Monitoring Programme
NE	north-east
NFEPA	National Freshwater Ecosystem Priority Areas
NH_3	ammonia nitrogen
NH_4	ammonium nitrogen

Ni	nickel
n.m.	not measured
No./no.	number
NO_2	nitrite nitrogen
NO_3	nitrate nitrogen
NOE	Nedbank Olwazini Estate
NRE	Natural Resources & the Environment (business unit of the CSIR)
n.s.	not specified
NTU	nephelometric turbidity unit(s)
O-PO_4	ortho-phoshate
Pb	lead
PO_4	phosphate
p.	page
pp.	pages
PSC	Project Steering Committee
PSP	Professional Service Provider
Ptn.	Portion
Q	flow or discharge
Q^n	ranking factor
R.	river
R^f	reduction factor
RET	riparian evapotranspiration
RHP	river health programme
RI_i	risk intensity index,
RQO	resource quality objective(s)
RU	Rand Uranium (formerly Harmony Gold Mining Company)
S.	spruit
SABS	South African Bureau of Standards
SAC	Satellite Applications Centre
SAKWG	South African Karst Working Group
SANS	South African National Standard
SANAS	South African National Accreditation System
SANBI	South African National Biodiversity Institute
SANParks	South African National Parks
SAR	sodium adsorption ratio (a calculated chemical parameter)
SASS	South African Scoring System
SAWS	South African Weather Service
Sbgp.	Subgroup (geological term)
SD	standard deviation
SDF	spatial development framework
SDM	synoptic discharge measurement
Se	selenium
SEM	scanning electron microscopy
Si	silicon
SI_c	saturation index, calcite
SI_d	saturation index, dolomite
SMOW	standard mean ocean water
SoE	state of the environment
SO_4	sulphate
Spgp.	Supergroup (geological term)
Sr	strontium
SRB	sulphate reducing bacteria
SRK	Steffen, Robertson and Kirsten (Consulting Engineers and Scientists)
SS	suspended solids
StatsSA	Statistics South Africa
SW	south-west

t	ton(s)
T	transmissivity
t/a	ton(s) per annum
t/d	ton(s) per day
t/m	ton(s) per month
t/ML	ton(s) per megalitre
T. Alk.	total alkalinity (as $CaCO_3$)
TCLP	toxicity characteristic leaching procedure
TDS	total dissolved salts
ToC	Table of Contents
TON	threshold odour number
ToR	Terms of Reference
TR_i	total risk index
TU	tritium unit(s) [1 TU = 1 tritium in 10^{18} hydrogen atoms]
Turb.	turbidity
TWQR	target water quality range
U	uranium
UNESCO	United Nations Educational, Scientific and Cultural Organisation
US	United States (of America)
V	vanadium
V_i	vulnerability index
VUKA	vulnerability mapping in karst terrains
WARMS	water authorisation and registration management system (a DWA system)
WBTWG	Western Basin Technical Working Group
WGC	Water Geosciences Consulting (now Metago Water Geosciences (Pty) Ltd)
WGS84	World Geodetic System 1984 (reference ellipsoid used in the Hartebeesthoek94 Datum)
WMA	water management area
WRC	Water Research Commission
WRDM	West Rand District Municipality
WSoG	Wits School of Geosciences
WWTW	wastewater treatment works
XRD	X-ray diffraction
XRF	X-ray fluorescence
Zn	zinc

INDEX TO SECTION AUTHORSHIPS

Section & Title	Author(s)	Position/Discipline & Affiliation
1 Introduction and Background	Hobbs, P.	Senior Hydrogeologist [CSIR]
2 Description of the Physical Environment	Hobbs, P.	Senior Hydrogeologist [CSIR]
3 Status Quo of Water Resource Monitoring	Hobbs, P.	Senior Hydrogeologist [CSIR]
4 Physical Hydrology	Hobbs, P.	Senior Hydrogeologist [CSIR]
5 Chemical Hydrology	Hobbs, P.	Senior Hydrogeologist [CSIR]
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8 Physical Hydrogeology	Hobbs, P.	Senior Hydrogeologist [CSIR]
9 Chemical Hydrogeology	Hobbs, P.	Senior Hydrogeologist [CSIR]
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	Van Tonder, D.	Senior Scientist [CGS]
	Hobbs, P.	Senior Hydrogeologist [CSIR]
11 Resource Quality Objectives	Hobbs, P.	Senior Hydrogeologist [CSIR]
12 State of the Environment Assessment	Hobbs, P.	Senior Hydrogeologist [CSIR]
13 Groundwater Resource Risk Assessment	Leyland, R.	Research Scientist [CSIR]
	Hobbs, P.	Senior Hydrogeologist [CSIR]
14 Fossil Site Hydrovulnerability Assessment	Hobbs, P.	Senior Hydrogeologist [CSIR]
15 Conclusions	Hobbs, P.	Senior Hydrogeologist [CSIR]
16 Recommendations	Hobbs, P.	Senior Hydrogeologist [CSIR]

1 INTRODUCTION AND BACKGROUND

1.1 Legal Framework

The UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage (1971), ratified by South Africa in 1997 and incorporated into South African law in terms of the World Heritage Convention Act (Act No. 49, 1999), in 1999 inscribed the fossil hominid sites of Sterkfontein, Swartkrans, Kromdraai and environs (known as the Cradle of Humankind) for protection in terms of their 'collective' cultural heritage (Strydom, 2009). The management of a protected area is undertaken by a management authority (MA) assigned such responsibility at either a national or a provincial level. The MA of the Cradle of Humankind World Heritage Site (COH WHS) and Dinokeng within the Department of Economic Development of the Gauteng Provincial Government, has this responsibility for the COH WHS. The COH WHS is among some 50 karst sites worldwide that have been inscribed (Hamilton-Smith, 2006), many of these for other values (e.g. cultural) than purely their karst landforms.

The successful execution of administrative responsibilities is not sufficient to ensure that desired results in terms of environmental management outcomes will be achieved. Successful achievement of environmental objectives such as appropriate water quality and adequate biodiversity require specific interventions. This highlights the importance of a soundly designed and executed monitoring programme to establish the current situation, trends of change, likely source(s) of undesirable constituents, etc. Knowledge of these forms the basis of sound management options that must be implemented to demonstrate responsible and effective management performance on the part of a management authority.

1.2 Aims and Objectives

In light of the above, the Management Authority (MA) of the COH WHS commissioned the consortium comprising the Council for Scientific and Industrial Research (CSIR), the Council for Geoscience (CGS), iThemba LABS (iTLABS) and individual sub-consultants Mr A Jamison and Ms D Hardwick, to assist with the establishment of a monitoring system for the COH WHS. The MA views this project as Phase 1 of a longer term project of which Phase 2 represents the development of a numerical (mathematical) model by a PSP still to be appointed.

The implementation of an appropriate integrated hydrologic and hydrogeologic monitoring programme is considered crucial to the successful management of water resources and the impact on these resources in the COH WHS area. An effective routine monitoring programme will be able to measure and demonstrate the success or failure of management efforts by the MA to protect the aquatic environment in the COH WHS. Such protection is not only required for the preservation of the karst features and their palaeo-anthropological treasures, but also for the water users who reside in the area and are dependent on local water resources (primarily groundwater) for their livelihood. Against this background, the main objectives of the project are (a) the development of an Environmental Monitoring System (EMS) focussed on the aquatic environment, and (b) the compilation of a Monitoring System Manual (MSM) that informs the EMS. These interventions, commissioned by the MA, are directed at ensuring the sustainable functioning of the karst ecohydrology of the COH WHS in the face of rapidly growing pressure from a variety of land use developments. Significantly, Ford and Williams (2007) report that karst resources are coming under increasing pressure worldwide, and have great need of sustainable management. This has no greater relevance than in a World Heritage Site.

In order to successfully achieve the study objectives, however, it is required to establish the situation regarding the interdependent hydrologic and hydrogeologic environments in the COH WHS study area. This entails developing a sound conceptual model of the groundwater regime not only in terms of flow directions, boundary conditions and water quality aspects based on historical information, long-term monitoring data and new data and information, but also in regard to the groundwater interaction with surface water resources. As indicated by Burke and Moench (2000), meeting this objective will satisfy a further secondary objective of the project, namely establishing a sound basis and appropriate framework for the later development of a numerical (mathematical) model of the study area in accordance with section 3, "Aim", of the enquiry/tender Terms of Reference (ToR) document BIQ005/2008.

The situation assessment set out in this document aims to establish the extent, detail and veracity of existing available hydrologic, geologic and hydrogeologic information for the study area with the aim of defining gaps in these components of the data environment. For example, the EMF/MP Status Quo Report (Beater and Kilian, 2009) identifies information in regard to sources, extent and affect of acid mine drainage (AMD) on the COH WHS as being deficient. The paucity of scientific information in this regard has led to the publication of unsubstantiated (and often alarmist) reports regarding possible negative impacts on the karst environment (e.g. Béga, 2008a; 2008b; 2010; Seccombe, 2008; Masondo, 2010; Groenewald, 2010). Apart from remedying this situation, better informing such aspects forms the basis and framework within which the surface water and groundwater monitoring system is developed.

1.3 Definition of the Study Area

The study area defined in Figure 1 represents the most appropriate demarcation based primarily on the harmonisation of the COH WHS boundary (as promulgated) with aspects such as drainage basin footprints, the distribution of geological strata with emphasis on the vulnerable dolomitic formations, and the location of known threats associated with mining, industrial and urban land uses. For example, the measure of congruence between the study area boundary and the quaternary catchments is evident in Figure 1. Similarly, the inclusion of the mining area in the extreme southern part of the study area recognizes the importance of this activity not only in terms of the attendant threat from acid mine drainage (AMD), but also the comparatively large amount of data and information related to this activity that already exists for this area. A third example is the inclusion of a portion of the upper Crocodile River in quaternary catchment A21E as far upstream as Muldersdrift in order to consider the impact of the Driefontein Wastewater Treatment Works (WWTW), together with that of the Percy Stewart WWTW located in the upper reaches of quaternary catchment A21D (see Figure 1 for the location of these facilities). The study area as demarcated in Figure 1 covers an area of ~64 900 ha, compared to the ~52 000 ha of the COH WHS.

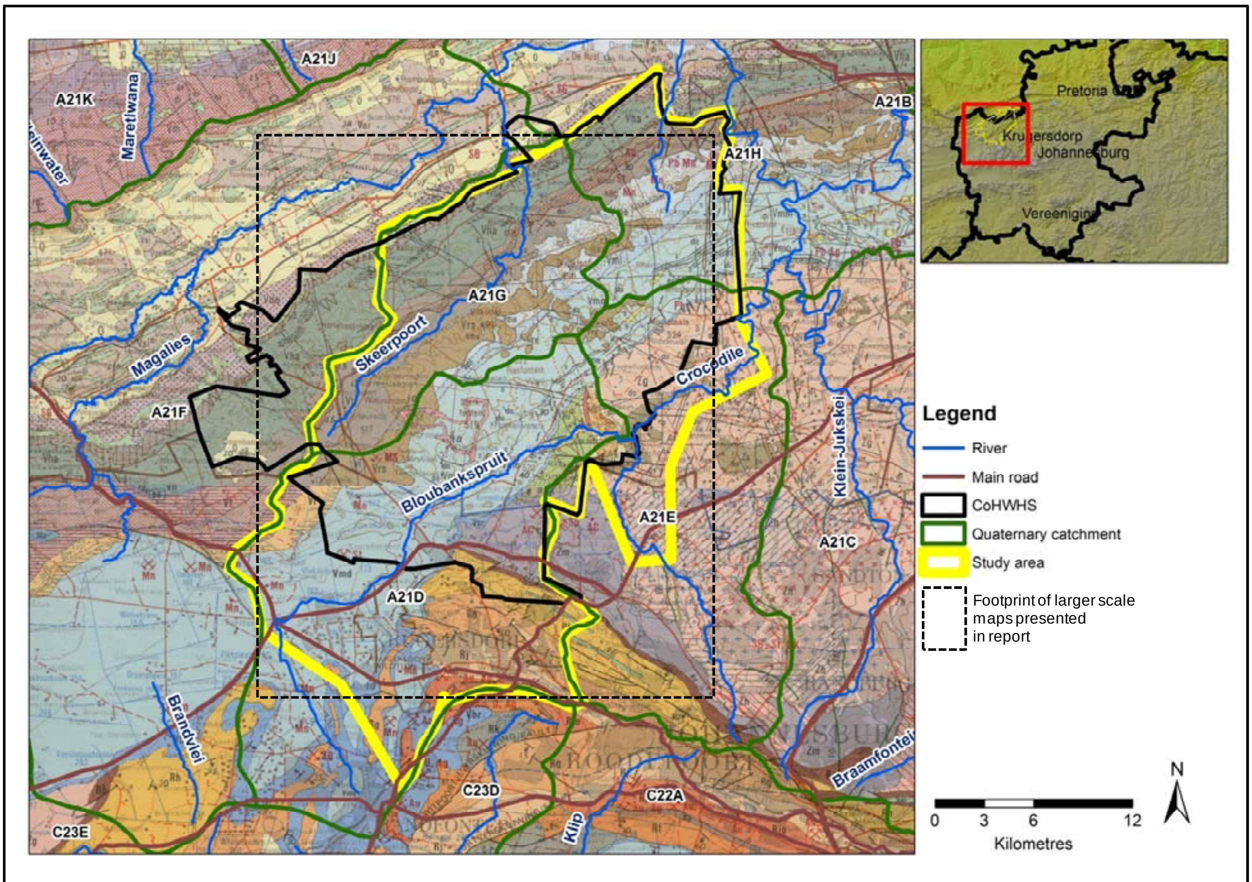

Figure 1. Definition of the study area in regard to the geology, surface water drainages and quaternary catchments in the COH WHS area and environs.

1.4 Rationale

The International Union for Conservation of Nature and Natural Resources (IUCN) publication by Watson et al. (1997) lists as some of the reasons for the protection of karst landscapes their provision of the following 'goods and services':

- habitat for endangered species of flora and fauna;
- sites containing rare minerals or unique landforms;
- **important sites for the study of** geology, geomorphology, **palaeontology** and other disciplines;
- **culturally important sites**, both historic and prehistoric;
- spiritual or religious features;
- specialized agriculture and industries;
- 'windows' into understanding regional hydrology (*and karst hydrogeology*[1]);
- sources of economically important materials, especially groundwater;
- tourism and its associated economic benefits; and
- purely recreational areas, both scenic and challenging.

Whilst the COH WHS was inscribed for its cultural heritage represented by the reasons shown as **bold** text in the above list, it is evident that a number of the other reasons (shown as underlined text) apply equally well to the COH WHS. The earlier activities of the IUCN-SA[2] Karst Working Group (Fourie, 2005) are recognized in the following text box, and in the WRC/IUCN/SAKWG (2010) publication titled "*The karst system of the Cradle of Humankind World Heritage Site*".

> *THE IUCN-SA KARST WORKING GROUP*
>
> *In May 2004, the South African country office of IUCN-The World Conservation Union, in collaboration with the Gauteng Department of Agricultutre, Conservation and Environment (GDACE) and the Cave Research Organisation of South Africa (CROSA), established a Karst Working Group, made up of more than 30 individuals from diverse backgrounds and disciplines, including national, provincial and local government, industry, four national universities and a number of voluntary caving organisations.*
>
> *Their task is to develop a holistic monitoring and management system for karst systems in South Africa, and they have chosen the Cradle of Humankind World Heritage Site as a pilot study, in part to support the Cradle in meeting its reporting obligations to the World Heritage Authority. One of the group's main concerns is the threat of water pollution in the Cradle area, and the effect of such pollution on the karst ecosystems.*
>
> *The group is supported by the GDACE, the Water Research Commission and the IUCN World Commission on Protected Areas Cave and Karst Taskforce. It is also establishing partnerships with research institutions in Europe, as well as international NGOs Flora & Fauna International and Earthwatch.*
>
> From Fourie (2005).

In regard to land and water resources issues, Vesper (2008) identifies the following characteristics unique to karst systems that require focussed study:

- close connections between surface and subsurface processes render karst systems highly vulnerable to impacts from surface activities;
- spatial heterogeneity hinders the ability to easily monitor and assess water quality and quantity;
- rates of physical processes are highly variable;
- subsidence may occur at an almost imperceptible rate or be nearly instantaneous,
- contaminants may be rapidly flushed through the system or trapped indefinitely; and
- water flow at springs may be consistent through time or change rapidly in response to storm events.

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[1] Added by PSP.
[2] South African country office of the IUCN-The World Conservation Union.

It is within this broader framework and against this background that the project seeks to have a material impact. Success in this regard will be measured by various factors, including:

- the level of acceptance of the outcome and findings by the scientific community;
- the level of acceptance of the outcome and findings by the stakeholder community;
- the realisation of a coordinated, appropriate, cost-effective and mutually beneficial water resources monitoring programme; and
- recognition (also internationally) of responsible and effective management demonstrated by the COH WHS Management Authority.

It is considered pertinent to close this section with the reminder that water resource protection is mandated in terms of s. 19 of the NWA (Act No. 36, 1998), "*Prevention and remedying effects of pollution*.", which requires of a landowner, person in control of land or person occupying or using land to take all reasonable measures to prevent pollution of a water resource from occurring, continuing or recurring. It is perhaps even more pertinent to recognize the need to address the popular perception of a large-scale "tragedy of the commons" as described by Hardin (1968) playing itself out in regard to water resource pollution and consequential loss of fossil site integrity in the COH WHS and, ultimately, loss of World Heritage Site status.

2 DESCRIPTION OF THE PHYSICAL ENVIRONMENT

2.1 Morphology and Drainage

The surface water drainage characteristics of the study area, including drainage pattern and mean annual runoff (MAR), are discussed in greater detail in section 4.1. The following discussion of this aspect therefore merely provides a synoptic overview.

The watershed that marks the continental divide between the Vaal River system to the south and the Limpopo River system to the north, also occupies the highest elevation (~1720 m amsl) in the study area. Extending to the north of this divide, the study area itself encompasses a diverse landscape that includes undulating terrain with low to moderate relief along a SW-NE strike roughly concordant with the main drainages. This terrain is flanked to the south-east by prominent ridges incised at right angles by mainly ephemeral tributaries, and to the north-west by sub-parallel ridges and valleys. The flanking landscapes mark a transition in the geology across the study area. At an elevation of 1664 m amsl, the peak of Spioenkop on the farm Danielsrust 518JQ represents the highest point in the study area, followed by the 1626 m amsl of Swartkop peak on the farm Zwartkop 525JQ near the eastern margin of the study area. The lowest elevation (~1200 m amsl) occurs at Broederstroom along the north-eastern margin of the study area. The above description fits that by Kruger (1983), who characterizes the terrain morphology as undulating hills and lowlands with relief in the range 130 to 450 m, a drainage density of 0.5 to 2 km/km^2, a stream frequency of 0 to 6 per km^2, and 20 to 50% of the area supporting slopes of <5%.

As shown in Figure 1, the study area spans portions of five quaternary catchments, namely A21D, A21E, A21F, A21G and A21H, in the Crocodile (West) and Marico Water Management Area (WMA). The extent of these catchments within the study area is given in Table 1. This shows that basins A21D (the Bloubank[3] Spruit system) and A21G (Skeerpoort River) together cover ~70% of the study area, followed in roughly equal proportions (~15%) by basins A21E (upper Crocodile River) and A21H (lower Crocodile River), with basin A21F (Magalies River) forming the miniscule balance (0.2%).

Table 1. Geographic definition of quaternary drainage basins spanned by the study area.

Quaternary Basin	Main Drainage	Total Area (km^2)	Proportion of Catchment Area in Study Area (km^2)	(%)
A21D	Bloubank Spruit system	372	303	46.7
A21E	Crocodile River (upper)	290	100	15.4
A21F	Magalies River	1001	1	0.2
A21G	Skeerpoort River	160	156	24.0
A21H	Crocodile River (lower)	514	89	13.7
	TOTAL	2337	649	100

2.2 Climate and Rainfall

The study area falls within the warm temperate summer rainfall region that characterizes the typical Highveld climate of the north-central interior. The following synoptic information is sourced from Schulze et al. (1997). The mean annual temperature (MAT) falls in the range 16 to 18°C, with daily mean temperatures in the range 20 to 22°C in summer (December/January) and 10 to 12°C in winter (July). The daily mean relative humidity falls in the range 58 to 60% in winter (July) and 66 to 68% in summer (December/January), with daily minima falling in the ranges 32 to 34% and 46 to 48% for these seasons respectively. The A-pan equivalent mean annual potential evaporation (MAPE) falls in the range 2200 to 2400 mm. The long-term A-pan evaporation recorded at OR Tambo International airport located at 26.13°S and 28.29°E, a distance of ~55 km ESE of the study area, is 2160 mm/a. This study has therefore accepted the lower bound of 2200 mm/a as representative of the A-pan evaporation value for the study area.

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[3] The spelling 'Bloubank' conforms to that used on the most recently published 1:50 000 scale topocadastral map 2527DD Broederstroom (5th ed., 2001), and not to that of 'Blaauwbank' used on earlier maps and in other reports (e.g. Holland et al., 2009; SRK, 2009).

As the principal driver of groundwater recharge, rainfall is an integral component of the hydrological cycle, rendering knowledge of its magnitude and distribution a key aspect of a study such as this. The distribution of selected rainfall gauging stations in the study area and surrounds is shown in Figure 2. The selected stations represent a good geographic distribution, and are operated by various entities identified as follows:

- the South African Weather Service (SAWS), located at police stations and municipal offices;
- the Rand Uranium mining house, located at various sites on the mine property;
- the Mogale City Local Municipality (MCLM), located at the Percy Stewart WWTW operated by this authority; and
- the Department of Water Affairs (DWA), located at Sterkfontein Caves.

An automated weather station established at the Sterkfontein Caves by the Gauteng Department of Agriculture and Rural Development (GDARD) has suffered a lack of maintenance severely compromising its functioning (E. van Wyk, personal communication). The installation has been returned to working order by the DWA, and will be operated and maintained by this authority in conjunction with that of its own rainfall gauging station on these premises (E. van Wyk, personal communication).

A daily precipitation record is maintained in most of the above-listed instances, the DWA station located at the Sterkfontein Caves (station SFC in Table 2) representing a cumulative (totalling) station. The length of record and other information associated with each station is given in Table 2. This shows that rainfall monitoring by the mining house Rand Uranium (RU) in the locus of (mine water) decant is comparatively recent. These circumstances reflect the importance that rainfall and associated recharge have on the rate of water ingress into, and the consequent rebound of water levels in the mine void, especially since the advent of mine water decant in late-August 2002.

Table 2. Rainfall monitoring stations in the study area and surrounds.

Station	Station Name	Operator	Coordinates(1)		Elevation (m amsl)	Start Date (mm/yyyy)
			Latitude	Longitude		
0475338	Randfontein	SAWS	26.13°S	27.70°E	1710	12/1954(2)
0475456	Krugersdorp Kroningspark		26.10°S	27.77°E	1699	07/1904
0475605(4)	Wits Botanical Gardens		26.08°S	27.85°E	—	04/1988
0512082	Hekpoort Nooitgedacht		25.87°S	27.55°E	1463	01/1972(3)
0512090	Magaliesburg Police Station		26.00°S	27.55°E	1480	01/1969
0512783(4)	Pelindaba		25.80°S	27.92°E	—	01/1965
PS(4)	Percy Stewart WWTW	MCLM	26.08°S	27.73°E	1590	01/2000
BRI(4)	Black Reef Incline	RU	26.11566°S	27.72319°E	1662	10/2004
HDS(4)	HDS Plant		26.13384°S	27.71579°E	1714	10/2004
SFC(4)	Sterkfontein Caves	DWA	26.01566°S	27.73413°E	1480	10/2004

(1) Reported as decimal degrees in Hartebeesthoek94 Datum, WGS84 ellipsoid.
(2) Closed 03/2009.
(3) Closed 11/2009. Not located within the footprint of Figure 2.
(4) Not used in WR 2005 (Middleton and Bailey, 2008a; 2008b)

The long-term mean annual precipitation (MAP) for a large part of the study area falls in the range 600 to 700 mm, with a smaller portion extending across the central south-western part falling in the range 700 to 800 mm (Middleton and Bailey, 2008a). These authors also report an A-pan evaporation rate for the study area in the range 2200 to 2600 mm/a.

The monthly precipitation record of the RU rainfall stations for the period October 2008 to May 2010 (Figure 3) reveals that the excessively wet 2009-'10 summer also extended into April 2010. The total rainfall in this period amounted to 809 and 734 mm for the HDS and BRI stations, respectively. Further inspection of the RU rainfall data collected in the past 18 months reflects the correlation shown in Figure 4. This indicates that the BRI station to the north of the continental divide on which the HDS plant is located, experiences a monthly precipitation that is generally ~14% less than that measured at the latter. The distance between these two stations is ~2200 m.

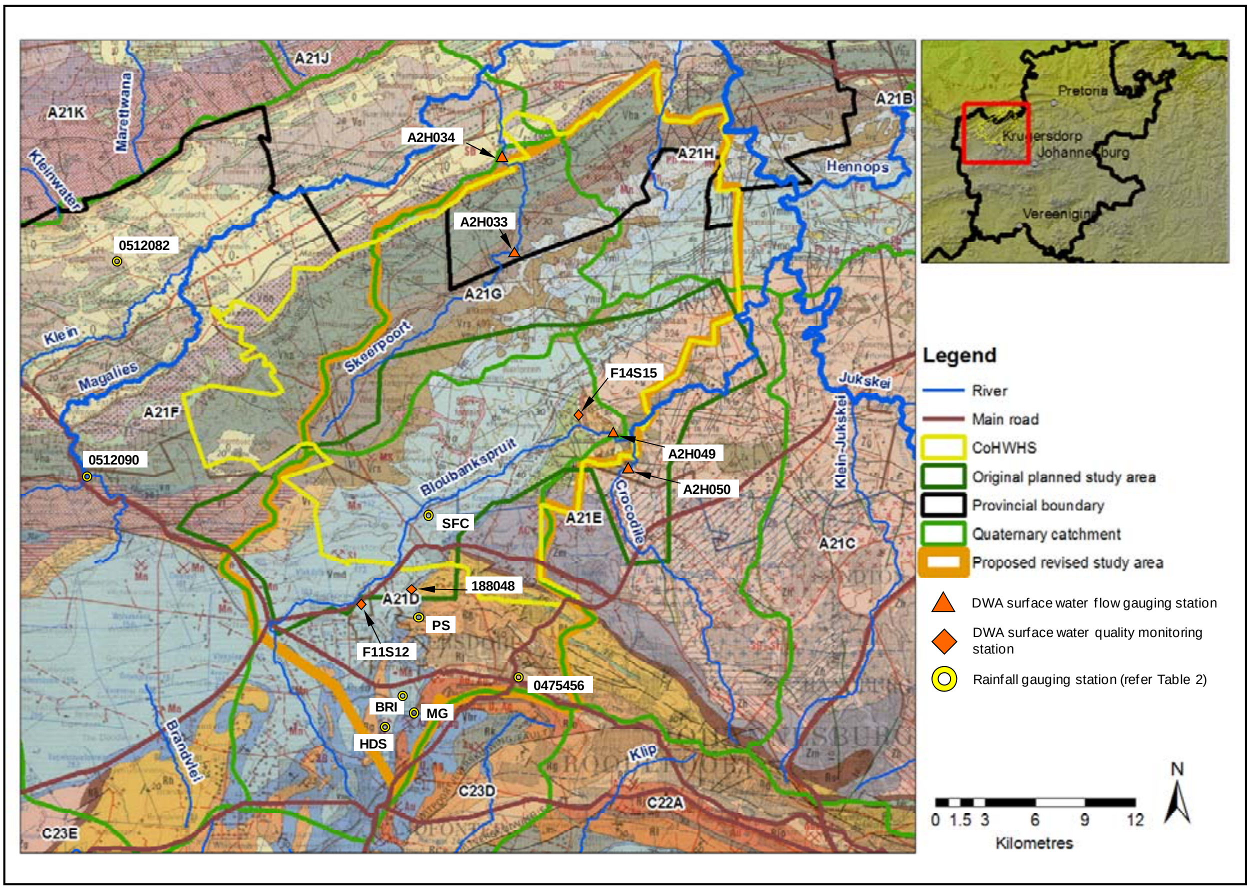

Figure 2. Locality map of rainfall, surface water flow and quality gauging stations.

The preceding discussion reveals that the mean annual potential evaporation in the study area exceeds the MAP by a factor of three. However, the drainages in the COH WHS are not characterized by large expanses of open water that promote evaporation losses. The dense arboreal vegetation along substantial reaches of the drainage channels provides a canopy that further inhibits evaporation.

Evapotranspiration (ET) has been identified in various studies (e.g. Hail and Prudic, 1998; Harlow et al., 2005; Martini and Kavalieris, 1976; Prudic et al., 1995; Schaefer et al., 2005) as representing the most important water 'loss' component of the water resources budget in karst environments. Rutledge and Mesko (1996) draw attention to the particular contribution of riparian evapotranspiration (RET) in this regard. Under circumstances where the depth to groundwater rest level is generally shallowest in proximity to surface drainages, it is inviting to speculate that RET might also represent the most significant water loss component in the hydro(geo)logic budget of the study area.

Bredenkamp and Van Staden (2009) report that the riparian tree zone mostly occurs on both banks of rivers and spruits (streams). Further, that this zone is typically 10 to 20 m wide and the vegetation is dense and almost forest-like, dominated by indigenous trees and very dense forest-like bush. Krige (2009) reports a calculated (R)ET value of 5 ML/d based on a total stream length of ~27.5 km on average 40 m wide and subject to an ET rate of 1674 mm/a (equal to 0.775 of the long-term A-pan equivalent of 2160 mm/a recorded at OR Tambo International Airport). Any postulation regarding the significance of RET in the COH WHS area must, however, be tempered by the observed depth to groundwater level in and along stream reaches as discussed in section 8.3.

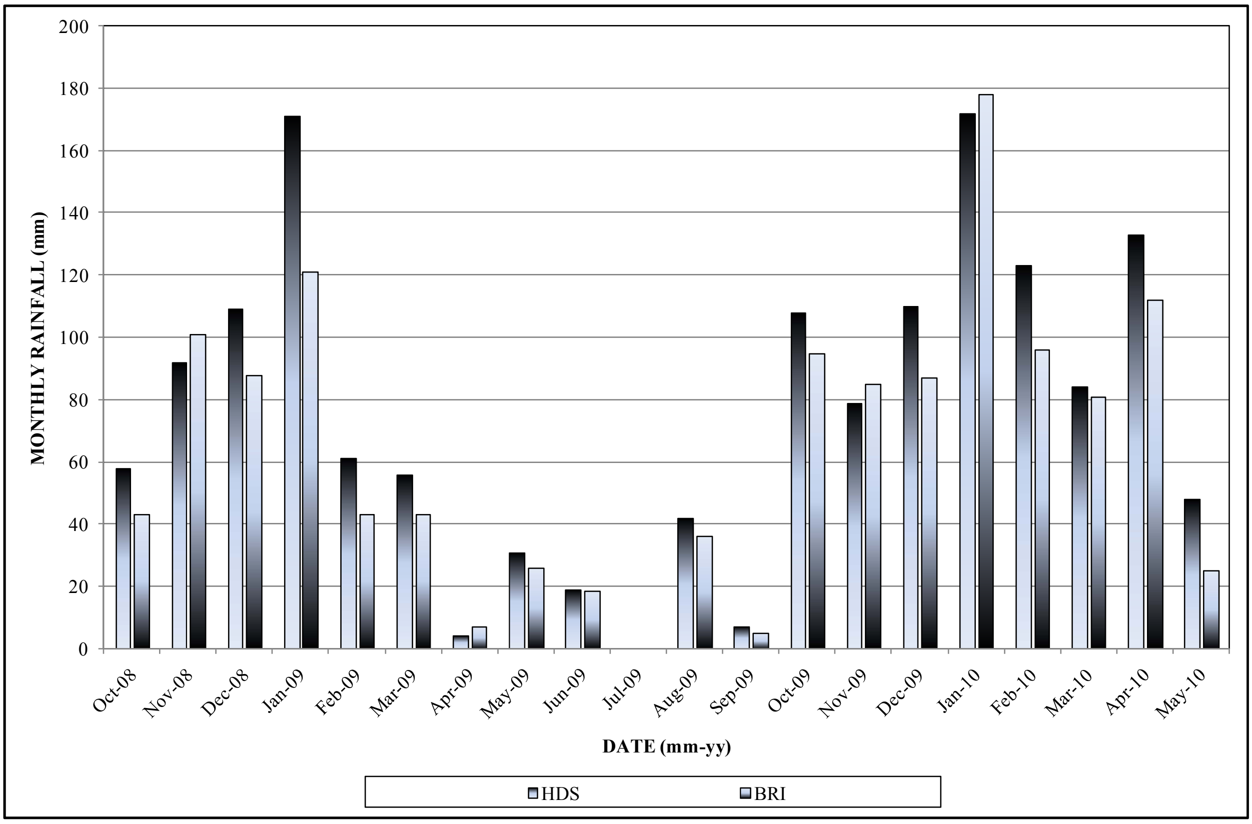

Figure 3. Monthly precipitation recorded at the Rand Uranium HDS and BRI rainfall monitoring stations in the period October 2008 to May 2010.

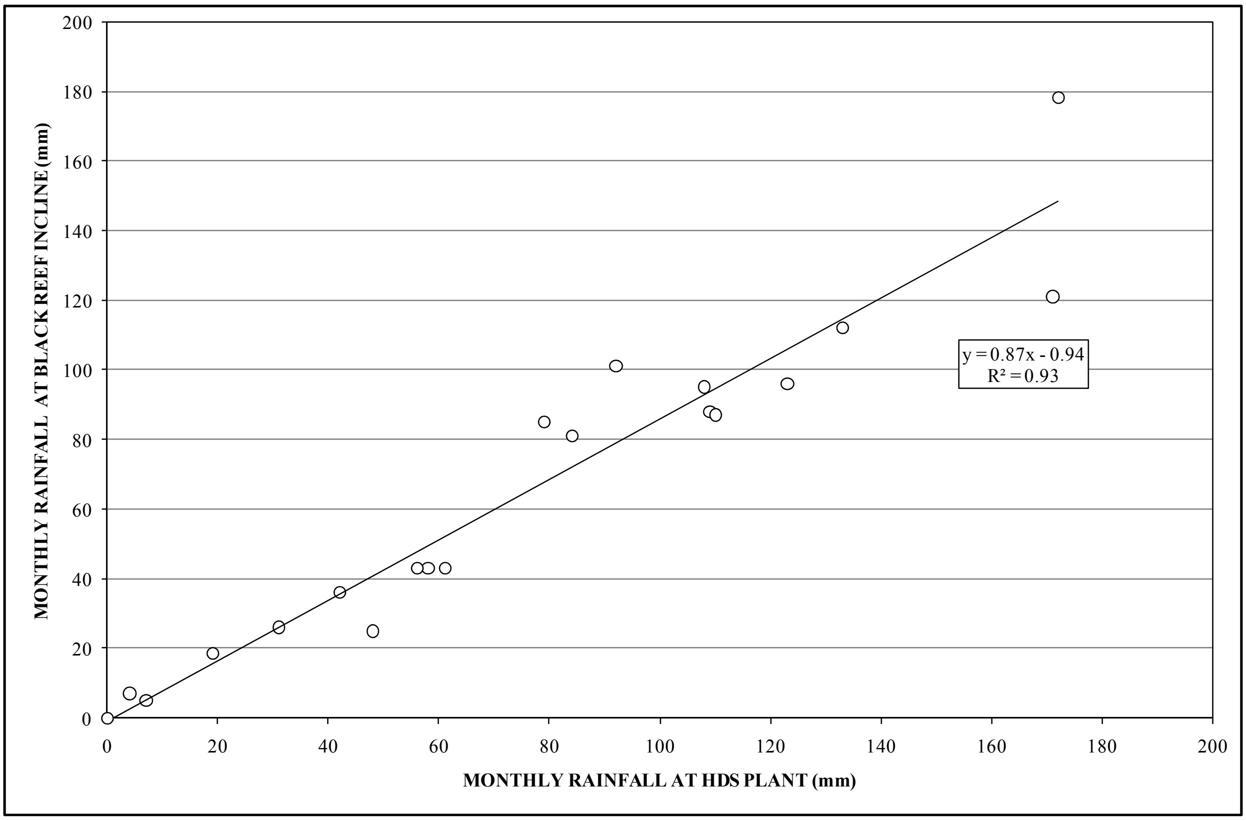

Figure 4. Correlation of monthly precipitation between the Rand Uranium HDS and BRI rainfall monitoring stations in the period October 2008 to May 2010.

2.3 Vegetation and Soils

The study area is covered by two biomes, namely the Grassland Biome and the Savannah Biome (Mucina and Rutherford, 2006). As shown in Table 3, the Grassland Biome is represented by two bioregions, and the Savanna Biome by one bioregion. Further subdivision of the bioregions recognizes the vegetation units identified in Table 3 as being present in the study area. A more comprehensive discussion of the vegetation types in the study area is provided by Bredenkamp and Van Staden (2009).

Table 3. Classification of the vegetation of the study area (after Mucina and Rutherford, 2006).

Biome	Bioregion	Vegetation Unit
Grassland (G)	Dry Highveld Grassland (Gh)	Carletonville Dolomite Grassland (Gh15)
	Mesic Highveld Grassland (Gm)	Soweto Highveld Grassland (Gm8)
		Egoli Granite Grassland (Gm10)
Savanna (SV)	Central Bushveld (SVcb)	Moot Plains Bushveld (SVcb8)
		Gold Reef Mountain Bushveld (SVcb9)
		Gauteng Shale Mountain Bushveld (SVcb10)
		Andesite Mountain Bushveld (SVcb11)

As the name implies, the Carletonville Dolomite Grassland (Gh15) vegetation unit covers the area underlain by dolomitic strata of the Malmani Subgroup (see Table 4). It therefore also covers the largest expanse of study area characterized mostly by the shallow Mispah and Glenrosa soil forms, with deeper red to yellow apedal soils of the Hutton and Clovelly forms occurring sporadically. The vegetation is characterized by species-rich grasslands forming a complex mosaic pattern with many species dominant (Mucina and Rutherford, 2006). A notable characteristic of this vegetation unit is the occupation of sheltered valleys and sinkholes by trees such as *Celtis Africana* (white stinkwood, *A.* witstinkhout), *Kiggelaria Africana* (wild peach, *A.* wildeperske) and *Leucosidea sericea* (oldwood, *A.* ouhout) that represent traces of temperate or transitional forest (Acocks, 1988).

The Soweto Highveld Grassland (Gm8) vegetation unit occurs along the southern margin of the study area underlain by quartzitic strata of the Witwatersrand Supergroup. The deep, reddish soils on flat plains are absent in the presence of outcropping bedrock. The landscape supports short to medium-high, dense, tufted grassland dominated by *Themeda triandra* (red grass, *A.* rooigras).

The Egoli Granite Grassland (Gm10) vegetation unit occurs along the south-eastern margin of the study area where it is underlain by Halfway House Granite that builds the Johannesburg Dome. The landscape supports leached, shallow, coarsely grained, sandy and nutrient-poor soils of the Glenrosa form. Grassland vegetation is dominated by *Hyparrhenia hirta* (common thatchgrass, *A.* dektamboekiegras) with some woody species on outcropping bedrock.

The Savanna Biome is represented by the Gold Reef Mountain Bushveld (SVcb9) and Andesite Mountain Bushveld (SVcb11) vegetation units that occupy very small portions along the south-eastern margin of the study area, and the Moot Plains Bushveld (SVcb8) and Gauteng Shale Mountain Bushveld (SVcb10) vegetation units found along the north-western margin. The latter two vegetation units are readily defined by their association with the mainly sedimentary strata (quartzite and shale) of the Pretoria Group that overlie the dolomitic strata (section 2.4). The soils vary from stony, colluvial, clay-loam, red-yellow freely drained forms to shallow Mispah. The low, broken ridges varying in steepness support short (3 to 6 m tall), semi-open thicket dominated by a variety of woody species including *Acacia caffra* (hook thorn, *A.* haakdoring) and *Cussonia spicata* (common cabbage tree, *A.* kiepersol).

2.4 Geology and Geophysics

The geology of the broader region is described in numerous texts, e.g. Clendenin (1989), Eriksson and Reczko (1995), Eriksson et al. (2001), Obbes (2000) and Robb and Robb (1998a). The geology of the study area is dominated by dolomitic rocks [chemical composition $CaMg(CO_3)_2$] associated with the Malmani Subgroup of the Chuniespoort Group within the Transvaal Supergroup succession of strata. The

Malmani Subgroup is subdivided into five units identified as the Oaktree Formation at the base (and therefore oldest), overlain (followed upwards) in turn by the Monte Christo, the Lyttelton, the Eccles and the Frisco Formations. In a regional context, these formations dip to the north-west at an angle of between 15° and 30°, disappearing beneath younger Pretoria Group sedimentary rocks (quartzite, sandstone and shale) along the north-western margin of the study area roughly coincident with the Skeerpoort River valley (Figure 1 and Figure 5).

The moderately rugged relief that occupies an elevation ranging between ~1400 and ~1600 m amsl between the Skeerpoort River draining the north-western portion of the study area, and the Bloubank Spruit system draining the southern and south-eastern portions (Figure 1 and Figure 5), represents the Escarpment-type karst morphology defined by Martini and Kavalieris (1976). These circumstances also reflect the degree of structural geological influence on the landscape in the project area. The much flatter terrain occupying an elevation between ~1560 and ~1660 m amsl that characterizes the Steenkoppies Compartment to the west represents the Plateau-type karst morphology of Martini and Kavalieris (1976).

The outcrop of individual karst formations is only defined north of latitude 26°S on published geological maps. Extension of this definition to the south by post-graduate students of the University of Pretoria is limited to the footprint of the COH WHS. Elsewhere south of 26°S, only the coarser lithostratigraphic subdivision represented by the Malmani Subgroup is defined as far west as longitude 27°15'E, beyond which the individual formations are again represented. Along the southern and south-eastern margin, the Malmani Subgroup strata rest on older sedimentary rocks of the Witwatersrand Supergroup and even older intrusive granitic and gneissic rocks forming the Archaean basement exemplified by the Halfway House Granite Dome. The stratigraphic relationship of the various lithologies (rock types) described above is illustrated in Table 4.

Table 4. Simplified lithostratigraphic subdivision of strata in the COH WHS area.

<table>
<tr><th>Basic Lithology(1)</th><th colspan="3">Lithostratigraphic Unit</th><th colspan="2">Era (Age)</th></tr>
<tr><td>Alluvium</td><td colspan="3">Quaternary sediments</td><td colspan="2">Late Cenozoic (<10000 yrs)</td></tr>
<tr><td>Dolerite / diabase / syenite [Jd]</td><td colspan="3">Dyke / sill intrusive structures</td><td colspan="2">early Mesozoic (150 – 190 Ma)</td></tr>
<tr><td>Andesite, basalt, subordinate shale [Vha]</td><td>Hekpoort Formation</td><td rowspan="3">Pretoria Group</td><td rowspan="5">Transvaal Supergroup</td><td rowspan="4">(~2224 Ma)
(~2430 Ma)</td><td rowspan="5">Vaalian</td></tr>
<tr><td>Ferruginous shale & quartzite, hornfels [Vt]</td><td>Timeball Hill Formation</td></tr>
<tr><td>Quartzite, shale, chert breccia [Vrs]</td><td>Rooihoogte Formation</td></tr>
<tr><td>Dolomite [Vmd]</td><td>Malmani Subgroup</td><td>Chuniespoort Group</td></tr>
<tr><td>Quartzite, shale [Vbr]</td><td colspan="2">Black Reef Formation</td><td>(~2650 Ma)</td></tr>
<tr><td>Graywacke conglomerate, volcanics [R-Vk]</td><td>Kameeldoorns Formation</td><td>Platberg Group</td><td>Ventersdorp Supergroup</td><td>(~2650 Ma)
(~2780 Ma)</td><td rowspan="5">Randian</td></tr>
<tr><td>Quartzite, conglomerate [Rjo]</td><td>Johannesburg Subgroup</td><td>Central Rand Group</td><td rowspan="4">Witwatersrand Supergroup</td><td rowspan="4">(~2780 Ma)
(~2970 Ma)</td></tr>
<tr><td>Shale, quartzite [Rj]</td><td>Jeppestown Subgroup</td><td rowspan="3">West Rand Group</td></tr>
<tr><td>Quartzite, greywacke [Rg]</td><td>Government Subgroup</td></tr>
<tr><td>Ferruginous shale, quartzite [Rh]</td><td>Hospital Hill Subgroup</td></tr>
<tr><td>Mafic & ultramafic rocks [Zm] and granite [Zg]</td><td colspan="3">Undifferentiated</td><td colspan="2">Swazian (>3100 Ma)</td></tr>
<tr><td colspan="6">(1) Lithology colours correlate broadly with those used in Figures 1 and 2.
Ma = million years.</td></tr>
</table>

The significance of dolomitic strata such as underlie so much of the COH WHS (and ~27 850 ha or ~43% of the study area) is neatly summarized by Hamilton-Smith (2006) who states that karst often has "…......

- *invaluable geological data (particularly in the cave floors);*
- *important geomorphic structures and processes;*
- *characteristic surface and often significant landscapes;*
- *important surface ecosystems and even more important subterranean ecosystems;*
- *fossils and cultural heritage (pre-historic, historic and living)"*; to which must be added
- significant quantities of fresh groundwater.

The hydrogeologic significance of the chert-rich dolomitic strata of the Monte Christo and Eccles Formations, versus that of the chert-poor strata of the Oaktree and Lyttelton Formations, bears mention. The chert-rich formations are associated with significantly greater water-bearing properties than the chert-poor formations, due mainly to preferential dissolution of the dolomite that is interlayered with the chert bands (Martini and Kavalieris, 1976). In outcrop, the insoluble chert bands are left standing proud of the adjoining dolomite horizons, as is illustrated in Plate 1. This process is enhanced in the presence of fractures and joints that intersect the rock mass and facilitate the movement of infiltrating rainwater.

Plate 1. Epikarst exposed in the form of a pinnacle ~2.5 m high in the Eccles Formation, showing the preferential dissolution of dolomite interlayered with less soluble and therefore more prominent chert bands, the slanting aspect of which also defines the overall dip of the strata ~10° to the north-west (bottom left of picture), with a partially wad-filled vertical joint ('slot') separating the pinnacle from the rock mass to the right of picture. (Photo: Phil Hobbs).

The structural complexity of the geologic environment in the study area presents a significant challenge. This challenge pertains, amongst others, to an understanding of the geologic control that structures such as faulting, folding and dolerite intrusions in the form of sills (subhorizontal intrusions) and dykes (subvertical intrusions) exercise on the hydrogeologic regime. Staff and students of the Witwatersrand University (Wits) School of Geoscience (WSoG) continue to carry out structural geologic mapping and other geo-environmental studies (including hydrogeology) in the region. It must be recognized, however, that the scope and magnitude of such work extends beyond the timeframe of this project and, as such, cannot be expected to completely inform this aspect of the geological and hydrogeological environments for the purposes of this study.

A number of geophysical surveys that help inform various aspects of the geological environment in the study area and wider surrounds have been carried out in the past. The most significant of these is considered to be the gravimetric survey carried out by the Department of Water Affairs (DWA) in the mid-1980s (Bredenkamp et al., 1986). This survey covered large segments of the eastern portion of the Steenkoppies Compartment and the western portion of the Zwartkrans Compartment, together spanning 90 km^2 at a grid interval of 100 m between measurement stations. The gravity survey was augmented with ground-based magnetic and electromagnetic surveys primarily to better define linear geological structures (mainly intrusive dolerite dykes) of possible hydrogeological significance. The magnetic surveys indicated that the dolerite intrusions exhibit a negative magnetic signature, i.e. possess a magnetic field strength that is less than that of the host rock intruded by these structures. The gravimetric data set has recently been converted to digital format (Wiegmans, personal communication) which facilitates its further application and use in a GIS environment.

More recently (*ca.* 2005), the DWA commissioned the Council for Geoscience (CGS) to carry out a regional aeromagnetic (airborne magnetic) survey including the West Rand and Far West Rand Gold Fields. The results were made available to the CSIR in 2007, and have been distributed to relevant members of the project team. The recent limited ground-based application of the magnetic, electromagnetic and resistivity tomography survey methods to identify potential subsurface conduits of acid mine drainage in the Krugersdorp Game Reserve (KGR) is reported by Coetzee et al. (2009). The CGS has also very recently (in mid-2010) carried out an airborne electromagnetic survey of the area previously covered by the aeromagnetic survey. Funded by the Department of Mineral Resources (DMR), the data generated by this survey was still being processed at the time of completion of this report. It is imperative, however, that the additional information generated by this survey be applied to further informing the geologic and hydrogeologic understanding developed in the current study.

Geophysical surveys carried out as part of this study have aimed to better define structures that inform the hydrogeology of the study area. For example, the structural setting of the Sterkfontein Caves was investigated using ground-based magnetic, electromagnetic and electrical resistivity surveys. Together with earlier geophysical data, the results have informed the optimal placement of a monitoring borehole for this site. Further, the available regional aeromagnetic data was re-evaluated to establish the presence of barrier boundaries suggested by steps in groundwater rest level. The information yielded by the various geophysical surveys is discussed and reported in greater detail in section 6.

2.5 Palaeontology, Archaeology and Ecology

The palaeontology/archaeology of the study area is intimately associated with the karst landscape and caves of the study area. Fossil sites often represent the erosional remnants of ancient cave systems and their contents (Esterhuysen, 2009) and, as such, are dynamic features that continue to evolve in response to natural (mainly geomorphological) processes and anthropogenic impacts. Whereas the natural processes such as weathering and erosion occur over extended periods of time (typically millennia), the anthropogenic impacts are often manifested in centuries or even decades. Partridge (1973) derived estimates for when the Sterkfontein and Swartkrans caves became drained of 3.26 and 2.57 Ma, respectively.

The most well known Australopithecine fossils associated with the Sterkfontein Caves site, namely the *Australopithicus africanus* species remains of ‘Little Foot’ (catalogue no. StW 573) and ‘Mrs Ples’ (catalogue no. StS 5), have been dated at 3.3 and 2.15 Ma respectively (Partridge et al., 1999). The Sterkfontein Caves site has yielded >500 hominin[4] fossils (Table 5) since the discovery of ‘Mrs. Ples’ in 1947 (Cooke, 1969). Thirteen fossil sites in the COH WHS (Figure 5) have been declared National Heritage Sites in accordance with the National Heritage Resources Act (Act No. 25 of 1999). Many fossil-bearing deposits and sites of palaeontological, archaeological, historical and cultural heritage importance (both categorized and uncategorized) are known to exist in the study area (Esterhuysen, 2009).

The COH WHS has already yielded ~35% of the total record of human evolution in Africa (McCarthy and Rubidge, 2005). The probable existence of yet undiscovered sites in the COH WHS area that may yield material of fossiliferous value is great. This is exemplified by the unveiling on 08/04/2010 of the *Australopithicus sediba* species fossils, dated at between 1.95 and 1.78 Ma, found at the recently discovered Malapa Cave system in the north-eastern part of the COH WHS area (Berger et al., 2010).

[4] Use of the term hominin after Berger (2001).

An important ecological aspect associated with the cave systems in the study area is their provision of refugia for stygobitic fauna (Tasaki, 2006). These aquatic cave-dwelling biota, typically blind amphipods, have been found in Sterkfontein Caves and two other caves (Koelenhof and Yom Tov) in the study area. All three these caves intersect the water table. It is probable, therefore, that investigation of other more remote and less accessible caves in the study area that intersect the groundwater level might yield results of ecological significance also in this regard. This might alter the situation where no 'hotspot' of subterranean biodiversity is identified on the African continent (Culver and Sket, 2000).

Whilst it is beyond the scope of this study to comment on the suitability of the current subsurface habitat(s) that support these fauna, it does provide information (e.g. water chemistry data) that, in the hands of appropriate experts, might better inform this aspect. Nevertheless, some discussion on this topic is provided in section 9.9.3. Further ecological significance is afforded the many cave features in the study area that provide a habitat for bat colonies (Durand and Peinke, 2010). The MA is as concerned for the protection of the pre-historic treasures of the COH WHS as it is for the current and future ecological sustainability of the area in support of all components of the environment, including human habitation and settlement (P. Mills, personal communication).

The hydrological and hydrogeological settings associated with the inscribed[5] fossil sites in the COH WHS are summarized in Table 5. Although some of the tabulated information (e.g. the groundwater compartment and groundwater rest level elevation information) is presented prematurely (i.e. without prior context in terms of this report), it is provided for completeness of this section of text. The observation that the geographic footprint of groundwater compartments (e.g. the Diepkloof Compartment in Table 5) spans adjacent (and hydrologically separate) surface drainage systems testifies to the hydraulic continuity that exists between surface water and groundwater systems in this karst environment.

Included in Table 5 is a synoptic description of the cave morphology associated with each of the fossil sites. This description, compiled with the assistance of Mr Peter Mills of the MA, attempts to classify the geometry/morphology of the cave system in relation to its setting in the landscape. Simplistically, a 'near-surface' morphology describes a cave system that does not extend deeper than ~5 m below surface, whereas an 'underground' morphology describes a cave system that exhibits a significant subsurface extension. The ultimate expression of the latter is intersection of the potentiometric surface (water table). Caves of this nature are classified as water table caves, whereas those that lie above the water table are classified as vadose caves (Ford and Williams, 2007).

The CGS (undated) reports that in all instances in the COH WHS, the important palaeontological finds are located within the top 10 m of the host cave system. Whilst this may be generally true, at least in the case of Sterkfontein Caves the 'Little Foot' find is located a greater depth (~25 m) below surface (Partridge et al., 2003). Given a (maximum) surface elevation of 1487 m amsl (section 8.1), this places the 'Little Foot' site at an elevation of ≥1460 m amsl, at least ~22 m above the current cave water level of ~1438 m amsl (section 8.4). These descriptions have specific relevance in section 14, where the vulnerability of each of the fossil sites (and their associated cave systems) is examined and discussed in the context of its hydrogeologic setting. The Malapa Cave system, recognized as the most recently discovered (and still to be inscribed) fossil site, understandably suffers from a relative paucity of information.

5 Registered with UNESCO for protection in terms of their cultural heritage as part of the COH WHS.

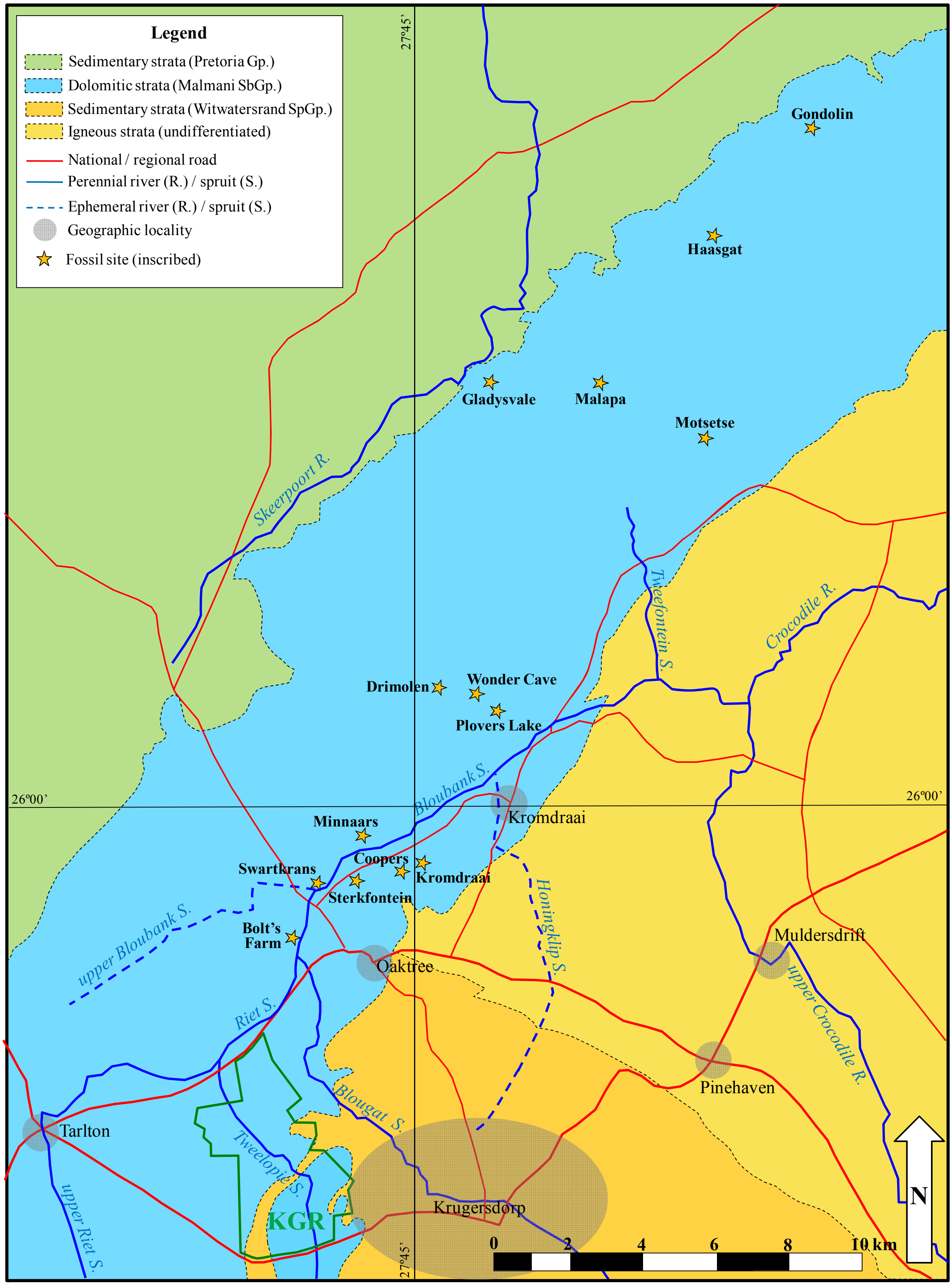

Figure 5. Locality map of the inscribed fossil sites in the study area superimposed on a simplified geological, surface water drainage and road map.

Table 5. Salient hydrologic and hydrogeologic aspects associated with the recognized fossil sites in the study area.

Fossil Site	Coordinates[(1)]	Quaternary Drainage	Main Surface Drainage	Groundwater Compartment	Synoptic Cave Morphology	SAAN[(2)] # with Brief Description and Main Significance
Bolt's Farm	26.03°S 27.72°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface & underground	SAAN–: comprises a complex of ~23 caves that include the oldest deposits in the Sterkfontein Valley on the basis of microfaunal dating
Swartkrans	26.02°S 27.72°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface & underground	SAAN–0021: well documented excavations and faunal analyses by CK Brain, hosts the largest collection of *Paranthropus robustus* fossils together with evidence for the use of fire and bone and horn tools; has yielded >500 hominin fossils
Sterkfontein	26.01566°S 27.73413°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface & underground	SAAN–0020: internationally recognized focus of the COH WHS and home of the *Australopithicus africanus* specimens Mrs. Ples (StS 5) and Little Foot (StW 573), has yielded >500 hominin fossils, and >25 000 identifiable fossils in total
Coopers	26.01°S 27.75°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface	SAAN–0023: specimens of *Paranthropus robustus* uncovered, including a face, uncovered; potential for more hominins and faunal dating
Kromdraai	26.01°S 27.75°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface	SAAN–0022: one of the earliest sites to be investigated, yielded the remains of at least three *Paranthropus robustus* individuals, and a few earlier Stone Age artefacts
Minnaars	26.01°S 27.74°E	A21D	Bloubank Spruit	Zwartkrans	Near-surface & underground	SAAN–0004: known for the excavation of an extinct jackal skull, has the potential for the discovery of hominin fossils
Plover's Lake	25.98°S 27.78°E	A21D	Bloubank Spruit	Krombank	Near-surface & underground	SAAN–0025: hosting breccias <1 Ma old and revealing no hominin remains as yet, this site retains the potential for revealing the remains of early modern humans associated with Middle Stone Age artefacts
Wonder Cave	25.97033°S 27.77143°E	A21D	Bloubank Spruit	Krombank	Underground	SAAN–0027: perhaps the foremost example of a tourist-centred (or show) cave, hosts no known hominin fossils as yet, but demonstrates the development of a recent talus cone containing semi-fossilised skeletal material
Drimolen	25.97°S 27.76°E	A21D	Bloubank Spruit	Danielsrust	Near-surface	SAAN–0024: has yielded ~75 *Paranthropus robustus* specimens and five *Homo sapiens* species, as well as bone and horn tools
Gladysvale	25.90°S 27.77°E	A21G	Skeerpoort River	Uitkomst	Near-surface & underground	SAAN–0001: also known as Uitkomst, has yielded several thousand Plio-Pleistocene mammalian remains, including some hominin (*A. africanus*) teeth
Motsetse	25.91°S 27.83°E	A21E	Crocodile River	Diepkloof	Near-surface	SAAN–0030: although not renowned for any significant discoveries, has research potential coupled with an attractive setting and accessibility for visitors
Haasgat	25.86°S 27.83°E	A21G	Skeerpoort River	Diepkloof	Near-surface	SAAN–: has yielded 83 craniodental fossils of the Cercopithecidae Family (Old World monkeys) primate *Papio angusticeps*, extinct relative of *Papio ursinus* (Chacma Baboon)
Gondolin	25.83°S 27.86°E	A21H	Crocodile River	Broederstroom	Near-surface	SAAN–0031: has yielded *Paranthropus robustus* specimens
Malapa	25.90°S 27.80°E	A21G	Skeerpoort River	Diepkloof	Near-surface & underground	SAAN–: host to *Australopithicus sediba*, the most recent significant anthropological find in the COW WHS

(1) All coordinates except for Sterkfontein Caves and Wonder Cave truncated to the 2nd decimal in order to protect these sites from unauthorized visitation.
(2) Site number reported by Berger and Brink (undated), together with a substantial amount of ancillary descriptive information including a mixed assemblage list of fauna.

3 STATUS QUO OF WATER RESOURCE MONITORING

An assessment of current water resource monitoring activities in the study area is integral to informing the development of a surface water and groundwater monitoring programme for the COH WHS. Such an assessment must also recognize the purpose of such activities. These aspects are discussed in the following sections.

3.1 Surface Water

3.1.1 Quantity

Monitoring of this parameter is typically accomplished at stream gauging stations built, operated and maintained by the DWA. Such stations are often located close to the downstream end of the main river draining a catchment. With reference to the information provided in Table 1, surface water runoff in the study area is currently gauged by the DWA at the four stations listed in Table 6 and shown in Figure 6. Each of these stations generates a **daily** discharge record expressed in the instantaneous flow unit m^3/s, also referred to as cumec. This record generates minimum, mean and maximum instantaneous discharge values for each month. The total surface water volume passing each station is also reported as Mm^3 per month (Mm^3/m), and aggregated to yield a total annual discharge expressed as Mm^3/a.

Table 6. Active surface flow gauging stations in the study.

Station	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
A2H033	Nouklip Spring (Skeerpoort River at Hartebeesthoek)	25.87483	27.78144	06/1964
A2H034	Skeerpoort River at Scheerpoort (Scheerpoort 477JQ)	25.82492	27.77181	02/1964
A2H049	Bloubank Spruit system at Zwartkop (Zwartkop 525JQ)	25.97681	27.83639	12/1971
A2H050	Crocodile River at Hoi Hoi (Driefontein 179IQ)	25.99136	27.84208	10/1973

3.1.2 Quality

Surface water quality monitoring in the study area is performed by the DWA at flow gauging stations A2H034, A2H049 and A2H050 (Table 6). The **monthly** frequency of monitoring has, on occasion in the past, been increased to bi-monthly and even weekly. Salient information obtained from the DWA database (e.g. parameters analysed, number of analyses, first and last date of individual parameter analysis) for these monitoring stations is presented in Annexures A.1, A.2 and A.3. This shows that the water quality monitoring activities date back to the late-1970s, and that the most commonly reported parameters are the following:

pH, EC, TDS, Ca, Mg, Na, K, Cl, SO_4, T.Alk., F, NH_4, NO_3+NO_2, PO_4, Si, SAR[6]

The DWA also monitors surface water quality at the localities identified in Table 7 and **Error! Reference source not found.**. These activities target the source-specific water quality impacts associated with the discharge of mine water into the Tweelopie Spruit, of treated sewage effluent from the Percy Stewart WWTW into the Blougat Spruit, and the natural discharge of the Tweefontein Spruit. The **monthly** monitoring frequency has not always been maintained in the period of historical record. The samples are analysed by the DWAs Directorate: Resource Quality Services (D:RQS) at Roodeplaat Dam for the following most commonly reported variables:

pH, EC, TDS, Ca, Mg, Na, K, Cl, SO_4, T.Alk., F, NH_4, NO_3+NO_2, PO_4, Si, Al, As, B, Ba, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, Zn, V

Salient information obtained from the DWA database (e.g. variables/parameters analysed, number of analyses, first and last date of individual variable analysis) for the 13 monitoring stations listed in Table 7 is presented in Annexures A.4 to A.16.

[6] Sodium adsorption ratio (SAR) is a calculated parameter used in assessing water quality for agricultural use.

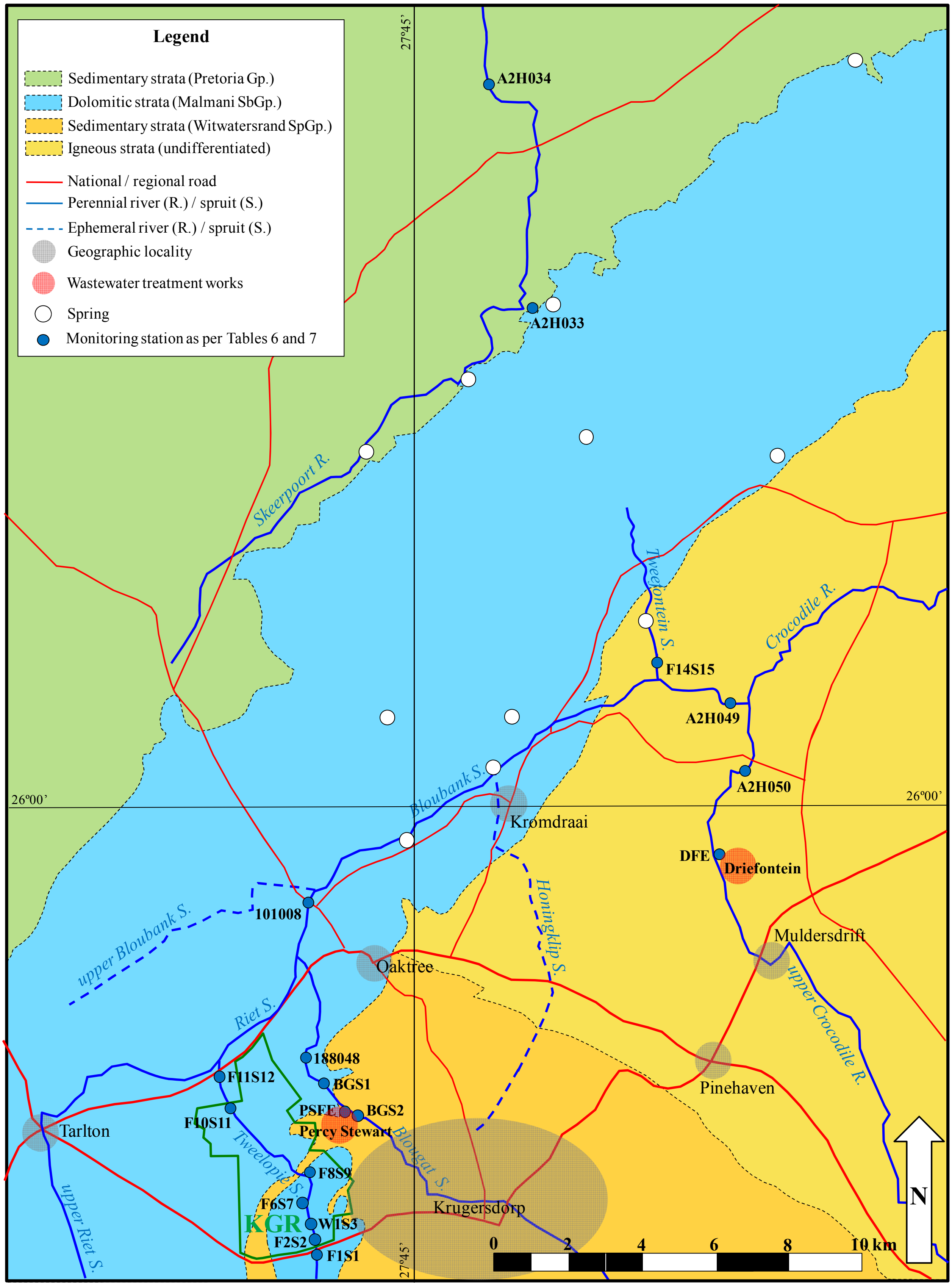

Figure 6. Location of DWA surface flow and water quality monitoring stations in the study area as per Table 6 and Table 7.

Table 7. Additional DWA surface water quality monitoring stations in the study area.

Station	Description (after DWA)	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
F1S1	Upstream of R24 at Randfontein Estates on Tweelopie Spruit	26.10752	27.72268	11/2003
F2S2	Willow tree in KGR on Tweelopie Spruit	26.10653	27.72227	11/2003
W1S3	Hippo Dam in KGR on Tweelopie Spruit	26.09917	27.72128	11/2003
BGS1	Blougat Spruit downstream of Percy Stewart WWTW	26.06555	27.72232	11/2002
BGS2	Blougat Spruit upstream of Percy Stewart WWTW	26.07138	27.72888	11/2002
PSFE	Percy Stewart WWTW final effluent discharge to Blougat Spruit	26.07483	27.72700	11/2002
F6S7	Cemetery Spring(1) (Spring 1) in KGR on Tweelopie Spruit	26.09671	27.71932	11/2003
F8S9	Lodge Spring(2) (Spring 2) at broad crest in KGR on Tweelopie Spruit	26.08527	27.70886	11/2003
F10S11	Northern fence in KGR	26.07620	27.69963	11/2003
F11S12	Tweelopie Spruit at the N14 intersection	26.06374	27.69589	11/2003
188048	Sterkfontein waterfall on tributary of Riet Spruit (Blougat Spruit downstream of Percy Stewart WWTW)	26.06417	27.72072	06/2004
F14S15	Tweefontein Spruit tributary of Bloubank Spruit on Bothasfontein 408JR	25.96478	27.81492	06/2004
DFE	Driefontein WWTW final effluent discharge to Crocodile River	26.01150	27.83530	11/2002
101008	Bloubank Spruit at R563 bridge crossing	26.02083	27.72083	06/2004

(1) There are three springs in close proximity to the cemetery in the southern portion of the KGR.
(2) Known as the Poplar Spring to the PSP, under circumstances where the name Lodge Spring is associated with station CSIR20 from the Hobbs and Cobbing (2007) study (see section 8.5.12 and Table 67).

The Mogale City Local Municipality (MCLM) currently assists the DWA with the collection of surface water samples at the localities identified in Table 8 in the south-western portion of the study area. These activities target the water quality impacts associated with the discharge of mine water into the Tweelopie Spruit. The frequency of this sampling at each station is indicated in Table 8, and the samples up until mid-2010 (pending renewal of the contract for analysis) were analysed by the ERWAT Laboratory Services for the following variables:

> pH, EC, TDS, Ca, Mg, Na, K, Cl, SO_4, T.Alk., NH_4, NO_3+NO_2, PO_4, Al, As, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb, Zn, Se, Hg, CN, COD, Suspended solids

Table 8. Surface water quality monitoring stations served by MCLM for DWA.

Station	Description	Frequency	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
Site 1	W1S3(1) (Hippo/Dry Dam) in KGR	Monthly	26.09942	27.72097	08/2002
Site 4	4x4 Track in KGR (discontinued)	Monthly	26.08673	27.71439	10/2003
Site 5	Tributary (Spring 3/Flip-se-Gat) in KGR	Bi-annual(2)	26.07620	27.69885	10/2003
Site 6	F10S11(1) (Aviary Dam) exit from KGR	Monthly	26.07433	27.69885	10/2003
F1S1(1)	Inlet (from mine area into KGR)	Monthly	26.10752	27.72268	08/2006

(1) Cross-reference Table 7. (2) Twice a year, in summer and winter.

3.2 Groundwater

3.2.1 Quantity

The DWA operates and maintains the 15 'historical' groundwater level monitoring stations listed in Table 9. The data provides a measure of the hydrostatic behaviour and response of the karst aquifer to stresses induced by recharge and abstraction. The **monthly** monitoring frequency has not always been maintained in the period of historical record. For example, station A2N0606 only reports 36 records generated in the 244 months since the start of monitoring at this facility (Table 62). Attention is also drawn to the recent closure of stations A2N0589, A2N0594, A2N0598 and A2N0606. These circumstances are discussed further in section 8.8.

Table 9. DWA groundwater level monitoring stations in the study area.

Station	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Record Period (mm/yyyy)
A2N0580	Exploration bore G36356 (Sterkfontein 173IQ)	*26.09470*	*27.66521*	05/1985 - present
A2N0582	Exploration bore G36338 (Helderblom A.H.)	26.08914	27.69633	06/1985 - present
A2N0583	Exploration bore G36337 (Beckedan A.H.)	26.07922	27.68628	06/1985 - present
A2N0584	Exploration bore G36334 (Sterkfontein 173IQ)	26.05844	27.69967	05/1985 - present
A2N0586	Exploration bore G36331 (Sterkfontein 173IQ)	26.04761	27.70903	05/1985 - present
A2N0589	Exploration bore G36320 (Zwartkrans 172IQ)	*26.01632*	*27.70823*	05/1985 - 02/2010
A2N0590	Exploration bore G36323 (Sterkfontein 173IQ)	26.02441	27.71527	05/1985 - present
A2N0592	Exploration bore G36324 (Sterkfontein 173IQ)	*26.03134*	*27.69753*	06/1985 - present
A2N0594	Exploration bore G36325 (Sterkfontein 173IQ)	26.03504	27.68205	01/1985 - 09/2008
A2N0598	Exploration bore G36332 (Sterkfontein 173IQ)	26.06581	27.66622	05/1985 - 02/2010
A2N0600	Exploration bore G37794 (Zwartkrans 172IQ)	26.01794	27.71106	04/1989 - present
A2N0602	Exploration bore G37786 (Sterkfontein 173IQ)	26.02772	27.70513	06/1987 - present
A2N0605	Exploration bore G37789 (Sterkfontein 173IQ)	*26.02875*	*27.68756*	04/1989 - present
A2N0606	Exploration bore G37792 (Sterkfontein 173IQ)	*26.03161*	*27.68227*	08/1989 - 11/2009
A2N0607	Exploration bore G37791 (Sterkfontein 173IQ)	*26.03254*	*27.68428*	10/1993 - present
Note: Italicized coordinate values denote DWA coordinates not verified by PSP.				

3.2.1.1 Quality

Groundwater quality monitoring in the study area is sparse compared to that of groundwater level monitoring. Amongst various reasons for this, not the least is the requirement to secure a ‘representative’ groundwater sample that inevitably requires the purge-pumping of a borehole prior to sample collection. The DWA employs the five groundwater level monitoring stations listed in Table 10 for groundwater quality monitoring purposes in the study area. The length of these records only dates back some 6 to 7 years, i.e. since shortly after the commencement of mine water decant. The frequency of this monitoring strives for a **bimonthly** (every two months) adjudication of the following variables:

> pH, EC, TDS, Ca, Mg, Na, K, Cl, SO_4, T.Alk., F, NH_4, NO_3+NO_2, PO_4, Si, Al, As, B, Ba, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Sr, Zn

Table 10. DWA groundwater quality monitoring stations in the study area.

Station	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
A2N0583	Exploration bore G36337 (Beckedan Agric. Holdings)	26.07922	27.68628	06/2004
A2N0584	Exploration bore G36334 (Sterkfontein 173IQ)	26.05844	27.69967	04/2003
A2N0586	Exploration bore G36331 (Sterkfontein 173IQ)	26.04761	27.70903	04/2003
A2N0590	Exploration bore G36323 (Sterkfontein 173IQ)	26.02441	27.71527	04/2003
A2N0600	Exploration bore G37794 (Zwartkrans 172IQ)	26.01794	27.71106	06/2004

The MCLM also currently assists the DWA with the collection of groundwater samples from seven sources (5 boreholes and 2 springs) in the south-western portion of the study area (Table 11).

Table 11. Groundwater quality monitoring stations served by MCLM for DWA.

Station	Description	Frequency	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
Site 2	F6S7(1) (Spring 1 at cemetery in KGR)	Bi-annual(4)	26.09799	27.71873	06/2003
Site 3	F8S9(1) (Spring 2 above Lodge in KGR)	Bi-annual(4)	26.09060	27.72050	06/2003
Ptn. 106	WBD2(2) (Krugersdorp Brickworks)	Monthly	26.06333	27.69672	08/2006
Ptn. 96/7	WBD3(2) (Môrester)	Monthly	26.05706	27.70183	08/2006
Ptn. 2/7/Rem	WBD4(2) (Royal Engineering)	Monthly	26.05357	27.70564	04/2008
Ptn. 8/2	WBD5(2) (P. Schutte)	Monthly	26.04756	27.71233	03/2008
Ptn. 65/25	IJ1(3) (I. Jardim)	Bi-annual(4)	26.03984	27.71942	06/2010
(1) Spring cross-referenced in Table 7. (3) Borehole number assigned by PSP.		(2) Borehole cross-referenced in Table 14. (4) Twice a year, in summer and winter.			

The frequency of this sampling is indicated in Table 11. The samples are analysed by the ERWAT Laboratory Services, under contract to the DWA, for the following variables:

pH, EC, Cl, SO_4, T.Alk., NH_4, NO_3+NO_2, Al, Cd, Cr, Cu, Co, Fe, Mn, Ni, Pb, Zn

In addition to the above, the MCLM also collects groundwater samples from four boreholes in the study area as identified in Table 12. Three of these are located in proximity to the Percy Stewart WWTW, and the fourth in the Rhino and Lion Game Reserve. The samples are analysed by the MCLM Scientific Services Water Laboratory for the following variables:

Apparent colour, odour, turbidity, temperature, Ca hardness, Mg hardness, Total hardness, pH, EC, TDS, NH_3-N, NO_3-N, Ca, Mg, Cl, SO_4, O-PO_4, T.Alk., Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Na, K, Zn, COD, HPC, Total coliforms, Faecal coliforms, *E. coli*, Suspended solids

Table 12. Groundwater quality monitoring stations served by Percy Stewart WWTW.

Station	Description	Frequency	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
PS/2	Borehole at Bergland Offices	Quarterly	26.07661	27.72452	03/1999
PS/3	Borehole at Foreman's residence	Quarterly	26.16364	27.72435	03/1999
PS/6	Borehole on neighbouring property	Quarterly	26.06333	27.71789	03/1999
PS/9	Borehole in Rhino & Lion Game Reserve	Quarterly	25.95677	27.77273	03/1999

3.3 Wastewater

3.3.1 Mine Water

It is understandable that mine water in the form of acid mine drainage (AMD) draws the most attention and greatest monitoring effort of any water source in the study area. The bulk of this effort is placed on the mining houses (Rand Uranium and Mogale Gold/Mintails) through the DWA directives (see section 3.3.1.3) that require regular and routine monitoring of specific variables at specific localities according to a specific frequency. The focus of this monitoring is on water quality (chemistry), although Rand Uranium closely monitors the hydrostatic head in various shafts and defunct opencast mines in order to establish the measure of 'saturation' of the inter-connected mining void that defines the source of AMD.

3.3.1.1 Quantity

The DWA directive (ref. 16/2/7/C231/R01 of 24/07/2009) requires that Rand Uranium (RU) measures the extraction rate of mine water from the Black Reef Incline, #8 Shaft and the pits, as well as the discharge of treated water into the 'Tweelopies-East'[7] Spruit, on a **daily** basis. As a consequence, RU in February 2007 installed a Parshall flume[8] flow gauging structure (Plate 2) at the end of the trench where treated mine water is released into the Tweelopie Spruit from the high density sludge (HDS) plant. The flume position immediately upstream of where the R24 road crosses the Tweelopie Spruit at the southern boundary of the Krugersdorp Game Reserve, might be regarded as the proverbial 'end-of-pipe' (EoP).

The original flume had a maximum rating of 0.382 m^3/s (33 ML/d), which was sufficient to gauge the volume of treated mine water initially discharged from the plant. This capacity was readily exceeded in periods of high rainfall, when runoff from the slope to the west also drains into the roughly 2-km length of trench upstream of the flume. As a consequence, the flume was modified to increase its gauging capacity, the maximum value of which has not been determined.

7 Earlier literature on the topic of acid mine water in this area refers to the Tweelopie Spruit as the 'Tweelopie-East' Spruit, to distinguish this drainage from the so-called 'Tweelopie-West' Spruit which in this study is represented by the upper Riet Spruit (section 4.1.2 and Figure 6).
8 Type of flume originally designed by R.L. Parshall of the US Soil Conservation Service (Parshall, 1950).

Following the recommencement of acid mine drainage in late-January 2010, RU installed a second Parshall flume to also measure the uncontrolled raw mine water discharge occurring adjacent to that from the HDS plant. Heavy rainfalls in mid-December 2010 and early-2011 resulted in the second flume being overtopped and severely eroded, leading Rand Uranium to install a third flume adjacent to the second in order to gauge the total raw mine water discharge into the downstream receiving environment.

The DWA directive further requires Rand Uranium to measure the discharge from the Aviary Dam at the downstream (northern) end of the Krugersdorp Game Reserve on a **weekly** basis. This is accomplished using the cross-sectional pipe section (chord length x velocity) method described in section 4.2.2.1.

Plate 2. View of the Parshall flume shortly after its installation at the end of the trench draining treated mine water from the Rand Uranium HDS Plant to its point of discharge (end-of-pipe) into the Tweelopie Spruit immediately upstream of the Krugersdorp Game Reserve. This structure was subsequently secured with a concrete abutment to protect the flume from erosion, and also fenced in with razor wire to safeguard the automated water quality monitoring instrumentation installed at this location from theft and/or vandalism. (Photo: Phil Hobbs).

3.3.1.2 Quality

It is necessary to distinguish between surface water and groundwater quality monitoring obligations placed on the mining houses (and in particular on Rand Uranium) by the DWA directive. The surface water quality monitoring obligations are summarized in Table 13, and the mine water and groundwater quality obligations in Table 14.

The water sample collection and analytical functions are currently carried out by the independent laboratory DD Science CC. Environmental Monitoring located at the Cooke Plant off the R559 on the West Rand. This monitoring activity commenced in January 2005, and targeted the ‘extraction from mine’ and ‘entrance to Krugersdorp Game Reserve’ sites listed in Table 13. Included in the Black Reef Incline location is the point discharge from the #17 Winze and #18 Winze mine structures, as well as the diffuse seepage that is collected and channelled to the plastic-lined dam where raw mine water is collected for pumping back to the HDS plant.

The information presented in Table 14 reflects the extent to which mine water and groundwater quality monitoring obligations imposed on Rand Uranium have expanded from 2005-’06 to 2009.

Table 13. Rand Uranium surface water quality monitoring directive obligations.

Location / Site Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Frequency & Variables
Extraction from the mine (Black Reef Incline[a], #8 Shaft[b] and pits)	[a]26.11518 [b]26.13542	[a]27.72282 [b]27.72014	Daily: pH, EC Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U & other heavy metals
Discharge into the Tweelopie-East Spruit (point of continuous monitor)	26.13420	27.71614	Daily: pH, EC Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U & other heavy metals
Upstream of the Krugersdorp Game Reserve (culvert under the R24 regional road)	26.10752	27.72224	Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U
Downstream of the Krugersdorp Game Reserve (Aviary Dam discharge)	26.07621	27.69948	Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U
Tweelopies-East Spruit upstream of confluence with the Tweelopies-West Spruit (Brick Dam)	26.06367	27.69597	Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U
Riet Spruit downstream of the confluence of the Tweelopies-East and -West spruits (Môrester)	26.05346	27.70261	Weekly: pH, EC, TDS, SO_4, Fe, Mn, Al, U

Clause 2.9 of the DWA directive 16/2/7/C231/C068 (Table 16) further requires Rand Uranium to "*Maintain a groundwater-monitoring programme to determine the footprint of the pollution plume from the discharge of the treated or any untreated extraneous water into the Tweelopies (East) Spruit*. This is given effect at the stations listed in Table 14 for the following variables[9] on a **monthly**[10] basis:

pH, EC, TDS, Ca, Mg, Na, Cl, SO_4, Fe, Mn, Al, U

The 'end-of-pipe' (EoP) flow gauging station was also equipped with automatic water quality recording devices measuring pH and electrical conductivity (EC) in June 2008 (B. van der Walt, personal communication). Unfortunately, the extremely hostile hydrophysical and hydrochemical conditions that prevail at this site severely test and compromise the integrity and functioning of the instruments and, consequently, the measurements they provide.

Table 14. Rand Uranium mine water and groundwater quality monitoring stations.

Station	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
RGC1	Borehole on Randfontein Golf Course	26.15679	27.71183	09/2009
RGC2	Borehole on Randfontein Golf Course	26.15372	27.71108	09/2009
#17 Winze	Mine shaft	26.12150	27.72136	01/2005
#18 Winze	Mine shaft	26.11514	27.72489	02/2005
BRI1	Scavenger borehole #1 at Black Reef Incline (BRI)	26.11419	27.72258	09/2009
BRI2	Scavenger borehole #2 at Black Reef Incline (BRI)	26.11117	27.72258	09/2009
RG1	Borehole north-east of BRI Dam	26.11217	27.72469	09/2009
RG3	Borehole west of Tweelopie Spruit, NW of BRI Dam	26.10992	27.72067	09/2009
MSD9	West of Tweelopie Spruit, south of R24	26.10781	27.72107	09/2009
SP1	F6S7[(1)] (Spring 1/Cemetery Spring in KGR)	26.09809	27.71926	09/2009
SP2	F8S9[(1)] (Spring 2/Lodge Spring in KGR)	26.09151	27.71974	09/2009
SP3	Site 5[(2)] (Spring 3/Flip-se-Gat/Lion Camp spring in KGR)	26.07692	27.69928	09/2009
WBD1	Caravan park borehole in KGR	26.07208	27.71308	09/2009
WBD2	Borehole on Ptn. 106 Sterkfontein 173IQ (KBW)	26.06333	27.69672	08/2006
WBD3	Borehole on Ptn. 96/7 Sterkfontein 173IQ (Môrester)	26.05706	27.70183	08/2006
WBD4	Borehole on Rem. 7/2 Sterkfontein 173IQ (Royal Eng.)	26.05365	27.70567	03/2008
WBD5	Borehole on Ptn. 8/2 Sterkfontein 173IQ (P. Schutte)	26.04756	27.71233	03/2008
(1) Cross-reference Table 7. (2) Cross-reference Table 8.				

9 Note the absence of groundwater level measurements (as made in boreholes) from the list of variables.
10 The previous DWA directive required a weekly monitoring frequency.

Further to the monitoring carried out by Rand Uranium, the mining company Mogale Gold/MintailsSA established three boreholes (Table 15) for groundwater monitoring purposes in July 2008 (Mogale Gold, 2009). The samples are analysed by DD Science CC. Environmental Monitoring for the following variables:

pH, EC, Ca, Mg, Na, Cl, SO4, T.Alk., Mn, Fe, CN, U

The suite of variables differs slightly from that prescribed by clause 2.9 of the DWA directive 16/2/7/C231/C068 (Table 16) adhered to by Rand Uranium. More recently, Mogale Gold/MintailsSA established an additional two monitoring boreholes (Table 15) located to the south-east of the North and South Pits currently used for the disposal of waste from reworked tailings.

Table 15. Mogale Gold/MintailsSA groundwater quality monitoring stations.

Station	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
MGP1	Borehole along East Gate road north of the West Wits pit	26.11423	27.73475	10/2008
MGP2	Borehole to the west of the West Wits pit	26.12068	27.73027	10/2008
MGP3	Borehole just east of Rand Uranium EoP north of the BRI	26.10800	27.72282	10/2008
MGP4	Borehole south-east of the South Pit	26.13137	27.73251	05/2010
MGP5	Borehole south-east of the North Pit	26.12381	27.73615	05/2010

3.3.1.3 DWA Directives

The quality of mine water chemistry authorized for release into the environment by the DWA in terms of directives issued to the mining houses warrants discussion. These circumstances are described in Table 16, which shows that three directives had been issued as of mid-2010. The periods of validity and variable-specific values defined in these directives are also described.

Perhaps the most striking aspect of the directives is their sequential relaxation of limiting values, most notably for EC, SO_4 and Mn. A second notable aspect is the fewer variables contained in successive directives, reducing from 16 in the first directive to only six in the latest/current directive (Table 16).

It is not the task of the PSP to interrogate the framework and circumstances that underpin the issuing of directives by the DWA. However, the implications of the observed relaxations in terms of their potential ramifications on the receiving environment must be a universal concern. An important aspect of these circumstances is the understanding that the DWA is not obligated to consult outside parties in the setting of directives (B. Govender, communication) such as are reflected in Table 16.

Table 16. Synthesis of DWA directives issued in regard to mine water releases into the Tweelopie Spruit.

Directive Metadata	Variable and Limiting Value					
Reference: 16/2/7/C231/C/257 Date issued: 29/03/2005 Expiry date: 31/03/2006 Validity period: 12 months	pH NH_4 F PO_4 B Fe	6.5 – 8.4 0.12 mg N/L 0.1 mg/L 0.1 mg P/L 0.03 mg/L <0.1 mg/L	EC NO_3 Na Cl Al	70 mS/m 0.45 mg N/L 56 mg/L 36 mg/L <0.06 mg/L	TDS SO_4 Mg Ca Mn	475 mg/L 200 mg/L 23 mg/L 72 mg/L 0.07 mg/L
Reference: 16/2/7/C231/R01 Date issued 24/07/2009 Expiry date: 31/01/2011 Validity period: 18 months(1)	pH SO_4 Mn U	6.5 – 9.5 <600 mg/L <10 mg/L <0.05 mg/L	EC Al Fe	100 mS/m <1 mg/L <1 mg/L		
Reference: 16/2/7/C231/C068(2) Date issued 26/05/2010 Expiry date: 31/01/2011 Validity period: 7 months	pH SO_4 Fe	6.5 – 9.5 <3000 mg/L <1 mg/L	EC Mn U	350 mS/m <10 mg/L <0.05 mg/L		

(1) Withdrawn in mid-2010 some 11 months after issue.
(2) Directive still in force at the completion of this study.

3.3.2 Municipal Wastewater

The quality of the treated wastewater effluent discharged from the Percy Stewart WWTW into the Blougat Spruit is monitored by the Mogale City Local Municipality. Records provided by this authority (Annexure A.17) indicate the **monthly** determination of the following variables:

> pH, EC, TDS, NH_3, NO_3, Cl, Chlorine (residual), O-PO_4, T.Alk., Cd, Cr, Cu, Pb, Mn, Na, Zn, COD, Soap oil or grease, Faecal coliforms, *E. coli*, Suspended solids

In addition to the effluent monitoring carried out by the MCLM, this authority also monitors the quality of groundwater produced from three boreholes located to the north and down-gradient of the WWTW. The irrigation of ~65 ha of cultivated grass (instant lawn) with treated wastewater effluent from the WWTW is the driver for this monitoring (Plate 3). Salient information associated with this monitoring activity is provided in Annexure A.18. The water sample collection function is carried out by staff of the Percy Stewart WWTW, and the analytical function by the MCLM laboratory. The following variables are adjudicated on a **quarterly** basis:

> Colour, pH, EC, TDS, Mg Hardness, Ca Hardness, Tot. Hardness, Odour, Temp., T.Alk., Turb., Cd, Cr, Co, Cu

Water chemistry data sourced from the DWA also contains records for the Driefontein WWTW (Annexure A.16). This facility is operated by Johannesburg Water, and discharges its effluent into the Crocodile River a distance of ~3 km upstream of the confluence with the Blougat Spruit at Zwartkop. Although **irregular** in terms of frequency and comparatively short (refer Annexures A.16 and A.17), the WWTW records provide a direct measure of the quality of treated effluent discharged from these facilities to the Blougat Spruit and the Crocodile River, respectively. Of the 19 variables adjudicated, the following 11 equal or exceed a count of 20 in the roughly 6 years of record:

> pH, EC, COD, Cl, F, NH_4, NO_3+NO_2, PO_4, SO_4, Suspended solids, Faecal coliforms

The recently released "Green Drop Report" (DWA, 2009) provides further insight into the overall performances of the Percy Stewart and Driefontein WWTW. This is reflected in Table 17, which indicates the much better score awarded the Driefontein facility compared to that awarded the Percy Stewart facility. The most concerning aspect of the Percy Stewart WWTW report card is its non-compliance with criteria 5 and 6. Further, the scores reflect a poor management performance, and substantial effort is required to improve the situation in regard to these management criteria. These circumstances possibly explain why Ellis and Grove (2010) identify the 'industrial activity' attributed to this plant as having the most severe impact on the COH WHS. It must be also considered, however, that the recently completed refurbishment of the Percy Stewart WWTW[11] at a cost of R14.5 million is not factored into the "Green Drop" assessment, and this might well improve the reported situation.

Table 17. Green drop report card results for the Driefontein and Percy Stewart WWTW facilities (from DWA, 2009).

Criteria	Report Card Result	
	Driefontein WWTW	Percy Stewart WWTW
1. Process control, maintenance and management skill	A	D
2. Monitoring programme efficiency	A	A
3. Credibility of wastewater sample analysis	A	C
4. Regular submission of wastewater quality results to DWA	A	A
5. Wastewater quality compliance	A	G
6. Wastewater failures response management	A	G
7. Wastewater treatment works capacity	A	A
Green Drop Score	94%	36%

[11] Information sourced at http://www.sabinet.co.za/abstracts/sh_san/sh_san_v4_n6_a11.html on 28/05/2010.

Although this refurbishment has returned the facility to its capacity of 15 ML/d, this is still below the current inflow that amounts to ~18 ML/d on average. It is understood (E. Maré, personal communication) that the planned extension of the plant to a capacity of 25 ML/d at a cost of R94.3 million commenced in mid-2010. This will enable the facility to adequately treat its current inflow, and also accommodate emerging housing developments and industrial development expected in the area by 2012.

Plate 3. View of Percy Stewart WWTW in background, showing area (~65 ha) irrigated with treated wastewater effluent in middle foreground. (Photo: Phil Hobbs).

3.4 Other Monitoring

A discussion of the status quo of water resource monitoring in the study area (with particular reference to mining-related impacts) must also recognize the activities carried out by the Council for Geoscience (CGS). The CGS commissioned the installation of automated water level and field water quality variable (pH, Eh and EC) monitoring equipment at various positions (Table 18) in the south-western portion of the study area. These stations were fitted with telemetric links for the electronic transmission of data to a service provider from where the CGS could download the data on a regular basis (B. Boonzaier, personal communication). Unfortunately all of these installations have become dysfunctional, and have not contributed data to the growing collective since *ca.* January 2008.

Table 18. CGS mine water, surface water and groundwater monitoring stations.

Station (after CGS)	Description	Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	Start Date (mm/yyyy)
9E Shaft	# 9E Shaft, Mogale Gold/MintailsSA	26.12633	27.72428	07/2005
Dry Dam borehole	Borehole at Hippo Dam in KGR	26.09989	27.71989	07/2005
Dry Dam	Hippo Dam in KGR	26.09937	27.72076	07/2005
Spring 3	Spring below Hippo Dam in KGR	26.09814	27.71958	07/2005
Lion Camp Dam	Weir outlet of Lion Camp Dam in KGR	26.08528	27.70895	07/2005

The Nedbank Olwazini Estate (NOE) Leadership and Management Development Centre (LMDC) located downstream of Kromdraai maintains its own surface water quality monitoring programme. The framework of this programme is based on the water uses outlined in section 4.3.2. The monitoring programme entails the **monthly** determination of water quality at numerous on-site stations. The most salient stations for the purposes of this study are those identified as the 'furrow' (the raw water source) and the Bloubank Spruit 'upstream' and 'downstream' of the estate. In the case of the 'furrow', the record extends back to at least November 2007, and to January 2009 in the case of the Bloubank Spruit. The 'furrow' samples are analysed for the following variables:

> Apparent colour, EC, Ca hardness, Mg hardness, Total hardness, odour, pH, temperature, T.Alk., TDS, turbidity, NH_3-N, NO_3-N, F, Ca, Mg, Cl, SO_4, Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Na, K, Zn, HPC, Total coliforms, Faecal coliforms, *E. coli*, Faecal streptococci

The Bloubank Spruit samples are analysed for the following variables:

> pH, NH_3-N, NO_3-N, O-PO_4, COD, Faecal coliform, Suspended solids

It has also been established that many of the agricultural activities that rely on either surface water or groundwater for irrigation purposes, are required to regularly subject representative samples of irrigation water to chemical analysis. This requirement is imposed on producers of agricultural produce in terms of the EurepGAP[12] standard and certification. Examples are the Olera Farmers on Kromdraai 520JQ who deliver fresh produce to a local fresh produce retailer, and the Jomajoco Farms operation on Vlakdrift 163IQ which supplies a large supermarket retail chain with fresh produce.

Similarly, it has been established that the Rhino and Lion Game Reserve maintains an excellent record of the abstraction from borehole RLGR4 which serves the chalets and Wonder Cave. The groundwater produced by this source is also analysed by the MCLM (station PS/9 in Table 12) every three months for the following variables:

> Apparent colour, odour, turbidity, temperature, Ca hardness, Mg hardness, Total hardness, pH, EC, TDS, NH_3-N, NO_3-N, Ca, Mg, Cl, SO_4, O-PO_4, T.Alk., Cd, Cr, Co, Cu, Fe, Pb, Mn, Ni, Na, K, Zn, COD, HPC, Total coliforms, Faecal coliforms, *E. coli*, Suspended solids

Another groundwater use that requires chemical analysis is the production of bottled water for wholesale distribution as mineral water. An example hereof is the product Exclusive Mineral Water produced on Plot 71 of the farm Sterkfontein 173IQ. A recent 'test report' of the raw water source is replicated in Annexure A.19, which shows the suite of variables that comprise this routine analysis.

It is recognized that there are almost certainly numerous other monitoring activities associated with water resources being undertaken in the study area. The more common and simplest of these is daily rainfall monitoring diligently recorded by individuals and landowners. Such data sets have great value, but will require a concerted effort to 'uncover' and obtain.

3.5 Resolution of Disparate Monitoring Station Coordinates

It is evident from the preceding analysis of existing monitoring stations that a number of these are referred to by various names. More concerning, however, is the observation that the coordinates of these stations varies depending on the source of this information. These circumstances are illustrated in Table 19. It is probable that the discrepancies are associated with the positions of the actual sampling localities rather than with the positions of the sources themselves.

[12] An international production standard for suppliers of agricultural products to the retail sector, originally comprising participating European supermarkets, but subsequently also adopted elsewhere in the world as a model of 'best practice'.

The coordinates assigned by the PSP to the stations reflecting disparate coordinates is based on a careful assessment and inspection of the relevant sites, and pertains to the actual sources rather than to the sampling positions. The PSP presumes that sufficient attention has been paid to the latter (by whichever source) to ensure that the sampling position produces a representative sample of the source water to be analysed. This is readily achieved by ensuring that the sampling position is as close to the source, whether exact in the case of a point source, or as close downstream of an aggregate discharge from diffuse sources, as possible. In the latter instance, sufficient distance must be allowed to ensure thorough mixing of the contributing diffuse sources if these differ substantially in the chemical composition of the water that each produces.

Table 19. Disparity and resolution of monitoring station coordinates.

Station	Latitude (dd.dddddºS)	Longitude (dd.dddddºE)	Source of Information	Recommended Coordinates	
				(dd.dddddºS)	(dd.dddddºE)
F6S7 (Spring 1) Site 2 (Cemetery) SP1 (Cemetery Spring)	26.09671	27.71932	Table 7 (DWA)	26.09694	27.71898
	26.09799	27.71873	Table 11 (MCLM)		
	26.09809	27.71926	Table 14 (RU)		
F8S9 (Spring 2) SP2 (Lodge Spring)	26.08527	27.70886	Table 7 (DWA	26.09092	27.72011
	26.09060	27.72050	Table 11 (MCLM)		
	26.09151	27.71974	Table 14 (RU)		
Flip-se-Gat Stream	26.07620(2)	27.69885(2)	Table 8 (MCLM)	26.08149(1)	27.69589(1)
SP3 (Spring 3)	26.07692(2)	27.69928(2)	Table 14 (RU)	26.07692(2)	27.69928(2)
F10S11 Site 6 Aviary Dam discharge	26.07620	27.69963	Table 7 (DWA)	26.07403	27.69853
	26.07433	27.69885	Table 8 (MCLM)		
	26.07621	27.69948	Table 13 (RU)		
F11S12 Brick Dam	26.06374	27.69589	Table 7 (DWA)	26.06374	27.69589
	26.06367	27.69597	Table 13 (RU)		

(1) Coordinates of the most westerly (highest) seepage that contributes to the aggregate discharge sampled at the accessible downstream aggregate sampling position located ~620 m to the north-east.
(2) Coordinates of the readily accessible downstream aggregate flow and water chemistry sampling position at the exit from the Predator Enclosure.

It is trusted that the recommended source coordinates will be accepted by the numerous and varied parties who have a direct interest in this very important aspect. Although the PSP does not show a preference for any specific source (or monitoring station) name, it is recommended that the station identifier assigned by the DWA (where such exists) be accepted as the definitive metric in this regard. The PSP further suggests that the recommended coordinates of the sources as presented in Table 19 be regarded as the definitive location metric, unless compelling argument and motivation to the contrary is made that suggests otherwise.

4 PHYSICAL HYDROLOGY

4.1 Surface Water Drainage

The study area encompasses the quaternary catchments and drainages identified in Table 1, section 2.1. It is recognized that the surface water resources (hydrology) of the study area are sparsely described in the literature. The reason for this is that little effort is expended in analysing the runoff characteristics of the main drainages that rise in and discharge from the study area. This is partly attributed to the paucity of flow gauging stations in the study area. It is typical to merely report the mean annual runoff (MAR) and catchment size. The MAR is reported either as a volume typically with units Mm^3 (million cubic metres), or as an equivalent depth of precipitation with units millimetres (mm). Runoff in the study area is gauged at the four stations listed in Table 6 (section 3.1.1). Whereas the adjoining Steenkoppies Compartment to the south-west is drained by a single high-yielding spring (Maloney's Eye) with a long-term mean annual discharge of 14.38 Mm^3 (456 L/s), but reduced to 9.8 Mm^3/a (311 L/s) in the last decade (Holland et al., 2009), the study area is drained by numerous and distributed such features. These feed either the Skeerpoort River or the Bloubank Spruit system, which are discussed in the relevant sections that follow.

4.1.1 Skeerpoort River

The DWA flow record for station A2H033 spans a period of 45 years. This station gauges the discharge of the Grootvlei Spruit, a tributary of the Skeerpoort River, just before its confluence with the latter (Figure 6). It provides the monthly discharge statistics presented in Table 20, and for which the annual discharge per hydrological[13] year is shown in Figure 7. The autumn months of March and April, and the spring month of September, reflect the lowest coefficient of variation (CoV) values of ~47%, and September also the lowest median monthly discharge value of 0.239 Mm^3 (92 L/s).

Table 20. Statistical analysis of monthly discharge data for station A2H033, Grootvlei Spruit.

Variable	Month											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Count (n)	41	40	42	37	36	35	37	37	40	39	41	41
Minimum	0.160	0.159	0.165	0.166	0.152	0.162	0.155	0.160	0.150	0.151	0.150	0.145
5%ile	0.169	0.166	0.177	0.183	0.167	0.176	0.188	0.173	0.159	0.163	0.164	0.159
Mean	0.370	0.393	0.402	0.430	0.414	0.394	0.394	0.382	0.342	0.349	0.336	0.306
Median	0.282	0.319	0.351	0.366	0.373	0.396	0.371	0.342	0.277	0.285	0.284	0.239
95%ile	0.733	0.978	0.736	0.819	0.770	0.724	0.749	0.710	0.704	0.712	0.685	0.562
Maximum	1.642	1.756	1.162	1.02	1.118	0.822	0.816	0.881	0.829	0.891	0.821	0.692
SD	0.262	0.305	0.215	0.224	0.226	0.185	0.182	0.189	0.179	0.182	0.171	0.142
CoV (%)	71	78	53	52	55	47	46	50	52	52	51	47
All units are Mm^3 unless otherwise indicated. Analysis excludes months with missing and station rating exceedance data, but includes unaudited (recent) and estimated data.												

Fed mainly by the Nouklip Spring, the instantaneous monthly flow pattern at station A2H033 for the complete record is shown in Figure 8. This reveals a distinct step up from 0.05 to 0.12 m^3/s in the 'base' values *ca.* October 1996. The DWA has been approached for an explanation that is still awaited. Also evident in the hydrograph (Figure 8) are distinct recession curves following peak discharge events, e.g. *ca.* July 1997 and May 2000. This record was analysed graphically by Holland (2007), who estimated a groundwater contribution to baseflow of 8.3 Mm^3 for 2005. This value significantly exceeds even the post-October 1996 median discharge of ~5.4 Mm^3/a_h derived from an analysis of the flow record for this station (Figure 7). Notably, the spring discharge of ~173 L/s measured on 19/05/2010 at the end of a very wet summer (section 8.5.7) also equates to an annual discharge of ~5.4 Mm^3. It is reported in section 8.5.7 that this station gauges the aggregate discharge of numerous springs, including a single high-yielding spring. Given that more than a single source generates the hydrograph might account for the much higher groundwater contribution to baseflow value derived by Holland (2007), compared to the observed long-term median discharge.

[13] A hydrological (or water) year runs from October to the following September and, as such, spans a complete and contiguous wet summer and dry winter season in the summer rainfall regime that characterizes the study area.

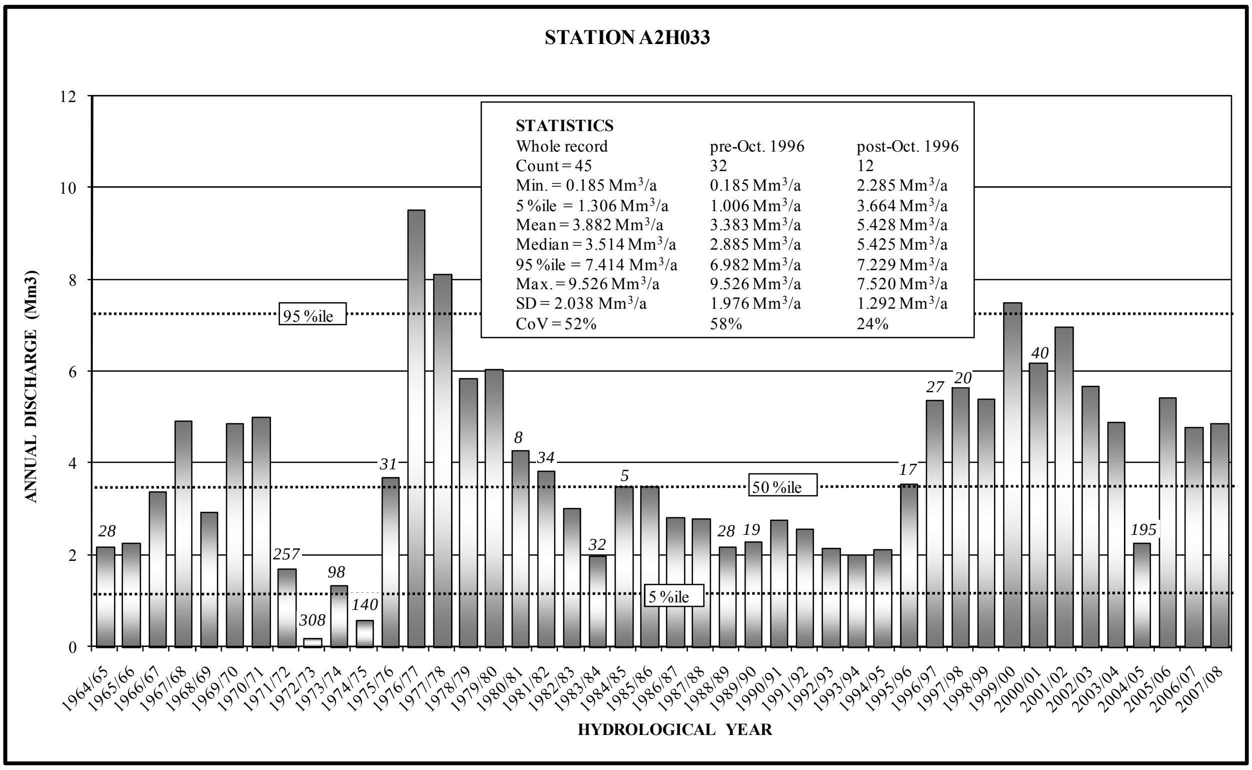

Figure 7. Graph of annual discharge at station A2H033, Grootvlei Spruit. Values in italics denote number of days with missing or inaccurate data.

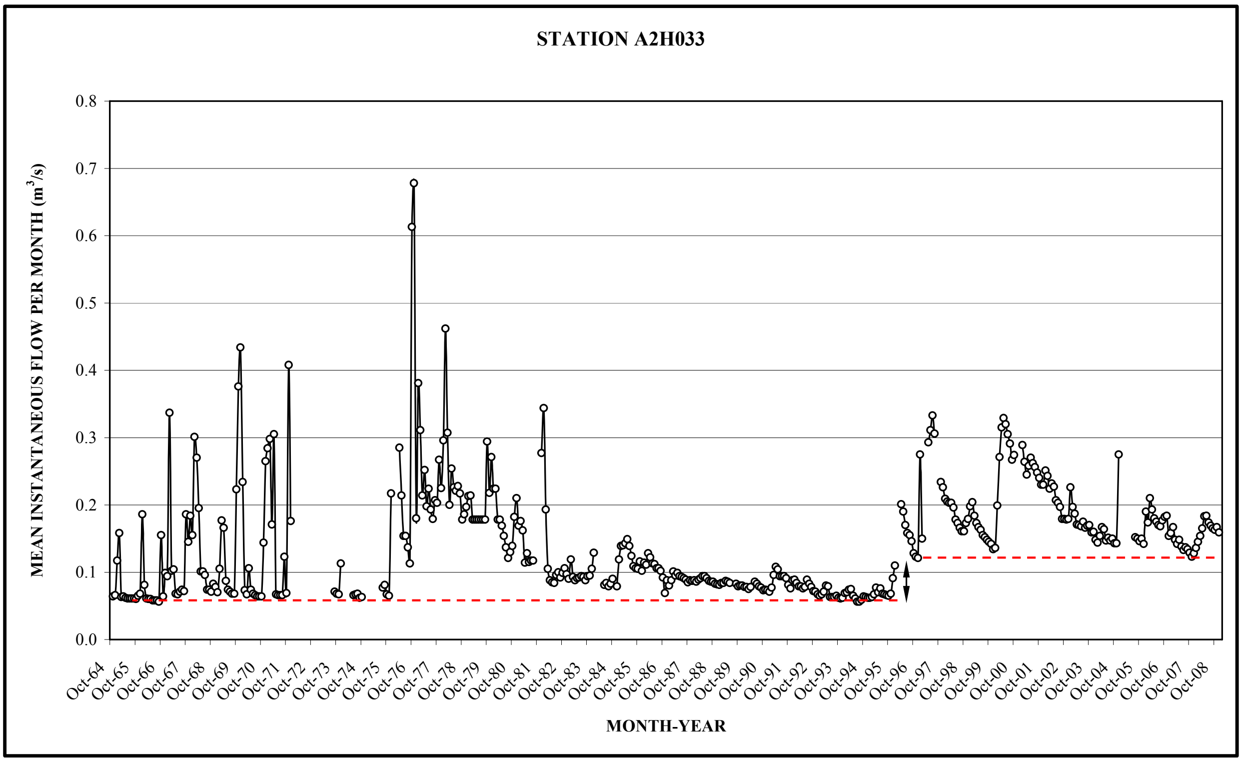

Figure 8. Long-term monthly hydrograph for station A2H033, Grootvlei Spruit.

It should be noted that the Skeerpoort River, at its confluence with the Grootvlei Spruit, already carries the discharge from at least one other high-yielding spring, namely the Nash Spring. This spring is located a distance of some 4.9 km (measured along the sinuous river reach) upstream of this confluence. The spring discharge was measured at ~130 L/s (11.2 ML/d) on 19/05/2010. Together with the preceding discussion, these circumstances further inform the discharge characteristics of the Skeerpoort River.

Flow in the Skeerpoort River itself is gauged at station A2H034 located ~7 km downstream of station A2H033 (Figure 6). At this location, the river has already left the largely undisturbed natural environment of the John Nash Nature Reserve, and also supports upstream agricultural activities in the vicinity of the confluence with the Witwatersrand Spruit. The flow record for station A2H034 spans a period of 45 years. It provides the monthly discharge statistics presented in Table 21, and for which the annual discharge per hydrological year is shown in Figure 9. The winter months of July and August reflect the lowest coefficient of variation (CoV) values of ~47%, and September the lowest median monthly discharge value of 0.639 Mm^3 (239 L/s). Once again, these circumstances reflect the constancy and perennial nature of the spring-supported autogenic discharge at this location.

Table 21. Statistical analysis of monthly discharge data for station A2H034, Skeerpoort River.

Variable	Month											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Count (n)	41	41	40	41	41	39	40	41	42	40	41	41
Minimum	0.266	0.349	0.353	0.397	0.333	0.334	0.321	0.362	0.405	0.452	0.401	0.334
5%ile	0.386	0.392	0.478	0.442	0.377	0.381	0.369	0.368	0.461	0.462	0.436	0.362
Mean	0.750	0.858	1.001	1.188	1.283	1.321	1.098	1.048	0.930	0.842	0.824	0.741
Median	0.711	0.757	0.845	1.062	0.924	1.147	0.795	0.721	0.720	0.730	0.662	0.639
95%ile	1.406	2.054	2.314	2.381	3.926	2.690	2.157	2.239	1.843	1.669	1.791	1.679
Maximum	2.078	2.25	3.498	3.132	6.625	8.55	5.581	6.231	4.396	1.972	1.902	1.843
SD	0.378	0.463	0.641	0.669	1.283	1.362	0.922	1.017	0.677	0.390	0.395	0.377
CoV (%)	50	54	64	56	100	103	84	97	73	46	48	51
All units are Mm^3 unless otherwise indicated. Analysis excludes months with missing and station rating exceedance data, but includes unaudited (recent) and estimated data.												

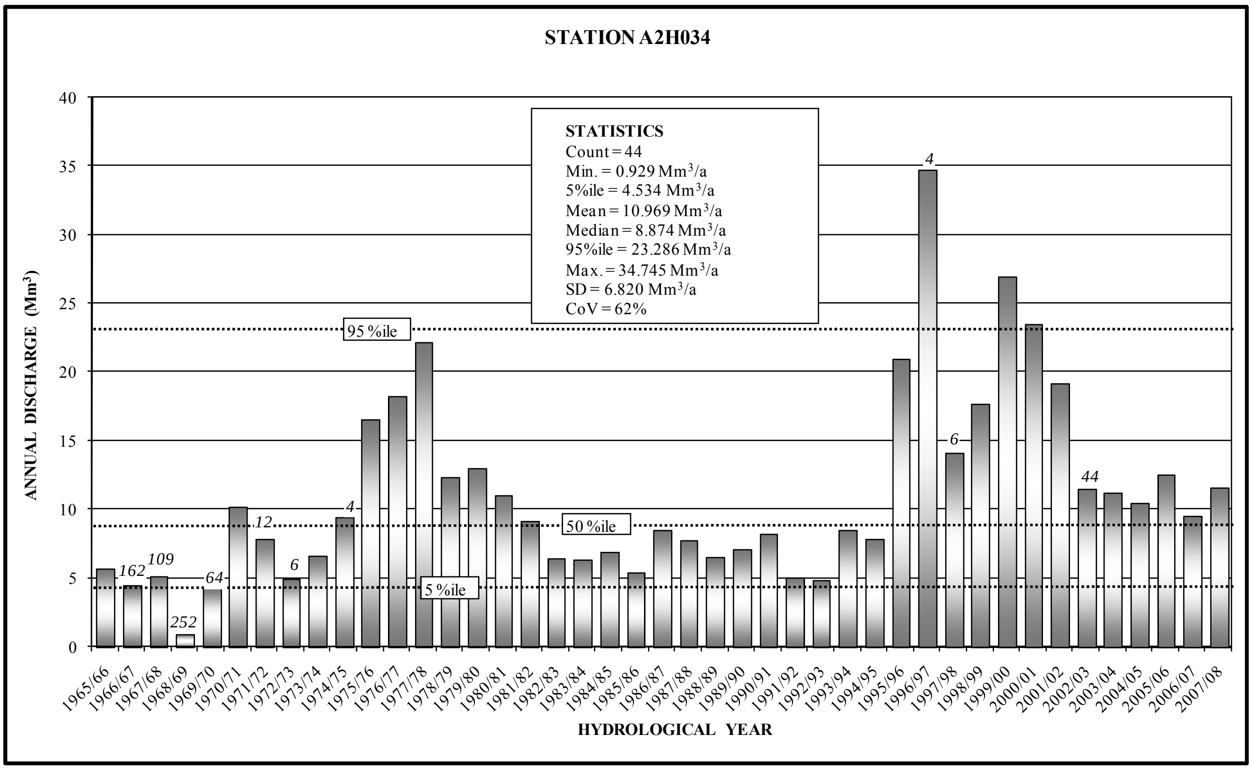

Figure 9. Graph of annual discharge at station A2H034, Skeerpoort River. Values in italics denote number of days with missing or inaccurate data.

The combined discharge (>300 L/s ≈ 28.5 ML/d) of the dolomitic springs feeding the Skeerpoort River (see sections 8.5.6, 8.5.7 and 8.5.8) translates into an annual discharge of at least 9.46 Mm^3. This is encouragingly close to the long-term mean and median values of 10.969 and 8.874 Mm^3/a, respectively, reported in Figure 9. The long-term median annual discharge represents ~5% of the 186.4 Mm^3 net capacity[14] (DWA, 2010a) of Hartbeespoort Dam. The instantaneous monthly flow pattern at station A2H034 for the complete record is shown in Figure 10. Although less evident than in Figure 8, distinct recession curves following peak discharge events, e.g. *ca.* October 1977 and October 2000, are also discernible in the hydrograph for station A2H034. As already indicated, station A2H034 is located a substantial distance downstream of its principal perennial sources at a location where agricultural impacts (abstraction) as well as the contribution of an ephemeral tributary (the Witwatersrand Spruit) are also probably manifested. These circumstances negate attempting a correlation between spring discharge and rainfall as has been done for Maloney's Eye and the Steenkoppies Compartment (Holland et al., 2009).

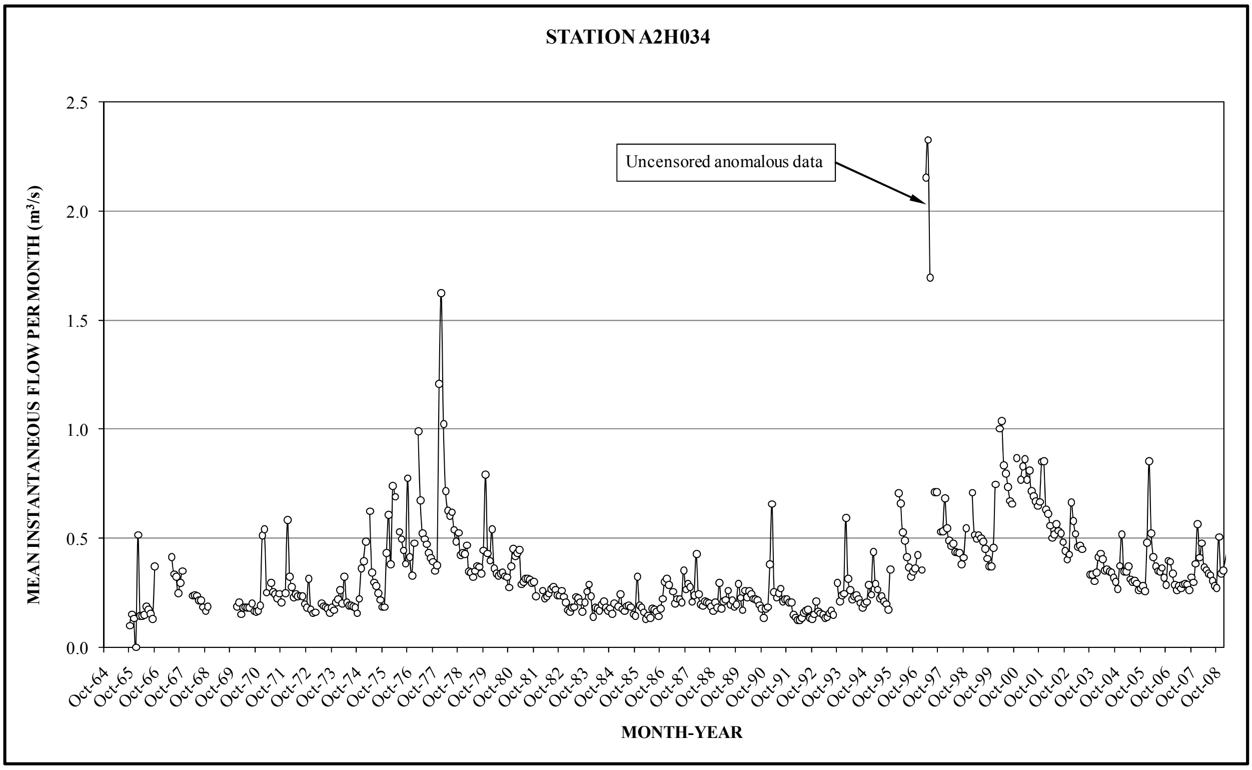

Figure 10. Long-term monthly hydrograph for station A2H034, Skeerpoort River.

4.1.2 Bloubank Spruit system

The Bloubank Spruit system comprises the following drainages, described sequentially from the uppermost (headwater) reaches. Figure 6 provides a reference for these descriptions.

- The Bloubank Spruit, which rises on the farm Reydal 165IQ north of Tarlton and flows north-eastwards past the Sterkfontein Caves and Kromdraai down to its confluence with the Crocodile River in the vicinity of Glenburn Lodge at Zwartkop. Its upper reaches are ephemeral.

- The north-westerly draining upper reaches of the Riet Spruit, which rises in Riebeeck Lake in Randfontein and flows past the Randfontein WWTW toward Tarlton, where it swings to the north-east. Its middle and lower reaches follow the N14 national road down to the confluence with the Bloubank Spruit in the Oaktree area.

- The Tweelopie Spruit, a tributary of the Riet Spruit, which rises in Robinson Lake between Randfontein and Krugersdorp and drains northward through the Krugersdorp Game Reserve to join the Riet Spruit at Glen Almond.

[14] The net capacity (equivalent to full supply capacity) of the dam is slightly less than its gross capacity of 195.1 Mm^3, which approximates the MAR of the contributing catchments. Note that Middleton and Bailey (2008b) report an observed long-term MAR of 193.9 Mm^3/a and a simulated MAR of 185.4 Mm^3/a for Hartbeespoort Dam.

- The Blougat Spruit, another tributary of the Riet Spruit, which rises in the Factoria industrial area of Mogale City and first drains in a north-westerly direction before flowing northward past the Percy Stewart WWTW to its confluence with the Riet Spruit in the Oaktree area.

- The Honingklip Spruit[15], a tributary of the Bloubank Spruit, which rises on the northern margin of Mogale City in the Rant-en-Dal and Paardekraal areas, and flows northwards to join the Bloubank Spruit at Kromdraai.

- The Tweefontein Spruit[16], which rises in the John Nash Nature Reserve and drains southward across the farm Rietfontein 522JQ to join the Bloubank Spruit near Brookwood Trout Farm.

The discharge of the Bloubank Spruit system is gauged by the DWA at station A2H049 located at the downstream end of this system (Figure 6) ~12 km from Sterkfontein Caves. The 37-year record provides the monthly discharge statistics presented in Table 22. The discharge per hydrological year is shown in Figure 11. The median annual discharge of ~19.2 Mm^3/a_h is a little more than twice that of the Skeerpoort River at station A2H034 (~8.9 Mm^3/a_h, Figure 9), and represents ~10% of the net capacity (186.4 Mm^3) of Hartbeespoort Dam. Table 22 shows that the dry winter month of August reflects the lowest CoV value of 37%, September the lowest median monthly discharge of 1.48 Mm^3 (558 L/s), and October the lowest minimum monthly discharge of 0.68 Mm^3 (255 L/s). These circumstances again reflect both the constancy and perennial nature of the natural (spring-supported) and artificial contributions to the flow in this drainage system.

Table 22. Statistical analysis of monthly discharge data for station A2H049, Bloubank Spruit.

Variable	Month											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Count (n)	35	35	36	36	37	37	37	35	36	36	35	35
Minimum	0.682	0.815	0.711	0.721	0.706	0.828	0.886	0.847	0.894	0.939	0.890	0.770
5%ile	0.784	0.843	1.033	1.066	0.895	1.019	1.126	0.943	0.936	0.951	0.905	0.795
Mean	1.618	1.643	1.974	2.405	2.346	2.621	2.092	1.978	1.806	1.768	1.646	1.517
Median	1.472	1.634	1.730	2.247	1.885	2.062	1.879	1.725	1.587	1.624	1.447	1.307
95%ile	2.813	2.696	3.342	3.608	4.883	5.811	4.108	4.272	3.104	2.876	2.561	2.570
Maximum	4.211	2.961	4.539	12.079	10.619	9.358	6.081	5.028	4.264	4.207	3.644	3.496
SD	0.759	0.613	0.840	1.836	1.833	1.863	1.065	1.016	0.732	0.680	0.612	0.621
CoV (%)	47	37	43	76	78	71	51	51	41	38	37	41

All units are Mm^3 unless otherwise indicated. Analysis excludes months with missing and station rating exceedance data, but includes unaudited (recent) and estimated data.

The instantaneous monthly flow pattern at station A2H049 for the complete record is shown in Figure 12. This reveals a comparatively constant lowest value of 0.25 m^3/s, which is double that of station A2H033. Again evident in the hydrograph (Figure 12) are distinct recession curves following peak discharge events, e.g. *ca.* January 1997, March 1997 and February 2000. Station A2H049, however, is not only located a substantial distance (5 to 10 km) downstream of its principal perennial sources, the Zwartkrans and Kromdraai Springs (Figure 6), but also receives the discharge of other 'lesser' springs (e.g. the Plover's Lake Springs) and ephemeral tributaries (e.g. the Honingklip Spruit). These circumstances again negate attempting a correlation between spring discharge and rainfall.

A discussion of the two most significant drainages that make up the Bloubank Spruit system, namely the Tweelopie Spruit and the Blougat Spruit, is presented in the following sections. These drainages are singled out for discussion due to (a) the artificial (anthropogenic) characteristics that dominate their flow regimes in terms of both water quantity and quality, and (b) the availability of historical flow and water quality data associated with the allogenic[17] sources.

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15 Name assigned to a drainage that for most of its path traverses the farm Honingklip 178IQ, but is unnamed on the 1:50000 scale topocadastral map 2627BB Roodepoort.
16 Name assigned to a drainage that is unnamed on the 1:50000 scale topocadastral map 2527DD Broederstroom.
17 See GLOSSARY OF SELECTED TERMS.

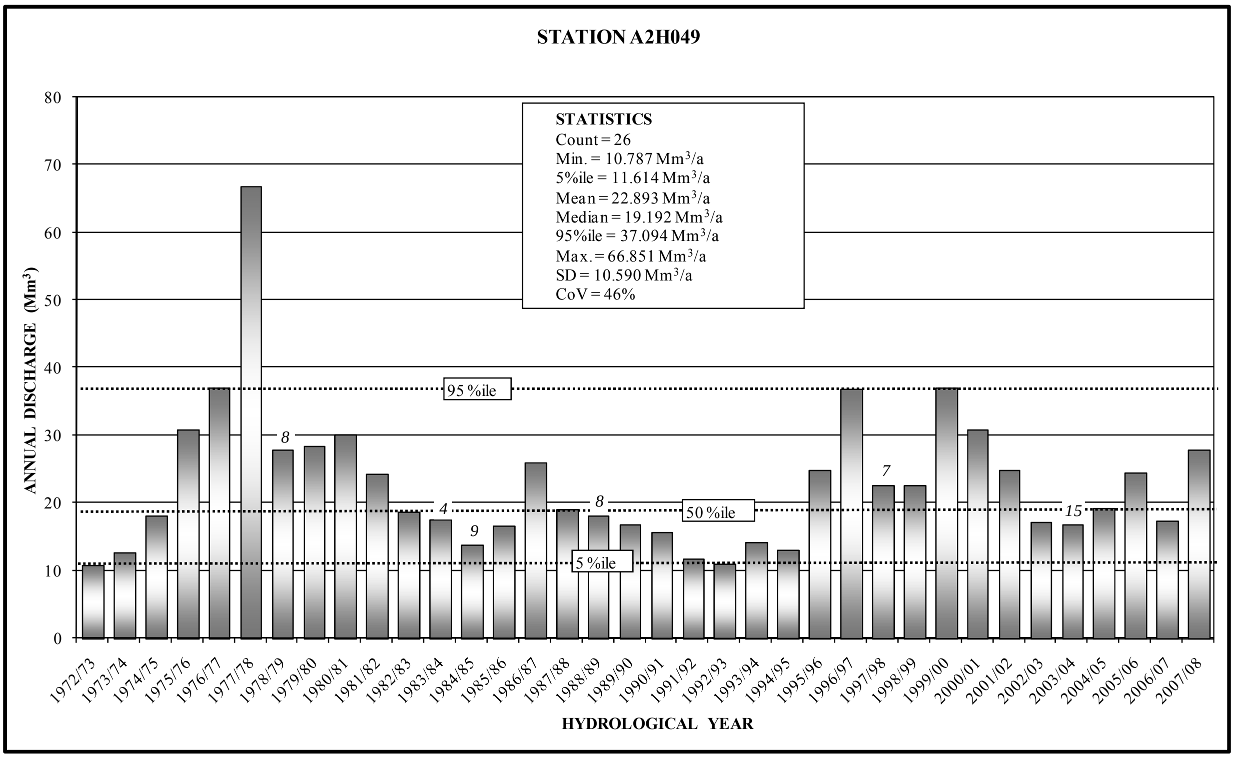

Figure 11. Graph of annual discharge at station A2H049, Bloubank Spruit. Values in italics denote number of days with missing or inaccurate data.

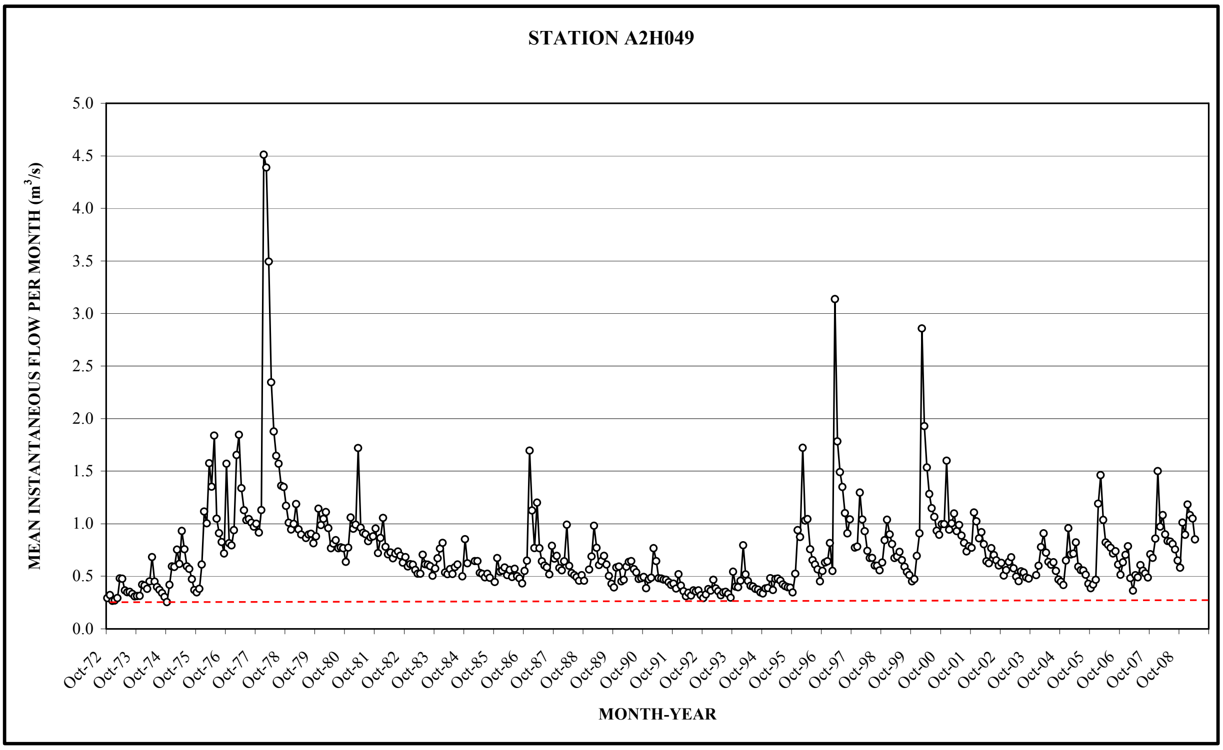

Figure 12. Long-term monthly hydrograph for station A2H049, Bloubank Spruit.

4.1.2.1 Tweelopie Spruit

The historical record of treated mine water discharge is shown in Figure 13. The long-term median discharge value of ~10 ML/d masks the higher median value of 15 ML/d associated with the second half of the record. Similarly, the long-term 95%ile discharge value of 27.4 ML/d is exceeded by the more recent value of 32.6 ML/d.

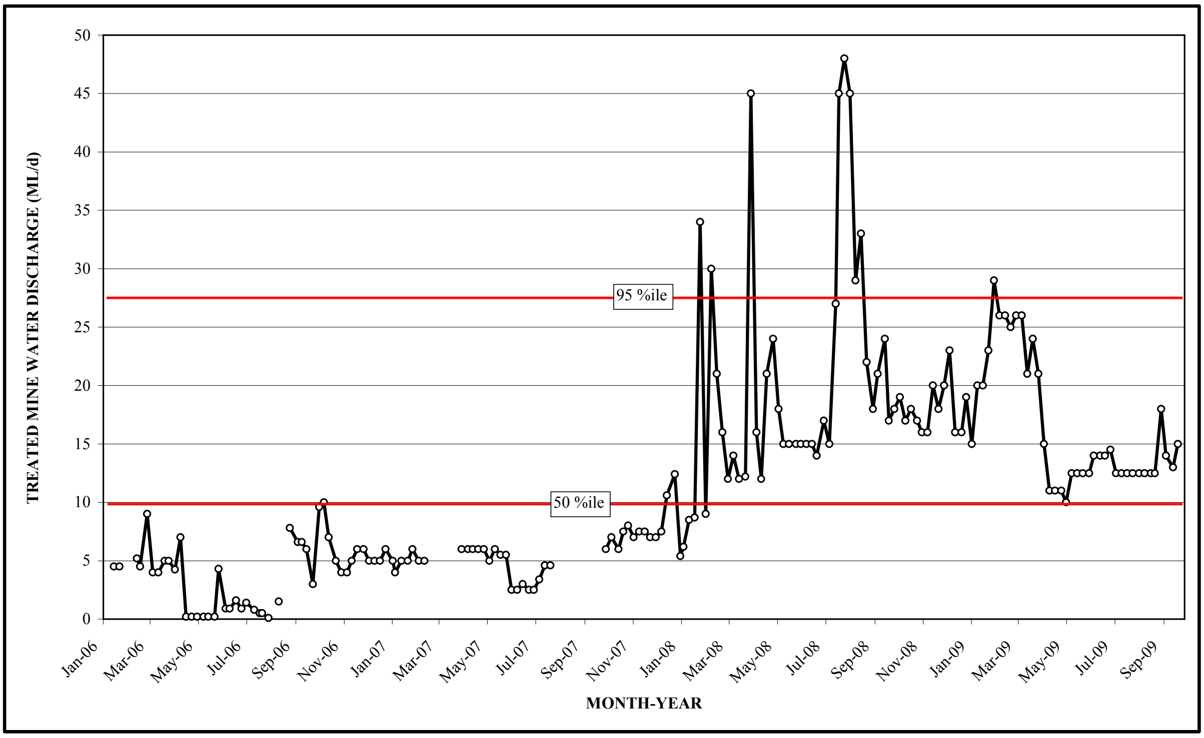

Figure 13. Historical pattern of treated mine water discharge into the Tweelopie Spruit upstream of the Krugersdorp Game Reserve.

The MCLM has carried out flow measurements at the inlet of the Aviary Dam inside the northern boundary of the Krugersdorp Game Reserve. A comparison of these readings with those of the Parshall flume at the Rand Uranium 'End-of-Pipe' provides a measure of the contribution from various springs in the KGR to the discharge of the Tweelopie Spruit in proximity to where it starts to lose water into the karst regime of the Zwartkrans Compartment. These results are discussed in section 4.2.2.1.

4.1.2.2 Blougat Spruit

The Blougat Spruit receives the effluent discharge from the Percy Stewart WWTW. This has turned an ephemeral stream into a perennial drainage since the commissioning of the facility in the 1950s. Designed to treat domestic sewage at a rate of of 25 ML/d based on a design norm chemical oxygen demand (COD) loading of 600 mg/L, the inclusion of low-cost housing and industrial wastewater increased the COD loading to 1000 mg/L, reducing the plant capacity to 15 ML/d. Lack of maintenance reduced this even further to 5 ML/d. Although recently completed refurbishment has restored the 15 ML/d capacity of the plant, the current inflow of 18 ML/d means that it still cannot comply with the DWA standards. The recent record of effluent discharge (Figure 14) indicates a median value of ~13 ML/d (~4.7 Mm^3/a) and a 95%ile value of ~17.4 ML/d (~6.4 Mm^3/a). The median discharge equates to 24% of the long-term median annual discharge at station A2H049 (Figure 11). The 2007-'08 summer discharge of ~18 ML/d reflects the rainfall of 831 mm gauged at the WWTW in this period, compared to the 584 mm gauged in the 2008-'09 summer and the average MAP of 659 mm for the last nine hydrological years. The graph also shows the pattern of median daily inflow received by the facility. A comparison of this volume with that discharged to the Blougat Spruit indicates that the latter represented 44% (on average) of the inflow in the period up to September 2008, and 77% (on average) in the more recent period of lesser inflow. The WWTW also discharges a portion of its treated effluent to the adjacent Bergland property for the irrigation of cultivated lawn (section 3.3.2). This amounted to some 1.3 ML/d (on average) in the period July 2007 to June 2009, i.e. the equivalent of 4.5% of the inflow into the plant, and 10% of the median discharge to the Blougat Spruit. The provision of treated effluent to the Krugersdorp Game Reserve, where it was used for game watering and the flood irrigation of kikuyu in the northern portion of the reserve, was curtailed on 08/08/2008 (Brink, 2008). Discharge from the WWTW prior to this amounted to some 0.97 ML/d (on average), the equivalent of 3.3% of the inflow received, and 7% of the discharge released to the Blougat Spruit.

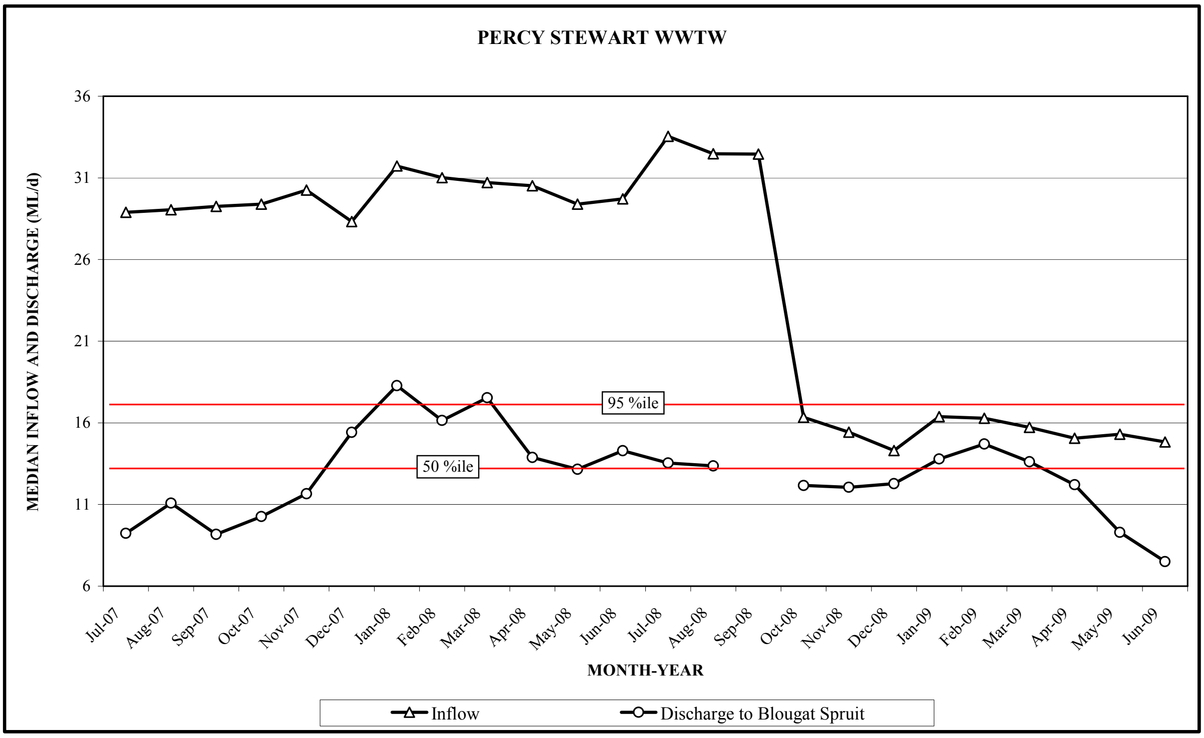

Figure 14. Recent pattern of inflow to and treated effluent discharge from the Percy Stewart WWTW to the Blougat Spruit.

4.1.3 Crocodile River

The Crocodile River drains the north-western quadrant of the Johannesburg Metropole via quaternary catchment A21E. This drainage flows northwards into Hartbeespoort Dam. Although it does not enter the COH WHS (Figure 1), it is included in the study area because it traverses the COH WHS buffer zone and receives the treated wastewater effluent discharged from the Driefontein WWTW operated and managed by Johannesburg Water. This facility collects and treats sewage from the northern areas of Roodepoort and Mogale City, has a treatment capacity of 25 ML/d, and in 2004 treated average flows of 18 ML/d. Gauging station A2H050 is located downstream of this facility (Figure 6). The DWA flow record for station A2H050 (Figure 15) spans a period of 36 years. It provides the monthly discharge statistics presented in Table 23. The annual discharge per hydrological year is shown in Figure 15. The median annual discharge of ~9.5 Mm^3/a_h is half that of the Bloubank Spruit, and represents 5.1% of the Hartbeespoort Dam net capacity. Table 23 shows that the dry winter month of August reflects the lowest CoV value of 69% and the lowest median monthly discharge value of 0.355 Mm^3 (137 L/s), and October the lowest minimum monthly discharge of 0.003 Mm^3 (1.2 L/s).

Table 23. Statistical analysis of monthly discharge data for station A2H050, Crocodile River.

Variable	Month											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Count (n)	34	36	36	36	34	35	36	34	35	34	34	35
Minimum	0.003	0.107	0.196	0.262	0.151	0.157	0.131	0.141	0.153	0.130	0.081	0.039
5%ile	0.064	0.168	0.306	0.333	0.218	0.191	0.191	0.163	0.177	0.173	0.155	0.120
Mean	0.642	0.841	1.116	1.823	2.057	1.762	1.166	0.896	0.711	0.611	0.516	0.488
Median	0.449	0.588	0.845	1.319	1.231	1.292	0.777	0.555	0.460	0.408	0.355	0.404
95%ile	2.014	2.299	2.786	4.104	7.384	4.469	3.293	3.254	2.030	1.456	1.215	1.200
Maximum	2.612	2.469	4.508	10.084	9.583	7.35	4.319	3.674	2.465	2.078	1.407	1.367
SD	0.616	0.657	0.913	1.850	2.379	1.627	1.024	0.911	0.593	0.451	0.356	0.360
CoV (%)	96	78	82	101	116	92	88	102	83	74	69	74
All units are Mm^3 unless otherwise indicated. Analysis excludes months with missing and station rating exceedance data, but includes unaudited (recent) and estimated data.												

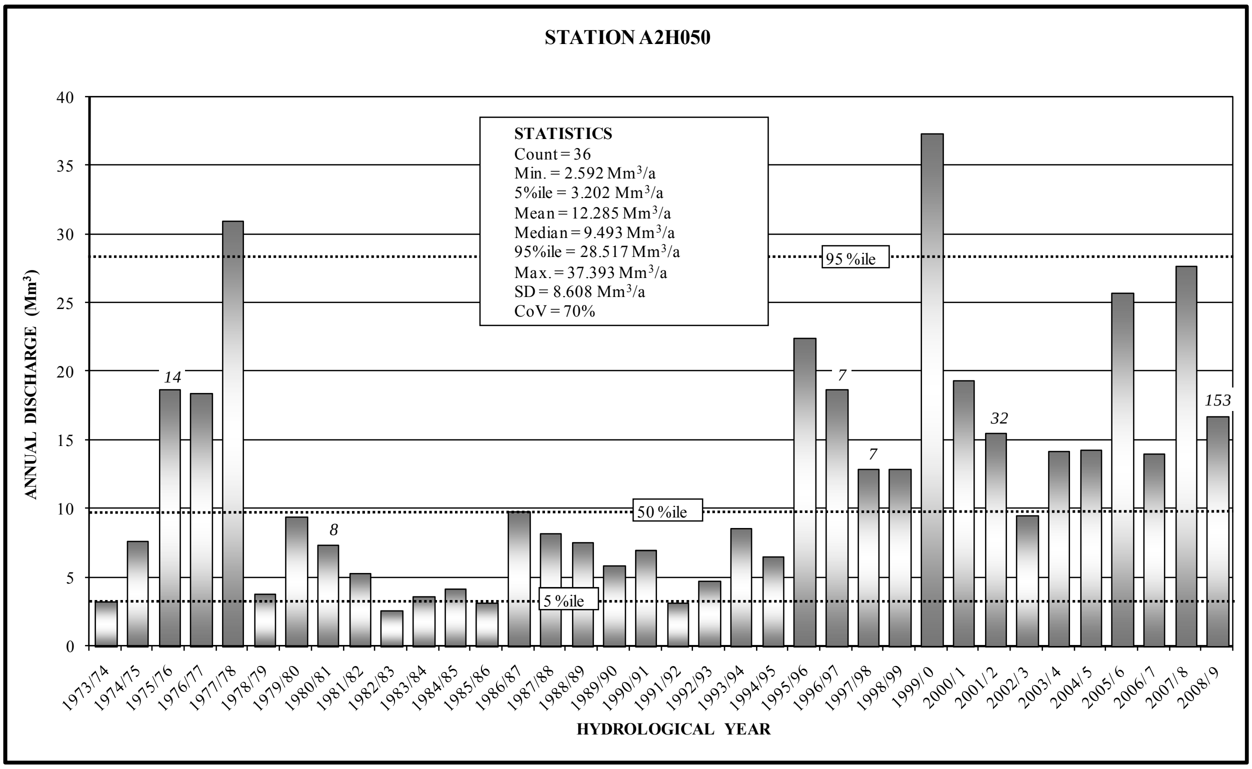

Figure 15. Graph of annual discharge at station A2H050, Crocodile River. Values in italics denote number of days with missing or inaccurate data.

The instantaneous monthly flow pattern at station A2H050 for the complete record is shown in Figure 16. This reveals a comparatively constant minimum value of <0.1 m^3/s for the period up to at least October 1995, followed by a gradual rise since October 2002 to a minimum value of 0.4 m^3/s in October 2008. This is attributed to the 'artificial' contribution from the Driefontein WWTW, Unit 2 of which was commissioned in 1988 with a treatment capacity of 15 ML/d, and increased in 2002 to 25 ML/d.

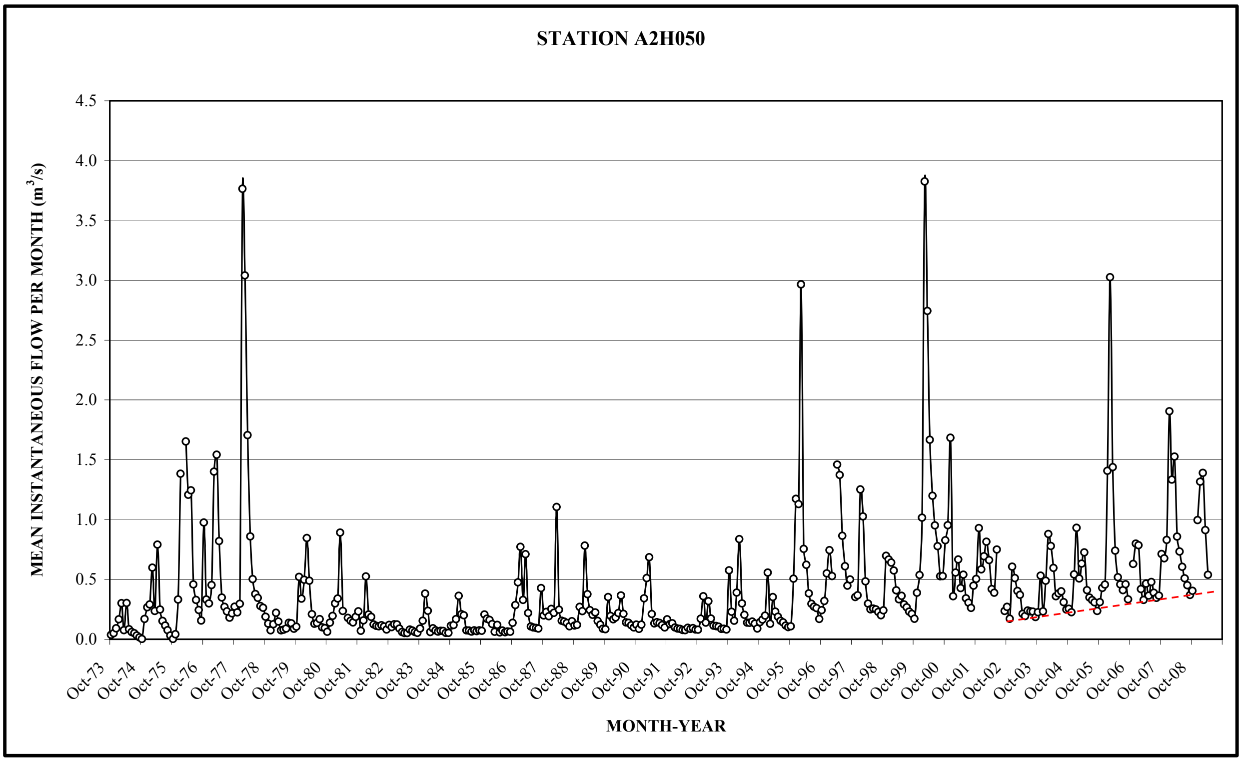

Figure 16. Long-term monthly hydrograph for station A2H050, Crocodile River.

4.2 Surface Water Gains/Losses

4.2.1 Historical Information

In a regional groundwater study by the DWA some 25 years ago (Bredenkamp et al., 1986), flow gaugings made at six locations on the Blougat Spruit, the Riet Spruit and the Bloubank Spruit sought to quantify surface water losses to the karst environment. The results presented in Table 24 are shown graphically in Figure 17. These suggest that flow losses occur more or less uniformly at a rate of ~23 L/s/km along the reach of measurement. Immediately downstream of the Zwartkrans Spring (locality 5, Table 24), the gaugings reflect a surface flow of 258 L/s (22.3 ML/d) in the Bloubank Spruit. This value is replicated in the 2004 water balance for the Zwartkrans Compartment presented by Van Biljon (2006). Subtracting the 13 L/s of locality 4 from this value indicates a spring discharge of 245 L/s. A more detailed 'final' water balance reported by JFA (2006) reflects a discharge of 208 L/s (18 ML/d) in the Bloubank 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*". The former component represents the start of the A-furrow (section 4.3.2) immediately downstream of the Zwartkrans Spring. Although the gain from locality 5 to locality 6 is also reported as a L/s/km value, it is more realistic to regard much of this as concentrated (point source) input from the Plover's Lake Springs (section 8.5.2) and the Kromdraai Spring (section 8.5.3).

Table 24. Flow gauging results *ca.* 1985 along the Blougat, Riet and Bloubank spruits (from Figure 7.1 of Bredenkamp et al., 1986).

<table>
<tr><th rowspan="2">Locality</th><th rowspan="2">Description (provided by PSP)</th><th rowspan="2">Distance (km)</th><th colspan="2">Flow</th><th colspan="2" rowspan="2">Gain/Loss Rate (L/s/km)</th></tr>
<tr><th>L/s</th><th>ML/d</th></tr>
<tr><td>1</td><td>Blougat Spruit downstream of Percy Stewart WWTW</td><td>0</td><td>200</td><td>17.3</td><td rowspan="2">–22.2</td><td>——</td></tr>
<tr><td>2</td><td>Riet Spruit upstream of Oaktree Agricultural Holdings</td><td>4.5</td><td>100</td><td>8.6</td><td rowspan="2">–40.7</td></tr>
<tr><td>3</td><td>Riet Spruit upstream of Sterkfontein Caves</td><td>6.0</td><td>39</td><td>3.4</td><td rowspan="2">–21.7</td></tr>
<tr><td>4</td><td>Riet Spruit opposite Sterkfontein Caves</td><td>7.2</td><td>13</td><td>1.1</td><td rowspan="2">+123</td></tr>
<tr><td>5</td><td>Riet Spruit downstream of Zwartkrans Spring</td><td>9.2</td><td>258</td><td>22.3</td><td rowspan="2">+23.3</td></tr>
<tr><td>6</td><td>Bloubank Spruit downstream of Plover's Lake</td><td>14.0</td><td>370</td><td>32.0</td><td>——</td></tr>
</table>

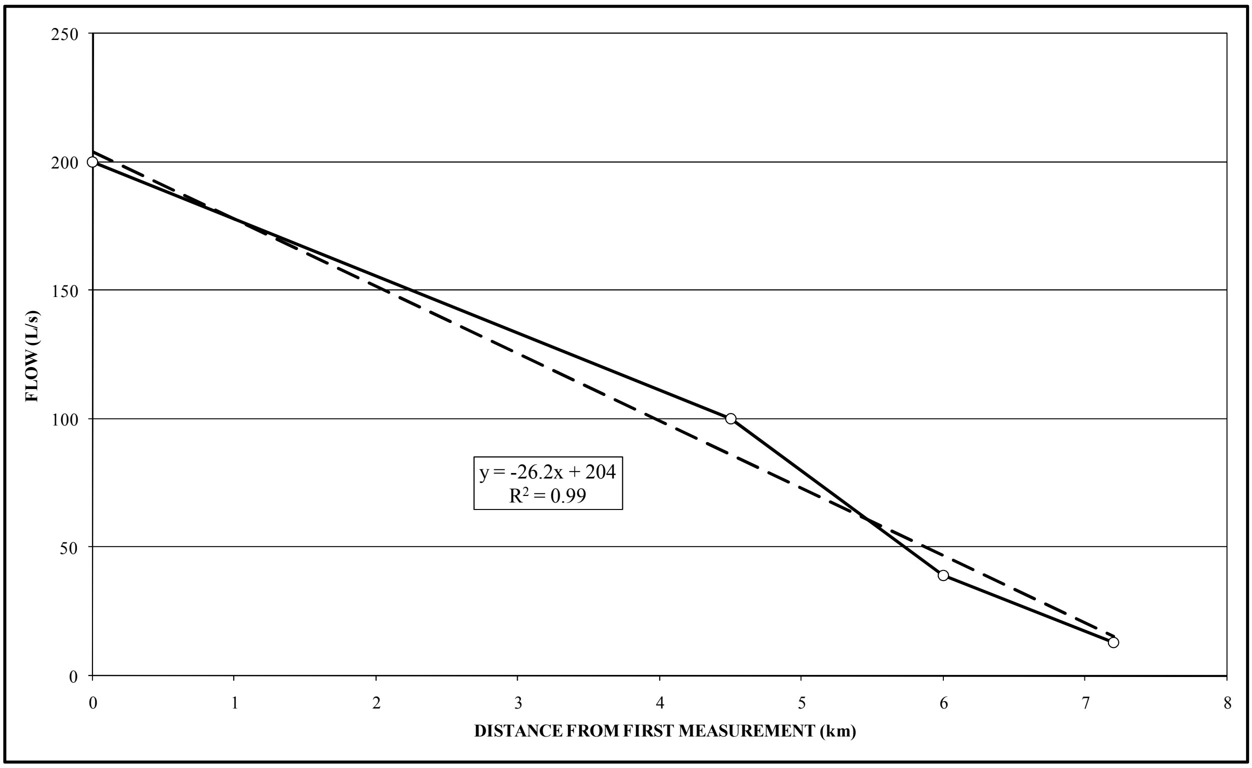

Figure 17. Graph of flow versus distance along the Blougat Spruit and its main stem, the Riet Spruit, upstream of Sterkfontein Caves (data from Bredenkamp et al., 1986).

Under normal flow conditions, the middle reach of the Riet Spruit (between Tarlton and its confluence with the Tweelopie Spruit) is dry, having lost the flow from its upper reaches (sustained mainly by the treated effluent discharge from the Randfontein WWTW[18]) to the westerly Steenkoppies Compartment (Barnard, 1996; Holland et al., 2009) by the time it reaches Tarlton. Whilst Hobbs and Cobbing (2007) verified only the former of these circumstances, Holland et al. (2009) present groundwater quality information that shows a WWTW effluent discharge signature in two samples, one sourced from a borehole located south of Tarlton in the Steenkoppies Compartment, and the other north-east of Tarlton in the Zwartkrans Compartment. The latter instance is provisionally considered to reflect the ingress of surface water bearing a WWTW effluent signature into the Zwartkrans Compartment under abnormally high flow conditions. It is under such circumstances that the upper Riet Spruit carries water past Tarlton in a north-easterly direction across the hydrogeologic boundary between the Steenkoppies and Zwartkrans compartments, whereafter it is lost through infiltration, evaporation, evapotranspiration and swallow holes in the river channel within a distance of ~3.4 km. Such circumstances occurred in early-2009 at the time the sample was collected in January 2009, and again in the first six months of 2010.

Flow rates measured in the 2005 winter at various locations on the Tweelopie Spruit as part of the Harmony Gold (now Rand Uranium) Environmental Impact Assessment (EIA) (JFA, 2006) represent a more recent attempt to quantify surface discharge in this portion of the study area. These measurements record an increase in discharge from 17 L/s (1.47 ML/d) designated as "……. *originating from the mine void* ……..." (i.e. in the locus of mine water decant), to 29 L/s (2.51 ML/d) where the 4x4 trail crosses the spruit at the Oukraal Lapa, to 50 L/s (4.32 ML/d) where the tar road crosses the spruit near the entrance to the lion enclosure, to 59 L/s (5.10 ML/d) at the Aviary Dam outlet in the KGR, before declining to just 9 L/s (0.78 ML/d) immediately upstream of where the N14 national road crosses the spruit. Discounting the possibility of surface water abstraction, these circumstances suggest that 50 L/s (4.32 ML/d) of stream flow were lost to the karst aquifer over a reach ~2 km in length. Although the loss rate of ~25 L/s/km closely matches the ~23 L/s/km obtained from the Bredenkamp (1986) data, it remains to be established whether groundwater resources (primarily springs) in the KGR contribute as much as 42 L/s (3.63 ML/d) to the flow in the Tweelopie Spruit along the reach in question. Especially the almost doubling in flow between the 4x4 crossing and the entrance to the predator sanctuary seems extraordinary in the absence of a known source. Admittedly outdated, especially against the background of known changes in the mine water discharge regime since 2005, these results are reported for the context they bring to similar measurements generated by the current study.

Krige (2009) further illuminates the JFA (2006) set of historical flow measurements for the Blougat Spruit, from the point of discharge of Percy Stewart WWTW effluent to a position 5.86 km downstream on the Bloubank Spruit near the Sterkfontein Caves, reporting a loss rate of 26.6 L/s/km. This is again similar to the ~23 L/s/km obtained from the Bredenkamp (1986) data. Although this result is time-constrained to late-winter 2005, the Percy Stewart WWTW contribution is represented by a mean effluent discharge figure of 19.3 ML/d rather than an 'instantaneous' measurement. Nevertheless, this result is again reported for the context it provides to the current study.

4.2.2 Recent/Current Information

4.2.2.1 Tweelopie/Riet Spruit

Stream flow measurements made at the inlet to the KGR (RU EoP) and the outlet from the KGR (Aviary Dam), as reported by DD Science Laboratory cc. at Western Basin Technical Working Group[19] meetings, unfortunately reflect equivocal results. This is probably attributable to the lower confidence afforded the accuracy of flow measurements at the downsream station (D. Dorling, communication).

[18] Data presented by Holland et al. (2009) indicate that the Randfontein WWTW discharged on average some 3.1 ML/d (~36 L/s) to the upper Riet Spruit in the 5-year period 2004 to 2008.

[19] The Western Basin Technical Working Group (WBTWG) is a forum convened by the Department of Water Affairs to address the issue of acid mine drainage in the West Rand Goldfield. Its bi-annual meetings are attended by a wide range of stakeholders representing environmental lobby groups, mining houses, provincial and national government departments, local and district municipalities and research councils.

The exceptionally wet 2009-'10 summer rainfall season again manifested an over-abundance of surface water discharge in the Tweelopie Spruit. This was driven mainly by the re-juvenation in late-January 2010 of active mine water decant in the mine area upstream of the Krugersdorp Game Reserve. The resulting discharge, comprising a mixture of treated mine water from the HDS plant and raw mine water subjected to intense in-stream liming at the point of release, again peaked at ~50 ML/d as it did in early-2008 under similar circumstances.

Field (2006) recognizes estimations of leakage rate through a streambed by any means other than synoptic discharge measurements (SDM) as a poor substitute for actually calculating flow differences between upstream and downstream reaches based on discharge measurements. Further, that the error will be unquantifiable and will range from insignificant to severe in all instances. The SDM data were obtained using a current meter[20] applied in two basic scenarios, namely (a) the classical cross-sectional flow section (width x depth x velocity) method (Plate 4) and (b) the cross-sectional pipe section (chord length[21] x velocity) method. Computation of the data was facilitated through use of an Excel spreadsheet algorithm.

Plate 4. SDM (synoptic discharge measurement) with current meter in progress at site F11S12, showing both the relatively 'clean' cross-sectional area of flow (from bottom left to right foot of meter operator) and the laminar nature of flow over the crest of the weir. (Photo: Phil Hobbs).

The results of flow measurements carried out on two occasions at a number of localities (Figure 18) in the downstream receiving drainages are presented in Table 25 and Table 26. These indicate a general loss of water down to locality 6, followed sequentially by a gain in water to locality 7 and a substantial loss of water to locality 8. Whereas localities 1, 5, 6 and 7 represent flow in the Tweelopie Spruit, locality 8 represents flow in the lower reaches of the Riet Spruit immediately before its confluence with the Blougat Spruit tributary. Flow measurements carried out at localities 6 and 7 on 19/08/2010 and 19/11/2010 similarly reflect a gain of +3.8 and +1.2 ML/d between these localities on these occasions, respectively.

Table 25. Change in stream flow with distance downstream of the mine area on 05/02/2010.

<table>
<tr><th colspan="2" rowspan="2">Locality</th><th colspan="2">Distance (m)</th><th colspan="3">Flow</th></tr>
<tr><th>Segmental</th><th>Cumulative</th><th>ML/d</th><th colspan="2">ΔML/d (+ gain; – loss)</th></tr>
<tr><td>1</td><td>KGR Inflow (raw & treated mine water)</td><td>0</td><td>0</td><td>40</td><td></td><td rowspan="2">−8</td></tr>
<tr><td>6</td><td>Aviary Dam inlet in KGR</td><td>4905</td><td>4905</td><td>32</td><td rowspan="2">+3</td></tr>
<tr><td>7</td><td>KBW Dam outlet at N14 (F11S12)</td><td>1540</td><td>6445</td><td>35</td><td rowspan="2">–28</td></tr>
<tr><td>8</td><td>Riet Spruit at Malmani Road (MRd1)</td><td>3900</td><td>10 345</td><td>7</td><td></td></tr>
</table>

[20] Flow velocity determined with an OTT C20 current meter with OTT Z400 signal counter set and impellor # 1-239627 (diameter = 125 mm, pitch = 0.25 m) mounted on a 20 mm diameter rod.

[21] Height of water flow through circular pipe section of known diameter.

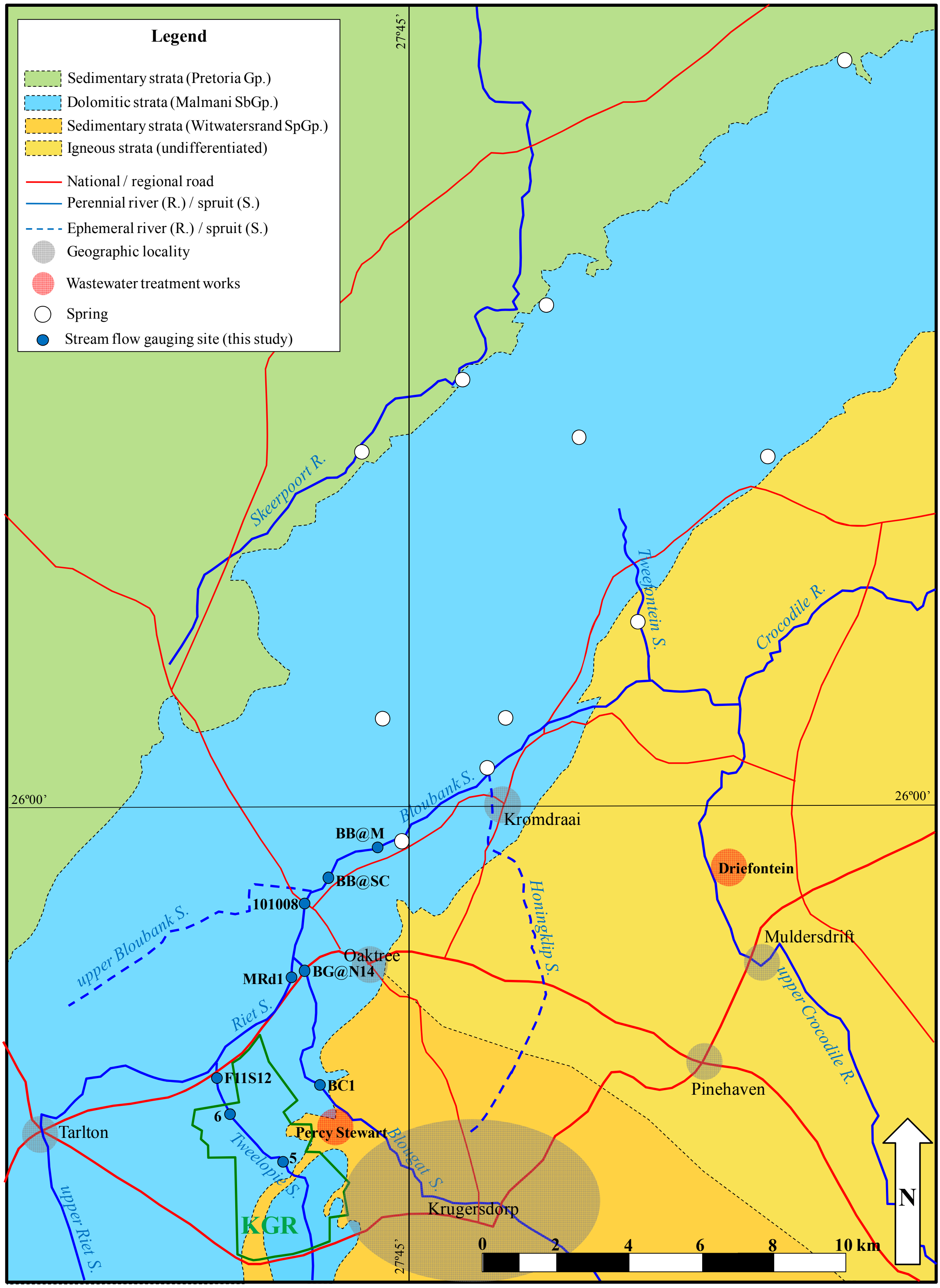

Figure 18. Stream flow gauging sites employed in this study.

Table 26. Change in stream flow with distance downstream of the mine area on 01/04/2010.

Locality		Distance (m)		Flow		
		Segmental	Cumulative	ML/d	ΔML/d (+ gain; − loss)	
5	4x4 Track at Oukraal Lapa in KGR	2815	2815	52		−16
6	Aviary Dam inlet in KGR	2090	4905	34	+6	
7	KBW Dam outlet at N14 (F11S12)	1540	6445	40		−30
8	Riet Spruit at Malmani Road (MRd1)	3900	10 345	10		

Measurements on 16 occasions (Table 27) at localities 7 (F11S12) and 8 (MRd1/MRd2[22]) quantify the magnitude of surface water loss to the receiving karst environment even further. Sites MRd1/MRd2 only witness surface flow under exceptional discharge conditions[23], since under 'normal' circumstances all of the discharge entering the Riet Spruit at Glen Almond via the Tweelopie Spruit has been lost primarily to recharge of the underlying karst aquifer before reaching this location. For example, flows of 11.9 and 14.9 ML/d were recorded at the upstream station F11S12 on 09/09/2009 and 22/09/2009 respectively, with no flow being observed at the downstream station MRd1 on these dates (Table 27).

Table 27. Quantification of stream flow loss rate in the Riet Spruit under extreme flow conditions.

Locality	Date	Electrical Conductivity (mS/m)	pH	Flow (ML/d)	Loss Rate	
					ML/d	L/s/km[(1)]
7 (F11S12)	09/09/2009	—	—	11.9	11.9	34
8 (MRd1)		—	—	0		
7 (F11S12)	22/09/2009	322	6.0	14.9	14.9	43
8 (MRd1)		—	—	0		
7 (F11S12)	05/02/2010	389	3.9	35.2	27.9	81
8 (MRd1)		358	4.1	7.3		
7 (F11S12)	16/02/2010	339	4.2	31.6	25.9	75
8 (MRd1)		335	4.2	5.7		
7 (F11S12)	23/02/2010	379	4.1	26.2	22.2	64
8 (MRd1)		383	3.9	4.0		
7 (F11S12)	09/03/2010	379	4.1	32.6	23.2	67
8 (MRd1)		353	4.0	9.42		
7 (F11S12)	01/04/2010	374	3.6	40.4	30.1	87
8 (MRd1)		358	3.4	10.3		
7 (F11S12)	14/04/2010	358	3.7	25.8	20.1	58
8 (MRd1)		347	3.6	5.7		
7 (F11S12)	06/05/2010	408	3.2	43.7	32.0	93
8 (MRd1)		420	3.3	11.7[(2)]		
7 (F11S12)	18/05/2010	335	5.5	35.7	24.7	71
8 (MRd1)		356	4.4	11.0[(2)]		
7 (F11S12)	09/06/2010	370	4.4	32.1	21.6	63
8 (MRd1)		373	4.5	10.5[(2)]		
7 (F11S12)	07/07/2010	374	4.0	29.9	23.7	69
8 (MRd1)		376	3.9	6.2		
7 (F11S12)	27/07/2010	407	3.7	31.6	25.1	73
8 (MRd1)		395	4.1	6.5		
7 (F11S12)	19/08/2010	383	2.6	25.8	20.5	59
8 (MRd1)		383	2.5	5.3		
7 (F11S12)	05/10/2010	307	3.0	13.8	13.4	39
8 (MRd2)		335	2.7	0.4		
7 (F11S12)	19/11/2010	338	2.8	22.2	18.8	54
8 (MRd2)		333	2.8	3.4		
(1) Based on a distance of 4 km between localities.						
(2) These measurements include discharge in second diversionary flow path.						

22 MRd2 is a new culvert, constructed to receive diverted surface water flow, commissioned in September 2010.

23 Caused by excessive and uncontrolled AMD overflow from the mining area together with excess surface runoff during extended periods of very high rainfall.

Table 27 indicates the magnitude of surface water loss occurring between stations F11S12 and MRd1, a distance of ~4 km, as measured on 16 occasions in the period September 2009 to November 2010. These data are shown graphically in Figure 19, and identify the Tweelopie Spruit as a source of allogenic recharge to the Zwartkrans Compartment karst system.

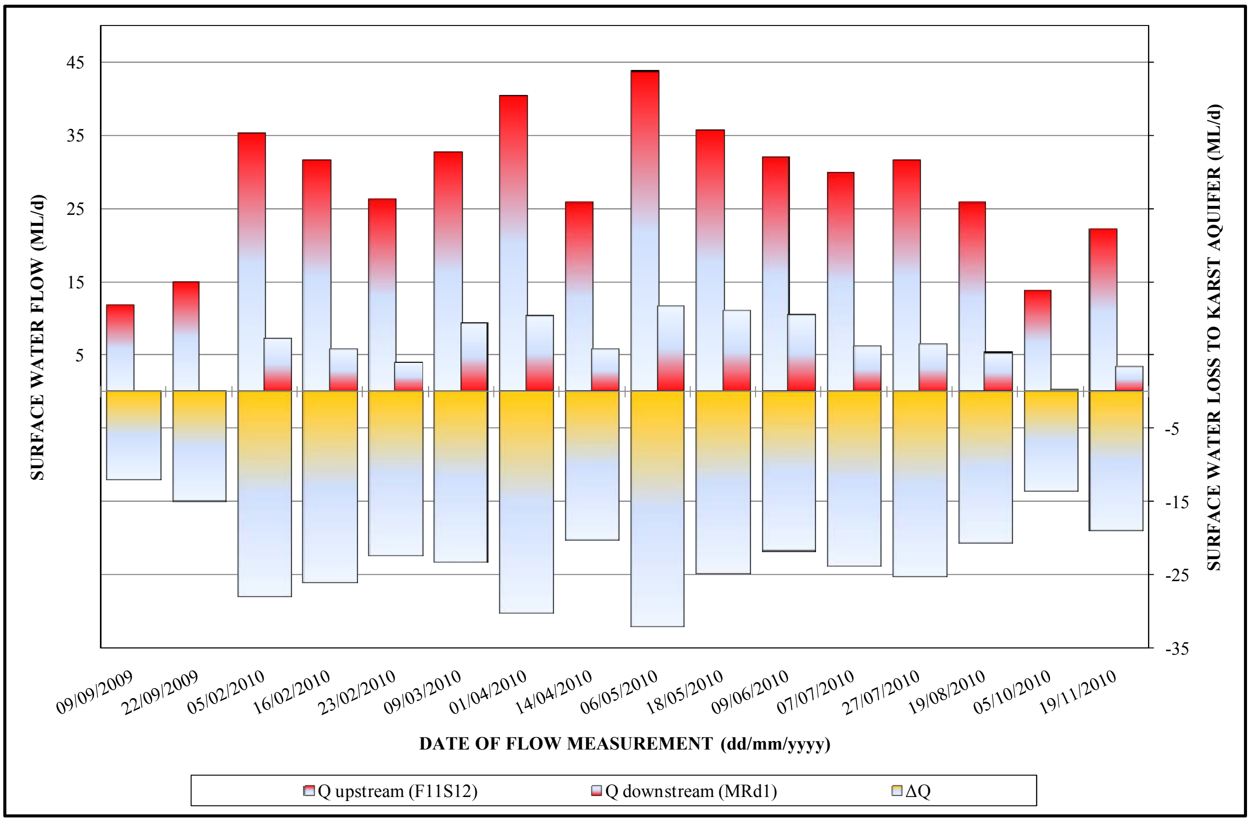

Figure 19. Graphical representation of stream flow and losses to the karst aquifer in the lower Riet Spruit valley.

It is acknowledged that not all of the water loss is to the karst aquifer, a percentage thereof being lost through evaporation and, perhaps more so, to evapotranspiration. This percentage is poorly quantifiable at best, but is considered small under circumstances where the depth to groundwater level still largely exceeds 10 m below surface (Table 64) along the trace of the Riet Spruit. The measured surface water losses equate to values of between ~60 and ~90 L/s/km (Table 27). This is three to four times the typical leakage rate per kilometre reported in earlier studies (section 4.2.1).

Figure 19 suggests that a threshold flow value exists at the upstream station F11S12. Below this value, all surface flow is lost to the karst aquifer and no flow passes the downstream stations MRd1/MRd2. Conversely, flow that exceeds the threshold value at F11S12 results in surface water flow past stations MRd1/MRd2. This observation is explored in Figure 20, which indicates that the ‘threshold’ value is in the order of 15 ML/d. The correlation coefficient (R^2) of 0.89 is quite reasonable, and suggests that the veracity of the flow measurements is acceptable. These circumstances also suggest that the ‘absorptive capacity’ and, therefore, also the ‘transmissive capacity’ of the epikarst along the reach of the Riet Spruit between stations F11S12 and MRd1/MRd2 functions with 100% efficiency at discharges of up to ~15 ML/d. Above this ‘threshold’, the ‘absorptive capacity’ is exceeded. The calcite saturation index (SI_c) of the recently infiltrating mine water falls in the range −3.2 to −4.0, reflecting undersaturation of the water in regard to this mineral. It is enticing to equate these circumstances to the conditions identified by Worthington and Ford (2009) whereby water that is undersaturated with regard to calcite enters a karst aquifer via point recharge from a sinking stream carrying a high discharge. Of concern in this regard, is that Worthington and Ford (2009) indicate that these circumstances typically result in the concentrated dissolution of carbonate strata in the receiving karst aquifer. This possibility is explored in greater detail in section 10.1.

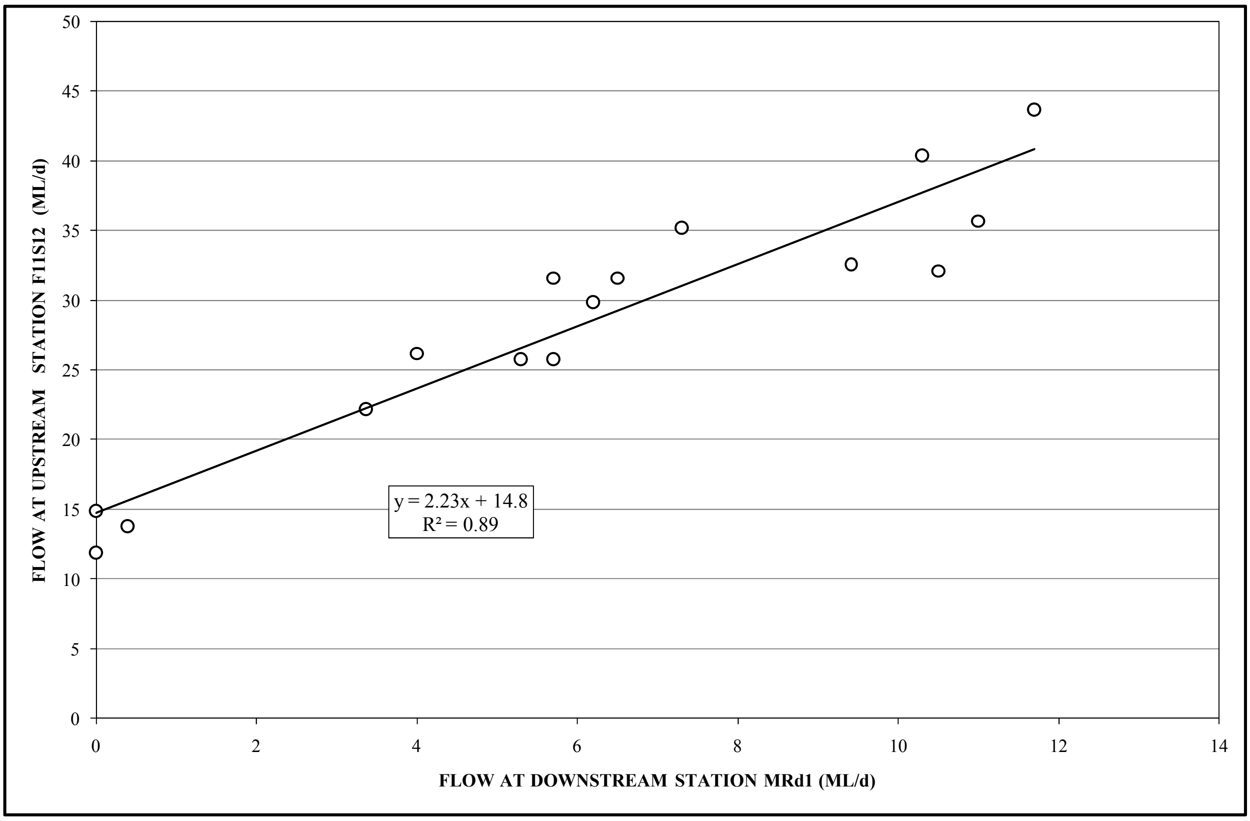

Figure 20. Correlation of stream flow measurements at the upstream (F11S12) and downstream (MRd1) monitoring stations in the lower Riet Spruit valley.

4.2.2.2 Blougat Spruit

Flow measurements carried out at two stations on the Blougat Spruit on 18/05/2010 corroborate the figures reported by Bredenkamp et al. (1986) for flow losses downstream of the Percy Stewart WWTW. The upstream station BC1 is a causeway across the spruit on the Bergland Instant Lawn property. The causeway is located ~1.1 km downstream of the Percy Stewart WWTW effluent discharge point into this drainage. The downstream station BG@N14 is located where the N14 national road crosses the Blougat Spruit. The distance between the two stations is ~3.5 km. The measurement results are given in Table 28. The loss rate of ~23 L/s/km is similar to the ~22 L/s/km reported by Bredenkamp et al. (1986) between localities 1 and 2 (Table 24). These circumstances similarly identify the Blougat Spruit as a source of allogenic recharge to the Zwartkrans Compartment karst system.

Table 28. Outcome of stream flow measurements in the Blougat Spruit on 18/05/2010.

Locality	Description	Flow[1]		Loss Rate (L/s/km)
		L/s	ML/d	
BC1 (upstream)	Causeway on the Bergland Lawn property downstream of the Percy Stewart WWTW (same as BGS1 in Table 7)	655	56.6	−23.1
BG@N14 (downstream)	Intersection of the Blougat Spruit with the N14 national road	574	49.6	

(1) Flow measurement based on the cross-sectional flow method using the average of six measured surface velocities of styrofoam flotsam over known distances. The relatively shallow flow depth (8 to 15 cm) negates reduction of the calculated flow values by 25% to account for a mean velocity that is less than the surface velocity (Brassington, 1998).

4.2.2.3 Bloubank Spruit

This drainage rises on dolomite in the western portion of the Zwartkrans Compartment, and traverses only dolomite in its path to the confluence with the Riet Spruit at Oaktree. Although it is an ephemeral drainage upstream of this juntion, these circumstances identify it as a source of autogenic recharge to the

Zwartkrans Compartment. A 17.7-km long profile spanning an elevation difference of 150 m, starting on the Tweelopie Spruit in the vicinity of Kemp's Cave in the Krugersdorp Game Reserve and ending near the Nedbank Olwazini Estate Leadership and Management Development Centre downstream of Kromdraai, indicates an average gradient of 0.0085 representing a fall of 1 m every 118 m. Flow measurements carried out in this drainage at localities bracketing (i.e. located upstream and downstream) the Sterkfontein Caves indicate an increase in surface water discharge rather than a loss (as observed further upstream). The outcome of two sets of measurements reflecting this are presented in Table 29. Note that the September 2009 value of 260 L/s for the downstream station closely approximates the 258 L/s reported by Bredenkamp et al. (1986) for locality 5 (Table 24) located downstream of the Zwartkrans Spring. Since the BB@M locality is located upstream of the Zwartkrans Spring, this observation indicates that recent late-winter flow in the Bloubank Spruit upstream of the Zwartkrans Spring is considerably greater than the historical observation shows. Consider also that the mid-1980s experienced one of the longer and more severe drought periods in the region, broken only in 1986.

Table 29. Outcome of stream flow measurements in the Bloubank Spruit.

Date	Locality	Description	Distance (km)	Flow[(1)]		Gain Rate
				L/s	ML/d	
09/09/2009	101008 (upstream)	Intersection with R563 regional road	2.95	225[(2)]	19.5[(2)]	+12 L/s/km +3.0 ML/d
	BB@M (downstream)	Intersection with Danielsrust road downstream of Sterkfontein Caves		260[(3)]	22.5[(3)]	
18/05/2010	BB@SC (upstream)	Intersection with Swartkrans fossil site road upstream of Sterkfontein Caves	2.2	311[(3)]	23.9[(3)]	+73 L/s/km +16.9 ML/d
	BB@M (downstream)	Intersection with Danielsrust road downstream of Sterkfontein Caves		472[(3)]	40.8[(3)]	

(1) Flow measurements carried out with the current meter described in footnote 20 (section 4.2.2.1).
(2) Flow measurement based on the cross-sectional flow method (width x depth x velocity).
(3) Flow measurements based on the cross-sectional pipe method (chord length x velocity).

Although damage to the outlets of two of the three culverts at the common downstream locality (BB@M) influence the accuracy of the 18/05/2010 SDM measurements, the margin of error is not considered greater than the observed difference in flow. This damage had not yet occurred on 09/09/2010, generating greater confidence in these SDM measurements at station BB@M.

On the basis of groundwater level and streambed elevation information, it is considered probable that these surfaces intersect at an elevation of ~1436 m amsl in the vicinity of the Makiti Wedding and Conference Centre property north-east of the Sterkfontein Caves. The significant recent gain in surface flow at the downstream locality (Table 29) also provides an explanation for the increase in EC and decrease in pH values observed at this locality in the period of maximum recent mine water impact (Figure 21). These trends are attributed to the significant loss of poor quality water[24] from the Riet Spruit into the karst aquifer upstream of the Oaktree area, and which inflow resurfaces in the Bloubank Spruit at the downstream end of the Zwartkrans Compartment. Although the elevated salinity will necessarily manifest itself in the lower reaches of the Bloubank Spruit, the more recent decline to nearly 'normal' values must not be overlooked. It is therefore premature to gauge the extent to which recent elevated EC values will impact on the long-term 95%ile EC value of 66 mS/m observed at station A2H049 (Table 38). This also holds true for the most recent impacts associated with the very high flow conditions experienced in mid-December 2010 (see Plate 7). As is evident in Figure 21, these circumstances precipitated the highest salinity and lowest pH values recorded at station BB@M in the course of this study. The fate of mine water discharge in the receiving drainages is discussed in greater detail in section 5.5.

The contribution of surface water losses in the Blougat Spruit (section 4.2.2.2) adds another dimension to the quantity and quality of the groundwater resources in this portion of the Zwartkrans Compartment. A particular concern relates to the recent performance of the Percy Stewart WWTW, in particular the poor bacteriological quality of the treated effluent discharged into the Blougat Spruit by this facility (section 5.1.2.2). These circumstances have resulted in bacterially contaminated surface water entering the karst

[24] Mainly water that originates in the mine area located in the upper reaches of the Tweelopie Spruit.

aquifer along the lower reaches of the Blougat Spruit at a nominal rate of 7 ML/d (Table 28). Whilst the introduction of bacterial contamination into a groundwater resource is an environmental tragedy, it is also possible that such contamination might in fact provide an energy (carbon) source that promotes the natural chemical process known as bacterial sulphate reduction (BSR). This process has relevance for the potentially remedial properties it exhibits toward the acid mine water impact on the karst aquifer in the zone of convergence. Further discussion of this topic is presented in section 10.2.

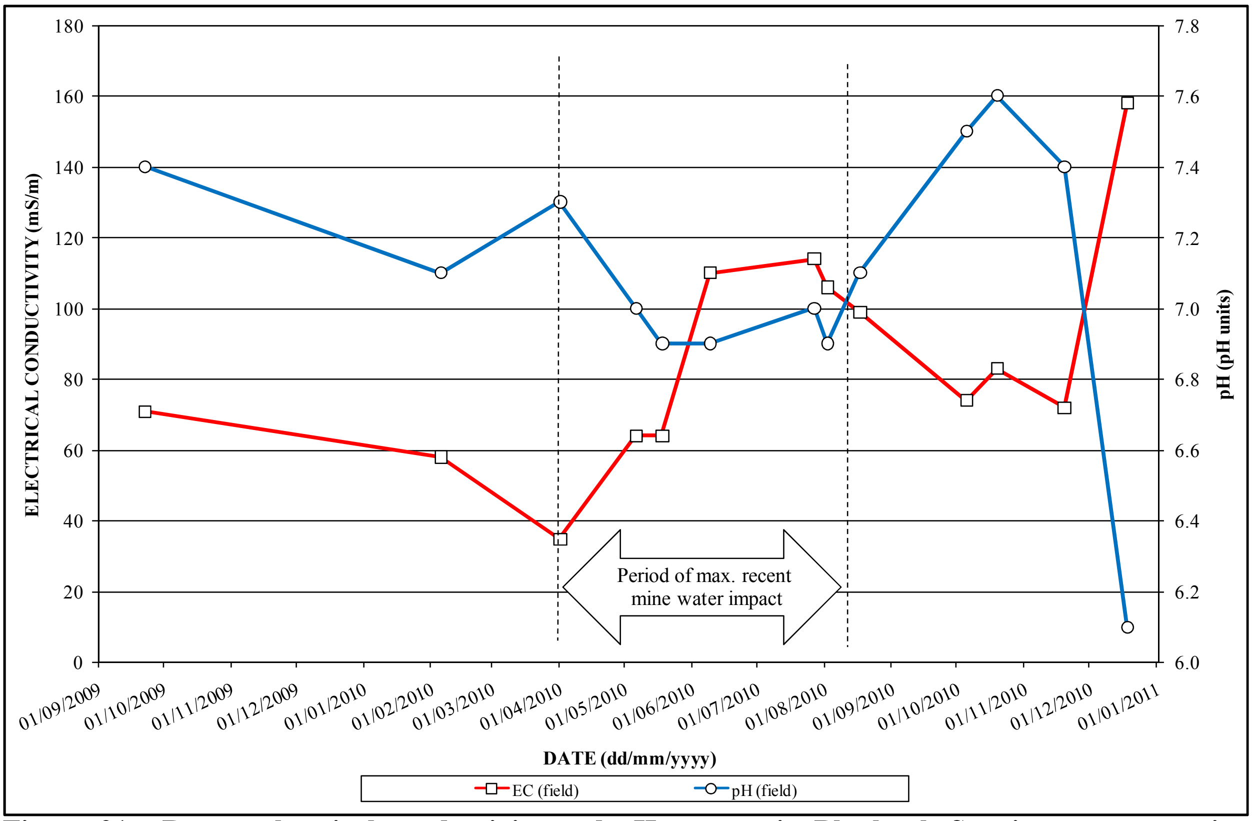

Figure 21. Recent electrical conductivity and pH pattern in Bloubank Spruit water at station BB@M downstream of Sterkfontein Caves.

4.3 Surface Water Use

4.3.1 WARMS Data

From an assessment of water use information sourced from the DWA Water Authorisation and Registration Management System (WARMS), Holland and Cobbing (2008) report a total surface water use of 3.5 Mm^3/a as being registered for mainly agricultural use in the Zwartkrans Compartment. Bredenkamp et al. (1986) and Van Biljon (2006) earlier report values of 5.52 and 6.62 Mm^3/a.

4.3.2 Canals

An important component of surface water use in the study area, in particular the Bloubank Spruit system, is the network of canals/furrows[25] that distribute water to riparian users. Due to their trans-property nature, the following canal systems have been identified in the study area.

- The defunct canal that starts at Glen Almond on the farm Sterkfontein 173IQ and follows the right bank[26] of the drainage for a distance of ~1.7 km, ending on Ptn. 8/2 of Sterkfontein 173IQ.

[25] The PSP recognizes a canal as a properly designed, engineered and constructed water transfer structure over a substantial distance traversing numerous properties, and a furrow as a simple hand-dug trench serving a similar but more local purpose over a considerably shorter distance typically limited to an individual property.
[26] By convention, the bank to the right of an observer facing downstream.

- The canal system managed by the Kromdraai Irrigation Board, as described by Mr M. Gomes[27] (personal communication). This system comprises the following components.

  - The canal that starts immediately downstream of the Zwartkrans Spring on the farm Zwartkrans 172IQ, and follows the right bank for a distance of ~7.3 km, ending in a state of disrepair on the Nedbank Olwazini Estate Leadership and Management Development Centre (LMDC). This canal is known as the **A-furrow** (Plate 5), and serves 18 properties. The allocation of water from the canal is made on a rotational basis that at any one time provides three properties with 70 L/s each for two days per week[28], and two half-days every other week. Theoretically, therefore, it carries an absolute minimum permanent discharge of 210 L/s fed by the Zwartkrans Spring. The discharge measured at Ptn. 8 of Kromdraai 520JQ on 27/07/2010 was ~154 L/s. A second measurement carried out further upstream at Ptn. 5 on 13/08/2010 returned a slightly higher value of ~176 L/s. Both measurements are in reasonable agreement with the 172 L/s reported by JFA (2006) (section 4.2.1). The very high flow conditions in mid-December 2010 not only caused significant damage to this furrow, but also silted up the sluice gate at its entrance, cutting off flow in the furrow.

  - A second canal, known as the **B-furrow**, no longer exists. This structure started at the junction of the Honingklip Spruit and the D374 road immediately south of the Kromdraai Gold Mine, and followed a northerly route to the east of the road for a distance of ~1.6 km.

Plate 5. View of the A-furrow on Ptn. 8 of Kromdraai 520JQ, looking upstream. Flow measured at ~154 L/s on 27/07/2010.

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[27] Current Chairman of the Kromdraai Irrigation Board.

[28] Based on a 6-day week, respecting Sunday as the Christian Sabbath, day of rest.

- The canal that starts immediately upstream of the Nedbank Olwazini Estate LMDC, and follows the right bank of the Bloubank Spruit for a distance of ~3.8 km, re-entering the spruit on the Kloofzicht Lodge Estate. The 'management' of this canal does not fall within the ambit of the Kromdraai Irrigation Board. The LMDC draws water from this canal for on-site treatment in a purification plant to potable quality for on-site use in the average amount of 40 $m^3/d \equiv 14\ 600\ m^3/a$ (H. Carpenter, personal communication). A water use licence application to the DWA for such use has been submitted and the outcome pending as of November 2010. The estate also operates its own wastewater treatment plant, and currently uses the treated wastewater effluent for landscape irrigation purposes. It is intended, however, that this water be returned to the Bloubank Spruit once approval from the DWA for such 'water use' is obtained. Since this canal/furrow also passes through a number of dams, many of which are stocked with trout, it is evident that this water supply function probably represents the main purpose of this structure.

The Skeerpoort River also feeds a canal that starts immediately upstream of where the D400 road crosses this drainage on the farm Hartebeesthoek 498JQ. This canal system, however, does not influence the discharge regime of the Skeerpoort River within the study area, and is therefore not discussed further.

5 CHEMICAL HYDROLOGY

5.1 Surface Water Chemistry

5.1.1 Skeerpoort River

Water quality in this drainage is monitored by the DWA at station A2H034 (Figure 6) shortly before its confluence with the Magalies River. An evaluation of this record yields the information presented in Table 30. It is evident that the SANS (2006) recommended limit for Class 1 drinking water is easily met in respect of the 95%ile value of each chemical parameter reported. A high degree of confidence is afforded the analytical results on the basis that the median (and mean) electrical balance values fall well within the ±5% limit (i.e. 95 to 105%) that defines an acceptable error margin for fresh water. The low measure of variability in the chemical composition of Skeerpoort River water illustrated in Figure 22 reveals the constancy that is inherent in the source (primarily dolomitic groundwater) of this water. Also evident is the dominant MgCa-HCO_3 composition of this water.

Table 30. Water chemistry statistics for station A2H034, Skeerpoort River.

Variable	Statistical Parameter for the period of record 01/1976 to 10/2008							SANS 241: 2006[(1)]
	n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)	
pH	1406	7.45	—	8.17	8.5	0.36	4.4	5.0 – 9.5
EC (mS/m)	1496	28.5	32.4	32.7	35.4	2.58	8.0	<150
TDS (mg/L)	1278	225	261.7	265.0	282.4	18.9	7.2	<1000
Ca (mg/L)	1299	25.7	31.4	32.0	34.7	3.2	10.1	<150
Mg (mg/L)	1299	18.4	21.2	21.5	23.4	1.8	8.4	<70
Na (mg/L)	1165	2.2	3.1	2.9	4.4	1.0	31.6	<200
K (mg/L)	1298	0.15	0.64	0.45	1.55	0.9	138.0	<50
Cl (mg/L)	1298	1.5	4.5	4.4	8.7	2.2	49.2	<200
SO_4 (mg/L)	1108	4.2	8.0	7.2	14.5	3.8	47.2	<400
HCO_3 (mg/L)	1308	153.5	189.7	193.0	208.4	16.9	8.9	n.s.
NO_3+NO_2 (mg N/L)	1378	0.22	0.71	0.65	1.28	0.36	51.4	<10
Si (mg/L)	1351	4.9	6.2	6.2	7.4	1.3	21.5	n.s.
Electrical balance (%)	996	−3.4	0.8	0.5	6.0	3.2	426	±5
(1) Recommended limit for Class 1 drinking water quality.								

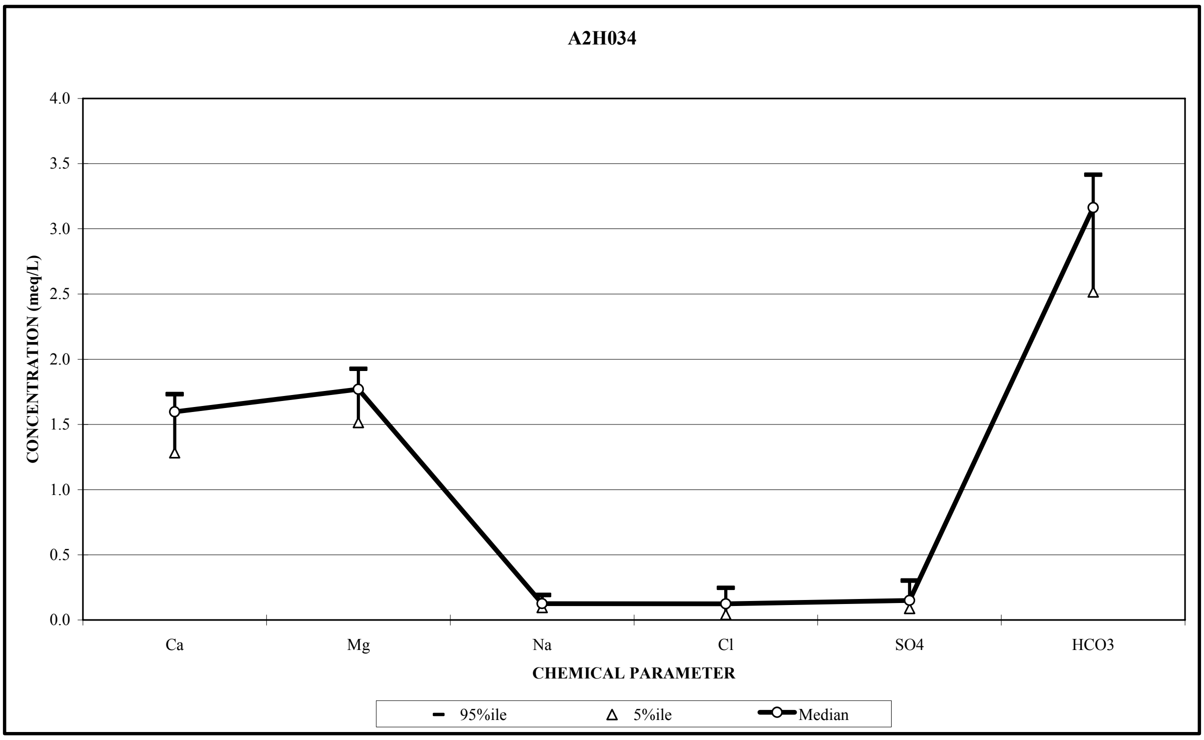

Figure 22. Long-term variability of Skeerpoort River water chemistry.

Monthly water quality monitoring by the DWA at station A2H035Q01 some 6 km upstream on the farm Hartebeesthoek 498JQ in the middle reaches of the Skeerpoort River was discontinued in July 1982 after only some 30 months, followed by four opportunistic analyses, one each in late-1986, early-1996, late-1998 and early-1999. These data have not been evaluated in this study.

5.1.2 Bloubank Spruit system

5.1.2.1 Tweelopie Spruit

The monitoring of surface water chemistry (quality) in the study area is heavily weighted in favour of the headwaters of the Bloubank Spruit system. Especially the Tweelopie Spruit, which encompasses the locus of mine water decant in its upper reaches, is intensively monitored by the DWA and Rand Uranium (RU) (sections 3.1.2 and 3.3.1.2). The quality of water in the Tweelopie Spruit is monitored by RU at the point of discharge (EoP) into the stream immediately upstream of the Krugersdorp Game Reserve (KGR), and by the DWA at station F11S12 shortly before its confluence with the Riet Spruit north (downstream) of the KGR. These circumstances provide a record of the treated mine water quality discharge as well as a record of the surface water quality that enters the karst environment of the Zwartkrans Compartment. The raw and treated (EoP) mine water chemistry is summarized in Table 31 and illustrated in Figure 23, Figure 24 and Figure 25 for the parameters TDS, EC and SO_4, respectively.

Table 31. Water chemistry statistics for raw and treated (EoP) mine water, Tweelopie Spruit.

Variable	Statistical Parameter for the period of record 04/2005 to 09/2009														SANS 241: 2006[(1)]
	n		5%ile		Mean		Median		95%ile		Std Dev		CoV (%)		
pH	231	202	**3.1**	**2.9**	—	—	**3.5**	7.1	**4.4**	**10.8**	0.4	2.5	11	36	5.0 – 9.5
EC (mS/m)	231	202	**436**	**294**	**507**	**401**	**510**	**402**	**583**	**501**	48	69	10	17	<150
TDS (mg/L)	231	201	**4945**	**2990**	**6467**	**4199**	**6580**	**4210**	**7525**	**5530**	785	777	12	19	<1000
Na (mg/L)	222	196	78	73	105	150	97	134	141	**270**	60	68	57	46	<200
Cl (mg/L)	223	194	25	30	46	46	40	44	76	72	19	13	42	29	<200
SO_4 (mg/L)	231	201	**3070**	**1780**	**3971**	**2615**	**4010**	**2680**	**4630**	**3240**	545	510	14	20	<400
Fe (mg/L)	231	202	**350**	0.1	**699**	**34.5**	**697**	**0.5**	**999**	**173**	209	99	30	286	<0.2

(1) Recommended limit for Class 1 drinking water quality.
Shaded columns associated with raw mine water.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

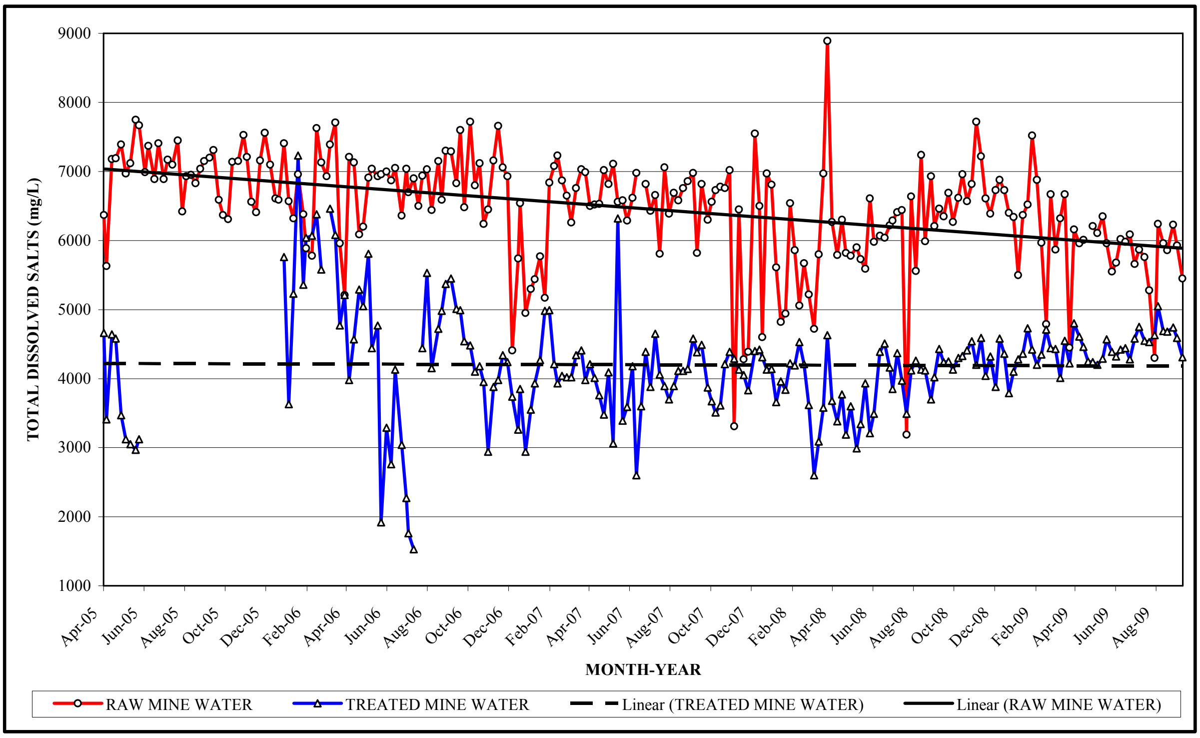

Figure 23. Long-term pattern and trend of tds in raw and treated/discharged mine water.

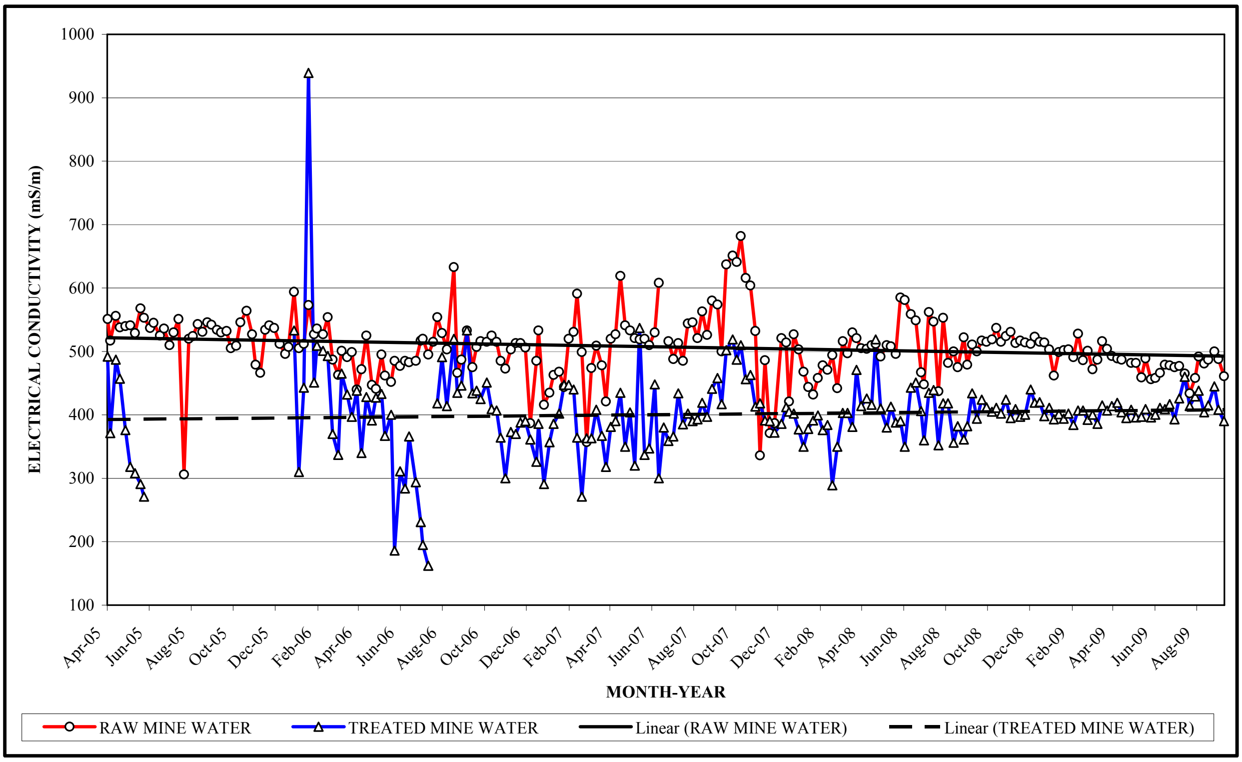

Figure 24. Long-term pattern and trend of EC in raw and treated/discharged mine water.

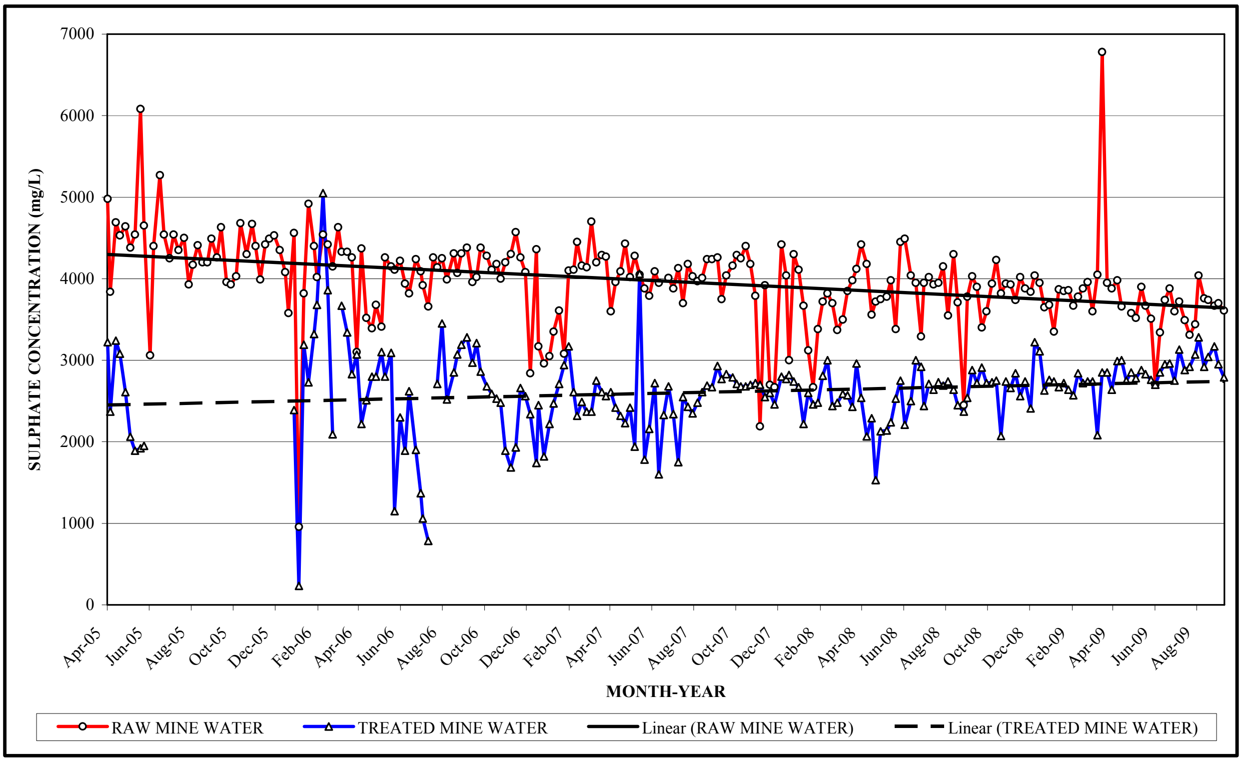

Figure 25. Long-term pattern and trend of SO_4 in raw and treated/discharged mine water.

The extent to which all of the reported treated mine water parameters except Na and Cl exceed the SANS (2006) Class 1 drinking water limit is indicated in Table 31. It is evident from the graphs that the raw mine water shows a persistent long-term decline in TDS (less marked in the case of EC) and SO_4. The trend in the treated (and discharged) mine water, on the other hand, is a slight but gradual increase in SO_4. The marked difference in mean and median Fe values in treated mine water (Table 31) is accounted for by the bias introduced by the pre-August 2006 concentrations as illustrated in Figure 26. Figure 26 also reveals a persistent long-term decline in the Fe concentration of raw mine water, as well as the considerable measure of success achieved by Rand Uranium in reducing the Fe levels in raw mine water to acceptable levels in the treated and discharged mine water.

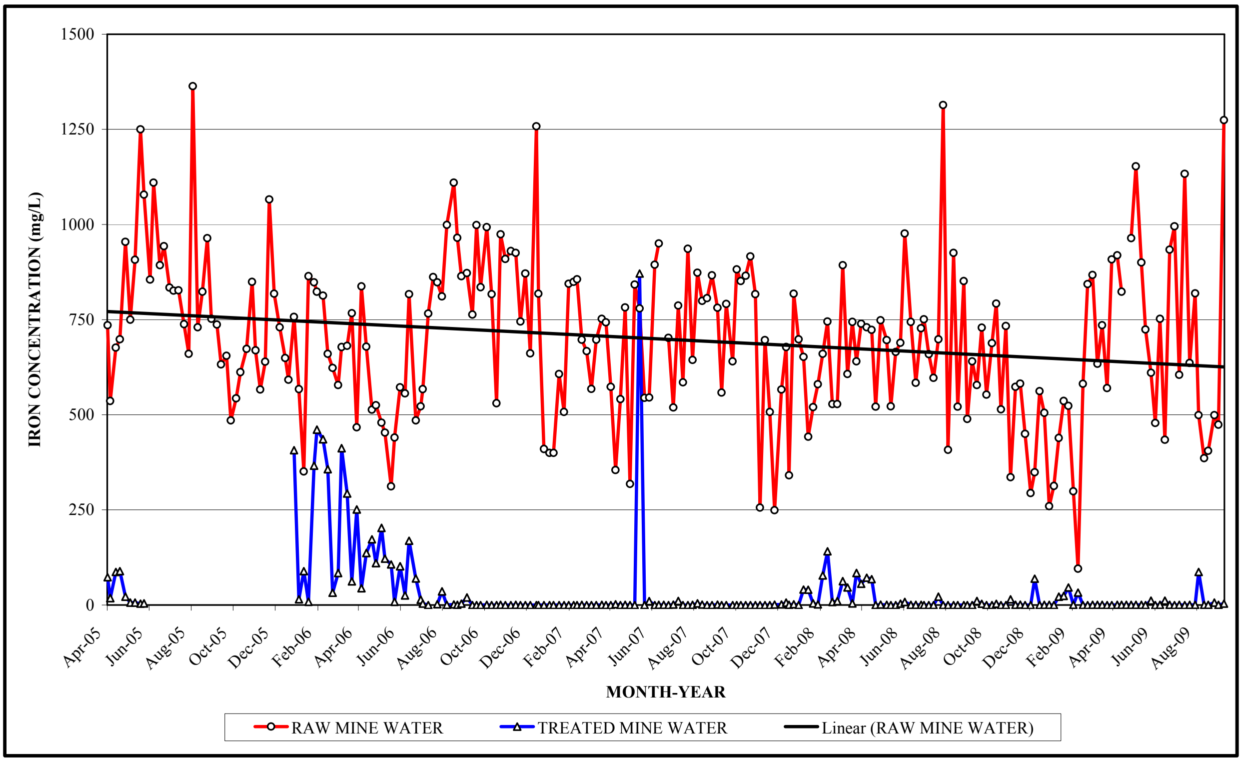

Figure 26. Long-term pattern and trend of Fe in raw and treated mine water.

The data presented in Table 32 summarize the results of the water quality monitoring at DWA station F11S12. It is evident from this information that the median TDS, Ca, SO_4 and Mn values exceed the SANS (2006) limits for these parameters, and that exceedance extends to a further four parameters (EC, Mg, Fe and Al) in respect of the 95%ile values. Despite these circumstances, which reflect the dominance of the mine water signature in the surface water at this location, the mean and median electrical balance values remain acceptable.

Table 32. Water chemistry statistics for station F11S12, Tweelopie Spruit.

Variable	Statistical Parameter for the period of record 11/2003 to 08/2008							SANS 241: 2006(1)
	n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)	
pH	53	3.3	—	7.2	8.0	1.4	21.4	5.0 – 9.5
EC (mS/m)	52	83.1	**167.7**	148.0	**285.0**	74.8	44.6	<150
TDS (mg/L)	45	580.4	**1247**	**1149**	**2293**	604.6	48.5	<1000
Ca (mg/L)	53	105.9	**238.7**	**209.1**	**428.1**	124.0	52.0	<150
Mg (mg/L)	52	31.9	59.1	53.5	**103.9**	21.8	36.9	<70
Na (mg/L)	53	21.4	68.4	43.9	141.7	45.2	66.1	<200
K (mg/L)	52	1.26	4.01	3.57	7.01	2.29	57.1	<50
Cl (mg/L)	53	13.3	22.6	20.5	34.8	7.4	32.9	<200
SO_4 (mg/L)	52	295.0	**882**	**797**	**1693**	507.0	57.5	<400
HCO_3 (mg/L)	47	11.8	40.0	36.5	81.1	20.5	51.2	n.s.
NO_3+NO_2 (mg N/L)	47	0.58	1.08	0.95	1.95	0.50	45.9	<10
Si (mg/L)	48	3.42	5.03	4.89	7.07	1.16	23.1	n.s.
Fe (mg/L)	53	0.006	**2.6**	0.014	**9.6**	11.7	443.1	<0.2
Mn (mg/L)	53	0.005	**14.0**	**7.6**	**59.8**	19.2	136.8	<0.1
Al (mg/L)	53	0.01	**1.38**	0.09	**8.57**	3.00	217.4	<0.3
Electrical balance (%)	43	−2.0	2.6	1.0	**13.9**	6.8	264	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

The measure of variability in the chemical composition of Tweelopie Spruit water at station F11S12 is shown in Figure 27. This reveals the significant variance associated with Ca and SO_4, which is to be expected given the dominance (as is also reflected in the Ca-SO_4 composition of this water) of these ions in the mine water that so strongly influences the chemical composition of this surface water.

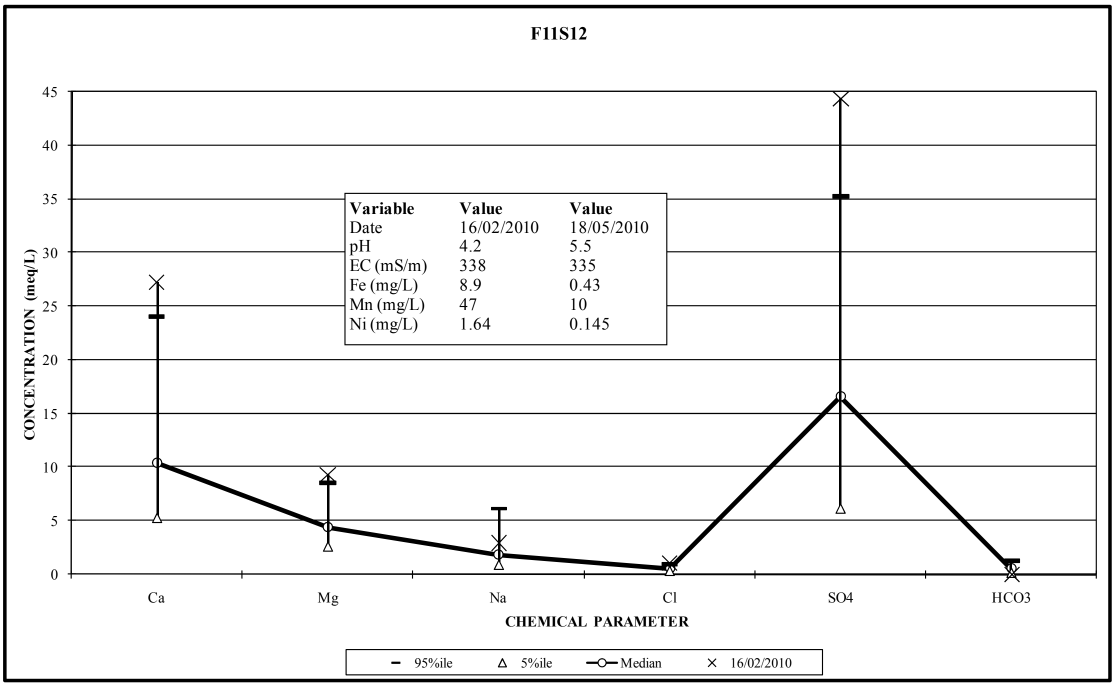

Figure 27. Recent Tweelopie Spruit water chemistry at station F11S12 (X symbol) superimposed on the statistical long-term variability at this station.

The EoP and F11S12 data reveal the change in water chemistry from upstream to downstream in the Tweelopie Spruit. This is illustrated in Figure 28 on the basis of electrical conductivity, which shows a persistent gradual increase in salinity in the downstream F11S12 record. This trend is of concern under circumstances where the EC of the RU treated mine water exhibits a constant value of ~400 mS/m. This suggests the addition of increasingly more saline water to this drainage upstream of station F11S12.

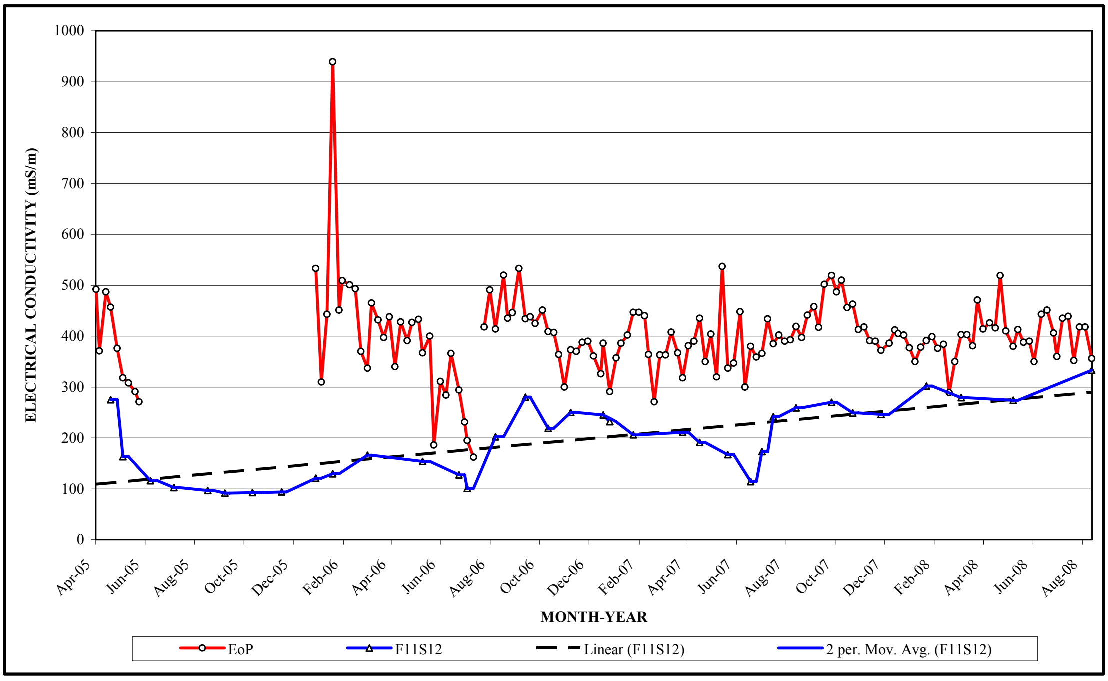

Figure 28. Comparison of upstream (EoP) and downstream (F11S12) EC values in Tweelopie Spruit surface water.

The recent chemistry of surface water at station F11S12 on the Tweelopie Spruit (analysis 16/02/2010 in Figure 27) is compared to that at station MRd1 in Figure 29 and Figure 30. The stations are ~4 km apart (Table 27). The close similarity of the major ion composition at the sampling localities is reflected in Figure 29. The concentrations of selected trace metals (Figure 30) indicate significant increases in Al and Mn at the downstream station, and a substantial decrease in the Fe concentration. The lower Fe concentration is readily explained on the basis of precipitation of this metal out of solution in the presence of oxygen and despite the low pH of <4. The latter, however, might also explain the increase in Al and Mn levels (Figure 30) possibly due to re-mobilization of these metals from streambed sediments at the observed low pH values (Table 27 and Figure 31). The temporal behaviour of electrical conductivity (EC) and pH at these stations over a period of ~10 months is illustrated in Figure 31.

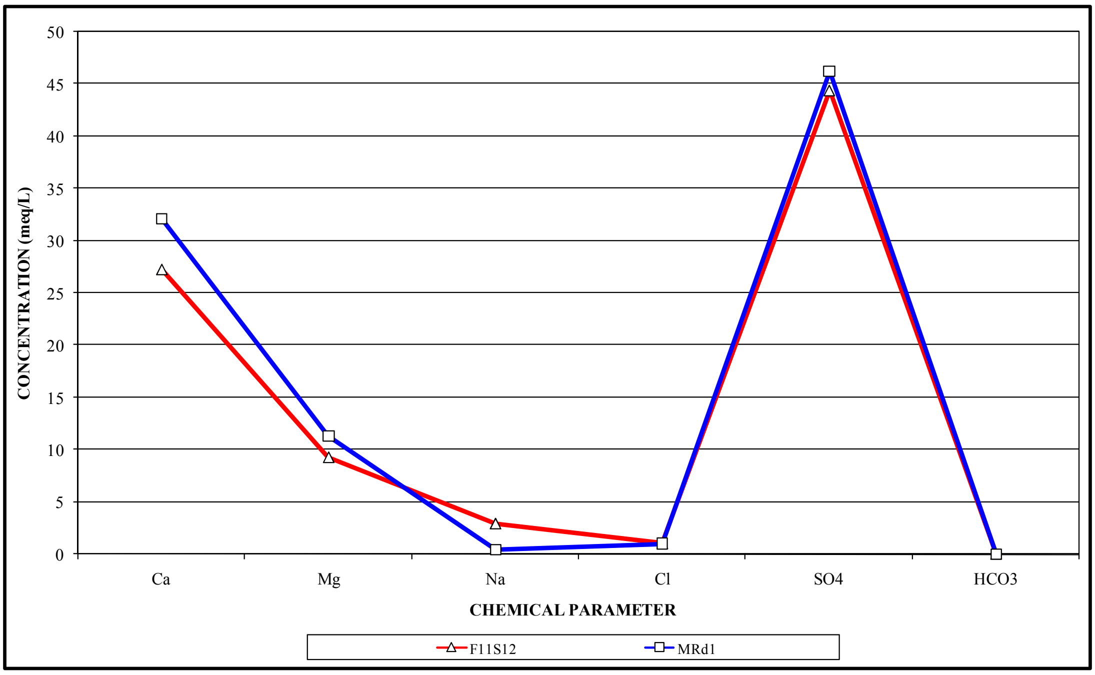

Figure 29. Comparison of major ion chemistry at two stations in the Tweelopie/Riet Spruit system for water samples collected on 16/02/2010.

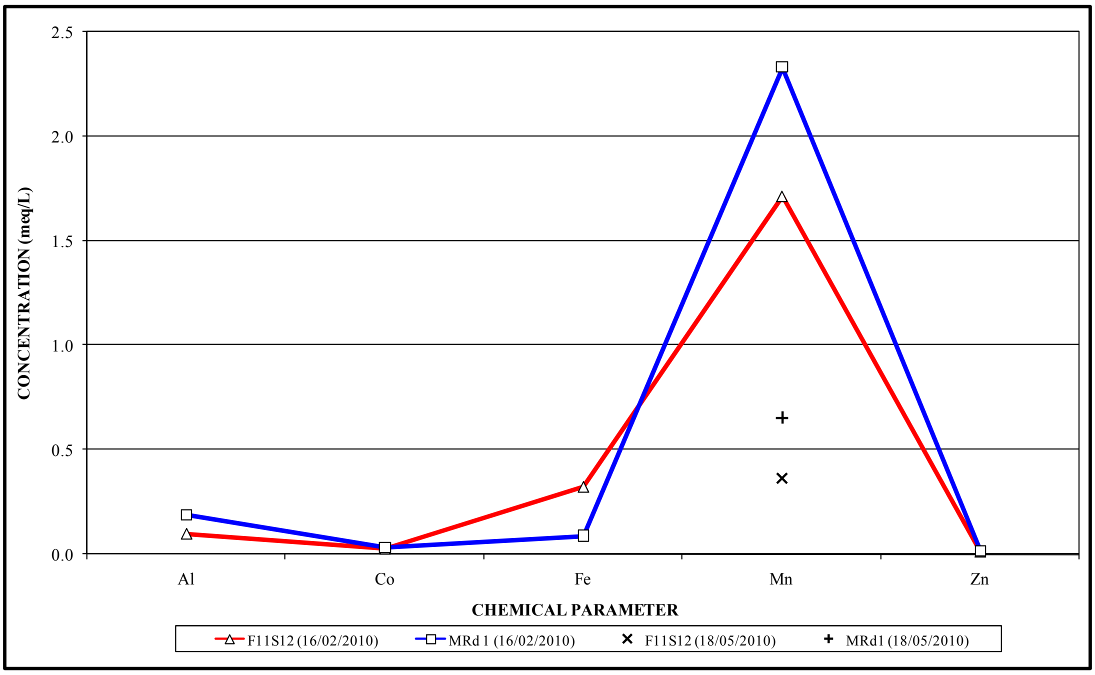

Figure 30. Comparison of trace metal concentration at two stations in the Tweelopie/Riet Spruit system for water samples collected on 16/02/2010. Note inclusion of Mn values for 18/05/2010.

Figure 31 reveals a general decrease in pH and increase in EC (based on field measurements) in the surface water between the upstream station F11S12 and the downstream station MRd1 up to 05/05/2010. The pH response is explained in section 5.5 as due to hydrolosis. The EC response is attributed to the increasing volume of raw mine water leaving the mine area due to a combination of increasing decant volumes and irregular pumpage of this water. The pattern after 05/05/2010 is much less distinct. The increasing decant volumes are directly attributable to enhanced recharge of the flooded mine workings in response to the extremely high rainfall experienced in the region in the 2009-'10 summer (section 2.2). The release of raw mine water into the downstream environment ranged from 15 to 33 ML/d in late-April and early-May 2010 (B. van der Walt, personal communication), equalling or exceeding the simultaneous release of ~15 ML/d of treated mine water. Table 27 indicates that a flow of >40 ML/d was gauged at station F11S12 on two of three occasions since 01/04/2010, compared to a flow of between ~25 and ~35 ML/d on the four occasions prior to this date.

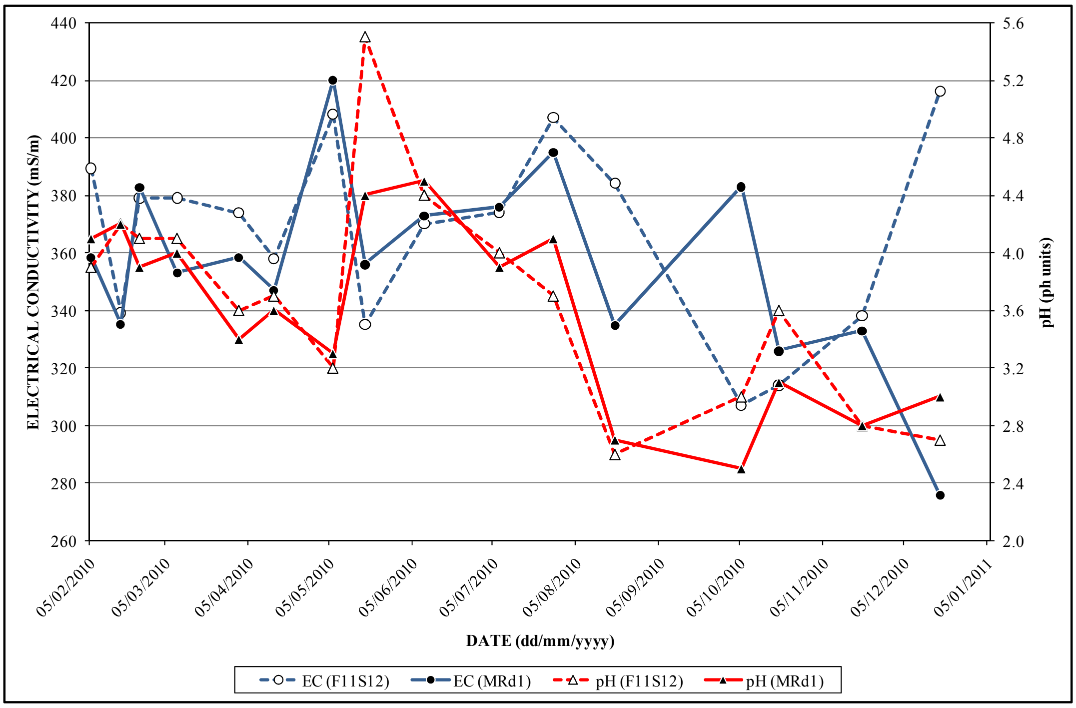

Figure 31. Temporal behaviour of EC and pH at two stations in the Tweelopie/Riet Spruit system in the period 05/02/2010 to 19/10/2010 (data from Table 27).

5.1.2.2 Blougat Spruit

The next tributary to the east of the Tweelopie Spruit, the Blougat Spruit is monitored by the DWA at station 188048 (Figure 6) downstream of the Percy Stewart WWTW discharge point and ~3.5 km before its confluence with the Riet Spruit. The data presented in Table 33 summarize the results of this monitoring. The median and mean electrical balance values only marginally exceed the acceptable error margin of ±5% and, considering the source of this water, render the veracity of the analytical results acceptable. The median values of NO_3+NO_2 and Mn, and the 95%ile values of EC, SO_4 and Fe, exceed the Class 1 limits (SANS, 2006). The treated wastewater origin of this discharge readily explains the SO_4 and NO_3+NO_2 exceedances, as well as the high measure of variance in the SO_4 concentration (Figure 32) and the rather poor mean and median electrical balance values (Table 33). Awofolu et al. (2007) report the results (Table 34) of trace metal analyses (Cd, Pb, Mn, Zn, Ni and Cu) in water samples collected on four occasions in late-2006 from three sites located downstream of the Percy Stewart WWTW. The sites coincide with the stations identified in this study as BG@N14 (Blougat Spruit at the N14), BB@M (Bloubank Spruit at Makiti) and BB@PL (Bloubank Spruit at Plover's Lake). The results confirm the elevated Mn concentrations revealed in Table 33, and also raise concern for the Mn and Fe concentrations in the municipal wastewater discharge. It is postulated that the presence of these metals in the plant discharge reflects the industrial wastewater component received by the facility, which was originally designed to receive only domestic wastewater.

Table 33. Water chemistry statistics for station 188048, Blougat Spruit.

Variable	Statistical Parameter for the period of record 06/2004 to 05/2008							SANS 241: 2006(1)
	n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)	
pH	42	4.1	—	6.7	7.8	1.1	17.1	5.0 – 9.5
EC (mS/m)	41	54.9	89.3	85.2	**158.0**	29.0	32.4	<150
TDS (mg/L)	40	380.0	550.0	498.5	940.1	177.8	32.3	<1000
Ca (mg/L)	42	34.6	56.3	53.3	77.3	16002	28.2	<150
Mg (mg/L)	42	6.6	9.1	9.4	12.3	1.8	20.1	<70
Na (mg/L)	42	51.4	86.1	88.5	119.5	22.1	25.6	<200
K (mg/L)	42	8.32	13.26	13.42	19.86	3.83	28.9	<50
Cl (mg/L)	42	44.7	65.2	65.8	79.6	13.5	20.7	<200
SO_4 (mg/L)	42	66.8	194.8	159.2	**434.1**	125.8	64.6	<400
HCO_3 (mg/L)	41	11.3	55.9	46.8	117.1	44.8	80.3	n.s.
NO_3+NO_2 (mg N/L)	41	0.26	**11.92**	**10.63**	**26.72**	9.11	76.5	<10
PO_4 (mg P/L)	40	0.700	3.841	2.742	11.881	3.257	84.8	n.s.
Si (mg/L)	41	3.49	6.67	6.76	9.41	2.40	36.0	n.s.
Fe (mg/L)	44	0.006	**0.700**	0.079	**4.691**	2.03	290.6	<0.2
Mn (mg/L)	44	0.009	**0.937**	**0.267**	**2.045**	3.69	394.5	<0.1
Al (mg/L)	44	0.008	0.157	0.035	0.279	0.68	434.8	<0.3
Elecrical balance (%)	41	−11.6	**5.5**	**5.6**	20.3	9.3	169	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

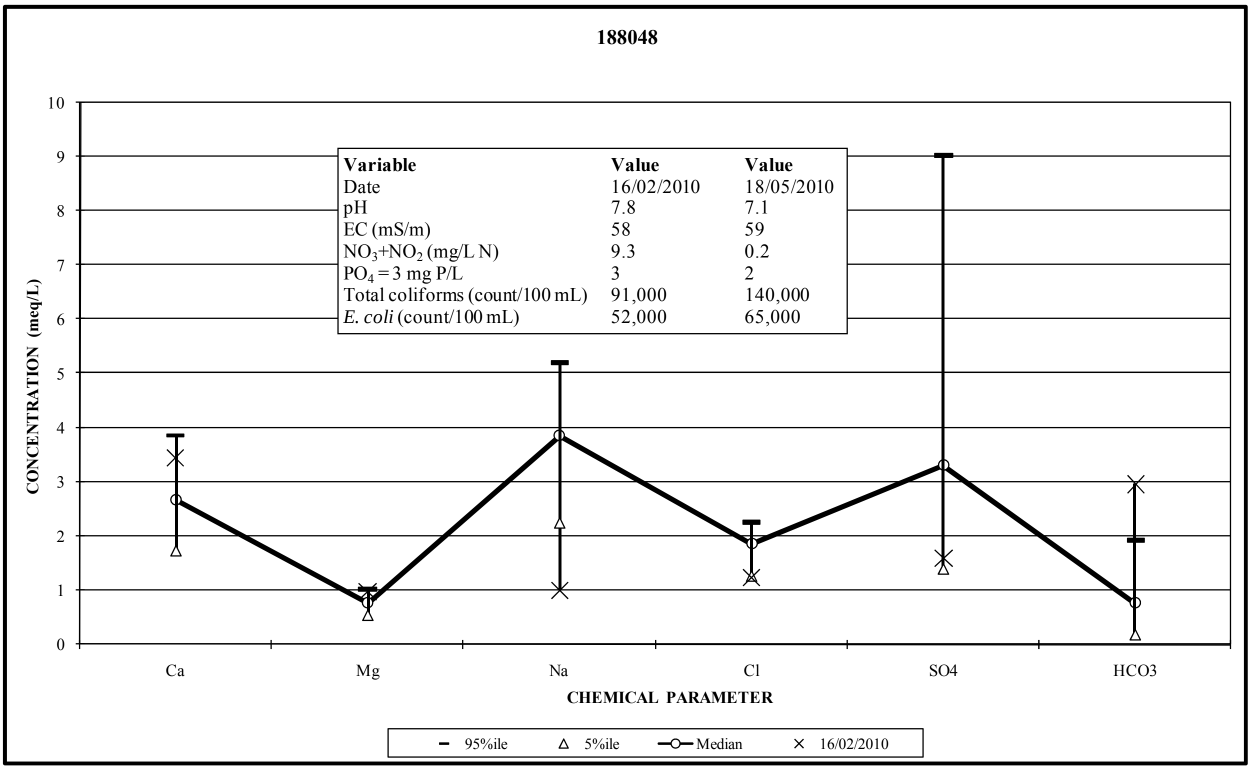

Figure 32. Recent Blougat Spruit water chemistry near station 188048 superimposed on the statistical long-term variability at this station.

Table 34. Concentrations of selected trace metals in surface water downstream of the Percy Stewart WWTW (from Awofolu et al., 2007).

Trace Metal	Concentration Value		SANS 241: (2006)
	Minimum (mg/L)	Maximum (mg/L)	
Cd	Trace (<0.002)	0.05	<0.005
Pb	Trace (<0.004)	0.13 ± 0.03	<0.02
Mn	4.35 ± 0.004	942 ± 7.26	<0.1
Zn	0.10 ± 0.002	0.41 ± 0.001	<5.0
Ni	0.08 ± 0.004	0.88 ± 0.002	<0.15
Cu	0.15 ± 0.003	0.742 ± 0.001	<1.0

The data presented in Table 35 summarize the recent chemistry of the treated wastewater effluent discharged by the Percy Stewart WWTW as reported by the MCLM. Since the analysis reveals compliance of all the inorganic and organic parameters (including NO_3+NO_2) with the SANS (2006) limits, the exceedances noted in Table 33 for station 188048 must pre-date July 2007. The significant exceedances shown by the bacteriological parameters in Table 35 are cause for considerable concern. See in this regard also the text box in Figure 32. Similarly, the mean and median PO_4 values of >4 mg P/L and the elevated COD values generate concern for potential eutrophication in downstream receiving water bodies. A notable exclusion from the MCLM analytical suite is SO_4.

Table 35. Water chemistry statistics for Percy Stewart WWTW discharge (MCLM data).

Variable	Statistical Parameter for the period of record 07/2007 to 06/2009							SANS 241: 2006[(1)]
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Std Dev**	**CoV (%)**	
pH	24	7.5	—	7.8	8.2	0.3	3.6	5.0 – 9.5
EC (mS/m)	24	83.0	100.3	100.6	119.8	11.7	40.3	<150
TDS[(2)] (mg/L)	16	698.5	782.6	781.0	882.8	72.4	9.2	<1000
Na (mg/L)	19	62.1	81.6	84.5	102.4	12.9	15.8	<200
Cl (mg/L)	24	63.3	72.3	73.9	80.2	5.7	7.9	<200
HCO_3 (mg/L)	16	250.5	311.8	314.6	366.8	34.0	13.3	n.s.
NO_3+NO_2 (mg N/L)	24	0.8	2.4	1.4	7.4	2.3	94.1	<10
NH_3 (mg N/L)	24	14.2	30.7	31.5	42.0	8.1	26.4	<1
PO_4 (mg P/L)	24	2.046	4.553	4.095	7.423	1.850	40.6	n.s.
COD (mg/L)	24	111.8	202.2	197.2	288.3	58.3	28.8	n.s.
Faecal coliforms (count/100 mL)	22	**69 150**	**359 075**	**244 834**	**801 883**	**371 560**	103.5	≤10 in 1% of samples
E. coli (count/100 mL)	6	**151 417**	**264 333**	**241 167**	**408 000**	**109 408**	41.4	≤1 in 1% of samples

(1) Recommended limit for Class 1 drinking water quality.
(2) TDS calculated as the sum of the reported TDS value (determined @ 180°C) and HCO_3.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

The data presented in Table 36 summarize the chemistry of the treated wastewater effluent discharged by the Percy Stewart WWTW as reported by the DWA. This record goes back to late-2002, compared to the shorter MCLM record (Table 35). The data support the observed exceedance of NO_3+NO_2 reported in Table 33, as well as that associated with the bacteriological parameters. Similarly, the even higher mean and median PO_4 values of >5 mg P/L again generate concern for potential eutrophication in downstream receiving impoundments. Encouragingly, the longer term mean and median COD values are significantly lower (~50%) than reported in Table 35.

Table 36. Water chemistry statistics for Percy Stewart WWTW discharge (DWA data).

Variable	Statistical Parameter for the period of record 11/2002 to 10/2008							SANS 241: 2006[(1)]
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Std Dev**	**CoV (%)**	
pH	21	6.0	—	7.2	8.2	0.7	9.4	5.0 – 9.5
EC (mS/m)	21	19.0	105.1	111.0	136.0	33.2	31.6	<150
Cl (mg/L)	20	64.3	81.6	82.5	102.0	20.0	24.6	<200
HCO_3 (mg/L)	19	22.2	189.3	142.6	408.3	160.8	84.9	n.s.
SO_4 (mg/L)	21	116.0	251.5	214.0	**600.0**	155.7	61.9	<400
NO_3+NO_2 (mg N/L)	20	0.1	7.4	2.6	**21.5**	9.5	128.0	<10
NH_3 (mg N/L)	13	0.01	0.68	0.05	**3.88**	1.44	211.8	<1
NH_4 (mg N/L)	21	8.9	31.0	34.2	59.8	17.3	55.9	<1
PO_4 (mg P/L)	21	1.7	5.6	6.1	9.9	3.2	56.5	n.s.
COD (mg/L)	21	5.0	128.0	72.0	363.0	170.9	133.5	n.s.
Total coliforms (count/100 mL)	10	763	174 876	27 000	865 050	466 288	266.6	n.s.
Faecal coliforms (count/100 mL)	22	**202**	**809 906**	**112 500**	**4 020 000**	**1 794 619**	221.6	≤10 in 1% of samples
E. coli (count/100 mL)	12	**7735**	**957 108**	**155 000**	**3 540 000**	**1 392 308**	145.5	≤1 in 1% of samples

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

5.1.2.3 Tweefontein Spruit

Still further downstream, the Tweefontein Spruit draining southwards from the John Nash Nature Reserve area is monitored for water quality at DWA station F14S15 (Figure 6). Although rising on dolomite, this drainage for much of its flow path follows the contact between older Witwatersrand and Ventersdorp Supergroup strata that outcrop along the south-eastern margin of the study area. The Witwatersrand strata are represented by quartzite of the Hospital Hill Subgroup, and the Ventersdorp Supergroup by shaly sandstone. The good quality water (Table 37) exhibits a distinct CaMg-HCO_3 composition (Figure 33).

Table 37. Water chemistry statistics for station F14S15, Tweefontein Spruit.

Variable	Statistical Parameter for the period of record 06/2004 to 05/2008							SANS 241: 2006[(1)]
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Std Dev**	**CoV (%)**	
pH	42	7.7	—	8.2	8.5	0.7	8.5	5.0 – 9.5
EC (mS/m)	42	50.9	59.1	60.0	65.5	4.7	7.9	<150
TDS (mg/L)	42	383.4	438.9	448.2	484.8	34.8	7.9	<1000
Ca (mg/L)	42	43.8	50.3	50.7	57.6	4.8	9.5	<150
Mg (mg/L)	42	25.8	30.5	30.9	34.1	2.6	8.5	<70
Na (mg/L)	42	11.1	23.9	26.2	32.1	7.5	31.5	<200
K (mg/L)	42	1.5	2.5	2.4	3.9	0.8	32.0	<50
Cl (mg/L)	42	19.3	32.9	35.3	41.7	7.4	22.6	<200
SO_4 (mg/L)	42	39.4	76.4	80.5	108.4	22.4	29.3	<400
HCO_3 (mg/L)	42	166.1	203.1	198.4	247.3	25.1	12.4	n.s.
NO_3+NO_2 (mg N/L)	42	0.96	4.16	3.97	6.92	2.54	61.0	<10
Si (mg/L)	42	5.26	6.22	6.11	7.36	0.75	12.0	n.s.
Fe (mg/L)	37	0.006	0.044	0.014	0.185	0.084	190.2	<0.2
Mn (mg/L)	37	0.001	0.028	0.006	**0.117**	0.051	185.4	<0.1
Electrical balance (%)	42	−1.6	1.6	2.4	4.7	2.7	162	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

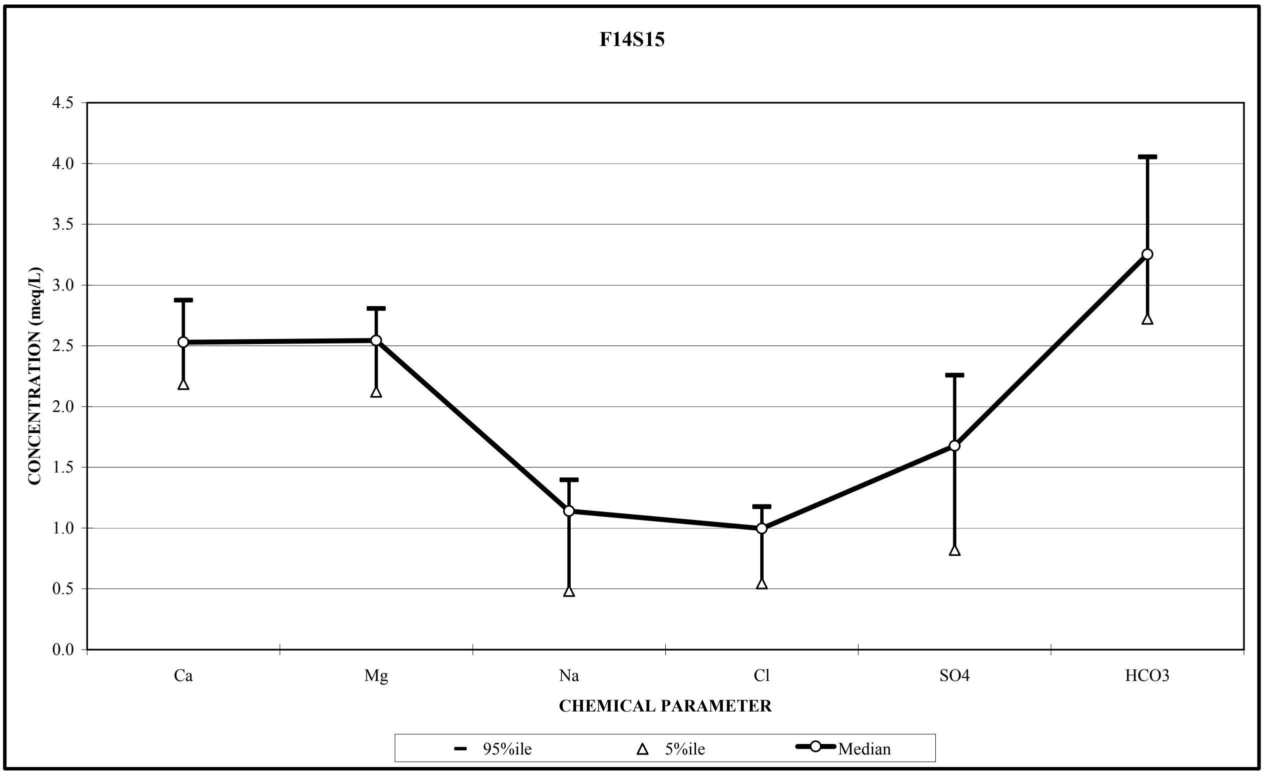

Figure 33. Long-term variability of the Tweefontein Spruit water chemistry at station F14S15.

5.1.2.4 *Bloubank Spruit*

At the lower end of the Bloubank Spruit system, the Bloubank Spruit water quality is monitored by the DWA at flow gauging station A2H049 (Figure 6) shortly before its confluence with the Crocodile River. A summary of the statistics that characterize this water quality record is presented in Table 38. Again, the median (and mean) electrical balance values afford the analytical results a high degree of confidence. The only parameter to exceed the Class 1 limit (SANS, 2006) at station A2H049 is Mn at the 95%ile limit. The distinct CaMg-HCO_3 composition of the water (Figure 34) again reflects the contribution of dolomitic groundwater from the karst environment in this catchment.

Table 38. Water chemistry statistics for station A2H049, Bloubank Spruit.

Variable	Statistical Parameter for the period of record 05/1979 to 06/2008							SANS 241: 2006(1)
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Std Dev**	**CoV (%)**	
pH	856	7.4	—	8.2	8.5	0.3	4.2	5.0 – 9.5
EC (mS/m)	962	50.9	59.1	60.0	66.0	5.6	9.4	<150
TDS (mg/L)	781	350.0	433.9	446.0	476.0	42.3	9.7	<1000
Ca (mg/L)	784	42.1	52.2	53.4	58.2	5.2	10.0	<150
Mg (mg/L)	784	24.8	32.0	32.4	37.0	3.8	11.8	<70
Na (mg/L)	782	9.8	20.7	20.8	30.6	6.1	29.7	<200
K (mg/L)	784	0.7	1.7	1.7	3.0	0.8	43.1	<50
Cl (mg/L)	784	19.6	30.9	31.5	39.5	5.5	17.9	<200
SO_4 (mg/L)	784	65.0	82.3	82.1	100.4	12.0	14.5	<400
HCO_3 (mg/L)	784	150.2	193.3	198.4	219.3	22.6	11.7	n.s.
NO_3+NO_2 (mg N/L)	854	2.99	4.49	4.30	6.09	1.74	38.8	<10
PO_4 (mg P/L)	855	0.006	0.085	0.048	0.304	0.099	116.3	n.s.
Si (mg/L)	856	5.1	6.0	6.0	6.8	0.8	13.8	n.s.
Fe (mg/L)	50	0.006	0.019	0.006	0.074	0.02	123.0	<0.2
Mn (mg/L)	50	0.001	0.029	0.002	**0.146**	0.077	261.9	<0.1
Al (mg/L)	50	0.003	0.029	0.015	0.091	0.039	133.0	<0.3
Electrical balance (%)	749	−2.1	2.9	2.9	8.5	3.9	134	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

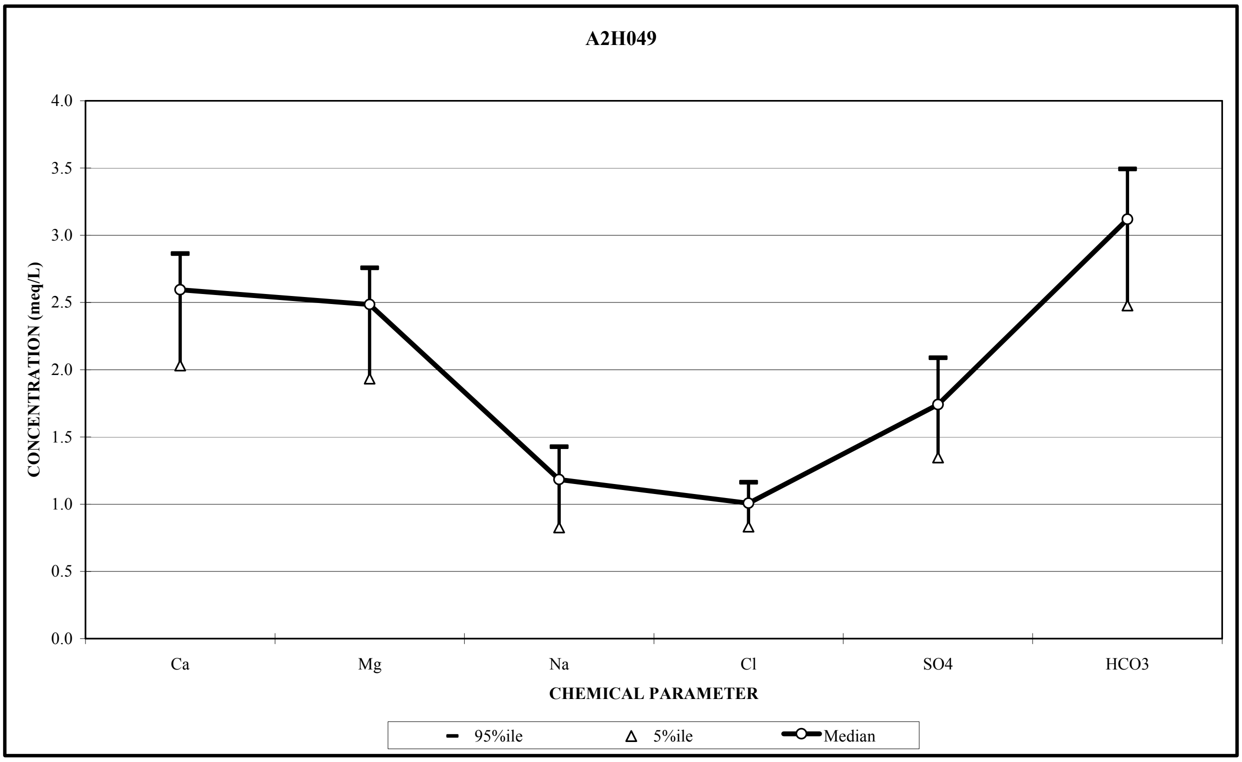

Figure 34. Long-term variability of Bloubank Spruit water chemistry at station A2H049.

An inspection of the water chemistry record for station A2H049 reveals a distinct trend exhibited by various parameters. The graphs presented in Annexure C illustrate these trends. Graph C.1a shows that the electrical conductivity increased from 50 to almost 70 mS/m in the first 10 years of record, followed by a levelling off at ~60 mS/m for the remainder of the record period (Graph C.1b). Graph C.2a shows a similar initially 'level' trend for the first decade in regard to Ca and Mg, but followed by a gradual decline in concentrations since *ca.* 1993 (Graph C.2b). The rate of decline is similar for both Ca and Mg. The associated Ca:Mg ratio trend is shown in Graph C.3a, and it is evident that the ratio remained constant at ~1.6 up to 1993, whereafter it steadily increased to a recent value of ~1.8 (Graph C.3b). Although the concentrations of Ca and Mg therefore show a gradual decrease since 1993 (Graph C.2b), the concentration of Ca relative to Mg increased in the same period (Graph C.3b). This observation suggests that a fundamental change in the physical and chemical hydrodynamics of the water resource regime in the Bloubank Spruit catchment manifested itself *ca.* 1993. Graphs C.4 and C.5 show that Na and Cl exhibit an increasing trend over the historical record, an observation also made by Huizenga (2004), whereas Graphs C.6 and C.7 show that N and SO_4 have remained more or less constant. It has already been shown that the Bloubank Spruit catchment relies heavily on its groundwater system(s), of which the karst aquifer is by far the most prominent. It is therefore likely that the change reflected by the Ca:Mg ratio trend occurred (and is still occurring) in the groundwater resource rather than in the surface water resource. The increasing Na trend suggests that the trends observed in regard to Ca, Mg and the Ca:Mg ratio are associated with cation exchange between Ca and Na, although why this well-known chemical process was only manifested *ca.* 1993 has not been established.

A suite of seven surface water samples collected on 18/05/2010 at as many stations within the Bloubank Spruit system provide a recent 'snapshot in time' of the surface water chemistry (and quality) in this system. The sampling station positions are shown in Figure 35, and the results presented in Table 39.

Table 39. Comparison of recent surface water chemistry in the Bloubank Spruit system.

Variable	**Sampling Station**							**SANS 241: 2006**(1)
	F11S12	**MRd1**	**BC1**	**BG@N14**	**BB@M**	**HS1**	**BB@PL**	
Date	18/05/2010							
pH (field)	5.5	**4.4**	7.1	6.9	6.9	6.9	7.0	5.0 – 9.5
EC (mS/m) (field)	**355**	**356**	59	51	64	22	60	<150
Ca (mg/L)	**662**	**689**	41	38	45	15	54	<150
Mg (mg/L)	70	81	10	11	15	18	29	<70
Na (mg/L)	115	103	55	48	52	5	34	<200
K (mg/L)	10.4	9.4	8.6	8.0	8.1	1.1	3.0	<50
Cl (mg/L)	43	44	52	45	50	12	40	<200
SO_4 (mg/L)	**1794**	**1819**	56	42	74	15	78	<400
HCO_3 (mg/L)	<6	<6	161	146	156	98	171	n.s.
NO_3+NO_2 (mg N/L)	0.6	0.6	0.2	0.5	3.2	1.9	6.0	<10
F (mg/L)	<0.2	<0.2	0.2	0.2	<0.2	<0.2	<0.2	<1.0
PO_4 (mg P/L)	<0.2	<0.2	2.0	2.5	2.4	<0.2	0.5	n.s.
Total coliforms (count/100 mL)	n.a.	n.a.	140 000	34 000	3500	0	720	n.s.
E. coli (count/100 mL)	n.a.	n.a.	**65 000**	**26 000**	**3000**	0	**470**	≤1 in 1% of samples
Si (mg/L)	0.8	1.7	5.2	4.9	5.4	5.3	5.3	n.s.
Fe (mg/L)	**0.431**	**0.934**	**0.528**	**0.682**	**0.906**	0.073	**0.358**	<0.2
Mn (mg/L)	**10**	**18**	**0.279**	**0.470**	**0.665**	0.087	**0.293**	<0.1
Al (mg/L)	<0.1	0.121	0.118	<0.1	0.134	<0.1	0.137	<0.3
Hg (mg/L)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
U (mg/L)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.07
Ni (mg/L)	0.145	0.117	0.049	0.035	0.029	<0.025	<0.025	<0.150
Sn (mg/L)	0.097	<0.025	0.153	0.138	0.167	<0.025	0.091	n.s.
Sr (mg/L)	0.500	0.395	0.123	0.117	0.096	0.036	0.054	n.s.
Zn (mg/L)	0.048	0.379	0.043	0.025	<0.025	<0.025	<0.025	<5.0
Electrical balance (%)	6.6	7.8	1.9	5.6	3.4	4.1	8.1	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

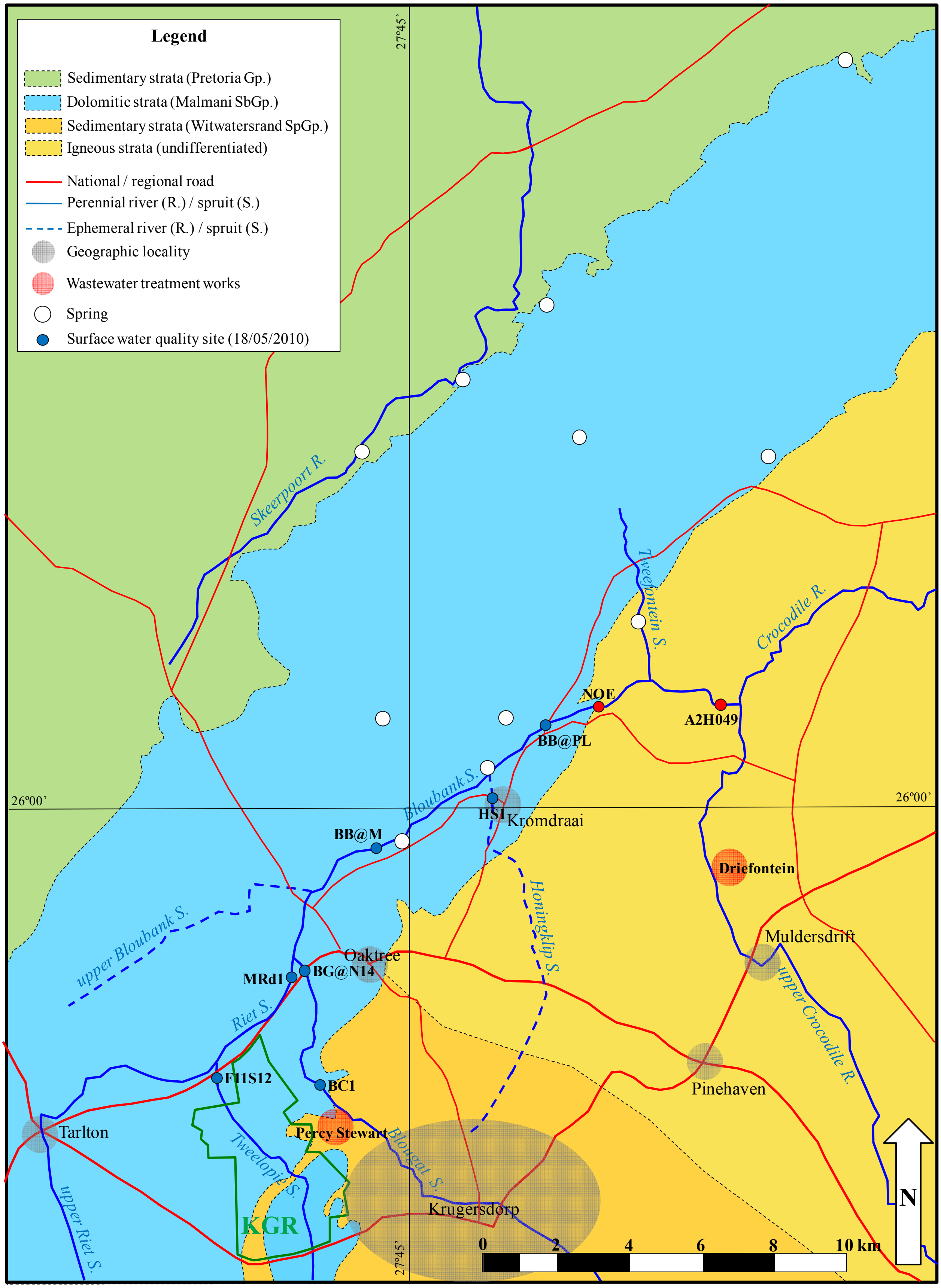

Figure 35. Surface water quality sites sampled on 18/05/2010.

A graphical comparison of the inorganic (major ion) chemistry is made in Figure 36. This reveals the extremely dominant Ca-SO_4 composition of the water at station MRd1 in the lower Riet Spruit due to the influence of mine water from upstream via the Tweelopie Spruit. It further reveals the similar Na-HCO_3 composition of surface water at stations BC1 and BG@N14 (both on the Blougat Spruit), and further downstream at BB@M on the Bloubank Spruit. The manifestation of Na as the dominant cation matches the long-term record at station 188048 (Figure 32). Since the latter also indicates SO_4 to be the dominant anion in the long-term, its replacement by HCO_3 in the recent analyses probably reflects the greater contribution of rainwater runoff, as opposed to effluent discharge from the Percy Stewart WWTW into this drainage, in early- to mid-2010. These circumstances illustrate the mitigating influence of the Blougat Spruit contribution to the inorganic component of surface water quality in the Bloubank Spruit.

The Ca-HCO_3 composition of the water at station BB@PL even further downstream on the Bloubank Spruit at Kromdraai reflects the contribution of dolomitic groundwater upstream of this station. The principal sources of this water are the Kromdraai, Zwartkrans and Plover's Lake Springs. The Mg-HCO_3 composition of the Honingklip Spruit water (station HS1, Figure 36) at Kromdraai contrasts markedly with that of the Bloubank Spruit at this location, and reflects the different geology of this catchment. This comprises quartzitic strata of the West Rand Group in the headwaters, and older basic and ultrabasic rocks (e.g pyroxenite, metagabbro and lava) in the middle to lower reaches before ending on dolomite.

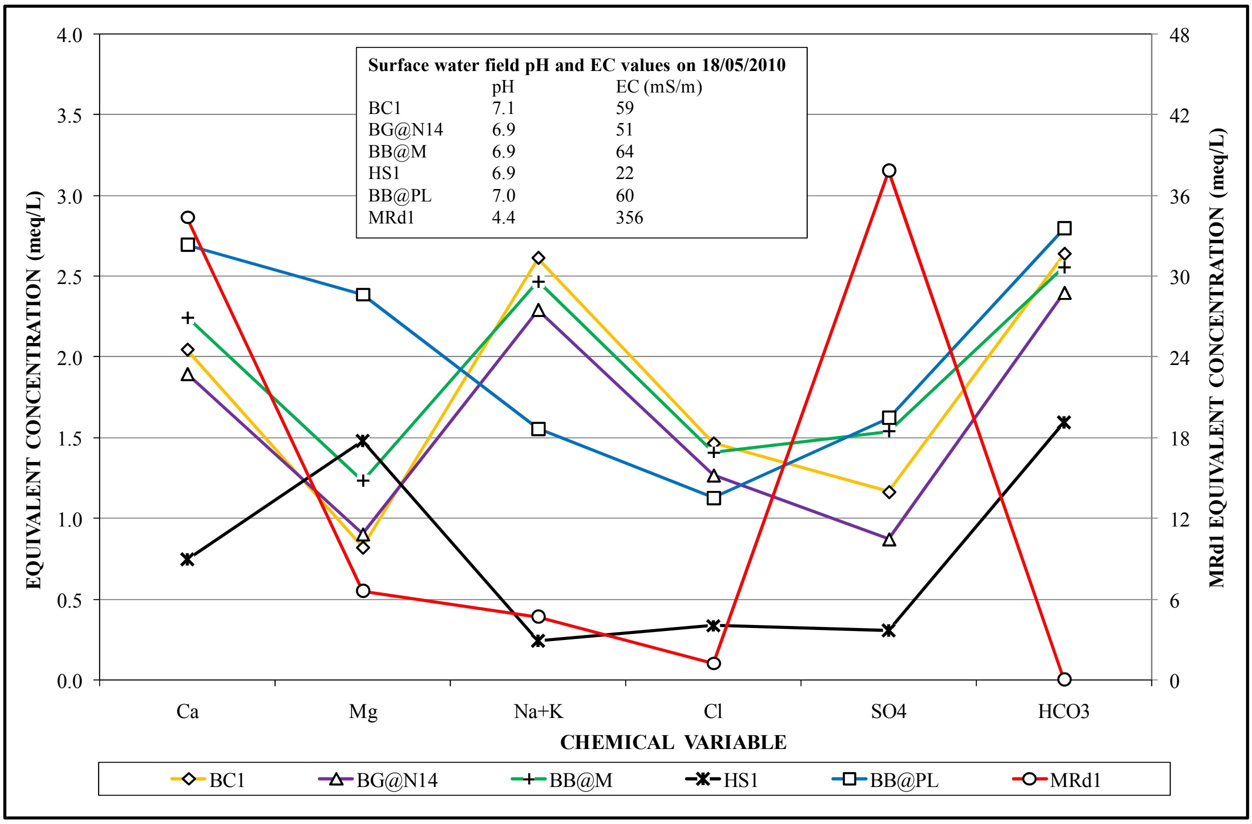

Figure 36. Comparison of surface water chemistry at various locations in the Bloubank Spruit system on 18/05/2010. Note the 12x difference in scale between the left and right vertical axes.

With the exception of the ephemeral Honingklip Spruit tributary, it is apparent from Table 39 that Fe and Mn are persistent trace metals in the other Bloubank Spruit system surface waters. This is also apparent for the persistence of poor bacteriological quality as reflected in the *E. coli* values (see also Figure 37). Encouragingly, the Honingklip Spruit displayed no bacteriological contamination on the date sampled. Equally encouraging is the observation that the *E. coli* value at the most downstream station BB@PL is two orders of magnitude less than at the most upstream station BC1 on the day of sampling. This observation must not be construed as suggesting that the circumstances are acceptable.

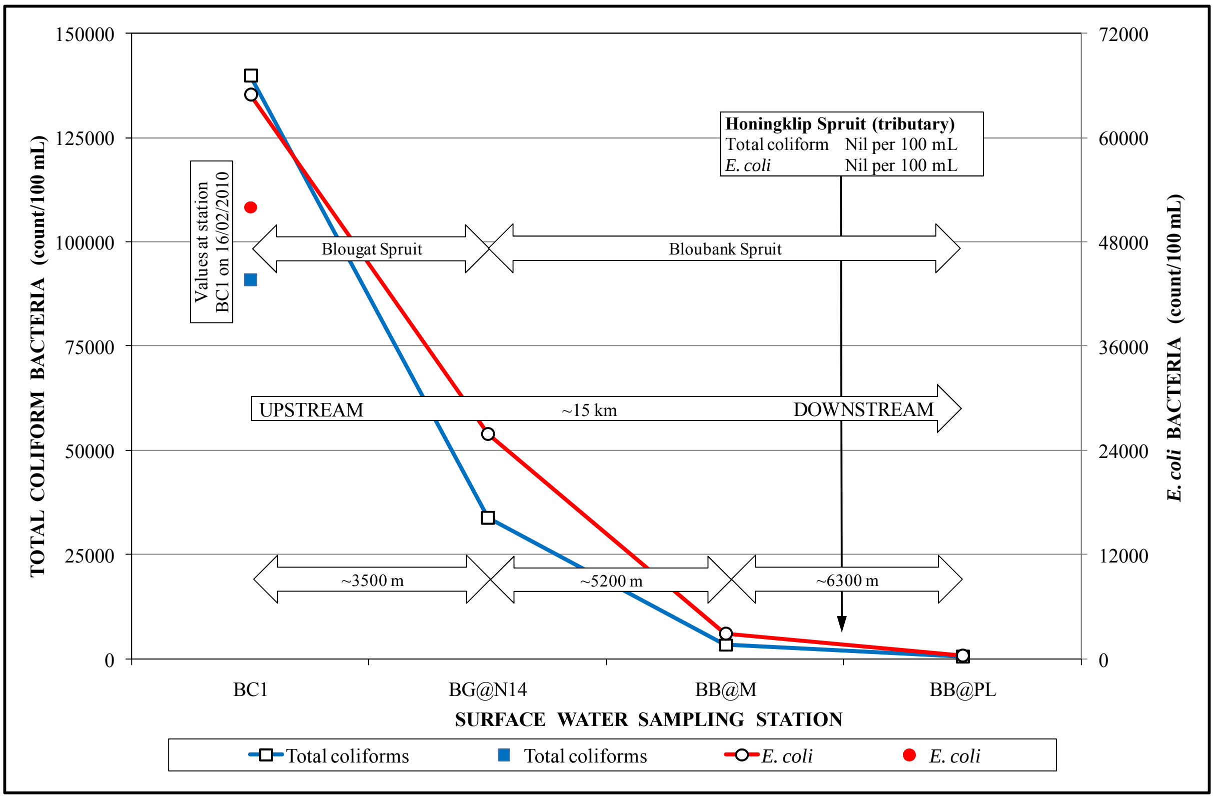

Figure 37. Comparison of bacterial concentrations in surface water at various locations in the Bloubank Spruit system on 18/05/2010. For comparison, note the earlier values at station BC1 as well as the ~2x difference in scale between the left and right vertical axes.

The surface water quality monitoring programme carried out at the Nedbank Olwazini Estate (section 3.4) (NOE) provides a valuable additional 'reference' of water quality in the lower reaches of the Bloubank Spruit. This monitoring has further significance due to its location in proximity to where this drainage leaves the dolomitic environment and traverses older strata down to its confluence with the Crocodile River. Unlike the water chemistry record for station A2H049, therefore, the Nedbank Olwazini Estate (NOE) data record represents only that which drains the karst portion of the catchment. These circumstances are reflected in Figure 35 and explored hereunder.

The nutrient (NO_3, PO_4 and COD) and bacterial concentrations in surface water at the upstream and downstream localities in the period January 2009 to October 2010 (22 months) are given in Table 40. Especially the mean values compare favourably with those obtained in May 2010 for the water sample collected at station BB@PL in proximity to the Plover's Lake traffic circle near Kromdraai.

Table 40. Analysis of Bloubank Spruit water nutrient chemistry at the Nedbank Olwazini Estate.

Variable	Sampling Locality	Statistical Parameter for the period of record 01/2009 to 10/2010					Concentration at BB@PL on 18/05/2010(1)	SANS 241: 2006(2)
		n	5%ile	Mean	Median	95%ile		
pH	Upstream	22	7.6(3)	—	8.1(3)	8.6(3)	7.0	5.0 – 9.5
	Downstream		7.7(3)	—	8.0(3)	8.5(3)		
NO_3 (mg N/L)	Upstream	22	4.0	8.0	7.6	13.7	6.0	<10
	Downstream		5.3	7.7	7.3	12.1		
O-PO_4 (mg P/L)	Upstream	22	0.0	0.4	0.3	1.0	0.5	n.s.
	Downstream		0.0	0.5	0.3	1.1		
COD (mg/L)	Upstream	22	7	58	55	133	n.a.	n.s.
	Downstream		11	46	44	86		
Faecal coliforms	Upstream	22	53	535	338	1270	470(4)	≤10 in 1% of samples
	Downstream		41	540	273	1995		

(1) From Table 39. (2) Recommended limit for Class 1 drinking water quality.
(3) Laboratory value. (4) *E. coli* value.

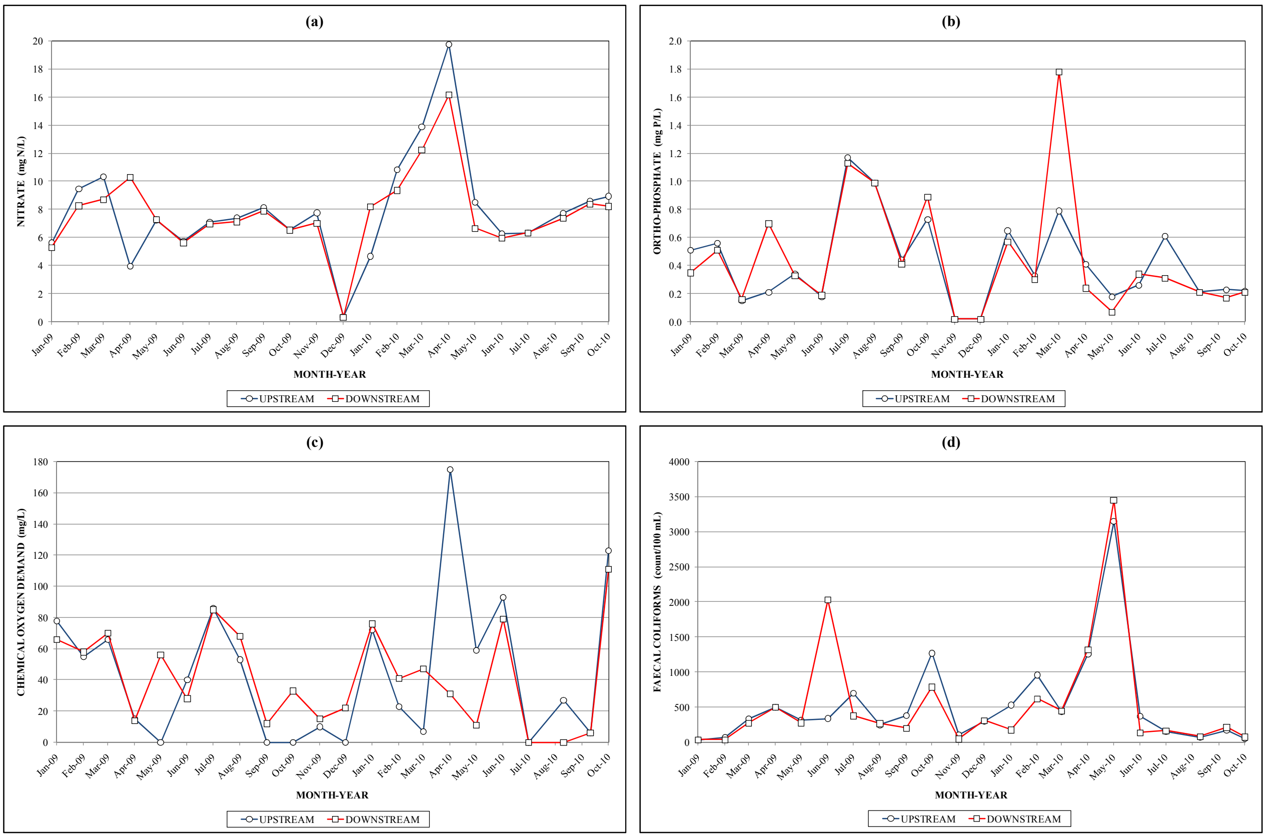

Figure 38. Recent temporal pattern of (a) NO_3-N, (b) O-PO_4-P, (c) COD and (d) faecal coliforms in Bloubank Spruit water at the Nedbank Olwazini Estate.

The chemistry of 'raw' water taken from the furrow for purification and on-site potable use is indicated by the information presented in Table 41. The favourable comparison of the mean and median values with those for the May 2010 analysis for station BB@PL is again evident. Unfortunately a more rigorous comparison with the chemistry record for station A2H049 is foiled by a lack of overlapping data. Nevertheless, the graphical comparison made in Figure 39 reveals the similar recent chemical composition of raw surface water used by the Nedbank Olwazini Estate and that passing station A2H049.

Table 41. Water chemistry statistics for the 'furrow' source at the Nedbank Olwazini Estate.

Variable	**Statistical Parameter for the period of record 11/2009 to 10/2010**					**Concentration at BB@PL on 18/05/2010**(1)	**SANS 241: 2006**(2)
	n	**5%ile**	**Mean**	**Median**	**95%ile**		
pH	12	7.1	—	7.5	8.5	7.0 (field)	5.0 – 9.5
EC (mS/m)	12	35	58	59	72	60 (field)	<150
TDS (mg/L)	12	237	364	364	482	415	<1000
Ca (mg/L)	12	29	44	45	55	54	<150
Mg (mg/L)	12	18	27	27	36	29	<70
Na (mg/L)	12	20	31	33	41	34	<200
K (mg/L)	12	1.7	2.4	2.5	2.9	3.0	<50
Cl (mg/L)	12	15	34	35	49	40	<200
SO_4 (mg/L)	12	32	93	72	205	78	<400
HCO_3 (mg/L)	12	136	206	199	284	171	n.s.
NO_3 (mg N/L)	12	0.9	4.3	4.4	8.1	6.0	<10
Fe (mg/L)	12	0.000	0.029	0.005	0.100	**0.358**	<0.2
Mn (mg/L)	12	0.006	0.183	0.075	**0.554**	**0.293**	<0.1
Al (mg/L)	12	0.000	0.013	0.000	0.058	0.137	<0.3
Electrical balance (%)	12	7.1	–4.2	1.3	–16.0	8.1	±5

(1) From Table 39.
(2) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

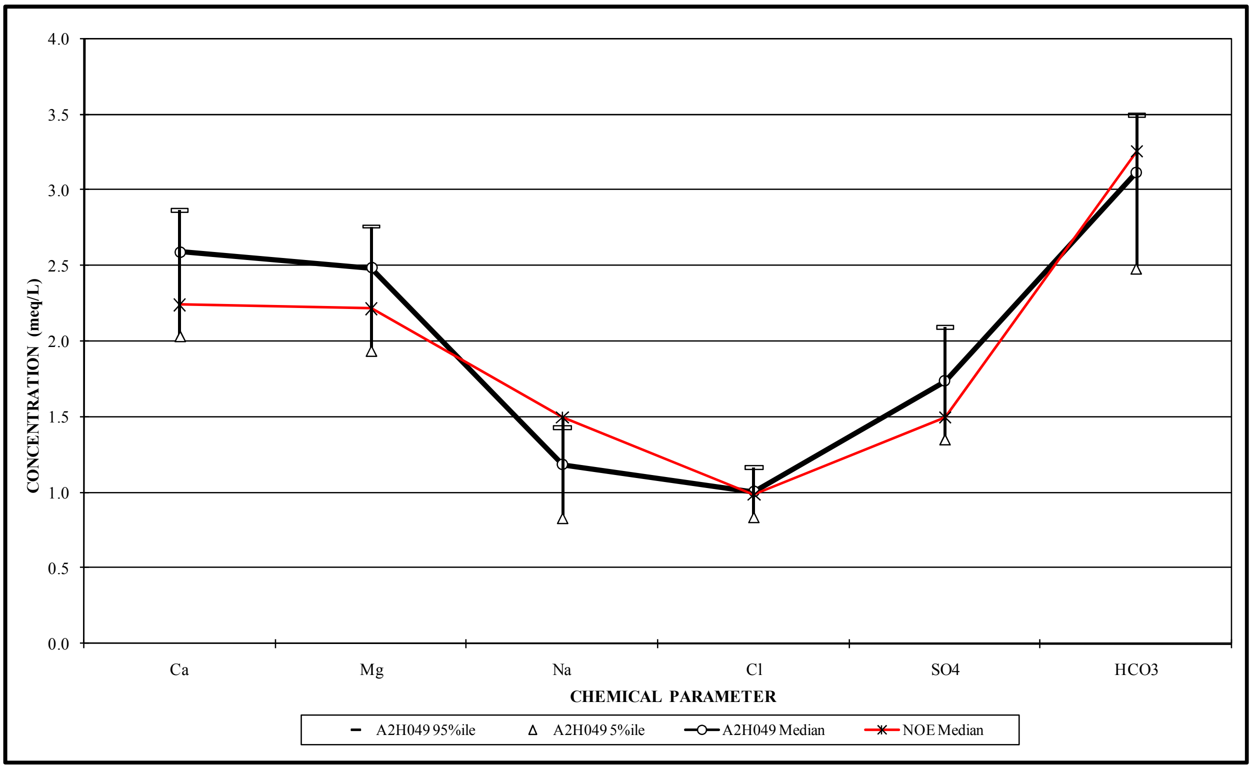

Figure 39. Comparison of the recent water chemistry at the Nedbank Olwazini Estate with the long-term water chemistry at station A2H049.

Unless it is associated with the comparatively short NOE record comprising 12 values, the reason that Na lies outside of the 5%ile-95%ile 'envelope' for station A2H049 is not readily explained.

5.1.3 Crocodile River

Water quality in this drainage is monitored at the DWA station A2H050 (Figure 6) shortly before its confluence with the Bloubank Spruit. The data (Table 42) show that the SANS (2006) Class 1 drinking water limit is only exceeded in respect of the 95%ile value for Mn, though Fe closely approaches its limit.

Table 42. Water chemistry statistics for station A2H050, Crocodile River.

Variable	**Statistical Parameter for the period of record 05/1979 to 06/2008**							**SANS 241: 2006(1)**
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Std Dev**	**CoV (%)**	
pH	861	7.0	—	7.9	8.2	0.4	5.1	5.0 – 9.5
EC (mS/m)	967	26.3	45.1	44.4	64.7	18.7	41.5	<150
TDS (mg/L)	786	175.5	289.2	285.0	416.8	73.5	25.4	<1000
Ca (mg/L)	789	16.6	25.8	25.4	35.5	5.5	21.3	<150
Mg (mg/L)	789	5.9	10.5	10.3	16.0	3.2	30.1	<70
Na (mg/L)	711	15.0	39.4	37.3	73.2	17.9	45.5	<200
K (mg/L)	788	4.0	7.9	7.6	13.2	2.9	37.1	<50
Cl (mg/L)	788	17.6	42.7	40.4	73.2	17.6	41.3	<200
SO_4 (mg/L)	789	18.8	38.0	30.8	84.7	21.9	57.7	<400
HCO_3 (mg/L)	790	64.4	110.2	110.3	154.6	27.0	24.5	n.s.
NO_3+NO_2 (mg N/L)	861	0.5	3.0	2.6	6.7	2.1	71.0	<10
PO_4 (mg P/L)	861	0.037	0.602	0.164	3.174	1.336	221.8	n.s.
Si (mg/L)	861	4.7	6.6	6.6	8.5	1.2	17.7	n.s.
Fe (mg/L)	51	0.006	0.054	0.021	0.186	0.079	147.0	<0.2
Mn (mg/L)	51	0.001	0.050	0.007	**0.237**	0.076	153.3	<0.1
Al (mg/L)	51	0.001	0.024	0.015	0.091	0.023	98.6	<0.3
Electrical balance (%)	688	−5.2	2.6	2.6	10.5	5.2	201	±5

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

The water exhibits a distinct Na-HCO_3 composition (Figure 40) that is representative of the predominantly granitic nature of this catchment. The alkali-rich granitic rocks comprise sodium feldspars ($NaAlSi_3O_8$), e.g. the sodium-plagioclase albite that contributes Na as a silicate weathering product. The higher Cl concentration compared to that of the Skeerpoort River and Bloubank Spruit water most likely reflects the municipal wastewater impact from the Driefontein WWTW on the quality of this water.

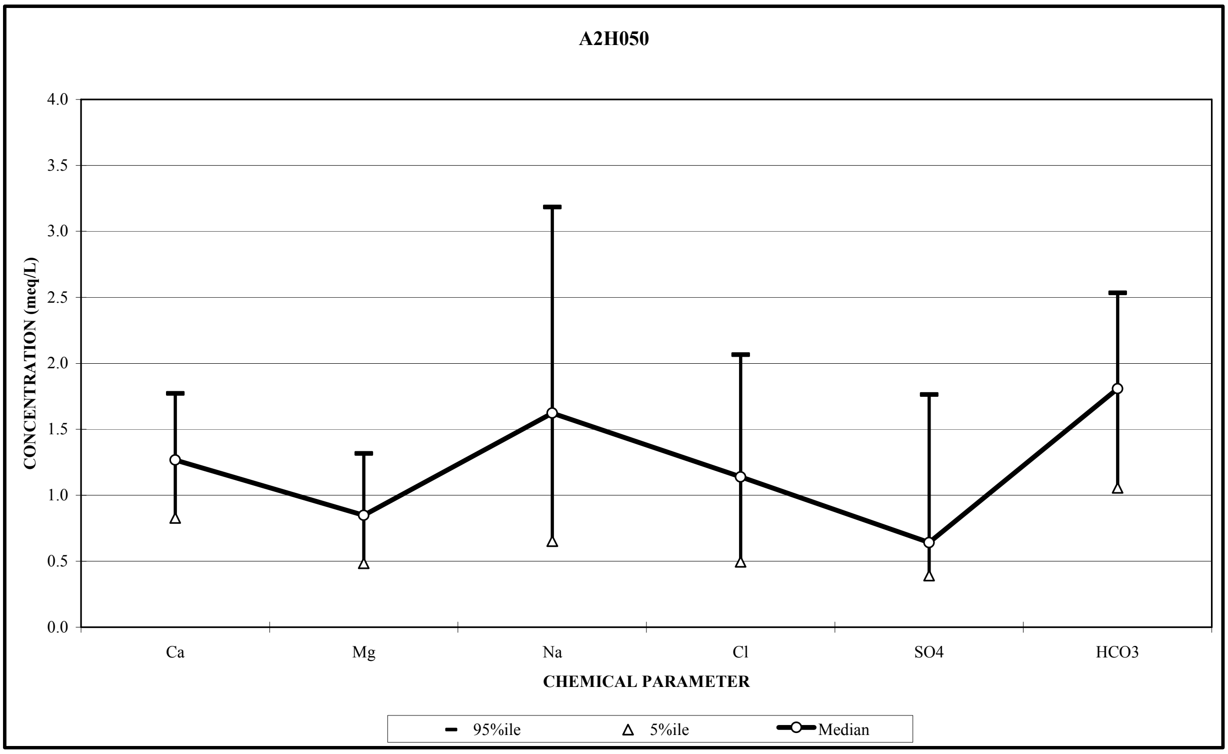

Figure 40. Long-term variability of Crocodile River water chemistry at station A2H050.

The data presented in Table 43 summarize the chemistry of the treated wastewater effluent discharged by the Driefontein WWTW as reported for station DFE by the DWA. Although this record only goes back to late-2002 compared to the much longer record of station A2N050 (Table 42), it provides an assessment of the effluent chemistry more recently discharged from this facility.

Table 43. Water chemistry statistics for Driefontein WWTW discharge (DWA data).

Variable	Statistical Parameter for the period of record 11/2002 to 10/2008							SANS 241: 2006(1)
	n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)	
pH	20	7.0	—	7.3	8.1	0.6	8.0	5.0 – 9.5
EC (mS/m)	22	49.1	55.8	55.5	64.9	8.6	15.4	<150
Cl (mg/L)	21	55.0	74.5	73.0	125.0	26.0	34.8	<200
HCO_3 (mg/L)	20	86.4	141.5	142.6	204.6	61.5	43.5	
SO_4 (mg/L)	22	34.1	50.2	46.5	59.7	26.1	51.9	<400
NO_3+NO_2 (mg N/L)	22	0.3	4.4	3.8	9.2	4.0	91.1	<10
NH_3 (mg N/L)	16	0.000	0.020	0.003	0.122	0.050	244.1	<1
NH_4 (mg N/L)	22	0.05	0.63	0.30	2.38	0.99	158.3	<1
PO_4 (mg P/L)	22	0.05	0.37	0.20	1.08	0.47	127.4	n.s.
COD (mg/L)	22	5.0	23.2	23.5	41.0	14.0	60.5	n.s.
Total coliforms (count/100 mL)	10	16	578	59	2880	1556	269.2	n.s.
Faecal coliforms (count/100 mL)	19	1	**219**	**16**	**1400**	**468**	213.7	≤10 in 1% of samples
E. coli (count/100 mL)	10	**3**	**828**	**39**	**3760**	**1664**	201.0	≤1 in 1% of samples

(1) Recommended limit for Class 1 drinking water quality.
Bold text denotes values that exceed the SANS (2006) recommended limit for Class 1 drinking water.

The statistics indicate that this facility meets the SANS 241 (2006) Class 1 limit in regard to all of the inorganic and organic parameters adjudicated. The exceedances in regard to the bacteriological parameters, whilst still a concern, are orders of magnitude smaller than those associated with the Percy Stewart WWTW (Table 36). Similarly, the mean and median PO_4 values of <1 mg P/L are an order of magnitude smaller than those for the Percy Stewart WWTW.

5.1.4 Synthesis of Surface Water Chemistry

The diagrams presented in Figure 41 are based on the median long-term major ion chemistry of surface water monitored in the Skeerpoort River, the Bloubank Spruit system and the upper Crocodile River. The diagrams characterize the respective sources. A comparison of the Piper diagram characterization with that of groundwater sources in the south-western portion of the study area (Figure 75) shows a marked similarity reflecting the measure of hydraulic continuity between surface and groundwater.

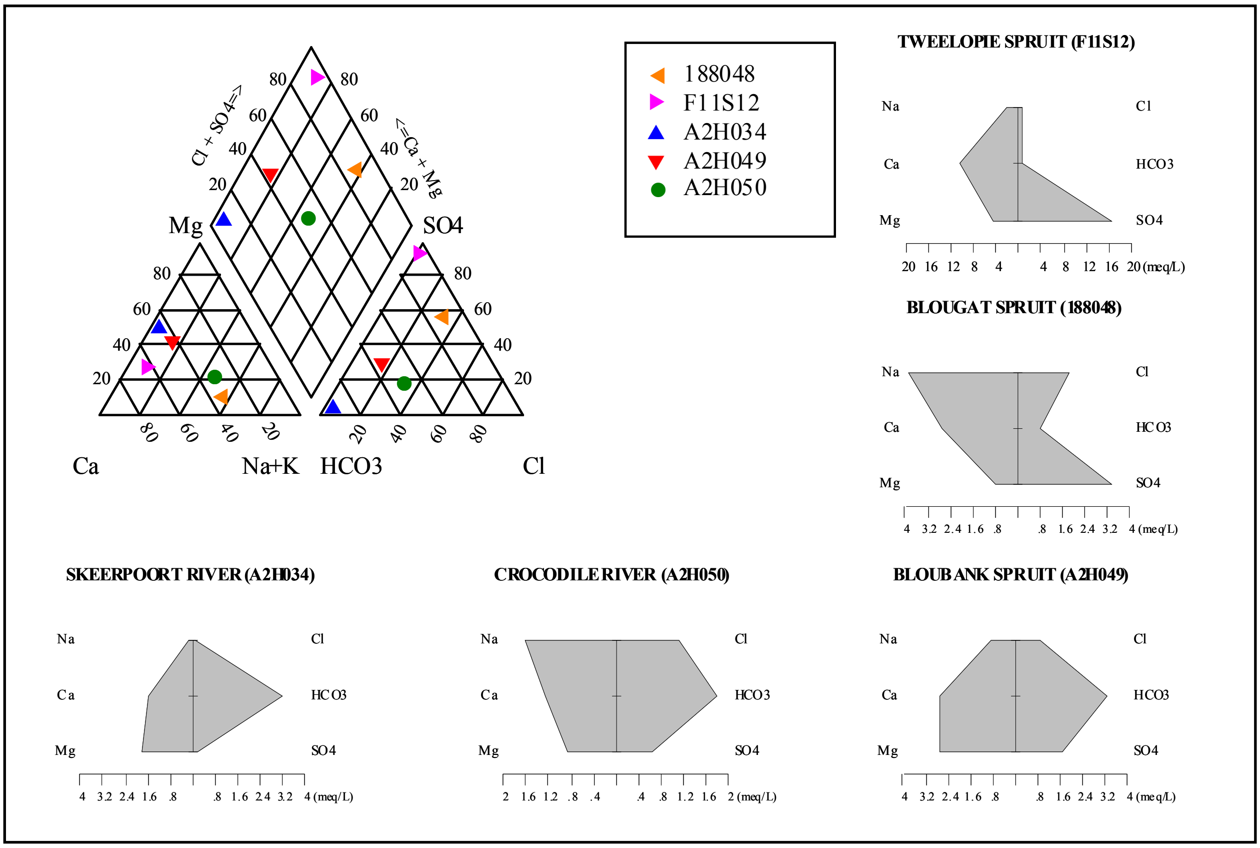

Figure 41. Piper diagram (top left) and Stiff diagrams (bottom and right) characterising surface water chemistry in the study area. Note the different Stiff diagram horizontal scales.

- The Skeerpoort River water with its MgCa-HCO_3 composition is representative of pristine dolomitic (karst) groundwater. As observed by Huizenga (2004), this drainage does not show any sign of pollution. As such, this water quality can serve as a benchmark against which to gauge the level of degradation associated with other rivers in the study area.

- The Bloubank Spruit system water chemistry varies with the main source as follows:
  - the Ca-SO_4 composition of the Tweelopie and Riet Spruit waters characterizes both raw and treated mine water;
  - the Blougat Spruit water reflects a Na-SO_4 composition when treated municipal wastewater contributes the bulk of flow in this drainage, and a Na-HCO_3 composition when rainfall runoff provides a significant contribution;
  - the Honingklip Spruit[29] generally delivers a good quality Mg-HCO_3 type water; and

[29] Not shown in Figure 41 due to the lack of a long-term water chemistry record for this drainage.

– the Bloubank Spruit downstream of its tributaries exhibits a CaMg-HCO_3 composition that reflects the significant contribution of karst spring water draining from the dolomitic strata that dominate this catchment; the elevated SO_4 concentration due to the influence of the mine and wastewater sources explains the shift in the Piper diagram plotting position relative to the Skeerpoort River water.

- The Crocodile River water exhibits a distinctly different Na-HCO_3 composition representative of the predominantly granitic nature of this catchment. This water also shows an elevated Cl concentration compared to that of the Skeerpoort River and Bloubank Spruit water that most likely reflects the municipal wastewater impact on the quality of this water.

5.2 Salt Load Assessment

5.2.1 Catchment Scale

A second aspect of water quality is the salt load associated with the respective water chemistries. Calculated as the product of concentration and flow volume, yielding a load value typically expressed as tons per day (t/d), the calculation might target individual elements such as SO_4 or NO_3+NO_2, or it may target a holistic parameter such as TDS. The latter approach has been taken to compare the annual total salt load that is discharged at each of the sampling stations A2H034, A2H049 and A2H050 (Table 44). The comparison is made on the basis of the median long-term discharge and TDS values previously reported for each station. It would appear that the upper Crocodile River contributes only a slightly greater salt load than does the pristine Skeerpoort River.

Table 44. Annual long-term TDS load discharged by main drainages in the study area.

Drainage	Station	TDS (mg/L)	Discharge (Mm^3/a)	TDS Load		
				t/d	t/a	% of total
Skeerpoort River	A2H034	265 (from Table 30)	8.874 (from Figure 9)	6.4	2352	17
Bloubank Spruit	A2H049	446 (from Table 38)	19.192 (from Figure 11)	23.5	8560	63
Crocodile River (upper)	A2H050	285 (from Table 42)	9.493 (from Figure 15)	7.4	2706	20

A more detailed comparison is made on the basis of the median long-term TDS concentration calculated for each calendar month of mutual flow and water quality record (Figure 42).

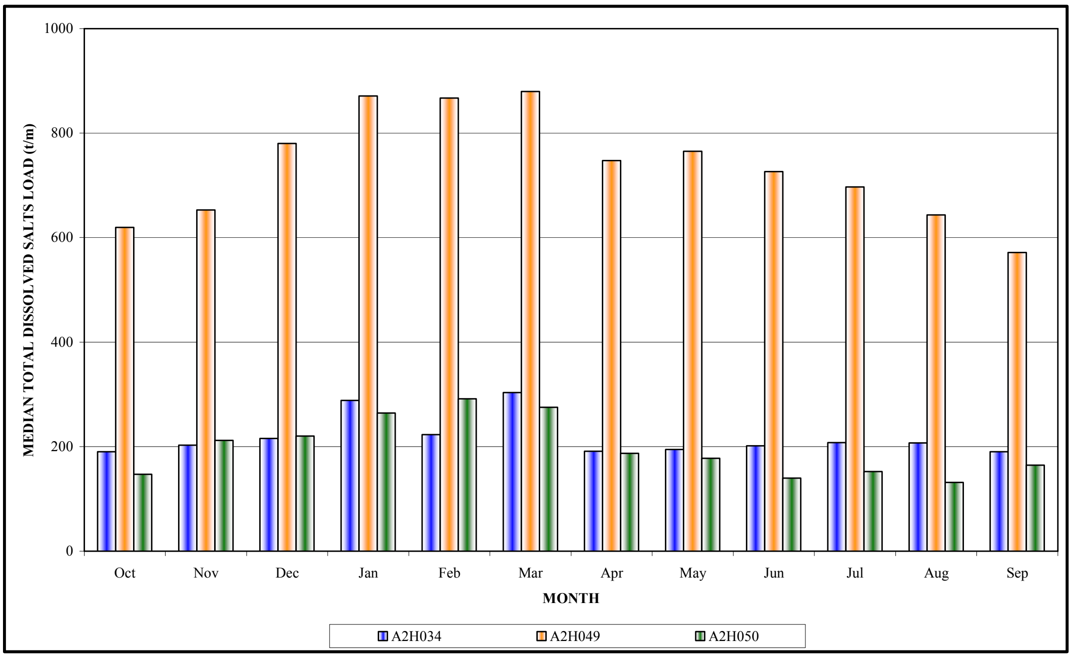

Figure 42. Comparison of long-term median monthly TDS loads carried by the main drainages in the study area.

Figure 42 shows that the Skeerpoort (A2H034) and Crocodile (A2H050) rivers carry similar TDS loads that are 3 to 4 times less than that carried by the Bloubank Spruit system (A2H049). The long-term monthly TDS load data for each of the main drainages were interrogated further to establish the variance associated with the data. The results (Figure 43, Figure 44 and Figure 45) show the exceptional variance for the summer months (especially February) that is common to all three drainages.

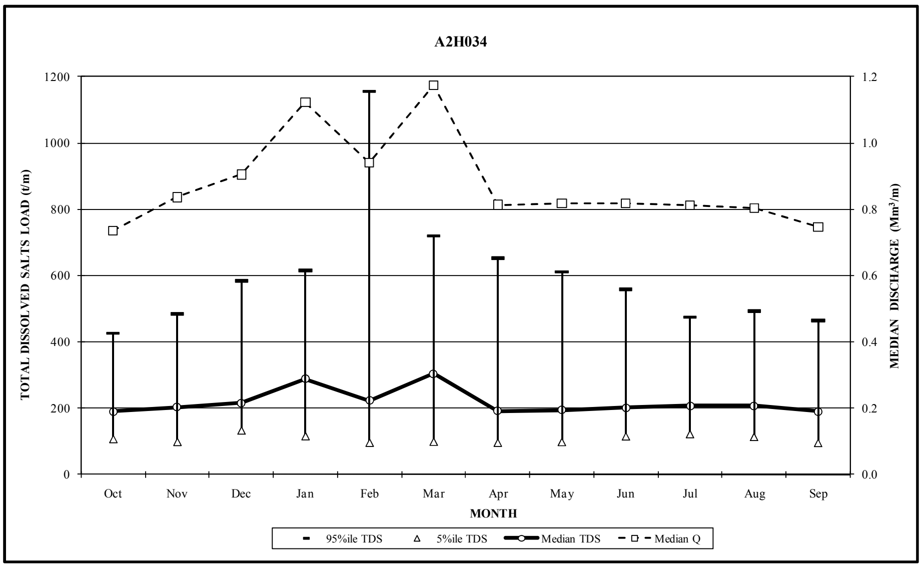

Figure 43. Variance in long-term monthly TDS load at station A2H034, Skeerpoort River.

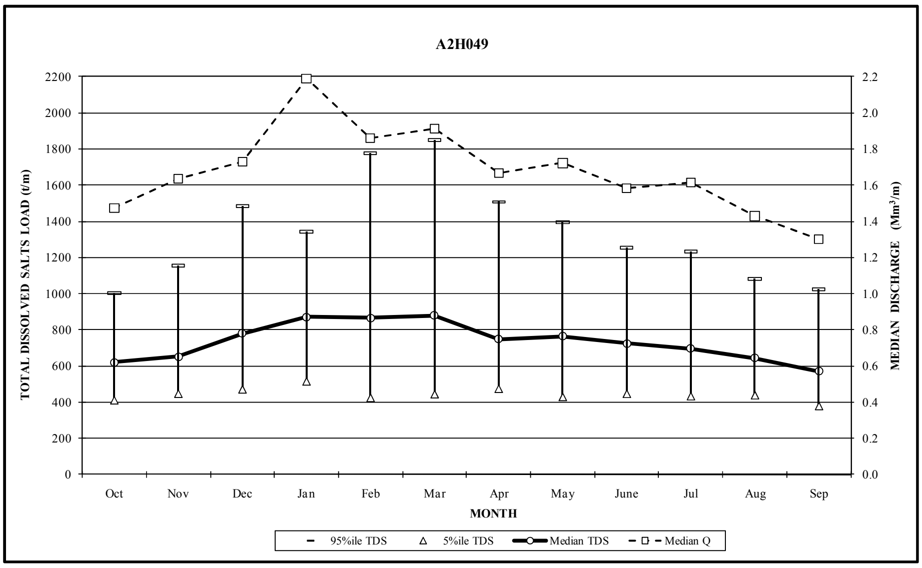

Figure 44. Variance in long-term monthly TDS load at station A2H049, Bloubank Spruit.

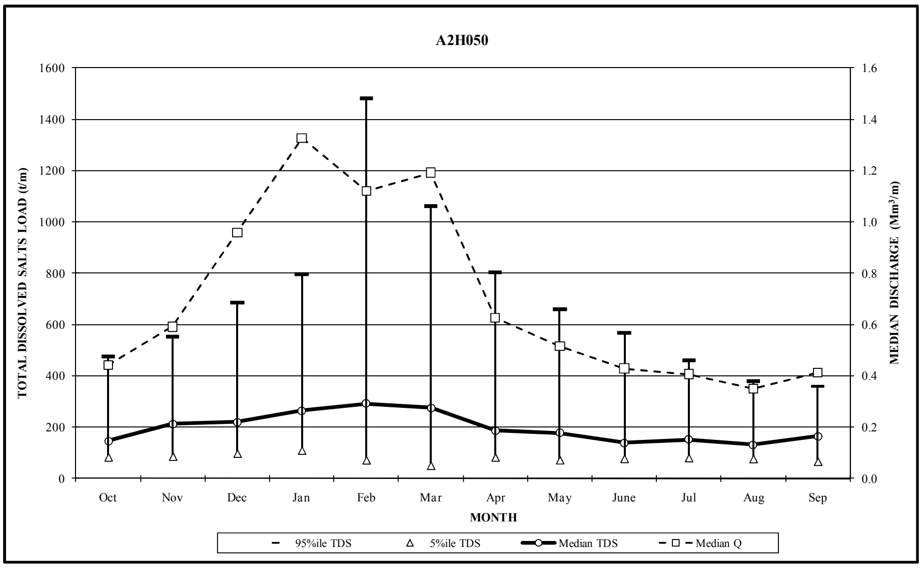

Figure 45. Variance in long-term monthly TDS load at station A2H050, Crocodile River.

Figure 43 also reveals the long-term constancy associated with the median TDS load over a hydrological year in the Skeerpoort River. This again reflects the over-riding contribution of the perennial karst springs to the discharge in this drainage. Also evident in all three figures is the bimodal nature of stream discharge in the study area with peaks in January and March of each hydrological year.

The long-term monthly trend in the TDS load delivered by the Bloubank Spruit and upper Crocodile River catchments is shown in Figure 46 and Figure 47. Both graphs indicate higher median and 95%ile load values in the more recent part of the record (since October 1995) compared to the whole record. This would also seem to be accompanied by a greater variance in monthly TDS load at both stations. Further inspection of the graphs shows that both stations reflect an increasing TDS load (as indicated by the arrows) since mid-2002. In the case of station A2H049, the coincidence with the commencement of mine water decant is tenuous and discussed hereafter, whereas the commissioning of Unit 2 of the Driefontein WWTW might explain this observation in regard to station A2H050 (refer section 4.1.3).

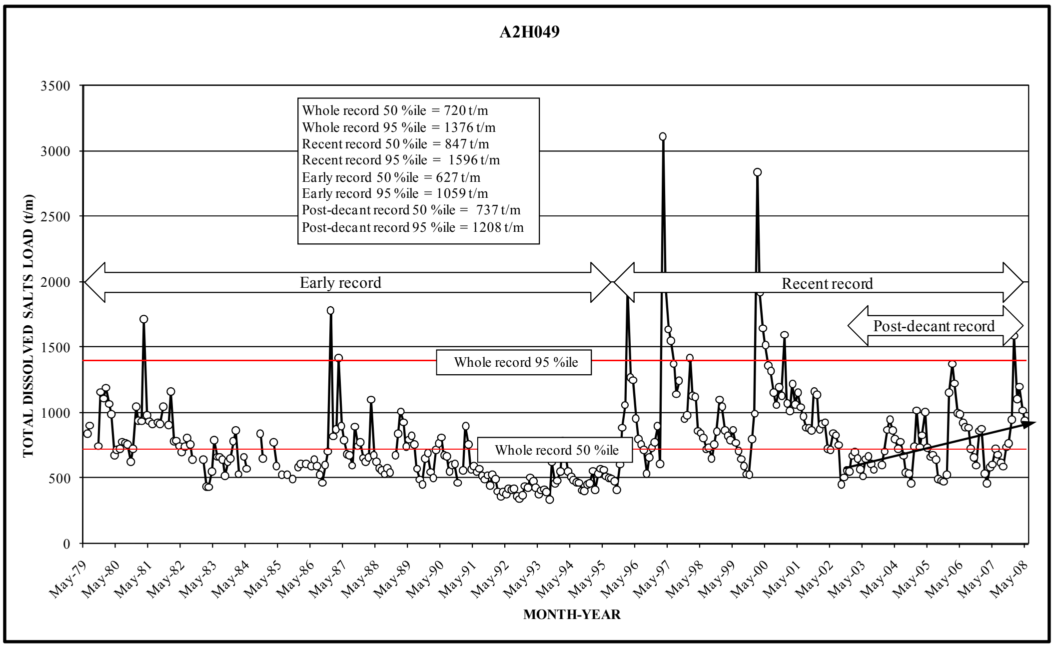

Figure 46. Long-term monthly TDS load pattern at station A2H049, Bloubank Spruit.

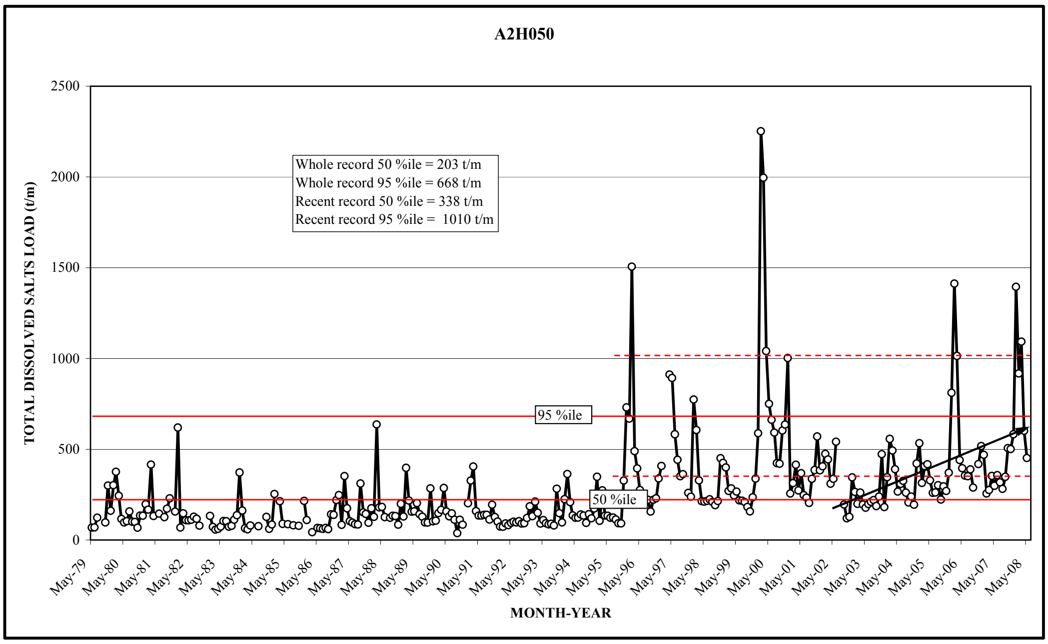

Figure 47. Long-term monthly TDS load pattern at station A2H050, Crocodile River (upper).

A closer inspection of the TDS and SO_4 loads at station A2H049 explores the possible impact of mine water decant from the Western Basin on the chemistry of surface water at the downstream end of the Bloubank Spruit system. This is attempted in Figure 48 showing the TDS and SO_4 load patterns since January 2002. Although a linear regression analysis of the data sets indicates a rising trend in both instances, the poor correlation coefficients (R^2 of 0.08 for TDS and 0.12 for SO_4) suggest that not much value can be attached to the trends. A visual fit through the wet season peak loads as represented by the pecked lines in Figure 48 suggests a more definitive, but still admittedly tenuous, trend. For example, the post-decant median and 95%ile values (Figure 46) are not much different from the whole record values.

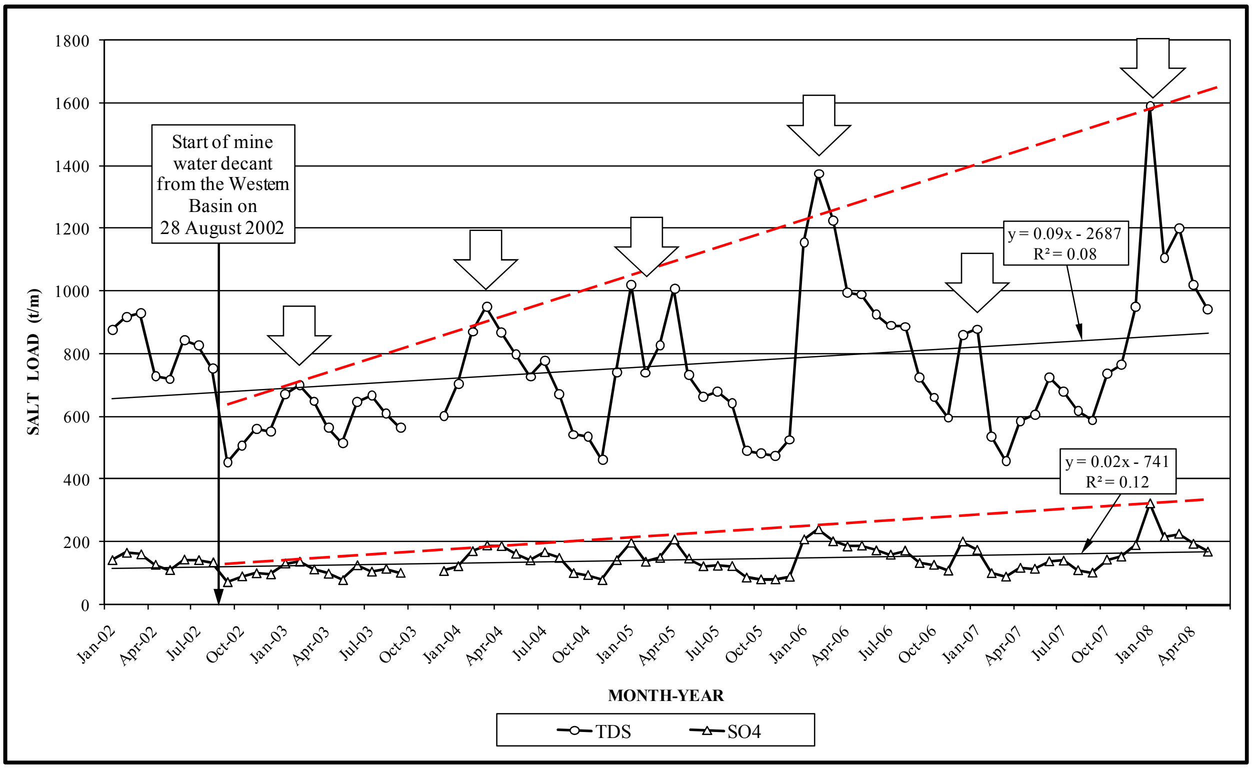

Figure 48. Comparison of monthly TDS and SO_4 loads at station A2H049 since the start of mine water decant from the Western Basin; arrows denote higher wet season loads.

A further analysis of the potential impact of AMD on the chemistry of surface water at the downstream end of the Bloubank Spruit system is based on the SO_4:TDS ratio at station A2H049. This is illustrated in Figure 49 for the period since the start of decant, and in Figure 50 for the entire record period. The rising trend reflected in Figure 49 indicates that SO_4 contributes an increasing proportion of the TDS concentration at station A2H049 in the more recent past. This trend is in marked contrast to the pre-decant trend revealed in Figure 50, which reflects a distinct decline in the SO_4:TDS ratio in the period 1986 to 2001. A possible explanation for the latter trend is the greater contribution of low in SO_4 dolomitic groundwater draining from the Zwartkrans and Krombank compartments following the breaking of the drought that characterized the early 1980s. The earlier rising SO_4 trend (Figure 50) possibly reflects the increasing impact of mine water releases (see also Graph C.7, Annexure C). These observations are considered to provide the clearest indication that AMD originating in the Western Basin has had an impact on the surface water chemistry produced by the Bloubank Spruit system. However, the magnitude of this impact remains comparatively small within the period of record for which the assessment is made.

The effects of the more recent large AMD discharges during the 2009-'10 and 2010-'11 rainfall seasons have not been established. A chemical analysis of Bloubank Spruit water in May 2010 returned SO_4 and TDS values of 76 and 410 mg/L, respectively, giving a SO_4:TDS ratio of ~19% in line with the later values shown in Figure 49. Of grave concern is that a January 2011 chemical analysis yielded a SO_4:TDS ratio of ~67% (SO_4 = 758 mg/L, TDS = 1123 mg/L). This clearly reflects the more recent manifestation of a greater mine water component in the middle and lower reaches of the Bloubank Spruit system.

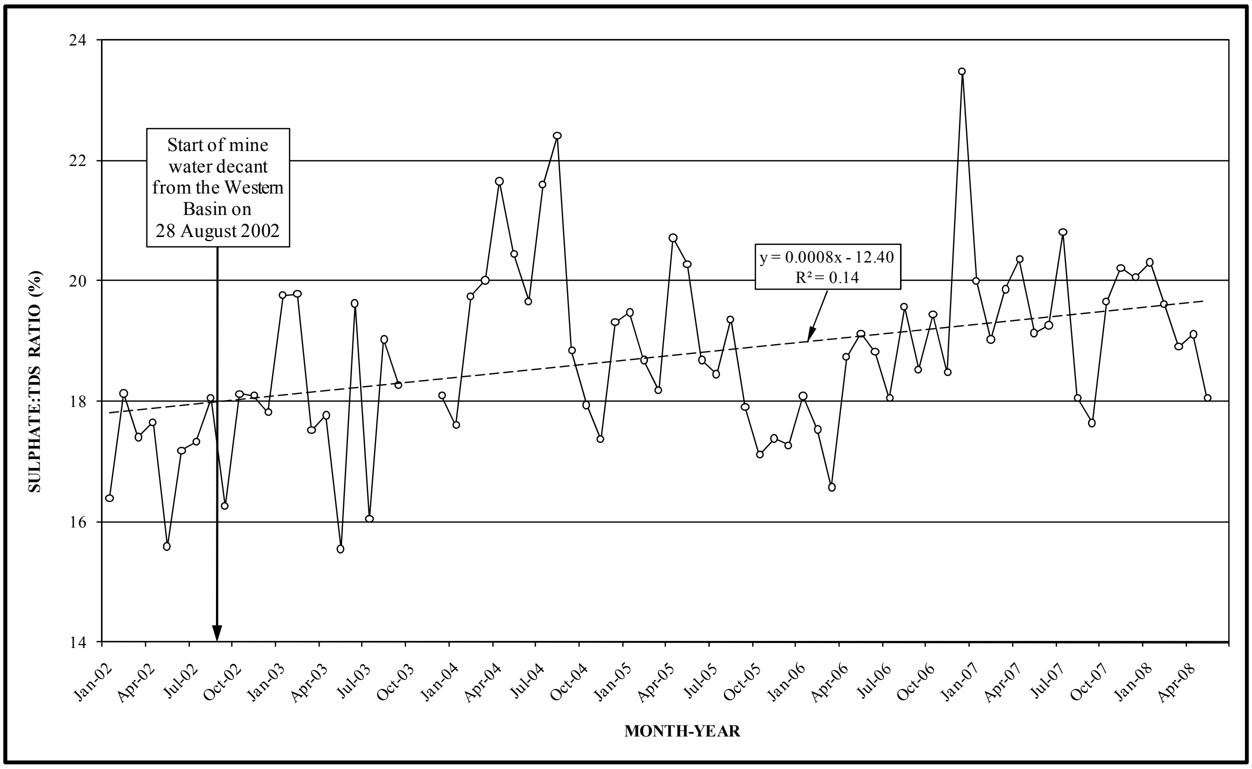

Figure 49. Trend in the SO_4:TDS ratio at station A2H049 since the start of mine water decant from the Western Basin.

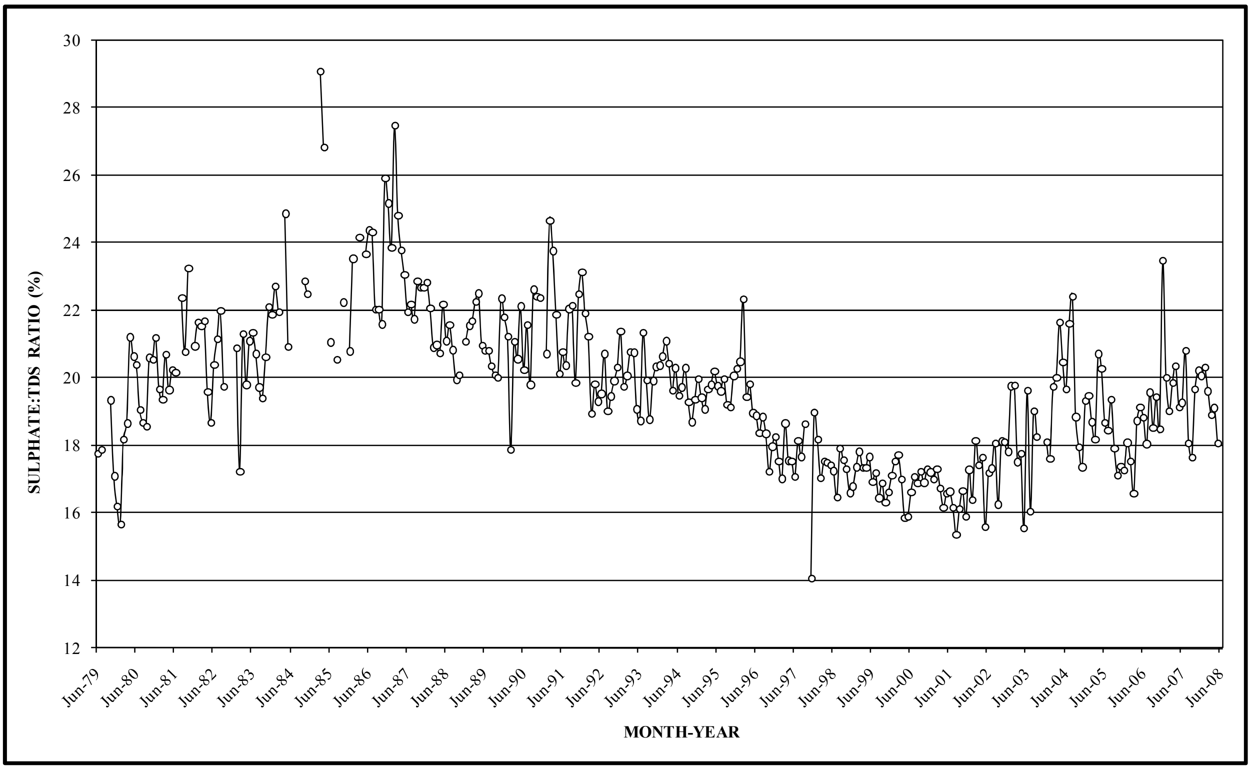

Figure 50. Long-term trend in the SO_4:TDS ratio at station A2H049.

The cumulative median long-term contribution of total salt loads delivered by the Bloubank Spruit and the upper Crocodile River to the Crocodile River downstream of their confluence is shown in Figure 51. The analysis reflects the roughly four times greater contribution of the Bloubank Spruit system compared to that of the upper Crocodile River catchment.

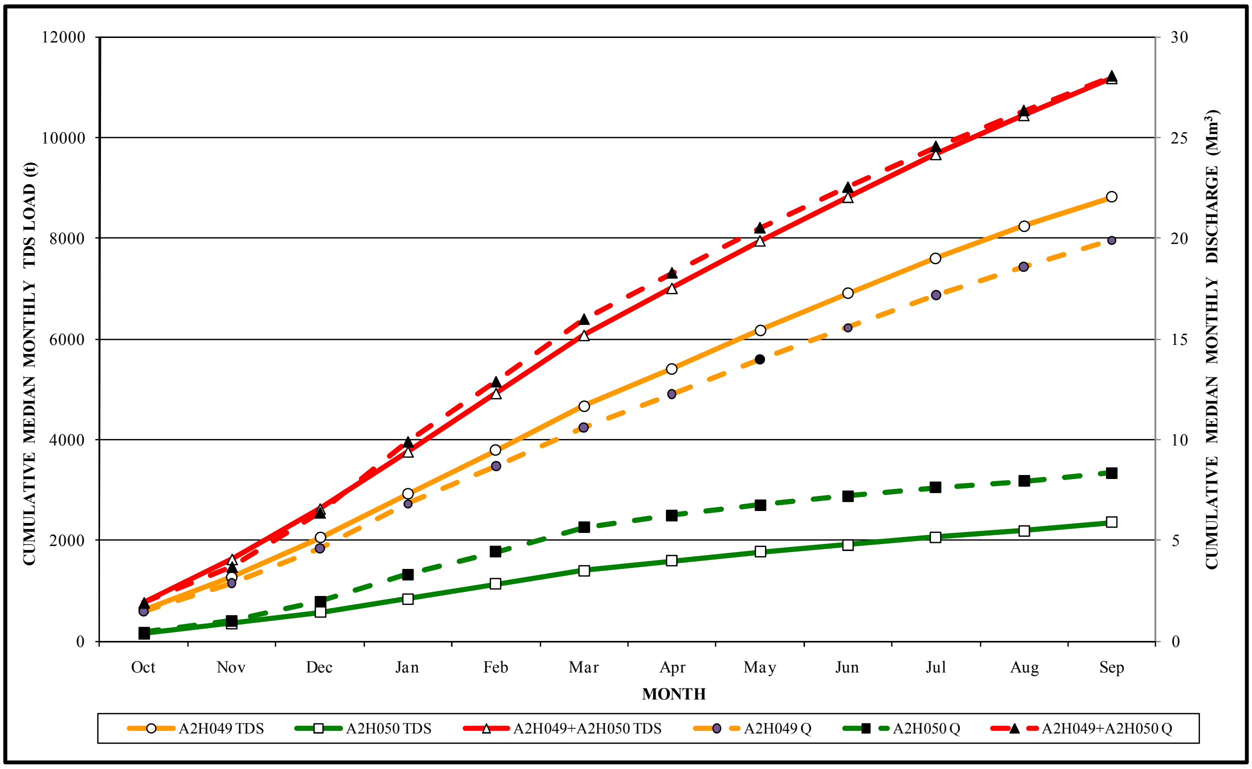

Figure 51. Long-term median monthly TDS load discharged by the Bloubank Spruit and the upper Crocodile River.

Perhaps of greater consequence for the downstream environment that includes the Hartbeespoort Dam, is the nutrient load delivered by the Bloubank Spruit and the upper Crocodile River catchments. In the recent past (July 2007 to June 2009), the Percy Stewart WWTW on the Blougat Spruit in the Bloubank Spruit system delivered a median orthophosphate (PO_4 as mg P/L) load of ~19.3 t/a to this catchment. This is calculated from a median PO_4 concentration of 4.1 mg P/L (Table 35) and a median plant discharge of ~4.7 Mm^3/a (section 4.1.2.2). An inspection of the average monthly flows and concentrations recorded at stations A2N049 (0.25 mg P/L at 27 Mm^3/a) and A2N050 (0.18 mg P/L at 25.3 Mm^3/a) in a similar period (mid-2007 to mid-2008) indicate loads of ~6.7 and ~4.6 t/a passing these stations, respectively. Since a salt load, unlike a concentration, cannot be diluted, the recent phosphate load of ~19.3 t/a determined for the Percy Stewart WWTW raises the question "Why the discrepancy with the much smaller load of ~6.7 t/a seen at station A2H049 located further downstream?" This question remains valid even if the comparative coarseness of the calculations is considered.

A possible answer to the above question lies in the observation that even the most severely impacted karst groundwater source (section 9.4) returned an ortho-phosphate concentration of <0.2 mg P/L, i.e. below the analytical detection limit. In contrast, Table 39 shows that PO_4 concentrations of ~2.4 mg P/L were observed at stations BB@N14 and BB@M on 18/05/2010, whilst at station BB@PL further downstream it amounted to only 0.5 mg P/L on the same day. This suggests that immobilization processes involving phosphorus and heavy metals such as aluminium and iron (see for example Johnson and Younger, 2006; Omoike and Vanloon, 1999; Strosnider and Nairn, 2010) might be responsible for the observed smaller downstream phosphate load(s). This possibility is also explored in section 10.2.

Nevertheless, it is evident from the above that the Bloubank Spruit system and the upper Crocodile River together recently delivered ~11.3 t/a of phosphate into the Hartbeespoort Dam catchment. By comparison, a quick appraisal of relevant DWA data for the period mid-2007 to mid-2008 shows that the Jukskei and Hennops River catchments contributed median phosphate loads of ~207 and ~126 t/a, respectively. Seen in context, the study area (including the upper Crocodile River) contributed ~3%, the Jukskei River ~60% and the Hennops River ~37% to the collective ~344 t/a phosphate recently entering Hartbeespoort Dam from these catchments. This analysis finds support in an evaluation and data presented by Roux (2010).

5.2.2 Subcatchment Scale

The information in Table 45 forms the basis for estimating the proportion of the total salt load contributed by various sources in the Bloubank Spruit system to that leaving this system at station A2H049.

Table 45. Estimated TDS load discharged by various sources in the Bloubank Spruit system.

Source (Station)	Description	Total Dissolved Salts (mg/L)	Discharge (Mm^3/a)	Salt Load (t/a)
Blougat Spruit (188048)	Treated municipal sewage effluent	499 (median)	4.745 (median)	2370
Zwartkrans Spring	Groundwater	244 (one value)	8.67 (one value)	2115
Plover's Lake Springs	Groundwater	110 (one value)	1.89 (one value)	208
Kromdraai Spring	Groundwater	364 (one value)	9.46 (one value)	3443
Bloubank Spruit (A2H049)	Surface water	446 (median)	19.192 (median)	8560

Table 45 shows that the TDS load at station A2H049 (~8560 t/a) is within 5% of the sum (~8136 t/a) of the contributions from the upstream sources represented by the Zwartkrans, Kromdraai and Plover's Lake Springs and the Blougat Spruit. The difference is readily explained by the unaccounted-for contributions of the Tweefontein Spruit and the ephemeral Honingklip Spruit. A recent analysis of the latter surface water shows a TDS value of only ~160 mg/L, and therefore a comparatively small salt load contribution. It is common knowledge that the Tweelopie and Blougat spruits represent the two most impacted contributing sources within the Bloubank Spruit system. The contribution of the Tweelopie Spruit is not accounted for in this estimate, since prior to early-2010 all of the discharge in this drainage into the Riet Spruit was lost to the karst aquifer.

The salt load assessment for the Blougat Spruit reflects a ~30% contribution to the salt load at station A2H049 compared to the ~70% of the combined spring water sources (Table 45). Drainage-specific salt loads are discussed in more detail in the following subsections.

5.2.2.1 Tweelopie Spruit

The salt load assessment for this drainage is based on the surface water quality monitoring record for both the treated mine water EoP station and the downstream station F11S12. The electrical conductivity relationship between these two stations has previously been discussed in section 5.1.2.1. Whereas the EoP station represents the worst case scenario, the PSP considers station F11S12 to be more appropriate for this study since it represents the quality of surface water where it enters (and is gradually lost to) the karst environment of the Zwartkrans Compartment. However, station F11S12 suffers the drawback that the water quality record is not matched by a discharge record, which circumstances oppose a rigorous load calculation at this station.

Figure 52 shows a median TDS load of ~45 t/d entering the Tweelopie Spruit from the mining area since January 2006, with a 95%ile value of 118 t/d. The TDS load discharge pattern is closely matched by that of SO_4, which amounts to a median load of 29 t/d and a 95%ile value of 74 t/d. SO_4 therefore typically accounts for ~64% of the total salt load in the treated mine water. By comparison, the SO_4 concentration of 2130 mg/L (~44 meq/L from Figure 29) and discharge of 31.6 ML/d recorded at station F11S12 on 16/02/2010 (Table 27) under more 'extreme' conditions represents a SO_4 load of 67 t/d. On the same day (Figure 29 and Table 27), this load had reduced to 23 t/d (SO_4 = 2221 mg/L, Q = 10.3 ML/d) where the Malmani Road crosses the Riet Spruit (station MRd1, Figure 35). This suggests that a SO_4 load of 44 t was lost to the karst aquifer between these two stations on this day. A similar calculation for 18/05/2010 returned SO_4 loads of 64 t/d at F11S12 and 20 t/d at MRd1 for the same net loss of 44 t to the aquifer. SO_4 accounts for 66% of the total salt load at station F11S12, and Ca for a further 18%. These two elements together therefore account for 84% of the surface water TDS load at the lower end of the Tweelopie Spruit. By contrast, the respective proportions of SO_4 and Ca to TDS at station A2H049 amount to only 19% and 12%, for a combined contribution of 31%.

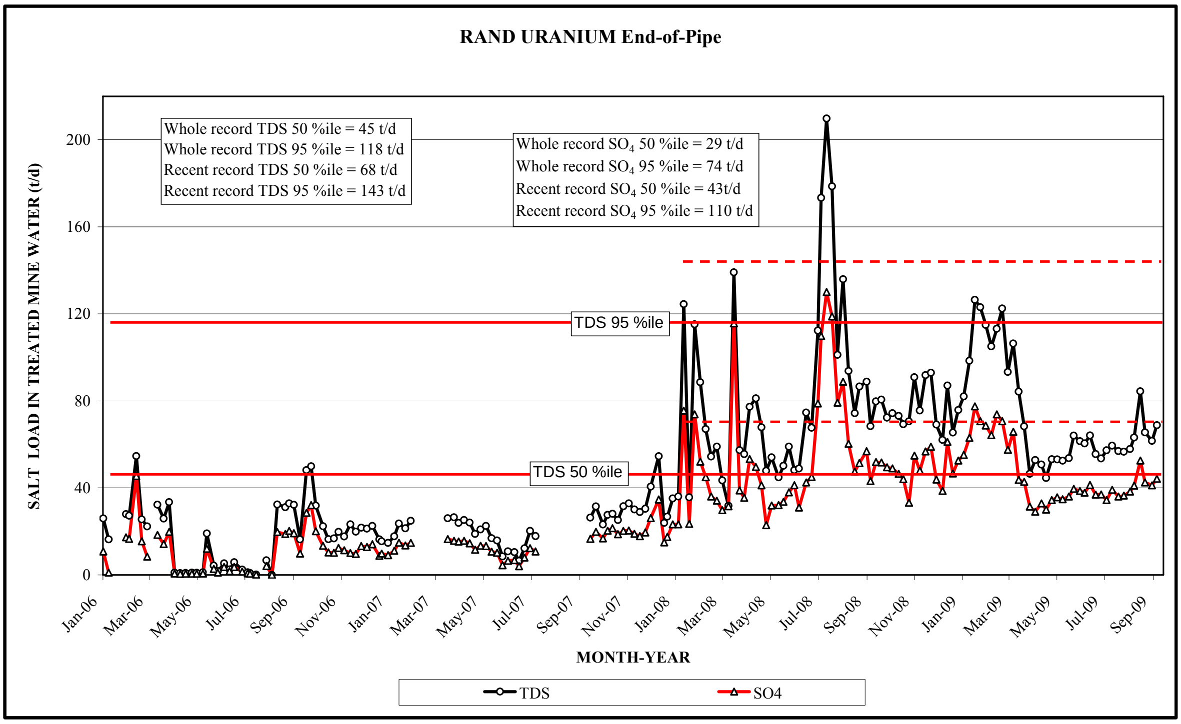

Figure 52. TDS and SO_4 loads in treated mine water discharged to the Tweelopie Spruit.

5.2.2.2 Blougat Spruit

The pattern of TDS load associated with treated effluent released into the Blougat Spruit from the Percy Stewart WWTW (Figure 53) closely resembles the discharge pattern (Figure 14, section 4.1.2.2). The median value of 10.7 t/d represents ~16% of the 68 t/d contributed more recently by the Tweelopie Spruit (Figure 52). Although the DWA reports the effluent chemistry dating back to November 2002, the absence of TDS from this analytical suite (see Annexure A.9) limits a load assessment for this parameter.

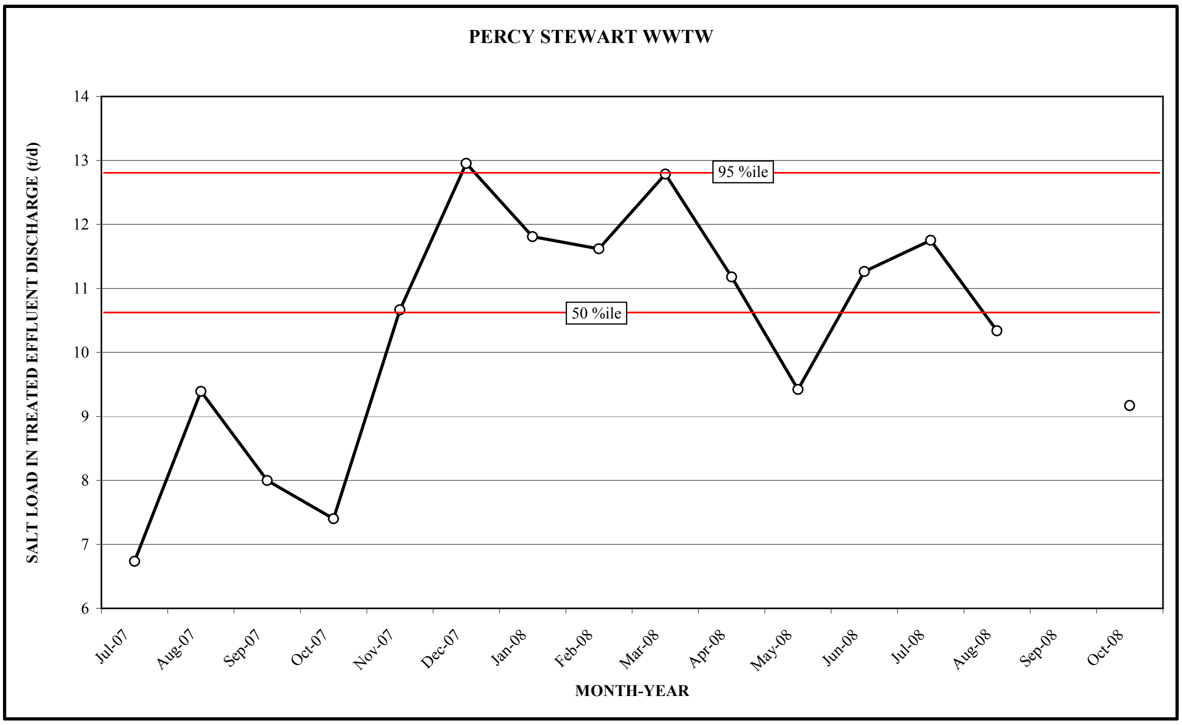

Figure 53. Pattern of recent TDS load associated with treated municipal effluent discharge to the Blougat Spruit.

5.3 Pollution Indicators

5.3.1 SO_4:Cl Ratio

A further hydrochemical perspective on the surface water is provided by the SO_4:Cl ratio (as meq/L). This ratio is an indicator of potential mining and/or industrial influence on water quality. Its median value for the near-pristine Skeerpoort River water is 1.3, with a 95%ile value of 3.6 (Table 46). Against this local benchmark, the Rand Uranium EoP median value of ~43 on the Tweelopie Spruit is quite evidently more than an order of magnitude larger, but improves at the downstream station F11S12. Encouragingly, the median values for the Bloubank Spruit and its other tributaries are only slightly greater than that for the Skeerpoort River. This reflects the comparatively unimpacted inorganic chemistry of the surface water in these drainages up to mid-2008. A ratio value of 1.4 is associated with a water sample collected on 18/05/2010 at station BB@PL (Table 39). The upper Crocodile River supports a median SO_4:Cl value of 0.6, which reflects the dominance of Cl over SO_4 in this surface water most likely attributable to the treated effluent discharge from the Driefontein WWTW (refer section 5.1.3).

Table 46. Statistical values of the SO_4:Cl ratio for drainages in the study area.

Drainage	Station	Statistical Parameter						
		n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)
Skeerpoort River	A2H034	1105	0.6	1.6	1.3	3.6	1.1	67.4
Tweelopie Spruit	RU EoP	194	25.9	43.7	42.7	59.5	126.4	12.1
	F11S12	51	15.2	27.1	26.4	42.5	11.8	43.7
Blougat Spruit	188048	42	1.1	2.1	1.9	4.4	1.1	52.7
Tweefontein Spruit	F14S15	42	1.4	1.7	1.7	2.3	0.3	18.9
Bloubank Spruit	A2H049	784	1.5	2.0	1.9	2.7	0.4	18.4
Crocodile River	A2H050	788	0.3	0.7	0.6	1.5	0.4	53.2

5.3.2 N:P Ratio

The DWAF (1996a) stresses that any assessment of the influence of inorganic nitrogen concentrations should be coupled to an evaluation of the inorganic nitrogen to inorganic phosphorus ratio, and vice versa. The N:P ratio for unimpacted systems typically is greater than 25 to 40 : 1, and less than 10 : 1 in most impacted (eutrophic or hypertrophic) systems.

The median N:P ratio values for selected drainages in the study area (Table 47) indicates the measure of impact associated with the Percy Stewart WWTW effluent discharge into the Blougat Spruit compared to the Bloubank Spruit at station A2H049. The variability of this parameter at station A2H049 for the entire record period is significant, but exhibits a smaller variability when only the last ten years of record is considered, whilst still reflecting a largely unimpacted character. Similarly, the Crocodile River exhibits a moderately impacted condition in both the long-term and the more recent past. Again, the last ten years of record reflect a smaller variability but similar moderately impacted character. By comparison, Zohary et al. (1988) reported a N:P ratio of between 7 and 1 for Hartbeespoort Dam.

Table 47. Statistical values of the N:P ratio for drainages in the study area.

Drainage (Station)	Period	Statistical Parameter						
		n	5%ile	Mean	Median	95%ile	Std Dev	CoV (%)
Blougat Spruit (Percy Stewart WWTW)	07/2007 – 06/2009	24	3.8	9.0	7.5	18.4	5.2	58.4
Blougat Spruit (188048)	06/2004 – 03/2008	41	0.03	6.3	3.3	26.0	9.6	151.5
Bloubank Spruit (A2H049)	04/1980 – 09/2008	851	16.0	199.6	83.9	654.4	475.0	237.9
	10/1998 – 09/2008	387	13.2	50.1	41.1	113.6	36.7	73.3
Crocodile River (A2H050)	05/1979 – 09/2008	852	0.3	26.2	17.3	71.3	43.1	164.8
	10/1998 – 09/2008	389	3.5	23.7	20.4	54.0	17.3	72.7

A concern in regard to PO_4-P is the concentrations recently observed at several surface water sampling stations in the Bloubank Spruit system (Table 39). For example, the values of 0.5 mg P/L and 6 mg N/L observed at station BB@PL (Table 39) return a N:P ratio of 12. This compares unfavourably with the median value of 41 observed for the period October 1998 to September 2008 at station A2H049 (Table 47). It also explains the degree of eutrophication experienced in the defunct trout dams at Plover's Lake.

5.3.3 Trace/Heavy Metals and Radionuclides

The presence of trace/heavy metals and radionuclides provides a further indication of especially mine water pollution. These variables also represent a concern for their impact on the quality of surface water further downstream in the Bloubank Spruit system. A surface water sample collected in May 2010 near the Sterkfontein Caves returned Fe and Mn values of 0.91 and 0.67 mg/L, respectively. A sample collected at Plover's Lake further downstream on the same day returned Fe and Mn values of 0.36 and 0.29 mg/L, respectively. Although both sets of values significantly exceed the long-term median values of 0.006 mg Fe/L and 0.002 mg Mn/L determined for these variables at station A2H049 (Table 38), the significant differences between the 'upstream' and 'downstream' samples caution against the direct comparison with the long-term values at A2H049. Whilst the observations may therefore be seen as reflecting the recent manifestation of a mine water impact, the COH WHS monitoring programme will better inform this matter in time to come.

Uranium concentrations in surface water nowhere exceeded the analytical detection limit of 0.001 mg/L. Strachan et al. (2008) report that the Klip River Radioactivity Monitoring Programme found a good linear correlation between the U concentration in water and the total radiation dose from all radionuclides. This prompted these authors to suggest that the U concentration might serve as an indirect measure of the total radiation dose from all radionuclides for screening and routine monitoring purposes in a catchment.

5.4 Surface Water Fitness

5.4.1 Potable Use

The fitness of water for human consumption is gauged against the SANS 241 (2006) standard for drinking water quality. The extent to which the water quality variables associated with the various surface water sources in the study area meet the Class 1 limits of the SANS 241 standard in the long-term is already reflected in the relevant tables (e.g. Table 30, Table 31, Table 32, Table 33, Table 37, Table 38 and Table 39). It is evident that drainages such as the Skeerpoort River (Table 30) and the Tweefontein Spruit (Table 37) carry an excellent quality water in all respects. It is equally evident, however, that the drainages receiving mine water (Tweelopie and Riet spruits) and treated sewage effluent (Blougat Spruit) experience exceedances in regard to EC, Ca, SO_4, Fe, Mn and Al.

It is evident from Table 35 and Table 36 that the Blougat Spruit additionally experiences severe exceedances in regard to the bacteriological quality as represented by the faecal coliform and *E. coli.* counts. These circumstances seriously compromize the use of the surface water in these drainages for human consumption. However, Table 39 and Figure 37 indicate that the situation improves significantly in the main stem represented by the Bloubank Spruit. Nevertheless, the persistent presence of bacteriological contamination in surface water of the Bloubank Spruit system cautions strongly against its unqualified use for human consumption without treatment. It has been established that the majority of riparian landowners in the Bloubank Spruit system demonstrate a distinct aversion to the use of surface water for any purpose except, perhaps, for garden irrigation.

5.4.2 Agricultural Use

5.4.2.1 Livestock Watering

Guidelines in this regard are provided in the DWAF (1996b) publication. The target water quality range (TWQR) limits for the major inorganic variables are typically less strict than for human consumption. For example, the TWQR for SO_4 (a variable that, together with TDS and Cl, effects the palatability of water also for livestock) is 1000 mg/L compared to the 400 mg/L for humans. This is also true for trace/heavy metals, e.g. Mn and Fe with a TWQR of <10 mg/L for livestock compared to a TWQR of <0.1 mg Mn/L and <0.2 mg Fe/L for humans. Even the observed presence of bacteriological contamination in surface water of the Bloubank Spruit system is rendered more acceptable for livestock by the faecal coliforms TWQR of <1000 c/100 mL in 20% of samples, compared to the <10 c/100 mL in 1% of samples for humans.

The chemical analysis results for surface water in the study area cautions against the unqualified use thereof for livestock watering. Water of the Tweelopie/Riet Spruit subsystem is characterized by an elevated salt load reflecting a dominant Ca-SO_4 composition that accounts for 84% of the TDS load in this water (section 5.2.2.1). This water is not, however, compromised in regard to its trace/heavy metals or bacteriological composition for livestock watering. Water of the Blougat Spruit, on the other hand, exhibits a suitable inorganic and trace/heavy metals composition, but is compromised by unacceptable levels of bacteriological contamination. Although these circumstances improve markedly in the Bloubank Spruit downstream of Sterkfontein Caves (section 5.1.2.4 and Figure 37), caution is still advised against its unqualified use for livestock watering.

5.4.2.2 Irrigation

The fitness of water for irrigation use is assessed on the basis of the sodium adsorption ratio (SAR) and salinity (expressed as electrical conductivity) of the water. The SAR is calculated as the ratio between the Na concentration and the combined Ca and Mg concentrations using the formula

$$SAR = Na / [(Ca + Mg)/2]^{½} \qquad \text{(variable concentrations as meq/L)}$$

to derive the sodium hazard (designated S) associated with the water. This value is graphed against the electrical conductivity value, which represents the salinity hazard (designated C), to derive an alpha-numeric classification (e.g. C#-S#) defined by the Wilcox diagram (Figure 54), and where the numeric component ranks from 1 = **low** through 2 = **medium** and 3 = **high** to 4 = **very high**.

The range of SAR values that represent the various surface water sources in the study area is presented in Table 48. The results (also shown graphically in Figure 54) indicate that the sodium hazard in no instance exceeds a low (S1) classification. However, the salinity hazard associated with the drainage impacted by mine water (stations F11S12 and MRd1) reflects a very high (C4) ranking. This limits the use of this water to the irrigation of crops with a very good salt tolerance on well-drained permeable soils.

Table 48. Range of representative SAR values for various surface water sources in the study area.

Station	**Range of Representative SAR Values**					**Classification per Median(1)**
	Source	**5%ile**	**Mean**	**Median**	**95%ile**	
A2H034	Table 30	0.08	0.10	0.10	0.14	C2-S1
A2H049	Table 38	0.30	0.56	0.55	0.77	C2-S1
A2H050	Table 42	0.81	1.65	1.58	2.56	C2-S1
F11S12	Table 32	0.47	1.03	0.70	1.59	C3-S1
	Table 39	1.14(2)				C4-S1
MRd1	Table 39	0.99(2)				C4-S1
188048	Table 33	2.10	2.81	2.94	3.33	C3-S1
BC1	Table 39	2.00(2)				C2-S1
BG@N14	Table 39	1.76(2)				C2-S1
F14S15	Table 37	0.33	0.66	0.72	0.83	C1-S1
BB@M	Table 39	1.71(2)				C2-S1
BB@PL	Table 39	0.93(2)				C2-S1
HS1	Table 39	0.21(2)				C1-S1

(1) Where applicable; refer to source tables for individual sample population sizes.
(2) Single value.

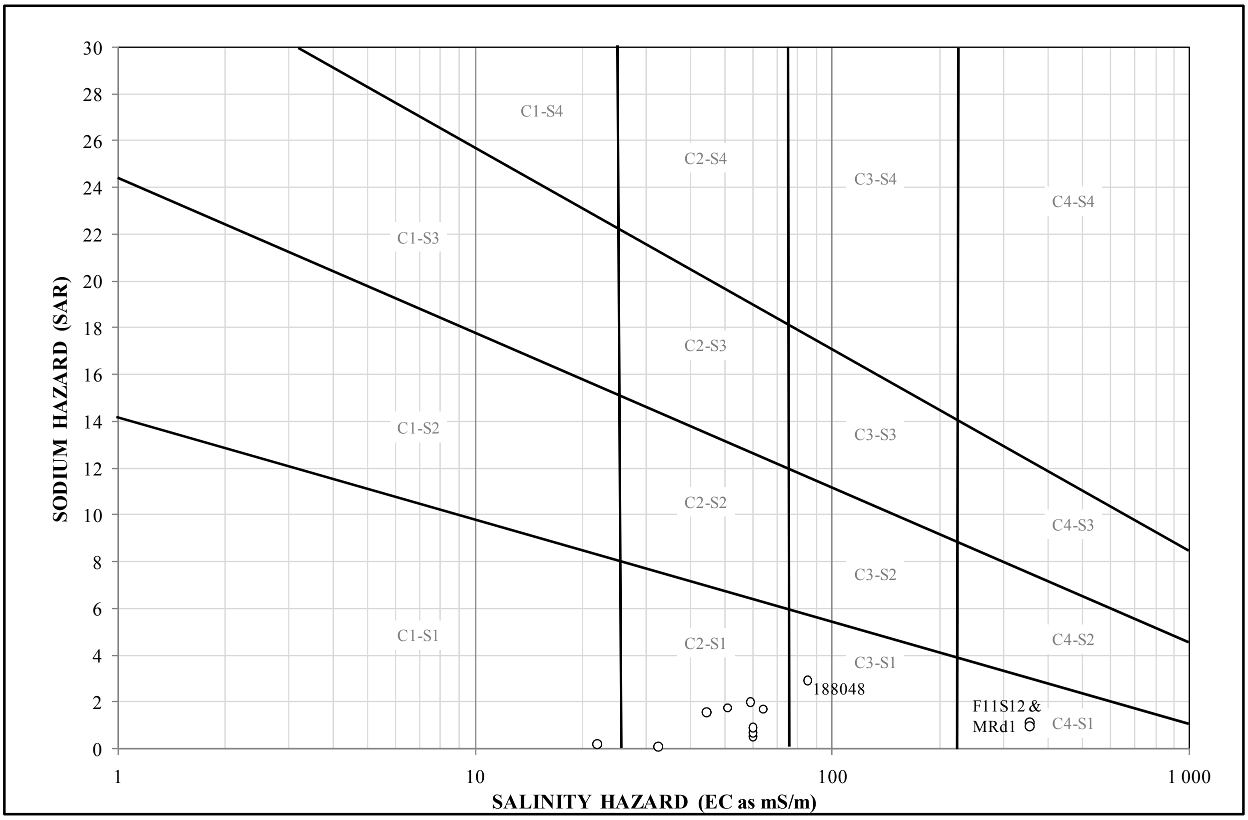

Figure 54. Wilcox diagram illustrating the classification of surface water chemistry for irrigation purposes (data from Table 48).

Other aspects of the water chemistry that have relevance to the irrigation use of the water are the N:P ratio and the corrosion tendency ratio (CTR) values. The N:P ratio is discussed in greater detail in section 5.3.2, where concern is expressed in regard to N:P ratio values as low as 12 recently observed at several surface water sampling stations in the Bloubank Spruit system. This compares unfavourably with the long-term median value of 41 observed for the period October 1998 to September 2008 at station A2H049, and might explain the degree of eutrophication experienced in the defunct trout dams at Plover's Lake.

The CTR is calculated as the ratio between the sum of the Cl and SO_4 concentrations and the total alkalinity ($CaCO_3$) concentration using the formula

$$CTR = [Cl + SO_4] / \text{Alkalinity as } CaCO_3 \qquad \text{(variable concentrations as meq/L)}$$

Used to estimate the corrosive tendency of Cl and SO_4 ions, a ratio ≤ 0.1 indicates general freedom from corrosion in neutral to slightly alkaline (pH 7 to 8) oxygenated waters (DWAF, 1996c), and increasingly higher ratios indicate a tendency towards more corrosive waters. The CTR values associated with the surface water samples collected at seven stations in the Bloubank Spruit system in May 2010 are presented in Table 49, together with other variables for which the DWAF (1996c) provides a target water quality range (TWQR) for irrigation use.

A chemical analysis of surface water collected at station BB@M in mid-January 2011 yielded a CTR value of 338 which, together with a pH value of ~3, indicated the water to be extremely corrosive. This is commensurate with the more recent manifestation of a greater mine water component in the middle to lower reaches of the Bloubank Spruit system especially during the 2010-'11 rainfall season (section 5.2.1). However, corrosion of pipelines and fittings is only likely to manifest as a problem through continued and medium- to long-term use of water with this chemical characteristic. The likelihood of this occurring depends on the success (or otherwise) of mine water treatment interventions in the locus of decant.

Table 49. Evaluation of Bloubank Spruit system surface water quality for irrigation use.

Variable	Sampling Station							DWAF TWQR[(1)]
	F11S12	**MRd1**	**BC1**	**BG@N14**	**BB@M**	**HS1**	**BB@PL**	
Date	18/05/2010							
pH (field)	**5.5**	**4.4**	7.1	6.9	6.9	6.9	7.0	6.5 – 8.4
EC (mS/m) (field)	**355**	**356**	**59**	**51**	**64**	22	**60**	≤40
Na (mg/L)	**115**	**103**	55	48	52	5	34	≤70
Cl (mg/L)	43	44	52	45	50	12	40	≤100
NO_3+NO_2 (mg N/L)	**0.6**	**0.6**	0.2	0.5	**3.2**	**1.9**	**6.0**	≤5.0[(2)] ≤0.5[(3)]
F (mg/L)	<0.2	<0.2	0.2	0.2	<0.2	<0.2	<0.2	≤2.0
E. coli (count/100 mL)	n.a.	n.a.	**65 000**	**26 000**	**3000**	0	**470**	≤1 in 1% of samples
Fe (mg/L)	**0.431**	**0.934**	**0.528**	**0.682**	**0.906**	0.073	**0.358**	≤5.0[(2)] <0.2[(3)]
Mn (mg/L)	**10**	**18**	**0.279**	**0.470**	**0.665**	0.087	**0.293**	≤0.02[(2)] <0.2[(3)]
Al (mg/L)	<0.1	0.121	0.118	<0.1	0.134	<0.1	0.137	≤5.0
U (mg/L)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	≤0.01
Ni (mg/L)	0.145	0.117	0.049	0.035	0.029	<0.025	<0.025	≤0.2
Zn (mg/L)	0.048	0.379	0.043	0.025	<0.025	<0.025	<0.025	≤1.0
N:P value	6	6	0.1	0.2	1.3	19	12	n.s.
SAR value	1.14	0.99	2.00	1.76	1.71	0.21	0.93	≤2.0
CTR value	772	783	1.0	0.9	1.2	0.4	1.0	n.s.

(1) Recommended target water quality range (TWQR) limit for irrigation use (from DWAF, 1996c).
(2) Effect on crop yield and quality.
(3) Effect on irrigation equipment (mainly drip irrigation systems).
Bold text denotes values that exceed the TWQR recommended limit for irrigation use.

5.5 Mine Water Chemistry in the Receiving Drainages

The ad hoc measurement of field pH and EC values triggered by the advent of excessive mine water decant in late-January 2010 provided the opportunity to gather valuable information on the chemistry of surface water in the receiving environment. Comprising a mixture of treated mine water from the HDS plant and raw mine water subjected to in-stream liming at the point of release, the pH and EC of this water was measured at various localities in the downstream receiving drainages. The data presented in Table 50 and Table 51 reflect the degree of change recorded on 05/02/2010 and 01/04/2010, respectively, in these variables with distance downstream of where the mine water left the mine property.

Table 50. Change in surface water chemistry with distance downstream of the mine water source on 05/02/2010.

Locality		Distance (m)		EC (mS/m)	pH	Flow (ML/d)
		Segmental	**Cumulative**			
1	KGR Inflow (raw mine water after in-stream liming)	0	0	354	4.5	21.0
2	KGR Inflow (treated mine water)			306	6.3	19.0
3	Hippo Dam outlet in KGR	950	950	332	5.6	n.m.
5	Poplar Grove in KGR	850	1800	324	4.3	n.m.
6	Aviary Dam inlet in KGR	3105	4905	302	4.0	32.1
7	KBW Dam outlet at N14 (F11S12)	1540	6445	302	3.9	35.2
8	Riet Spruit at Malmani Road (MRd1)	3900	10345	278	4.1	7.3
9	Bloubank Spruit downstream of Makiti (BB@M)	5050	15395	45	7.1	43.2
10	Bloubank Spruit at A2H049	12000	27255	44	7.2	n.m.
11	Blougat Spruit tributary of the Riet Spruit at N14 (BB@N14)		10835[(1)]	51	6.9	~36.0[(2)]
12	Honingklip Spruit tributary of the Bloubank Spruit at Kromdraai (HS1)		18905[(1)]	19	7.2	n.m.

(1) Distance of confluence with main stem downstream from the mine water source.
(2) Difference between flow measured at localities 8 and 9.
n.m. denotes not measured.

The measurements reveal the following hydrochemical responses.

- The decrease in the pH of the water with distance downstream of the mine water source area, from a value of ~5.6 at the Hippo Dam outlet to a value of ~3.9 at the Krugersdorp Brickworks Dam outlet, followed by values of 4.1 and 3.4 in the Riet Spruit at the Malmani Road crossing. This response is readily accounted for by hydrolysis reactions (Hem, 1985) which, in this instance, increases the hydrogen ion activity (pH decreases) as a result of the precipitation of primarily iron out of the surface water as illustrated in the reaction (amongst many similar such reactions)

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_{3(s)} + 3H^+$$

  in which ferric iron (Fe^{3+}) is hydrolized by water to precipitate as an orange ferric oxyhydroxide [$Fe(OH)_3$] (an insoluble solid residue also called “ochre” or “yellow boy”) and free hydrogen ions, i.e. acidity which maintains the solubility of the ferric iron (Banks, 2004).

- The significant improvement in surface water quality downstream of the Riet Spruit/Blougat Spruit confluence, as indicated by the EC values of 45 and 27 mS/m and the pH values of 7.1 and 7.3 measured in the Bloubank Spruit downstream of Makiti, compared to the 278 mS/m and pH of ≤4.1 measured in the Riet Spruit at the Malmani Road crossing (station MRd1). This is attributed to the mitigating influence of the significant discharges (estimated at ~36 and ~118 ML/d, respectively) contributed by the better inorganic quality of Blougat Spruit water characterized by an EC in the range 30 to 50 mS/m and a pH in the range 6.9 to 7.3. It is evident from the information presented and discussed in section 5.1.2.2, however, that the microbiological quality of this water is a grave concern.

Table 51. Change in surface water chemistry with distance downstream of the mine water source on 01/04/2010.

Locality		Distance (m)		EC	pH	Flow
		Segmental	Cumulative	(mS/m)		(ML/d)
3	Hippo Dam outlet in KGR	950	950	406	5.5	n.m.
4	Poplar Grove in KGR	850	1800	322	3.6	n.m.
5	4x4 Track at Oukraal Lapa in KGR	1015	2815	302	3.5	52.3
6	Aviary Dam inlet in KGR	2090	4905	293	3.4	34.4
7	KBW Dam outlet at N14 (F11S12)	1540	6445	290	3.6	40.4
8	Riet Spruit at Malmani Road (MRd1)	3900	10345	278	3.4	10.3
9	Bloubank Spruit downstream of Makiti (BB@M)	5050	15395	27	7.3	128.7
11	Blougat Spruit tributary of the Riet Spruit at N14 (BB@N14)		10835(1)	28	7.5	~118(2)
12	Honingklip Spruit tributary of the Bloubank Spruit at Kromdraai (HS1)		18905(1)	14	7.4	n.m.

(1) Distance of confluence with main stem downstream from the mine water source.
(2) Difference between flow measured at localities 8 and 9.
n.m. denotes not measured.

Peak flow (flood) conditions were experienced in the Tweelopie Spruit, the lower Riet Spruit and the Bloubank Spruit following the high rainfall experienced in mid-December 2010. Various sources in the area reported precipitation in the order of 130 to 140 mm in a period of some 24 hours *ca.* 16/12/2010. The rainfall gauging station operated by Rand Uranium at the Black Reef Incline in the locus of decant in the upper reaches of the Tweelopie Spruit recorded ~90 mm (B. van der Walt, personal communication) between 07h00 on 16/12/2010 and 07h00 on 17/12/2010. The aftermath of the flood event was still visible on 18/12/2010 (Plate 6 and Plate 7), when a series of surface water field chemistry measurements were made at ‘key’ locations along the effected drainages (see Figure 2 in appended Supplementary Report F prepared following a fish mortality event in the study area in mid-January). The measurement results are presented and discussed in the appended Supplementary Report F and replicated in Table 52.

Perhaps the most significant impact of the flood was the disruption of flow into the A-furrow (section 4.3.2). Flow into this furrow was only restored, albeit partially, on 10/01/2011 (M. Gomes, personal communication), i.e. a day before the fish mortality event. Concern was expressed for the yellow appearance of the furrow water and its suitability for various uses including stock watering and irrigation. Unaware of the fish mortality event, this communication precipitated another round of field water quality monitoring on 12/01/2011, the results of which are also reported in Table 52. Further, a surface water sample was collected at station BB@M for more complete laboratory chemical analysis[30]. The result of this analysis is presented in the appended Supplementary Report F.

Table 52. Surface water field chemistry variables sourced on 18/12/2010 and 12/01/2011.

Station	Field Chemical Variable							
	pH		EC (mS/m)		Eh (mV)		Temp. (°C)	
	18/12/2010	12/01/2011	18/12/2010	12/01/2011	18/12/2010	12/01/2011	18/12/2010	12/01/2011
F11S12	2.7	2.5	416	397	230	243	21.3	21.1
MRd1	3.0	2.3	276	410	217	254	24.1	25.0
BG@N14	n.m.	8.2	n.m.	53	n.m.	–65	n.m.	26.1
BB@M	6.1	2.9	158	155	51	221	24.8	23.9
BB@PL	n.m.	6.8	n.m.	94	n.m.	12	n.m.	21.3
A2H049	n.m.	7.7	n.m.	87	n.m.	–37	n.m.	22.3

The salinity (EC) values of 158 and 155 mS/m recorded at station BB@M are the highest recorded at this station in the year-long course of the main study, and the pH values of 6.1 and 2.9 similarly the lowest observed. These circumstances reflect the dominant contribution of raw mine water discharge to the chemistry of surface water at this locality on this occasion. Of specific relevance to the fish mortality event is the very low pH value of 2.9 observed on 12/01/2011. A further inspection of the 12/01/2011 data (Table 52) reveals the following hydrochemical characteristics:

- The very low pH values and elevated salinity values of ~400 mS/m at the uppermost two stations F11S12 and MRd1 indicating a strong mine water signature at these localities.

- The generally good inorganic quality associated with the Percy Stewart WWTW discharge via the Blougat Spruit (station BG@N14) into the Bloubank Spruit system as shown by the high pH value and low salinity (EC) value; note that this does not imply an acceptable bacteriological quality.

- The very low pH and elevated salinity of the surface water at station BB@M, again indicative of a mine water impact on the quality of the surface water at this locality. Whereas the pH value represents the most extreme value observed at this station in the project period, the EC value is only exceeded by that observed on 18/12/2010 (Table 52). Significantly, the Eh value of 221 mV (indicative of an oxidizing environment) approximates those observed at the upstream stations F11S12 and MRd1.

- The improvement in quality at the downstream station BB@PL, as reflected in a higher pH and lower EC compared to that at station BB@M, is attributed to the mitigatory influence contributed by the ~307 L/s Kromdraai Spring.

- The still quite 'acceptable' pH and EC values at station A2H049 at the bottom end of the Bloubank Spruit system at Glenburn Lodge near Zwartkop, although the pH value approaches the long-term 5%ile value of 7.4, and the EC value exceeds the long-term 95%ile value of 66 mS/m recorded at this DWA flow gauging and water quality monitoring station. In fact, the observed EC value of 87 mS/m exceeds the maximum value of ~75 mS/m recorded in the 29-year period May 1979 to May 2008 that represents the historical record of water chemistry data available for this station from the DWA (Table 22), and is cause for grave concern.

[30] It was observed that the oxidation of dissolved iron in the water sample resulted in the precipitation of an iron oxide in the sample bottle during transport and laboratory storage. This was not seen in the acidified sample bottle.

The PSP was notified on 13/01/2011 of fish mortalities had been 'discovered' on Koelenhof Farm upstream of the Kromdraai Store T-junction (M. Liefferink, personal communication). The mortalities occurred in an off-channel irrigation water storage dam fed by the A-furrow, and not in the natural stream course of the Bloubank Spruit (G. Krige, personal communication). It is therefore probable that the restored flow of A-furrow water into this dam resulted in oxygen depletion associated with the precipitation of iron hydroxides in this low energy impounding environment. It is also probable that the slow rate of iron precipitation resulted in the accumulation of this precipitate in the gills of fish, compounding the suffocating effect of a depleted oxygen supply and contributing to the observed fish mortalities in this impoundment. These circumstances are also likely to have similar consequences for crustaceans and macro-invertebrates resident in these dams. Enquiries by the PSP also established that above average fish mortalities had recently been experienced at the Brookwood Trout Farm located downstream of station BB@PL (Table 52) (H. Carpenter, personal communication). The Koelenhof Farm fish mortality event precipitated further field studies on 14/01/2011 by the PSP and Mr P. Mills of the MA. The results are presented in Table 53 and discussed in greater detail hereunder.

Table 53. Surface and groundwater field chemistry variables sourced on 14/01/2011.

Station	Field Chemical Variable				
	pH	EC (mS/m)	Eh (mV)	DO (%)	Temp. (°C)
Bloubank Spruit at Makiti (BB@M)	6.0	21.9	48	106	21.1
Zwartkrans Spring (ZWSp)	7.3	73.6	–19	66	19.1
A-furrow @ Lotz (upstream of KFD)	6.2	24.0	44	101	21.1
Koelenhof Farm dam (KFD)	3.6	128.7	178	60	24.0
Koelenhof Farm furrow downstream of KFD	5.6	126.8	72.2	103	21.5
Sterkfontein Caves lake	7.8	55.8	–49	66	16.7

The nature of the event that precipitated the 14/01/2011 studies necessitated the inclusion of dissolved oxygen (DO) as an additional field water chemistry variable. An inspection of the data presented in Table 53 reveals the following hydrochemical characteristics:

- In regard to the station BB@M:
  - the low pH value indicative of, amongst other sources, a combination of very low pH mine water and low pH rain water runoff in the discharge at this position in the Bloubank Spruit;
  - the very low EC value of ~22 mS/m compared to the value of 155 mS/m measured two days earlier on 12/01/2011 (Table 52), which similarly reflects the significant contribution of fresh water in the river on 14/01/2011; and
  - the high level of oxygen saturation reflected by the DO value of 106%, which is readily explained by the degree of turbulence exhibited in the strong-flowing river and natural diffusion of gaseous oxygen (O_2) from the atmosphere into the water (DWAF, 1996a); the super-saturated oxygen state is possibly indicative of eutrophication associated with a high nutrient load attributable to the presence of sewage wastewater effluent.

- The similar variable values observed at the station A-furrow @ Lotz as observed at station BB@M, which establishes the direct hydraulic link between the Bloubank Spruit surface water and that flowing in the A-furrow.

- The very low pH and DO[31] values, and the elevated EC and temperature[32] values of the Koelenhof Farm dam water, which likely represent an artefact of the water quality conditions that gave rise to the fish mortality event.

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[31] The Target Water Quality Range (TWQR) for the DO level in aquatic ecosystems brackets the range 80 to 120% of saturation, and a DO level below the Minimum Allowable Value (MAV) defined by a 7-day mean minimum value of >60% (sub-lethal) in combination with a 1-day minimum value of >40% (lethal), is likely to cause acute toxic effects on aquatic biota (DWAF, 1996).

[32] High water temperatures combined with low DO levels can compound stress effects on aquatic organisms (DWAF, 1996).

- The saturated oxygen content of the furrow water downstream of the Koelenhof Farm dam compared to the 60% DO concentration of the dam water.

- The similar variable values (except for temperature) associated with the Zwartkrans Spring and Sterkfontein Caves lake water, which establishes the hydraulic connection between these two groundwater sources. [Note: The historical and more recent cave water level response is discussed in greater detail in section 8.4.] Whereas the Zwartkrans Spring field salinity of ~74 mS/m is similar to its more recent 'historical' value, the cave water field salinity of ~56 mS/m is slightly lower than the typical 59 to 62 mS/m range that characterizes this cave water quality variable. The fresher nature of the cave water is attributed to the influence of considerably fresher rain water directly infiltrating the cave environment from above. For comparison, the DWA reports a salinity value[33] of 74 mS/m in April 2001.

Plate 6. Discharge at station F11S12 on 18/12/2010. Compare with Plate 4 and Plate 13 to note the complete submergence of the causeway. (Photo: Phil Hobbs).

Plate 7. View looking north of the discharge at BB@M on 18/12/2010. (Photo: Phil Hobbs).

[33] It is not evident whether this is a field- or laboratory-derived value, although the latter is typical of this source.

In light of the above, it is considered appropriate to close this section with a visual representation of the impact of recent raw and treated mine water decant into the Tweelopie Spruit and its main stem, the Riet Spruit. This is illustrated in Plate 8 and Plate 9. Plate 8 shows the build-up of iron hydroxide [$Fe(OH)_{3(s)}$] and gypsum ($CaSO_4$) sludge deposits in the Hippo Dam located ~700 m downstream of where mine water leaves the mine property. The excessive sludge build-up is due to the in-stream liming[34] of the raw mine water where it leaves the mine property. Plate 9 shows the dual precipitation of iron hydroxides and gypsum on the floodplain of the Tweelopie Spruit at its confluence with the Riet Spruit on the Glen Almond property a distance of ~6.3 km downstream of the Hippo Dam.

Plate 8. Sludge deposition in the upper reaches of the Hippo Dam in the Krugersdorp Game Reserve, the first impoundment receiving raw and treated mine water downstream of the locus of decant, as a result of emergency liming of raw mine water to raise its pH. (Photo: Stephan du Toit).

Plate 9. View of the Tweelopie Spruit, draining from right to left, near its confluence with the Riet Spruit on the Glen Almond property. Visible across the middle foreground is the iron hydroxide (coloured orange) and gypsum (coloured white) precipitate on the flood plain. The main channel is demarcated by the taller vegetation in the middle distance, indicating that the precipitates are associated with mine water induced flood conditions at this location. (Photo: Phil Hobbs)

[34] In-stream liming was employed as an emergency water treatment measure in the period March to June 2010.

5.6 Assessment/sufficiency of Monitoring and Identified Gaps

5.6.1 Assessment/sufficiency

The sufficiency of the DWA surface water quality monitoring programme has suffered in the past few years (since mid-2008) from severe analytical capacity constraints experienced at the D:RQS laboratory at Roodeplaat Dam (section 3.1.2). It is understood that this laboratory has been refurbished and that analysis of samples recommenced in January 2011 (S. Jooste, personal communication). Although the historical sufficiency and adequacy of this programme and service has therefore been restored, a gap of 2.5 years exists in the data record. Critically, this gap spans the very wet 2009-'10 and 2010-'11 rainfall seasons that caused unprecedented volumes of raw and treated mine water to enter the Bloubank Spruit via the Tweelopie Spruit and Riet Spruit tributaries. Fortunately, the water quality monitoring undertaken at the Nedbank Olwazini Estate in the lower half of this drainage (section 3.4) compensates partly for the gap in DWA data. The statistical veracity of this 'compensation' is illustrated in Figure 39.

5.6.2 Identified Gaps

In contrast to its headwater tributaries, and cognizant of the circumstances described in section 5.6.1, the Bloubank Spruit itself suffers from a paucity of water quality monitoring data except at its downstream end (station A2H049). The water quality monitoring undertaken at the Nedbank Olwazini Estate (section 3.4 and section 5.6.1) only partly covers this deficiency. It is required that monitoring of the Bloubank Spruit water quality also be carried out further upstream, preferably upstream of the Zwartkrans Spring.

6 GEOPHYSICS AND STRUCTURAL GEOLOGY

6.1 Regional/Subregional Geophysical Surveys

The south-western portion of the study area has been subjected to a gravimetric survey carried out by the DWA in the mid-1980s. As indicated in section 2.4, these data have recently been converted to digital format. The survey data defined the geometry of the karst groundwater environment in terms of zones of less dense (i.e. more highly leached implying greater water-bearing potential) and more dense (i.e. less highly leached implying poorer water-bearing potential) subsurface material. More importantly, the results were successfully used by the DWA to locate drill sites for the establishment of 18 high-yielding (≥25 L/s) water supply boreholes (Bredenkamp et al., 1986) out of a total of 38 sites explored.

6.2 Local Geophysical Surveys

6.2.1 Krugersdorp Game Reserve

The possibility of contaminant transport via fractures in the subsurface of the KGR was investigated using ground-based geophysical methods (Coetzee et al., 2009). Two roughly perpendicular survey lines, trending N-S and E-W respectively, were surveyed using the magnetic, electromagnetic and resistivity tomography methods. The magnetic anomalies were found to largely coincide with outcrops of banded ironstone formations. The resistivity and electromagnetic surveys located two significant conductive zones. It was postulated that these zones might represent water-bearing fractures possibly filled with poor quality (more saline) groundwater. As a consequence, these geophysical anomalies were targeted for investigative drilling as part of the COH WHS monitoring project.

6.2.2 Sterkfontein Caves

Geophysical surveys on the Sterkfontein Caves property (the Isaac Edwin Stegmann Nature Reserve) were precipitated by groundwater quality observations that suggested the cave system water is to some degree protected from the impact observed in the Zwartkrans Spring water. This impact, which is attributable to upstream anthropogenic activities, is discussed in greater detail in section 9.7.1. The geophysical investigation activity is described at length in the CGS technical report appended as Supplementary Report A of this document. The surveys comprised ground-based magnetic and electromagnetic (EM34) surveys, as well as targeted direct current (DC) resistivity soundings. The outcome of these surveys has confirmed the existence of WNW-ESE striking structures that are displaced in a N-S direction to form a disjoint series of strike-sympathetic anomalies.

6.2.2.1 Survey Results

The residual total magnetic field contour map generated for the survey area is presented in Figure 55. The positions of anomalies inferred from the electromagnetic and electrical resistivity surveys are also shown. The composite data reveal the presence of E-W trending magnetic ('hot' colours) and non-magnetic ('cool' colours) bodies. Cutting across the centre of the survey area is a consistent E-W striking and linear non-magnetic (compared to the background field strength) anomaly that is interpreted as a shear zone. The significance of this inferred structure for groundwater occurrence and flow is indeterminable with the available information.

The location of the caves at the northern end of resistivity traverse R1 (Figure 55) appears to coincide with a non-magnetic anomaly which probably reflects the non-magnetic character of dolomitic strata. However, an E-W trending magnetic anomaly is prominent immediately to the south of the caves. It would appear that east of the caves, this anomaly is displaced toward the north along a N-S fault. The rather narrow and linear geometry of this anomaly suggests that it might be associated with a positively magnetized dyke structure. An extensive magnetic body to the south of the inferred shear zone might represent the presence of a subhorizontal intrusive sill structure. Such features in the area are known from previous mapping efforts (Wilkinson, 1973).

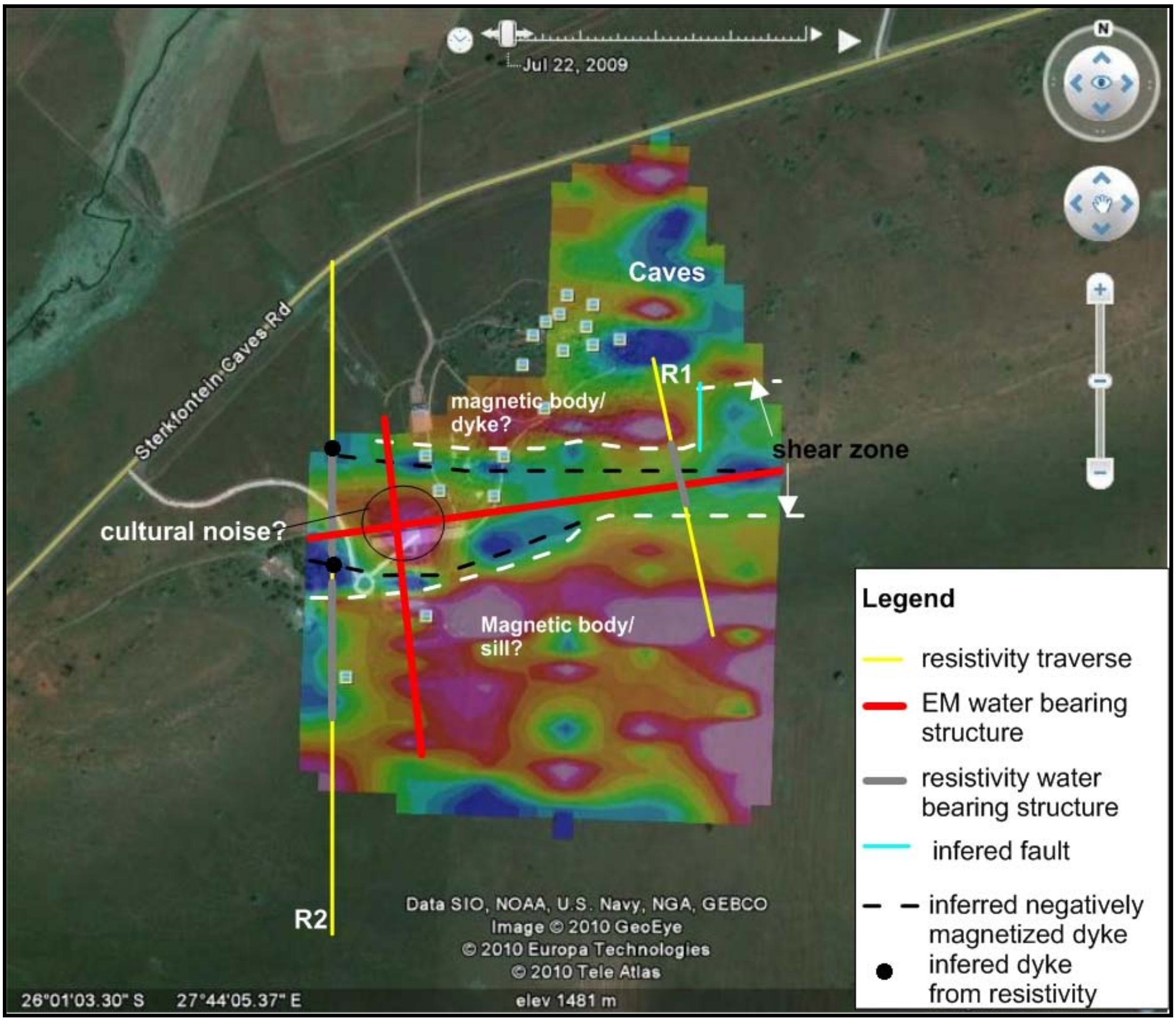

Figure 55. Interpreted residual total magnetic field contour map; yellow lines R1 and R2 with grey interpretation markings, indicate the direct current resistivity traverse locality.

The EM survey data reveal the presence of two linear zones of higher conductivity that bisect the survey area in roughly equal quadrants (Figure 55). The more prominent of these is the apparent WSW-ENE striking zone, which intersects a SSE-NNW striking zone at the eastern end of the tourist complex (circled in Figure 55) on the property. The anomalies gain (increase) in conductivity westwards and northwards respectively (refer Figure 60, section 6.3.2.2). The congruence of the more prominent WSW-ENE anomaly with the similarly oriented magnetic anomaly is self-evident.

The southern portion of the SSE-NNW trending EM anomaly approximates the western boundary of the extensive magnetic body that underlies the south-eastern portion of the survey area. The southern margin of the extensive magnetic body similarly coincides with an E-W striking EM anomaly (not shown). On the basis of available information, the significance of the inferred EM anomalies for groundwater occurrence and flow is inscrutable.

The results of the electrical resistivity survey are portrayed as cross-sections (profiles) for traverses R1 (Figure 56) and R2 (Figure 57) located as shown in Figure 55.

The results of traverse R1 confirm the strike extension of the interpreted shear zone inferred from the magnetic survey, the EM survey and resistivity traverse R2. By extrapolation, the highly conductive zone most likely corresponds to compartment 3 in Figure 57. The resistive body to the south is interpreted to represent the sill structure indicated in Figure 55 and Figure 57.

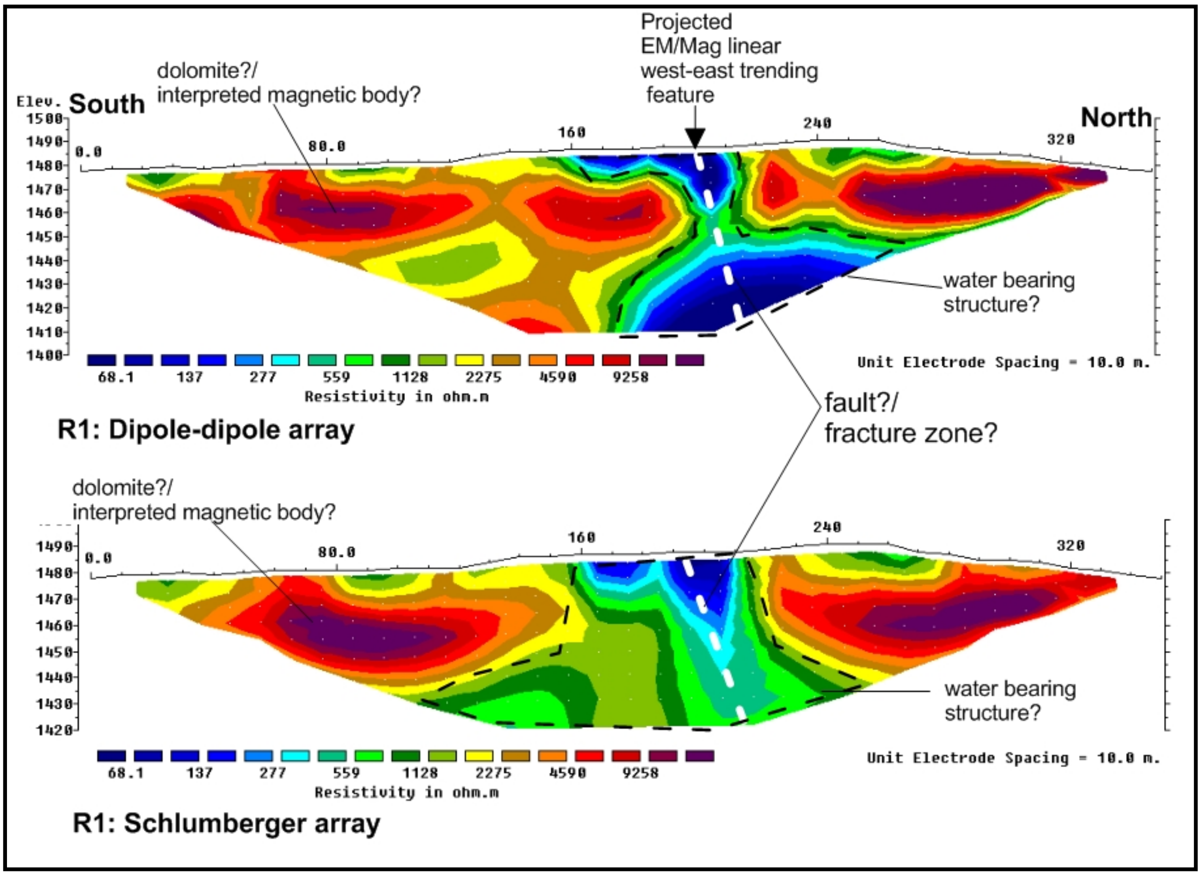

Figure 56. Interpreted resistivity-depth sections for traverse R1.

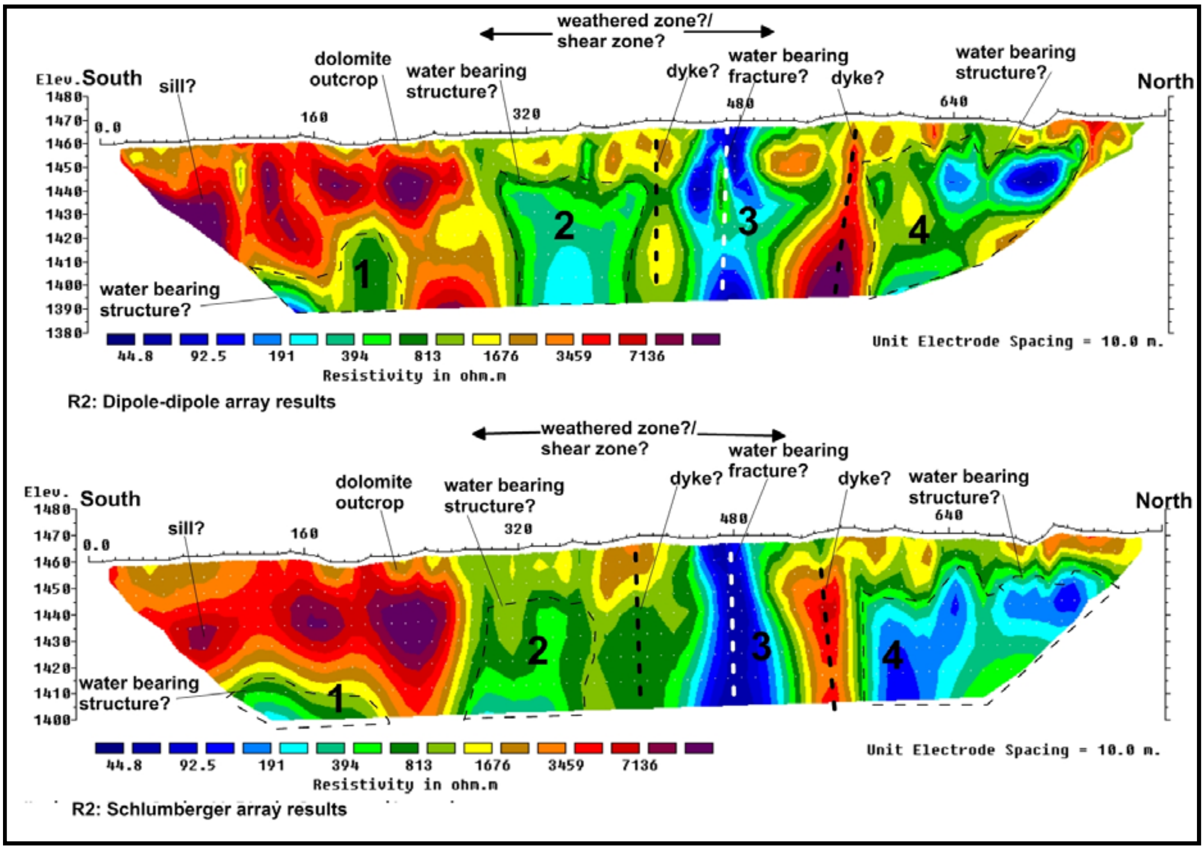

Figure 57. Interpreted resistivity-depth sections for traverse R2; numbers 1 to 4 indicate interpreted 'compartments' discussed in the text.

Resistivity survey R2 (Figure 57) reveals a broad zone of moderate to very low resistivity between stations 280 m and 500 m. This zone is interpreted as coinciding with the shear zone (probably weathered) identified in Figure 55. Figure 57 also shows the subdivision of the cross-section into four 'compartments' based on zones of contrasting resistivity. The shear zone encompasses two of these 'compartments'.

The inferred dyke structures located at stations 400 m and 530 m coincide with the linear non-magnetic anomalies interpreted as negatively magnetized dykes (Figure 55). The significant difference in resistivity values associated with the dyke structures suggests a difference in the degree of weathering associated with each. The dyke at station 530 m is considered to be more competent (less weathered), and may therefore constitute a hydraulic barrier. Between the dyke structures, at station 480 m, is a highly conductive ~50 m wide structure located at the centre of 'compartment' 3.

A very resistive zone (Figure 57) with a 'root' between stations 230 m and 280 m and extending southwards, corresponds to the outline of the extensive magnetic body (Figure 55) that has been interpreted as a sill intruding the dolomite. The 'root' of the interpreted sill may similarly act as a hydraulic barrier in the hydrogeologic environment.

6.2.2.2 Conclusions

Geophysical surveys entailing the magnetic, frequency domain electromagnetic and multi-electrode resistivity methods carried out on the Sterkfontein Caves site precipitate the following main conclusions.

- The surveys provided a quick means of mapping subsurface geological (and possibly hydrogeological) structures with a fair to good correlation in results. These structures, variously interpreted as representing intrusive sills and dykes and a shear zone, were successfully imaged.

- The intrusive structures were delineated on the basis of being more magnetic and resistive than the surrounding materials, while the shear zone was delineated as a linear magnetic discontinuity and conductive structure. The resistivity technique mapped the extent and dimensions of the shear zone and the dykes and the probable root of the sill to the south of the study area.

6.2.2.3 Recommendations

It is important to carry out more multi-electrode resistivity traverses in order to fully define the outline and characteristics of the interpreted shear zone and the vertical structures. It is therefore recommended that at least one long resistivity traverse be carried out ~300 m east of and parallel to resistivity traverse R2. There is also a need to integrate the geophysical interpretation with hydrogeological and structural geology mapping results of the study area in order to minimize uncertainty associated with geophysical interpretation.

6.3 Structural Geology

The complex structural geology that characterises the COH WHS was recognized as an important aspect of the physical environment that required a better understanding of its role in determining the hydrogeologic framework of the area. The whole of the project area is covered by airborne magnetic survey data generated by the CGS for the DWA. This data set has been exhaustively interrogated by Mr. T. Jamison and Dr. G. Cooper with a view to better informing the structural geology of the study area. The results confirm the complex pattern of structural lineaments, associated left lateral shear folding and deformation of the dolomitic strata and the associated igneous sills.

The results of the regional mapping and aeromagnetic survey results discussed in section 6.3.1, and the geological mapping on the Sterkfontein Caves property are integrated with the local geophysical survey information in section 6.3.2. These studies yielded additional information regarding the COH WHS hydrogeologic framework and the water resources monitoring programme.

6.3.1 Regional Structure

There are two sets of identifiable fracture lineaments crossing through the study area. The first set is represented by WNW-ESE striking fracture, joint and shear zones comprising en-echelon sub-parallel linear elements identified as follows:

- brecciated and/or schistose, near-vertical features in the eastern and western sidewalls of the larger sinkholes and dolines;
- axes of excavations of manganiferous and ferruginous workings in the dolomitic strata;
- axes of folded dolomitic and cherty strata; and
- loci of caves, avens and fissures.

The second set of fractures typically consists of dyke-filled fractures, fissured joints and silicified felsitic ridges with a NNW and occasionally NNE trend cutting across the WNW fractures, or sometimes "doglegging" along the latter for short distances. The dykes are generally fresher and more impervious than the heavily weathered and ferruginous fill of the WNW fractures.

Locations of the majority of sinkholes, dolines, fissures, mined manganiferous wad and slate excavations, linear stream segments and WNW plunging anticlinal fold axes coincide very closely with corridors of WNW lineaments identified on aerial photos, geophysical potential field data and topographical features. Further geophysical testing of these fractured lineaments for their geohydrological significance is suggested for the future.

6.3.2 Sterkfontein Caves

6.3.2.1 General Structure

The Sterkfontein Caves area (Figure 55) was selected as a test and focus area for defining geological and structural patterns in the COH WHS due to its ready accessibility and critical importance as the 'flagship' fossil site under the jurisdiction of the Management Authority, as well as its ostensibly vulnerable location within the possible path of AMD impact.

Geological interpretation of aerial photos indicates that the Sterkfontein Caves and other nearby caves occur on the northern flanks of folded WNW trending anticlines in the lower Monte Christo Formation of the Malmani Subgroup dolomite. Eight clusters of cave systems and excavated slots are located in the Sterkfontein-Zwartkrans-Kromdraai area (Figure 58). Each of the cave systems is clearly associated with the surface trace of a WNW fracture zone or branch(es) thereof. [Note that not all of the shear/fracture zone branches are shown in Figure 58]. Significantly, the high-yielding Kromdraai Spring delivering ~307 L/s is also located on a shear zone (S-11a) which coincides with the position of a fault mapped by Obbes (2000) in this area.

Part of the principal fracture trace in the Sterkfontein Caves passes through the fossil site surface excavation and the underlying Milner Hall cavern within the caves. Mapping the surface geology around the caves revealed several important features described as follows:

- A basal Slatey Chert Breccia (SCB) occurring at the base of the Monte Christo Formation and above a poorly exposed igneous sill lying at the top of the Oaktree Formation (Plate 10).

- Intense folding and shearing of the lower Monte Christo Formation occurs on the north side of the WNW fracture zone adjacent to the fossil site excavation. Oolitic layers in the dolomite are distorted and crumpled with oolites stretched in a WNW axial trend. Bedding and cleavage dips in these folded units are highly variable.

- Anticlinal folds are identifiable in the layout of the solution passageways in the northern part of Sterkfontein Caves (Figure 59).

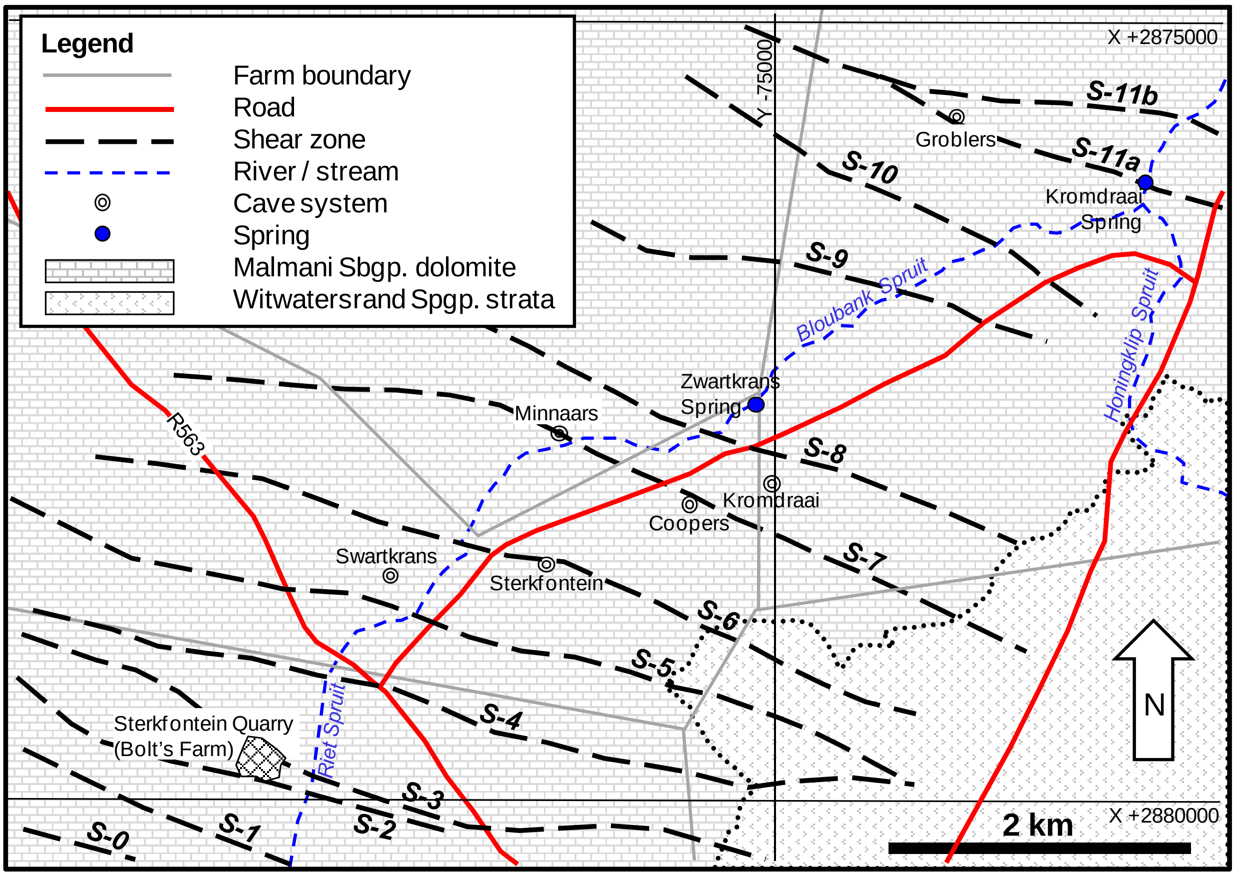

Figure 58. Map of shear zones and cave systems in the Sterkfontein-Zwartkrans-Kromdraai area.

Plate 10. View of the Slatey Chert Breccia (SCB) unit at Sterkfontein Caves looking north-west across the strike of the north-dipping mylonitic shear zone. (Photo: Tony Jamison).

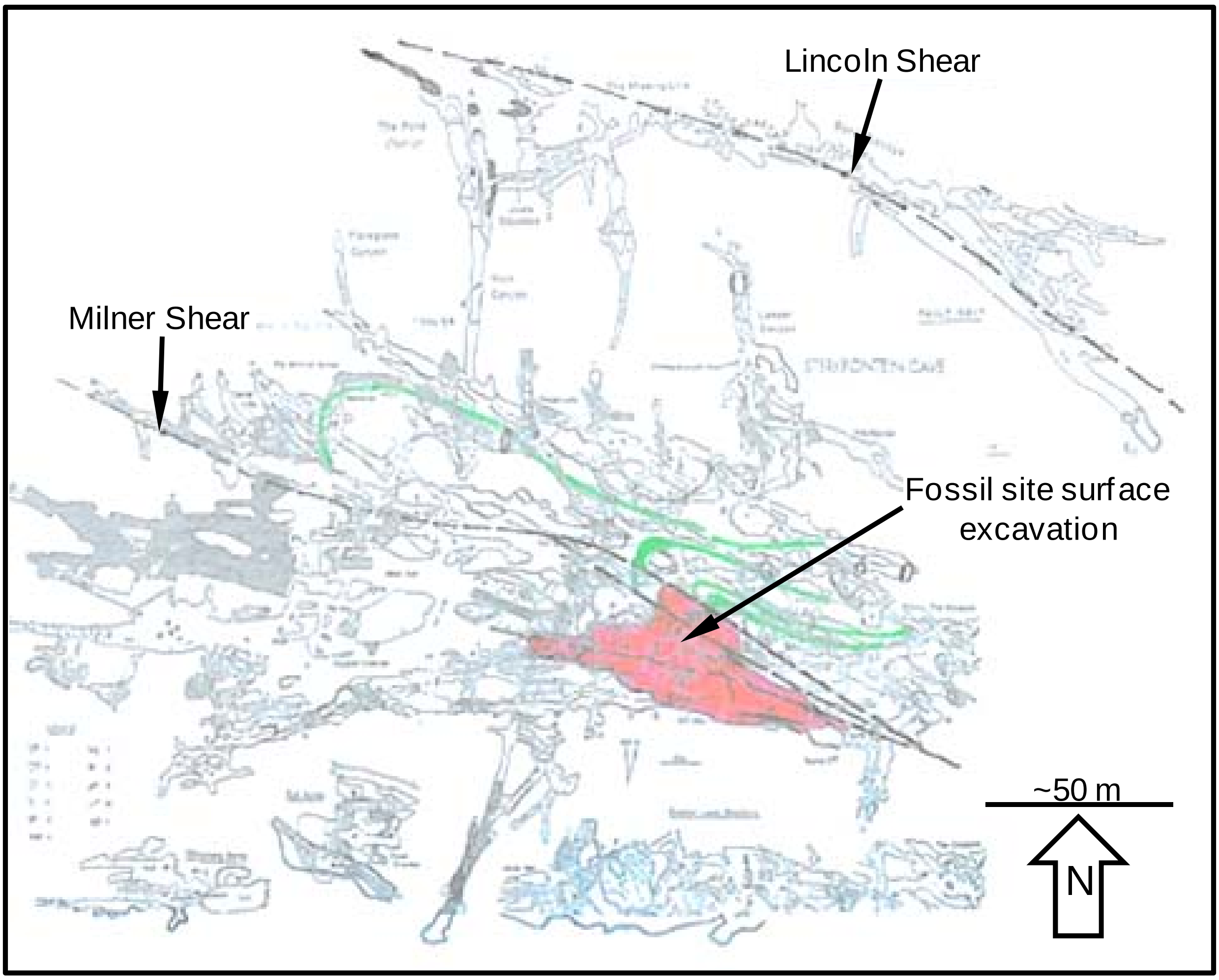

Figure 59. Composite layout of Sterkfontein Caves compiled from surveys by Martini et al. (2003) and showing folded lithological layers (green) expressed as solution passageways (from Jamison, in prep.).

6.3.2.2 Integration with Geophysical Information

Since the Sterkfontein Caves contain water bodies which are perceived to be under threat from pollution, it was deemed necessary to further detail the controlling geological features of the Caves and how they interface with the geohydrology and monitoring requirements. The geophysical surveys are discussed in section 6.2.2.

The conductivity contour map (Figure 60) shows 4 positive anomalies (labelled A, B, C and D) each having an en-echelon WNW axis striking 285°, but together forming an apparent SSE-NNW strike parallel to the regional strike of the Slatey Chert Breccia (SCB) striking 075°. The positive anomalies are interpreted to represent the sheared en-echelon portions of a shear zone (S-6) incorporating portions of a folded igneous sill which is mapped as underlying the SCB zone and could act as a partial aquiclude separating water-bearing structures.

The fossil site surface excavation lies 200 m further north, coincident with a WNW trending conductivity low. This low lies on the mapped location of the Milner Shear Fault in the Caves, and coincides with the regional S-6 shear zone. Where the S-6 shear trend intersects the SCB south-east of the caves, the SCB is disrupted by a gap and fragments of SCB are hard to find, being also attenuated as slivers. Where the S-6 shear intersects the Bloubank Spruit west of the Caves, there is a 70 m left lateral dogleg of the drainage.

The residual total magnetic field contour map (Figure 55) also shows the influence of an igneous intrusive as a series of positive lozenge-shaped anomalies to the south of the "conductive zone", and an offset "lozenge" to the north corresponding with the conductivity anomaly D in Figure 60. Again, the fossil site surface excavation is associated with a magnetic low trending WNW in approximately the same position as the S-6 shear zone.

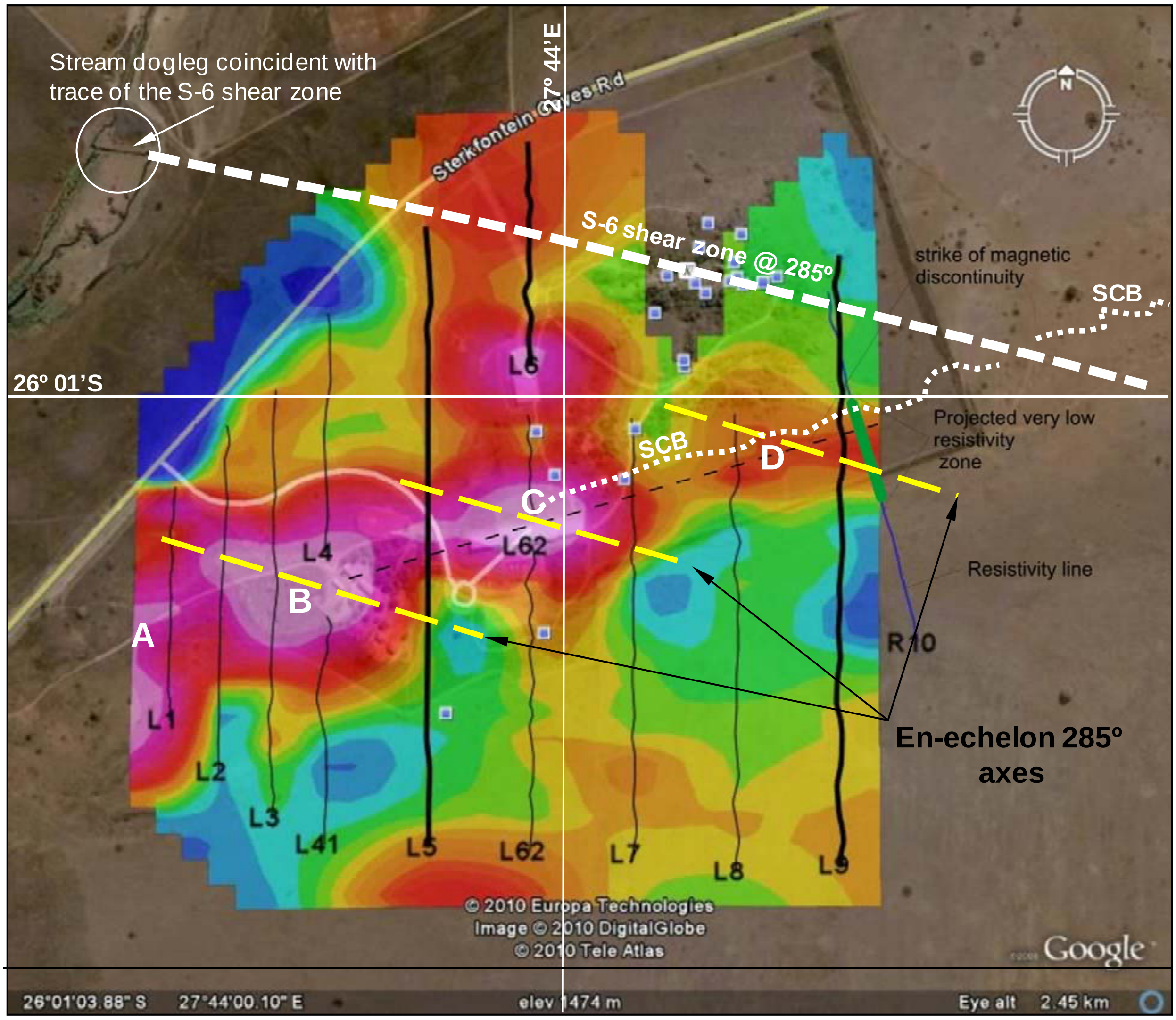

Figure 60. Terrain conductivity map of the Sterkfontein Caves area showing the various interpreted structural geological components.

The two resistivity profiles also indicate the same features in their projected positions (Figure 56 and Figure 57), where the "water-bearing fracture" (S-6) identifies with the conductive zone in the R1 and R2 profiles (Figure 55), respectively.

6.3.2.3 Summary Discussion

The mapped geology of the Sterkfontein Cave System and its surrounds thus agrees with the interpretation of the aerial photos, and is further supported by the geophysical data and its interpretation. WNW trending shear zones composed of serial en-echelon elements cut across the strata contacts of the Oaktree and Monte Christo formations and the mapped SCB and sills. The Caves are developed in the basal folded cherty Monte Christo Formation above a left laterally sheared and folded tectonite (SCB) and igneous sills. The WNW trending shear zone is a conductive water-bearing fracture zone which is subdivided into compartments by the tectonite SCB and the igneous sills. Weathered intrusive dykes may be masked within the shear zone.

7 SEDIMENT CHEMISTRY

The chemical composition of sediments in environments impacted by mining activities on the Witwatersrand has been reported on by Coetzee et al. (2002; 2006), Robb and Robb (1998b), Rösner et al. (2001) and Wade et al. (2002), amongst others. Whilst the majority of these studies has understandably focussed on the presence of radionuclides in sediments, the presence of heavy metals such as Al, As, Cd, Co, Cu, Fe, Mn, Ni, Pb and Zn is of equal concern. For example, Von der Heyden and New (2004) identify precipitation (Fe, Al and Cu) and adsorption (Co, Ni and Zn) of metals onto suspended solid surfaces, and their subsequent settling within a wetland, as primary processes leading to metal accumulation within sediment. More significantly, these authors show the sediment to be a potentially important source of pollutants, with downstream pollution possibly continuing for a century after the cessation of effluent discharge into the wetland.

7.1 Previous Studies

The study by Awofolu et al. (2007) reported in section 5.1.2.2 also provides results of trace metal analyses (Cd, Pb, Mn, Zn, Ni and Cu) of sediment samples collected at the sampling locations shown in Figure 61. The results are presented in Table 54 for each of the metals listed.

Table 54. Concentrations of selected trace metals in streambed sediments downstream of the Percy Stewart WWTW (from Awofolu et al., 2007).

Trace Metal	Concentration Values (mg/kg)		Observations by PSP
	Minimum	Maximum	
Cd	Trace	0.12 ± 0.001	Lowest concentration of trace metal selection at all four stations on all four sampling occasions.
Pb	Trace	0.71 ± 0.03	Next lowest concentration of trace metal selection (after Cd) at all four stations on all four sampling occasions.
Mn	12.3 ± 0.14	2957 ± 18.4	Maximum value observed at station S1 on 4th sampling occasion. S1 also returned highest values on all four sampling occasions.
Zn	0.13 ± 0.01	2.57 ± 0.03	Maximum value observed at station S2 on 4th sampling occasion. Highest values distributed between all four stations on all four sampling occasions.
Ni	0.39 ± 0.001	1.96 ± 0.04	Maximum value observed at station S2 on 4th sampling occasion. S2 also returned highest values on three sampling occasions.
Cu	0.18 ± 0.001	2.84 ± 0.03	Maximum value observed at station S3 on 3rd sampling occasion. Highest values shared by S2 (1st and 2nd sampling occasions) and S3 (3rd and 4th sampling occasions).

Manganese (Mn) returned the highest concentration of all six elements at all three sampling localities on each of the four sampling occasions. Further, the sediment at sampling locality S1 on the Blougat Spruit (Figure 61), and therefore closest to the Percy Stewart WWTW, consistently returned the highest Mn concentration. This is in keeping with the statistical analysis of surface water chemistry in this drainage (section 5.1.2.2 and Table 33), which reflects exceedances of the mean, median and 95%ile Mn values in a population of 44 analyses in the period June 2004 to May 2008.

7.2 This Study

The stand-alone report on this activity is appended as Supplementary Report B. Greater detail describing the sediment sampling and analysis exercise is documented therein.

7.2.1 Purpose and Rationale

Sediment samples were collected at eight localities (Figure 61 and Table 55) in the southern portion of the study area in order to determine the chemical composition of streambed material at various positions along the Tweelopie Spruit, the Riet Spruit, the Blougat Spruit and the Bloubank Spruit. This was precipitated by the comparatively sparse data of this nature for the drainages that receive either raw and/or treated mine water via the Tweelopie Spruit, and treated municipal wastewater effluent via the Blougat Spruit. The 'once-off' sampling campaign therefore took the form of an occurrence survey (see Glossary).

The sampling localities focussed on the inflow or upstream ends of surface water impoundments where possible, or else within the stream channel where flow conditions are conducive to sediment deposition. This site selection method is described by EPS (1994) as non-statistical, deterministic (or judgemental). The sites include a pristine karst spring to provide a background/reference analysis. Two of the sites (5 and 7) coincide with the localities S1 and S2 of Awofolu et al. (2007). The depth of sampling ranged from 200 to 500 mm, mostly beneath a water column of ≤1 m, and typically two samples were collected at each locality (refer Table 55 for greater definition). The aggregation of certain samples reflected in Table 55 (sites 2, 4, 5, 6, 7 and 8) sought to obtain a more representative single 'site' sample made up of two 'subsite' samples (Herr and Gray, 1997), and also reduce analytical costs at this screening level investigation. The sampling protocol emulated that used by the CGS elsewhere on the Witwatersrand when sampling mining-related wetlands (McCarthy and Venter, 2006).

Table 55. Description of sediment sampling localities.

Site	Latitude Longitude	Description and Rationale for Selection	Sample No.	Analysis Description
1	26.06452°S 27.69613°E	Hippo Dam inlet on the Tweelopie Spruit in the Krugersdorp Game Reserve. First impoundment downstream of the mine area receiving AMD.	JV10/001 JV10/002 JV10/003 JV10/004	BL/Alk./TCLP/AR/XRF BL/Alk./TCLP/AR/XRF BL/Alk./TCLP/AR/XRF XRD/ICPMS metals
2	26.10235°S 27.72122°E	Lion Camp entrance dam inlet on the Tweelopie Spruit in the Krugersdorp Game Reserve. Third impoundment downstream of the mine area receiving a mixture of AMD and better quality karst groundwater.	JV10/005 JV10/006	BL/Alk./TCLP/AR/XRF Combined with JV10/005
3	26.10345°S 27.72145°E	Krugersdorp Brickworks Dam inlet on the Tweelopie Spruit. Fifth impoundment downstream of the mine area receiving a better quality mixture of AMD and karst groundwater.	JV10/007	BL/Alk./TCLP/AR/XRF
4	26.08570°S 27.70988°E	Inlet of dam on Ptn. 8/2 of Sterkfontein 173IQ on the Riet Spruit. Seventh impoundment downstream of the mine area receiving a mixture of AMD and karst groundwater.	JV10/008 JV10/009	BL/Alk./TCLP/AR/XRF Combined with JV10/008
5	26.04800°S 27.71213°E	Lower end of the Blougat Spruit receiving treated municipal wastewater effluent from the Percy Stewart WWTW.	JV10/010 JV10/011	BL/Alk./TCLP/AR/XRF Combined with JV10/010
6	26.02203°S 27.72005°E	Bridge where the R563 crosses the Bloubank Spruit, receiving primarily the discharge from site #5.	JV10/012 JV10/013	BL/Alk./TCLP/AR/XRF Combined with JV10/012
7	26.04003°S 27.72110°E	Causeway over the Bloubank Spruit downstream of Makiti, receiving primarily the discharge from site #6.	JV10/014 JV10/015	BL/Alk./TCLP/AR/XRF Combined with JV10/014
8	25.97883°S 27.74323°E	Stilling basin of Danielsrust Spring. Off-channel natural spring serving as 'pristine' background sample.	JV10/016 JV10/017	BL/Alk./TCLP/AR/XRF Combined with JV10/016

The analyses were carried out on unsieved samples following standard procedures employed by the CGS. Beltrán et al. (2010) suggest that the chemical speciation in sediments from acid rivers are independent of the sediment grain size considered. The samples were analysed as follows:

- X-ray fluorescence (XRF) to determine major and trace elements, i.e. total chemical composition;
- batch leach (BL), toxicity characteristic leaching procedure (TCLP) and acid rain (AR) leaching tests to simulate the likelihood of elements to be mobilized under certain environmental conditions, i.e. the mobility and bio-availability of metals as represented by their extractable fractions; and
- X-ray diffraction (XRD) on one sample to determine the mineralogic composition.

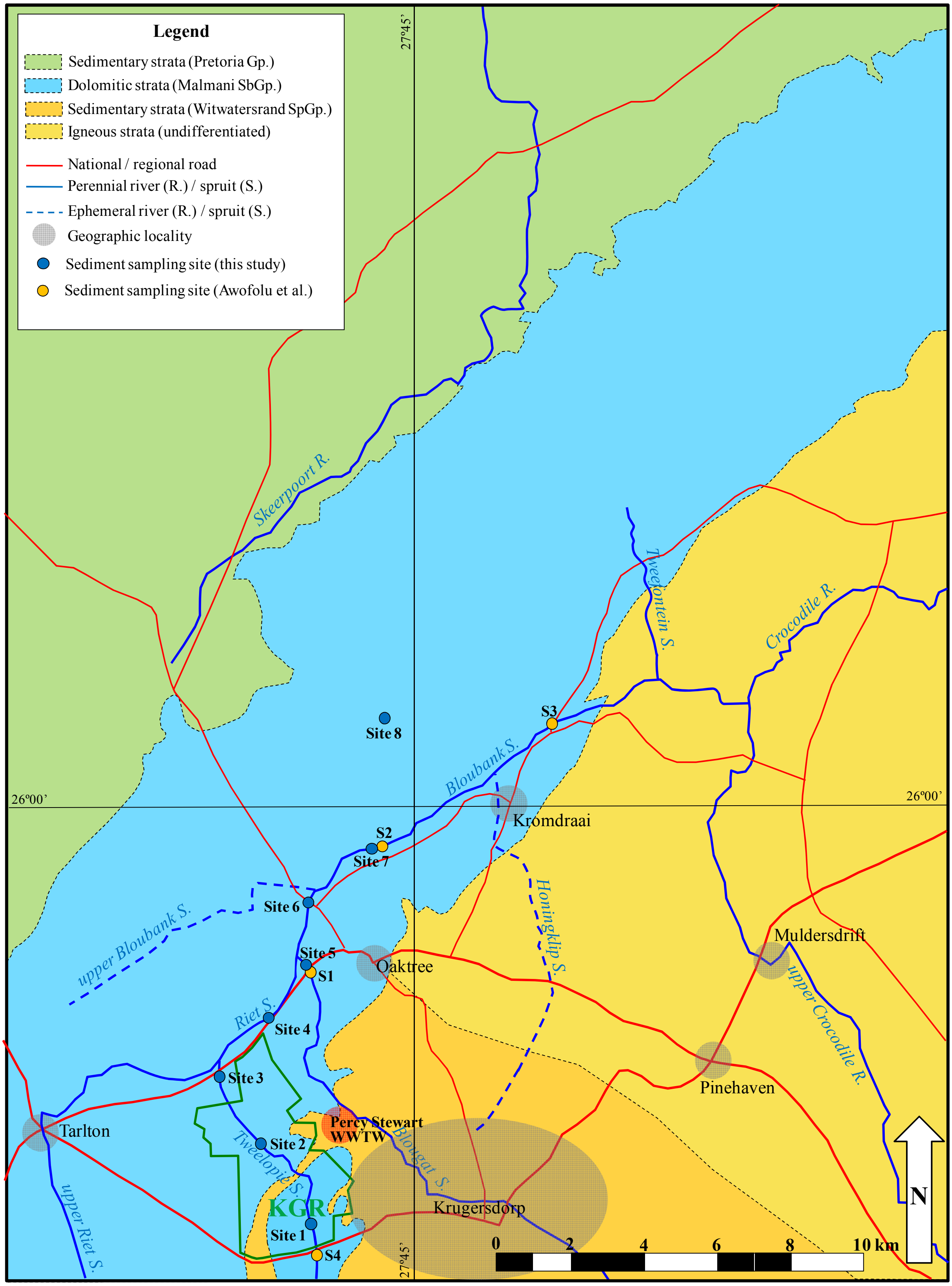

Figure 61. Locality map of sediment sampling sites.

7.2.2 Results

The results of the analyses performed are presented in appended Supplementary Report B. In order to assess whether downstream contamination of sediment is present, a Tier 1 risk assessment (Ingersoll et al. 1997) was applied to the data.

The trace metal concentrations determined from XRF analysis are ranked in order of decreasing maximum detected value in Table 56 for each of the samples and sites. It is apparent that site 1 (the Hippo Dam) supports the maximum concentration of 16 of the 24 elements represented. Site 2 (the Lion Camp Dam) supports a further four of the elements, leaving site 6 (the Bloubank Spruit at the R563 crossing) to support the remaining four elements. The elevated Fe and Mn levels at site 6, compared to those at site 1 for example, are not readily explained. It is possible, however, that these circumstances reflect the historical impact of Percy Stewart WWTW effluent, with its characteristic elevated Fe and Mn concentrations (Table 33), on the downstream receiving drainages. The discharge from this facility via the Blougat Spruit has manifested a perennial (albeit artificial) flow regime in the long-term, compared to the much more recent ephemeral character of mine water discharge via the Tweelopie Spruit into the Riet Spruit (section 4.1.2.1).

Table 56. Ranking of trace metal concentrations in sediment samples by maximum value.

Variable	Site and Sample No[(1)]											Maximum Value (mg/kg)
	Site 1				Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	
	001	002	003	004	005	007	008	010	012	014	016	
Al[(2)]	48314	66014	38001	5088	56290	5897	41198	13037	50322	17144	5897	66014
Fe[(3)]	50579	9658	53900	19600	60900	4276	36934	18783	62916	34821	4276	62916
Mn[(4)]	4565	213	77	620	7850	120	4349	1057	8747	8498	120	8747
Zn	216	72	460	263	943	430	261	53	56	81	12	943
Ba	531	120	122	13	173	549	307	101	751	446	21	751
Ni	313	134	720	623	497	607	196	38	111	68	6.7	720
Cr	603	425	290	37	401	367	339	223	413	214	95	603
Co	119	17	202	227	154	149	72	11	28	25	1.7	227
Zr	227	213	143	16	197	154	164	61	177	50	21	227
Cu	105	60	135	34	174	49	57	15	46	35	4.2	174
V	126	137	100	15	116	99	84	30	97	51	9.6	137
Ce	100	126	130	29	83	100	48	<10	48	31	<10	130
U	41	35	107	13	50	6.3	9.9	<2	3.6	<2	<2	107
As	83	9.3	65	9.3	83	18	14	6.4	15	7.8	<4	83
Nd	30	61	73	20	61	46	29	10	27	10	<10	73
La	37	57	62	16	66	64	37	5	33	18	<10	66
Pb	52	25	31	3.9	32	29	37	9.4	13	17	2.9	52
Sr	30	11	39	49	27	38	16	14	17	19	2.1	49
Rb	28	35	23	4.4	43	37	42	9.4	47	17	7.5	47
Y	18	31	36	7.4	41	26	18	4.8	18	7.6	1.9	41
Sc	16	19	17	11	17	16	14	5.1	16	7.4	<3	19
Ga	13	16	11	1.8	14	13	11	3.7	12	4.9	2	16
Nb	10	13	8.9	2.7	10	9.4	9	3.6	9.6	4	2.5	13
Th	10	8.6	8.7	<3	8.4	7	6.3	<3	7.2	3.7	<3	10

(1) Sample no. to be prefaced with JV10/ (e.g. JV10/001) to match the numbering used in Figure 62 and Figure 63.
(2) Calculated from weight% concentration of Al_2O_3.
(3) Calculated from weight% concentration of Fe_2O_3(t).
(4) Calculated from weight% concentration of MnO.
All values are as mg/kg.
Shaded cells denote location of maximum element value.

It is important to note that the sample bearing the highest concentration of an element will not necessarily release the greatest extractable fraction of that element. Table 54 indicates that Awofolu et al. (2007) recorded maximum Zn, Ni and Cu values at site S2. A comparison of the results with those recorded for these elements at site 7 (the same locality) of the current study reveals significant differences. In all instances, the Awofolu et al. (2007) results are an order of magnitude lower.

7.2.2.1 *Tier 1 Risk Assessment*

In this method, the measured concentrations are compared to a regulatory standard (exclusion limit) to derive a risk quotient (*RQ*), calculated as:

$$RQ = \text{Measured concentration } (C_x) \text{ / Regulatory exclusion limit} = C_x \text{ / 0.2 Bq/g (for U)}$$

An *RQ* >1 indicates circumstances where the measured concentration exceeds the regulatory standard, requiring follow-up studies and possible remedial action (Coetzee et al., 2006). Since South Africa does not yet have freshwater sediment guidelines (Gordon and Muller, 2010) or legislated limits for most contaminants in soil (Coetzee et al., 2006), values from the European Union (EU) and the National Nuclear Regulator (NNR) were used. Figures 2 and 3 in Supplementary Report B (appended) show *RQ* values for U and Ni, respectively, at each of the sampling sites. These variables are characteristic trace metals associated with mining, and their *RQ* ranking describes the following circumstances:

- risk quotients below 0.5 pose no risk;
- values between 0.5 and 2 allow for any sampling and/or laboratory errors (risk quotients in this range might pose a risk and may warrant follow-up studies); and
- risk quotients that are above 2 definitely pose a risk.

The colour-coded results shown in Figures 2 and 3 in Supplementary Report B are replicated in Table 57. It should be noted, however, that the risk quotients are based on the total concentration as measured by XRF analysis (Appendix B of Supplementary Report B). It is not implicit that all of this concentration is mobilizable, as is shown in section 7.2.2.2.

Table 57. Tier 1 risk quotients for U and Ni associated with each sediment sampling site.

Site No.	Site Description	Tier 1 Risk Quotient	
		Uranium	Nickel
1	Hippo dam on the Tweelopie Spruit in the KGR	>2	>2
2	Lion Camp dam on the Tweelopie Spruit in the KGR	>2	>2
3	Krugersdorp Brickworks dam on the Tweelopie Spruit	<0.5	>2
4	Dam on Ptn. 8/2 of Sterkfontein 173IQ on the Riet Spruit	0.5 to 2	>2
5	Lower end of the Blougat Spruit	<0.5	0.5 to 2
6	Bridge where the R563 crosses the Bloubank Spruit	<0.5	>2
7	Causeway over the Bloubank Spruit downstream of Makiti	<0.5	0.5 to 2
8	Danielsrust Spring (background/reference site)	<0.5	<0.5

7.2.2.2 *Extractable/Mobilizable Fraction*

The BL, TCLP and AR leach tests described in section 7.2.1 were performed to determine the extractable (mobile) fraction of the total concentration of elements measured by XRF. The results for uranium and nickel are shown in Figures 4 to 6 of Annexure F for each of the three types of leach test. These two elements were chosen as indicators of gold mining activity. None of the leach tests extracted a U concentration greater than the regulatory exclusion limit of 16 mg/kg (0.2 Bq/g) as proposed by the NNR (Coetzee et al., 2006). The pie charts presented in Figure 62 and Figure 63 show the fraction (expressed as a % of the total concentration) of Ni and U, respectively, extracted from the sediment samples of each site by each of the leach test methods used. The results show that the TCLP method consistently mobilized the greatest fraction, followed by the acid rain and the batch leach methods.

The highest Ni concentration (~12% or 71 mg/kg) was extracted from the site 3 sample, followed by the site 1 sample (~9% or 28 mg/kg) and the site 4 sample (~7% or 13.7 mg/kg). Since the highest total Ni concentration was measured at site 1 (the Hippo Dam sample JV10/003), further investigations into site-specific conditions might explain this result. Site 3 is also the only site where the extractable fraction of ~71 mg/kg (by the TCLP method) is twice the regulatory limit of 35 mg/kg proposed by the EU (ANTEA, 2000 in Coetzee et al., 2006). These results also put those of the Tier 1 risk assessment quotients (section 7.2.2.1) into perspective, especially in regard to Ni.

It is probable that a Tier 1 risk assessment based on extractable concentrations (as opposed to total concentrations) will return a greater number of Ni risk quotient values in the range 0.5 to 2, rather than >2. These circumstances mitigate to a certain extent the risk associated with the mobilization/remobilization of sediment-bound trace/heavy metals.

The highest U concentration (~5% or 5.4 mg/kg) was extracted from the third of the site 1 samples, followed by the first of the site 1 samples (~2.5% or 1 mg/kg) and the site 5 sample (2% or 0.02 mg/kg). The reference/background site 8 (sample JV10/016) yielded no extractable U (unsurprising given the <2 mg/kg concentration reported in Table 56) or Ni for any of the three leach tests employed. This site did, however, yield extractable fractions of Al, Fe, Mn and Cu for at least two of the three leach tests. It is therefore likely that sediments associated with 'pristine' karst groundwater sources in the study area may produce extractable metal concentrations despite the natural (pristine) chemical composition of the water produced.

7.3 Conclusion

The finding that the measure of extractable U and Ni concentrations is an order of magnitude lower (smaller) than the total observed concentrations provides a measure of mitigation of the risk associated with the mobilization/remobilization of sediment-bound trace/heavy metals. However, the cumulative mass/volume of sediment contained in the various impoundments cautions against minimization or downplaying of the associated risk.

Plate 11. Sediment sampling at site 2 in the Tweelopie Spruit by CGS Earth Scientists. (Photo: Phil Hobbs).

Figure 62. Pie charts of extractable (mobile) fractions expressed as a percentage of total nickel concentration per sediment sample as produced by the three leach test methods used. Note that each 'sliver' is a fraction of 100%.

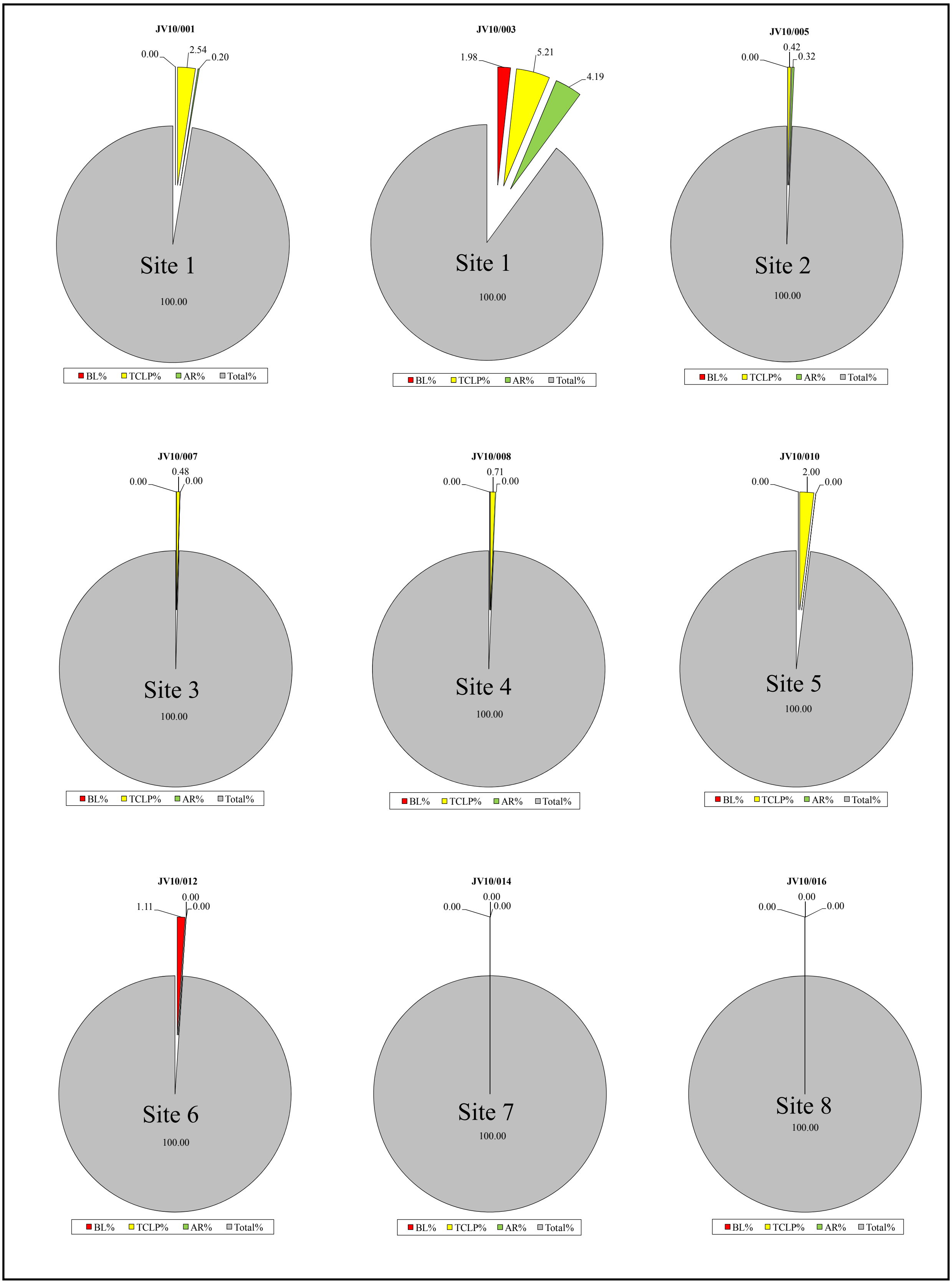

Figure 63. Pie charts of extractable (mobile) fractions expressed as a percentage of total uranium concentration per sediment sample as produced by the three leach test methods used. Note that each 'sliver' is a fraction of 100%.

8 PHYSICAL HYDROGEOLOGY

8.1 General Discussion

An early reference to the groundwater resources (hydrogeology) of the study area is found in Cooke (1969) who states simply that "*The water table is regional and the underground lake is 186 feet below the crest of the hill with the ape-man quarry.*" The depth of 186 feet (56.7 m) places the 'water table' at an elevation of ~1430 m amsl for a crest elevation of ~1487 m amsl as interpolated from the 1:10000 scale orthophoto map 2627BA5 Sterkfontein (2nd ed., 1987). The most recent information available to the PSP places the current elevation of the free water surface in Sterkfontein Caves at ~1438 m amsl (section 8.4.1). The interpolated elevation of the Zwartkrans Spring located ~1 km down-gradient/downstream of the caves is 1432 m amsl.

The most comprehensive regional groundwater study is considered to be that by Bredenkamp et al. (1986), primarily for the reason that it saw the execution of a regional gravimetric survey and the establishment of 38 large-diameter boreholes directed at evaluating the groundwater supply potential of portions of the dolomitic aquifers represented by the Steenkoppies and Zwartkrans compartments. A test pumping programme established 18 of the DWA exploration boreholes as high-yielding (≥25 L/s), with a maximum recommended long-term yield of 100 L/s in three instances. The DWA boreholes were sited primarily on the basis of the gravimetric survey data (section 6.1). From Table 58 it is evident that relevant to the COH WHS project, this study enumerated 326 private water supply boreholes from which 131 groundwater level measurements and 29 groundwater quality determinations were obtained.

The DWA study divided the Zwartkrans Compartment into nine subcompartments on the basis of perceived steps in the groundwater rest level, it does not provide a holistic potentiometric map to substantiate such subdivision, relying mainly on the postulated presence of intrusive dyke-like structures to construct the subcompartments on the premise of very weak (essentially flat) hydraulic gradients in each subunit. The latter premise was also put forward as the reason for not contouring the water level data (Bredenkamp et al., 1986). It is notable that the difference in 'representative water level' between the five more northerly subunits B, C, D, E and F 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.

The above 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-compartmentalization. The PSP has developed and puts forward a simplified subdivision of the Zwartkrans Compartment to represent subregional hydrogeologic 'boundary conditions' (section 8.2).

Table 58. Groundwater data sources relevant to the COH WHS project obtained from the Bredenkamp et al. (1986) study.

Topocadastral Farm	No. of Private Boreholes Enumerated	No. of Water Levels Determined	No. of Water Quality Determinations	No. of State Boreholes Drilled
Vlakplaats 160IQ	141	75	5	12
Vlakdrift 163IQ	86	21	1	3
Sterkfontein 173IQ	49	22	4	15
Zwartkrans 172IQ	7	3	1	0
Reydal 165IQ	41	10	0	3
Eljeesee Agicultural Holdings	2	00	0	0
Danielsrust 518JQ	0	0	3(1)	0
Elandsvlei 249IQ	0	0	3(1)	0
Kromdraai 520JQ	0	0	8(1)	0
Rietfontein 522JQ	0	0	4(1)	0
TOTAL	326	131	29	33
(1) No coordinates available.				

Bredenkamp et al. (1986) state further that "*Ground-water in the Zwartkrans compartment drains north-east to the Danielspruit and Kromdraai springs.*" It is presumed that reference to the Danielspruit Spring should, in fact, read Danielsrust Spring. Although not mentioned, it must also be presumed that the much stronger Zwartkrans Spring delivering 258 L/s (Bredenkamp et al., 1986) also drains this compartment under circumstances where the Danielsrust and Kromdraai Springs[35] delivered only 3 and 28 L/s respectively (according to Bredenkamp et al., 1986). A much more recent study by Holland et al. (2009) reports discharges of 260, 3.2 and 371 L/s for the Zwartkrans, Danielsrust and Kromdraai Springs, respectively. The order of magnitude discrepancy in regard to the Kromdraai Spring discharge is a confirmed typing error (K. Witthüser, review comment). In an earlier issue paper compiled for the IUCN Karst Working Group, Holland et al. (2005) discuss the geology, surface water and groundwater aspects of the COH WHS in very broad and qualitative terms.

The portion of the Riet Spruit upstream of the Oaktree area, including its tributary the Tweelopie Spruit, has recently been the subject of hydrogeological studies (Hobbs and Cobbing, 2007; Hobbs, 2008a) that have helped define the impact of acid mine drainage on the groundwater resources of the locus of decant in the upper reaches of this spruit as well as downstream of its confluence with the Riet Spruit at Glen Almond. The study by Hobbs and Cobbing (2007) enumerated 54 geosites (41 boreholes, 6 springs, 7 mine shafts), 48 of which provided a 'ground'water (including mine water) level. The water level data facilitated the construction of a potentiometric (water level) contour map for the extreme south-western portion of the current study area.

An inspection of aquifer transmissivity data generated by the Bredenkamp et al. (1986) study from pumping tests performed on exploration boreholes in the Zwartkrans Compartment indicates a zone of higher transmissivity as defined in Figure 64. The zone is demarcated by 13 exploration boreholes (Table 59) that returned transmissivity values greater than ~1000 m^2/d. The geometry of this zone (Figure 64), notably its width and slightly more northerly position and SW-NE orientation, suggests that it coincides with the position of the chert-rich Monte Christo Formation and its associated generally greater water-bearing potential (refer section 2.4).

Table 59. DWA exploration boreholes with T-values greater than ~1000 m^2/d (from Bredenkamp et al., 1985).

DWA Exploration Borehole No.	DWA Geosite No.	Coordinates		Transmissivity (m^2/d)
		Latitude (dd.ddddd°S)	Longitude (dd.ddddd°E)	
G36320	A2N0589	*26.01632*	*27.70823*	3000
G36321	A2N0593	*26.02319*	*27.68882*	13900
G36323	A2N0590	26.02441	27.71527	20500
G36324	A2N0592	*26.03134*	*27.69753*	11200
G36326	A2N0588	*26.03766*	*27.70903*	3700
G36327	A2N0587	26.03668	27.71534	900
G36328	A2N0595	*26.04684*	*27.67811*	13600
G36329	A2N0596	*26.05139*	*27.67215*	2400
G36330	A2N0597	*26.05403*	*27.68415*	5400
G36331	A2N0586	26.04761	27.70903	2100
G36332	A2N0598	26.06581	27.66622	4300
G36335	A2N0599	*26.06585*	*27.66623*	1500
G36336	A2N0581	*26.07942*	*27.66628*	1200
Note: Italicized coordinate values denote DWA coordinates not verified by PSP.				

35 Field data and information sourced in this study indicates that the Kromdraai Spring(s) referred to by Bredenkamp et al. (1986) and Holland (2009) are in fact the Plover's Lake Springs referred to in this report. This study identifies the Kromdraai Spring (section 8.5.3) as a single groundwater source quite separate from the Plover's Lake Springs (section 8.5.2); the plural in regard to the latter denotes a grouping of springs and seeps, as opposed to a single source. The Krodraai Spring discharge of ~307 L/s is considerably greater than the ~60 L/s of the Plover's Lake Springs. It is presumed, therefore, that the Kromdraai Springs referred to by Bredenkamp et al. (1986) and more recently by Holland et al. (2009), in fact represent the Plover's Lake Springs. Both Bredenkamp et al. (1986) and Holland et al. (2009) show the position of the Kromdraai Springs to be coincident with the Plover's Lake Springs location. Further discussion of this 'discrepancy' is presented in section 8.5.

A study by Leyland et al. (2008) applied the concept of vulnerability mapping to the COH WHS area. This study built on various internationally recognized methods and approaches to develop a South African version that takes account of local conditions. A recent improvement on this approach, including the results of its application to the COH WHS, is presented in section 13. An investigation by Holland (2007) applied the concept of groundwater resource directed measures (GRDM) to the COH WHS area. This study proposed a groundwater recharge value of 114 mm/a, equal to 16% of a mean annual precipitation (MAP) of 650 mm, for the study area. The veracity of this proposition has not been tested, but it represents the average of values in the range 15 to 21% (95 to 132 mm/a) for an MAP of 630 mm postulated by Bredenkamp et al. (1986). In addition to the 26 geosites provided by the Hobbs and Cobbing (2007) study, Holland (2007) enumerated a further 41 geosites (boreholes) in the COH WHS area (including 16 DWA boreholes) for which depth to groundwater level values are recorded. Most of these sites have been incorporated into the COH WHS project data base.

8.2 Compartment Definition

The phenomenon of compartmentalization of the South African late-Archaean (2.64 to 2.50 Ga) karst systems is well known (Martini and Kavalieris, 1976). The phenomenon transforms a heterogeneous and anisotropic aquifer of considerable regional extent into smaller portions, allowing for more meaningful subregional analysis and understanding of the hydrogeologic environment. White (1993) refers to these as “karstic ground-water basins”, recognition of which in the COH WHS reveals a degree of compartmentalization that contributes significantly to a more informed understanding of the groundwater environment. A total of ten compartments, two of which comprise subcompartments, are identified in the study area. These are described and discussed in greater detail in the following sections. The schematic layout presented in Figure 64 provides a visual reference for this discussion.

8.2.1 Zwartkrans Compartment

The Zwartkrans Compartment is drained by the Zwartkrans Spring located ~1.4 km north-east (downstream) of Sterkfontein Caves on the farm Zwartkrans 172IQ. The compartment spans an area of ~9800 ha bounded in the south-west by the Tarlton Dyke system, in the north-east by the Zwartkrans Dyke, to the north-west by the geological contact between the Malmani Subgroup dolomite and the overlying Pretoria Group sedimentary strata, and along the south-eastern boundary by the geological contact between the Malmani Subgroup and Witwatersrand Supergroup quartzitic strata.

The Zwartkrans Compartment was subdivided by Bredenkamp et al. (1986) into nine subcompartments identified alphabetically by the letters A to I. The subdivision is 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 subcompartment. The weak hydraulic gradients were also put forward as the reason for not contouring water levels (Bredenkamp et al., 1986). It is notable, however, that the difference in ‘representative water level’ between the five subcompartments B, C, D, E and F is only ~70 m over a distance of ~8 km, i.e. little more than 10 m/km or 14 m per subcompartment. These circumstances and the comparatively sparse set of water level data used to derive the subcompartments, raises doubt over the recognition of an overly disrupted groundwater flow pattern due to barrier boundaries and associated sub-compartmentalization (Hobbs and Cobbing, 2007). For example, subcompartment F is recognized in this study as a separate compartment, namely the Krombank Compartment (section 8.2.2). The PSP proposes a simplified subdivision of the Zwartkrans Compartment into the three subcompartments described in the following sections.

8.2.1.1 Vlakdrift Subcompartment

The Vlakdrift Subcompartment (~2360 ha) forms the upper reaches of the Zwartkrans Compartment. Its western margin is the Tarlton East Dyke that marks the boundary with the Steenkoppies Compartment to the west (Holland et al., 2009). The eastern boundary is represented by the roughly N-S striking Beckedan Barrier, the northern boundary by the Sterkfontein Dyke, and the southern margin by the lithological contact with the older Witwatersrand Supergroup.

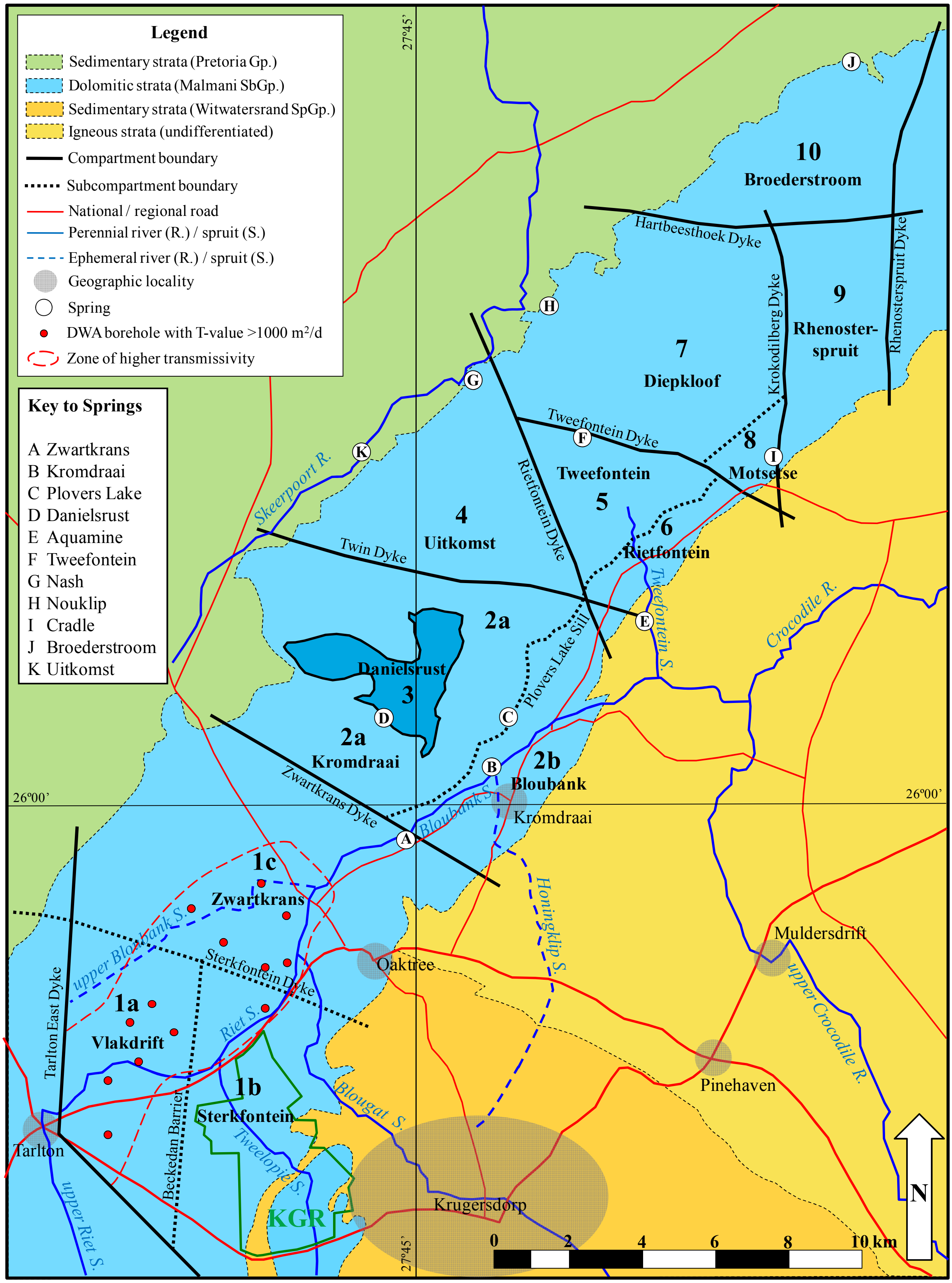

Figure 64. Definition of dolomitic compartments/subcompartments in relation to the springs draining these hydrogeologic units.

Both the Sterkfontein Dyke and the Beckedan Barrier[36] are recognized by Holland et al. (2009) as hydrogeological boundaries. An upward step in water level elevation of between 45 and 50 m from west to east across the Beckedan Barrier characterizes the influence of this boundary on the potentiometric surface in the southern portion of the Vlakdrift Subcompartment and the adjoining Sterkfontein Subcompartment. This is reflected in the groundwater elevations in boreholes CSIR17 (1520 m amsl) and CSIR3 (1570 m amsl), and CSIR31 (1503 m amsl) and A2N0583 (1548 m amsl).

The main recharge to this subcompartment is from rainfall, although the anthropogenic (and allogenic) contribution from excess surface flow via the upper Riet Spruit past Tarlton, as is described in section 4.2.2.1, represents a significant secondary input. The outflow from this subcompartment northwards into the Zwartkrans Subcompartment is a postulated subsurface drainage that coincides with a zone of higher transmissivity as described in section 8.1.

8.2.1.2 Sterkfontein Subcompartment

The Sterkfontein Subcompartment (~2450 ha) forms the south-central portion of the Zwartkrans Compartment. It receives primarily allogenic recharge in the form of mine water via the Tweelopie Spruit. The boundaries of this subcompartment are defined by the Beckedan Barrier in the west, the Sterkfontein Dyke to the north, and the lithologic contact with the older Witwatersrand Supergroup strata to the south-east. The discontinuity in the potentiometric surface ('water table') in the Oaktree area created by the Sterkfontein Dyke is revealed by the following:

- potentiometric elevation differences of 15 to 20 m between boreholes AM1 and ME1 (at 1467 m amsl) to the south, and boreholes PD1 and CSIR9 (at 1450 m amsl) to the north; and
- the apparent northerly displacement of the mine water impact on karst groundwater quality (as revealed by elevated EC and SO_4 levels) in the Oaktree area.

The outflow of this subcompartment over/through the Sterkfontein Dyke into the Zwartkrans Subcompartment is similar to that of the adjoining Vlakdrift Subcompartment, namely subsurface drainage coincident with a zone of higher transmissivity that intersects the Sterkfontein Dyke (Figure 64). The principal groundwater flow vector at this position is northwards, and is considered to be partly driven by an artificial groundwater 'mounding' effect created by the accumulation of infiltrating mine water (delivered by the Riet Spruit) and treated municipal wastewater (delivered by the Blougat Spruit) at the confluence of these drainages.

8.2.1.3 Zwartkrans Subcompartment

The Zwartkrans Subcompartment covers ~51% (~4990 ha) of the Zwartkrans Compartment. Its boundaries are defined by the Sterkfontein Dyke to the south, the lithologic contact with the younger Pretoria Group strata to the north-west, the lithologic contact with the older Witwatersrand Supergroup strata to the south-east, and the Zwartkrans Dyke to the north-east. The latter gives rise to the Zwartkrans Spring. It also gives rise to diffuse (and difficult to quantify) seepage in an area on the opposite (left) bank that is collected and channelled into trout dams on the Boland Farm property on Danielsrust 518JQ.

Groundwater rest levels measured in three boreholes that straddle the dyke structure reveal that it marks a step down in groundwater level, from west to east across the structure, of ~12 m. The potentiometric surface in the Zwartkrans Compartment immediately upstream of the dyke occupies an elevation of ~1432 m amsl (the approximate elevation of the Zwartkrans Spring), and an elevation of ~1420 m amsl in the Krombank Compartment (section 8.2.2) immediately downstream of the dyke. It is postulated that the zone of higher transmissivity (Figure 64) might extend in a north-easterly direction to intersect the Zwartkrans Dyke, thus also providing a subsurface outflow component into the Krombank Compartment.

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[36] Note that Bredenkamp et al. (1986) assigned the name Sterkfontein Dyke to this structure, whereas this name is assigned to the roughly NW-SE trending structure (Figure 64) by both this study and Holland et al. (2009). It also seems probable that the western extension of this structure might form part of the Maloney's Eye Dyke recognized by Bredenkamp et al. (1986).

An equally over-looked discharge component is that which is represented by the intersection of the water table with the bed of the Bloubank Spruit immediately upstream of the Zwartkrans Spring. Flow measurements described in section 4.2.2.3 indicate a surface water 'gain' in the order of 17 ML/d (197 L/s) in this reach of the Bloubank Spruit. This 'gain' is considered to be provided by in-channel (streambed) springs that are considerably more difficult to pinpoint than the 'point-source' off-channel Zwartkrans Spring. Note in this regard that a monitoring borehole sunk within 50 m of the Bloubank Spruit ~700 m upstream of the Zwartkrans Spring revealed unconsolidated sedimentary material down to 14 m bs with a water table at ~2 m bs, i.e. a saturated thickness of ~12 m. Nevertheless, together with the ~100 L/s discharge attributed to the Zwartkrans Spring (section 8.5.1 and Table 60), the aggregate discharge from the Zwartkrans Subcompartment approaches 300 L/s. Given the hydraulic continuity with the 'upstream' Sterkfontein and Vlakdrift Subcompartments, this discharge must also represent that of the Zwartkrans Compartment as a whole. As such, it necessarily excludes the potential contribution 'lost' to groundwater abstraction, e.g. for agriculture, in this compartment. Estimates of the latter range from ~9 to ~26 Mm^3/a (section 8.7), which translate into equivalent values of ~285 to ~824 L/s.

Although the Zwartkrans Subcompartment hosts the Sterkfontein Caves, the latter are located along the south-eastern margin of this subcompartment. It is postulated that this places the Sterkfontein fossil site to the south and outside the main groundwater flow vector that collects the subsurface discharge of both the Vlakdrift and Sterkfontein Subcompartments, and directs these toward the Zwartkrans Spring along the trace of the 'dry' Bloubank Spruit upstream of its confluence with the Riet Spruit. These circumstances recognize the possible existence of a subsurface 'thalweg'[37] associated with the relic surface expression of the ephemeral upper reaches of the Bloubank Spruit. The most visual discharge feature of this subcompartment and its contributing upstream subcompartments remains the Zwartkrans Spring (section 8.5.1).

8.2.2 Krombank Compartment

This compartment (total area ~5080 ha) comprises two subcompartments identified as the Kromdraai Subcompartment drained by the Plover's Lake Springs and the Kromdraai Spring located on the farm Kromdraai 520JQ, and the Bloubank Subcompartment that straddles the Bloubank Spruit. The name 'Krombank' (a combination of the names <u>Krom</u>draai and Blou<u>bank)</u> used to describe this compartment denotes the degree of hydraulic continuity considered to exist between these subcompartments.

8.2.2.1 Kromdraai Subcompartment

The Kromdraai Subcompartment covers an area of ~3470 ha (necessarily excluding the footprint of the separate and 'perched' Danielsrust Compartment) bounded to the south-west by the Zwartkrans Dyke, to the north-west by the geological contact between the Malmani Subgroup dolomite and the overlying Pretoria Group sedimentary strata, to the north-east by the Twin Dyke structure, and along the south-eastern boundary by a syenite sill intrusion provisionally named the Plover's Lake Sill. This sill marks the common boundary with the Bloubank Subcompartment. The potentiometric surface intersects the land surface at an elevation of ~1419 m amsl at the Plover's Lake Springs. The discharge of these springs (~60 L/s) is, however, too small to account for the postulated surface extent of this subcompartment. It is considered very probable that structural discontinuities along the south-western trace of the Plover's Lake Sill form additional flow paths for groundwater discharge from this subcompartment into the Bloubank Subcompartment. The Kromdraai Spring (section 8.5.3) with a discharge of ~307 L/s almost certainly represents one such outlet.

8.2.2.2 Bloubank Subcompartment

The Bloubank Subcompartment straddles the course of the Bloubank Spruit for a distance of some 8 km from the Zwartkrans Dyke to where this drainage leaves the karst environment in the vicinity of

[37] See GLOSSARY OF SELECTED TERMS. Used in the context of this report to describe a preferential subsurface flowpath such as a large channel (or network of channels) that might develop and occur in a karst aquifer and act as a '*subsurface groundwater stream*' (from Martini, 2006, p. 664) or a '*master drain*' (after White, 1993).

Brookwood Trout Farm. Encompassing an area of ~1610 ha, its south-eastern boundary is formed by the contact between the Malmani Subgroup dolomite and the older Witwatersrand Supergroup quartzitic strata. The north-western margin is formed by the Plover's Lake Sill intrusion that follows a trace which runs subparallel to that of the south-eastern boundary. This subcompartment receives:

- the overflow from the Zwartkrans Compartment via the Zwartkrans Spring and a postulated subsurface discharge zone that breaches the Zwartkrans Dyke;
- discharge from the Kromdraai Subcompartment along its north-western margin via structural discontinuities in the bounding Plover's Lake Sill (section 8.2.2.1); and
- infiltrating river water from losing sections of the Bloubank Spruit between the Zwartkrans and Kromdraai springs.

It is especially the latter circumstances that give rise to the high discharge (~307 L/s) of the Kromdraai Spring which, as shown in Table 60, returns an unrealistically high equivalent recharge of ~30% of MAP (when combined with the Plover's Lake Springs but excluding the Danielsrust Spring contribution) to represent the 'recharge input' over the Krombank Compartment footprint of 5080 ha. The allogenic nature of the surface water contribution might account for the EC value of 56 mS/m associated with the Kromdraai Spring water, compared to the 38 mS/m associated with the Plover's Lake Spring water (Figure 91). More typically, the principal groundwater flow vector in this subcompartment follows the arcuate course of the Bloubank Spruit in a north-easterly direction.

Anomalous groundwater rest level elevations in the extreme north-eastern corner of the subcompartment (e.g. stations VW1 and PvW1) are attributed to further sub-compartmentalization formed by the NW-SE striking diabase dyke (named the Rietfontein Dyke) at this location (Figure 64). The small area (~30 ha) encompassed by this subcompartment, however, negates recognition thereof as an important part of the hydrogeologic regime in the COH WHS, and it has been aggregated with the Bloubank Subcompartment.

8.2.3 Danielsrust Compartment

Located on the farm Danielsrust 518JQ, the Danielsrust Compartment (name newly coined) defines a perched karst aquifer (barré[38]) that supports a groundwater rest level located at an elevation of >1490 m amsl, i.e. 50 to 70 m above the 1420 to 1440 m amsl elevation in the regional karst aquifer defined by the Kromdraai Compartment. The cross-section in Figure 72 illustrates the postulated hydrogeological relationship that describes the position of this groundwater system in the regional hydrogeological framework. The footprint of this compartment is defined by the dolerite outcrop (not recognized by Obbes, 2000) which forms a quasi 'ring' structure (Figure 64), and straddles the boundary between the farms Danielsrust 518JQ (west) and Sterkfontein 519JQ (east). This structure, measured around its outer perimeter, encompasses an area of ~740 ha. It is postulated that the dolerite forms an impermeable basin that serves to contain groundwater which decants naturally at the Danielsrust Spring with an elevation of ~1490 m amsl. According to the landowner, the long-term discharge of this spring is 100 000 L/h (28 L/s) (P. van der Merwe, personal communication). The establishment of three water supply boreholes within this compartment has added an artificial loss component to the water balance of this aquifer.

In order for the ~740 ha extent of the Danielsrust Compartment to support a spring discharge of 28 L/s, it would be required that rainfall recharge amounts to ~17% of a mean annual precipitation (MAP) of 710 mm (from Holland, 2007). This value compares favourably with the 16% of MAP reported by Holland (2007) as the most appropriate regional mean recharge value for the karst environment. Four different calculation methods used in the earlier study by Bredenkamp et al. (1986) yielded recharge values in the range 14% to 21% for an MAP of 630 mm. Further support for recognition of the Danielsrust Compartment as a distinctly separate hydrosystem is found in water chemistry data. Firstly, the electrical conductivity field value of 26 mS/m associated with the Danielsrust Spring water is notably lower than the 40 to 46 mS/m associated with the dolomitic groundwater in the wider area. Secondly, the stable isotope results (Holland, 2007 and this study as reported in section 9.7.4) compare favourably with those of 'pristine' karst groundwater in the study area.

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[38] See GLOSSARY OF SELECTED TERMS.

The above circumstances place all of the responsibility for the protection of this groundwater resource on those landowners of property located within the Danielsrust Compartment. The greatest threat to this resource is considered to be that associated with on-site sanitation facilities, particularly those which carry a potentially elevated load. The greatest part of the compartment supports game farming, which affords most of this resource an excellent measure of protection from pollution. However, the adjacent commercial tourist lodge and camp facility on the farm Sterkfontein 519JQ represents a concern that needs to be considered. The location of the lodge near the 'downstream' end of the compartment means that much of this resource (i.e. the area located upstream of the camp) is 'immune' to contamination from this source. This does not apply to the spring located only ~500 m down-gradient of the lodge. Furthermore, abstraction from the lodge water supply borehole located immediately upstream of the spring exacerbates this threat by drawing groundwater closer. Although the spring does not currently serve a water supply function for any purpose, protection of its quality is mandated by s. 19 of the NWA (Act No. 36, 1998), "*Prevention and remedying effects of pollution.*", which requires of a landowner, person in control of land or person occupying or using land to take all reasonable measures to prevent pollution of a water resource from occurring, continuing or recurring. These circumstances identify the Danielsrust Compartment as a candidate groundwater management unit (GMU).

8.2.4 Uitkomst Compartment

This compartment encompasses the southern portion of the extensive John Nash Nature Reserve. It is postulated that this compartment is drained by the Nash Spring (JNNR3) located at an elevation of ~1365 m amsl. The discharge of the Nash Spring (~130 L/s) suggests a substantial catchment area. A provisional assessment recognizes the triangular footprint defined in Figure 64 as a suitable description of this compartment spanning ~2860 ha. It is named the Uitkomst Compartment (coined by the PSP) since ~55% of its postulated extent is located on the farm Uitkomst 499JQ. The spring discharge of ~130 L/s represents 149 mm of rainfall recharge per annum, or 21% of an MAP of 710 mm. The compartment boundaries are defined by the Twin Dyke structure in the south, the geological contact between the Malmani Subgroup dolomite and the overlying Pretoria Group sedimentary strata along the north-western margin, and the NW-SE striking Rietfontein Dyke to the north-east.

The Nash Spring elevation of ~1360 m amsl (Table 65) ties in with the groundwater elevation of 1365 m amsl reported for the borehole MVR1 on the Moon Valley Ranch property (Ptn. 38 of Rietfontein 522JQ) in the upper reaches of this compartment. Although these geosites are located a distance of ~3.8 km apart, they are both located in the Skeerpoort River catchment (A21G). Data sourced from station MVR1 and station RLGR5 on the Rhino and Lion Game Reserve property in the Kromdraai Subcompartment to the south, reveals a difference in groundwater level elevation of ~55 m across the Twin Dyke structure that separates these two stations and compartments (Figure 64and Figure 72). This is an abnormally large difference between contiguous karst compartments, and indicates as complete a hydraulic separation as might reasonably be conceived in practical terms.

8.2.5 Tweefontein Compartment

The enumeration of the Tweefontein and Nash Springs in the John Nash Nature Reserve (sections 8.5.6 and 8.5.8) and the Cradle Spring in the Motsetse Nature Reserve (section 8.5.10) provide a better definition of groundwater elevations (and associated compartmentalization) in the north-eastern portion of the COH WHS area. This area has long suffered from a paucity of hydrogeological information, and the groundwater rest level elevations in this portion of the study area remains poorly defined due to the scarcity of boreholes in this largely pristine natural landscape.

This study postulates that the Tweefontein Compartment encompasses a much smaller area than suggested by previous studies. For example, Holland (2007) and Holland and Witthüser (2009) indicate this compartment to extend from the Twin Dyke system north-eastwards all the way to almost 27.9°E, a longitude that coincides with the eastern extremity of Hartbeespoort Dam north of the village of Broederstroom, and encompassing an area of ~12 750 ha. The current study provides information such as quantified spring discharges and spring surface elevations (that serve as a proxy for the lowest potentiometric surface elevation of the contributing compartment) which, together with spring water chemistry (including isotope data) and likely recharge rates, provide material on which to base a redefinition of this compartment as shown in Figure 64.

The Tweefontein Spring elevation of ~1450 m amsl is some 30 m above the potentiometric surface in the Krombank Compartment to the south-west. It is hypothesized on the basis of the relatively small discharge (~30 L/s) of the Tweefontein Spring (section 8.5.6), that it drains a 'perched' aquifer of limited surface extent described by the triangular footprint defined in Figure 64. This footprint encompasses ~1160 ha. Under these circumstances, the spring discharge of ~30 L/s represents 82 mm of rainfall recharge per annum. This is 12% of an MAP of 710 mm. It is proposed, therefore, that the boundaries of this compartment are defined by the NW-SE striking Rietfontein Dyke (name newly coined) to the west, the Tweefontein Dyke (named newly coined) to the north-east, and the northern extension of the syenitic Plover's Lake Sill along the south-eastern margin. The tritium concentration of ~3 ± 0.3 TU in the spring water (section 9.7.6) suggests that this compartment is also characterized by comparatively recent and rapid rainfall recharge and a 'shallow' subsurface circulation regime (see footnote 48).

In light of the above, this study proposes that the Tweefontein Compartment located to the north-east of the Krombank Compartment constitutes a 'perched' aquifer of limited extent. As such, it is similar to the Danielsrust Compartment with its outlet, the Tweefontein Spring, providing autogenic recharge northwards into the Diepkloof Compartment (section 8.5.6).

8.2.6 Rietfontein Compartment

The Rietfontein Compartment (~540 ha) comprises a rectangular footprint adjoining the south-eastern margin of the Tweefontein Compartment. It therefore shares the northern extension of the Plover's Lake Sill as the common boundary with the Tweefontein Compartment to the north-west. Although the Aquamine Spring represents the most logical discharge (outflow) of groundwater from this compartment, the yield of the latter (<2 L/s) does not adequately reflect the extent of the contributing karst aquifer. Not considered to be of consequence to the broader aims and objectives of this study, these circumstances nevertheless might attract further investigation in future hydrogeologic studies.

8.2.7 Diepkloof Compartment

This compartment represents the comparatively poorly defined karst environment in the north-eastern portion of the COH WHS. The north-westerly groundwater flow pattern in the Diepkloof Compartment (name newly coined) is based mainly on the surface drainage pattern that is characterized by deeply incised streams such as the Snake Stream and the Grootvlei Spruit. The elevation of the Nouklip Spring (~1330 m amsl) in the lower reaches of the Grootvlei Spruit supports this hypothesis. The substantial yield of this spring (~143 L/s) again reflects a highly transmissive aquifer of substantial surface extent.

A provisional assessment recognizes the rectangular footprint defined in Figure 64 as a suitable geometric description of this compartment spanning ~3800 ha. This recognizes the Tweefontein Dyke as the southern boundary, the E-W striking Hartbeesthoek Dyke (name newly coined) as the northern boundary, the N-S striking Krokodilberg Dyke (name newly coined) as the eastern boundary, and the geological contact between the Malmani Subgroup dolomite and the overlying Pretoria Group sedimentary strata the western margin. The spring discharge of ~143 L/s represents 119 mm of recharge per annum (17% of MAP).

8.2.8 Motsetse Compartment

The Motsetse Compartment (name newly coined) forms a small catchment (Figure 64) located in the Motsetse Nature Reserve. It encompasses only ~270 ha, and is drained by the Cradle Spring at a rate of ~2 L/s. This discharge represents 23 mm of rainfall recharge per annum (~3% of MAP). Since this compartment is largely enclosed within a proclaimed nature reserve, its preservation in a natural state is reasonably well ensured.

8.2.9 Rhenosterspruit Compartment

This compartment of ~1550 ha is located in the north-eastern portion of the COH WHS (Figure 64) where the karst environment is comparatively poorly defined in terms of its hydrogeology.

8.2.10 Broederstroom Compartment

This compartment is located in the extreme north-eastern portion of the COH WHS (Figure 64) where the karst environment is comparatively poorly defined in terms of its hydrogeology. It encompasses an area of ~2050 ha. The Broederstroom Spring (section 8.5.11) on the Glen Afric Country Lodge property south of Broederstroom represents one of the more prominent features draining this compartment. It is known, however, that this area supports a number of lower yielding springs that have not been enumerated as yet. Their discharge, added to the ~21 L/s of the Broederstroom Spring, might well double or even treble the rainfall recharge contribution of ~4% associated with the Broederstroom Spring (Table 60).

8.2.11 Synthesis of Compartment Definition

The information presented in Table 60 summarizes the definition of groundwater compartments in the COH WHS. The estimated size of each compartment and subcompartment is derived from planimetric measurements of the compartment footprints. Where possible, the veracity of these values is gauged against the natural discharge as represented by measured spring flows converted to an equivalent recharge from rainfall. This approach is encapsulated in the groundwater basin concept described, amongst others, by White (1993; 2007). The rainfall recharge values (Table 60) range from ~2 to ~30% of MAP, but excluding the anomalously high and low values more typically fall in the range ~11 to ~20%. The latter is in reasonable agreement with both the regional/subregional range of values reported in section 8.1, and the similarly extreme-exclusive range of ~9 to 18% of MAP (extreme-inclusive range ~3 to 23%) reported by Kok (1992) for 12 dolomitic springs in South Africa.

Table 60. Summary information of groundwater compartments identified in the COH WHS.

Compartment	Sub-Compartment	Extent (ha)		Outflow Feature	Discharge (L/s)		Discharge (ML/d)	Recharge mm	Recharge %MAP[1]
Zwartkrans	Vlakdrift (1a)	2360	9800	Subsurface	143[2]		12.39[2]	78	~11
	Sterkfontein (1b)	2450		Subsurface					
	Zwartkrans (1c)	4990		Zwartkrans Spring	100		8.64		
Krombank	Kromdraai (2a)	3470	5080	Plover's Lake Springs	60	339[3]	29.23[3]	210	~30
	Bloubank (2b)	1610		Kromdraai Spring	307				
Danielsrust (3)			740	Danielsrust Spring	28		2.42	119	~17
Uitkomst (4)			2860	Nash Spring	130		11.23	143	~20
Tweefontein (5)			1160	Tweefontein Spring	30		2.59	81	~11
Rietfontein (6)			540	Aquamine Spring	<2		<0.17	11	~2
Diepkloof (7)			3800	Nouklip Spring	143[4]		12.36[4]	119	~17
Motsetse (8)			270	Cradle Spring	2		0.17	23	~3
Rhenosterspruit (9)			1550	Not established					
Broederstroom (10)			2050	Broederstroom Spring	21		1.81	31	~4
TOTAL			27 850		938		81.04		

(1) Mean annual precipitation = 710 mm.
(2) Value based on a theoretical inflow that represents the difference between 17% natural recharge to the Krombank Compartment and the calculated 30%.
(3) The Plover's Lake and Kromdraai springs are combined to represent the theoretical groundwater discharge of the Krombank Compartment excluding the autogenic recharge of 28 L/s contributed by the Danielsrust Spring.
(4) Excludes the autogenic recharge of 30 L/s contributed by the Tweefontein Spring.

The 'anomalously' high recharge value for the Krombank Compartment has been discussed in section 8.2.2.2. The higher recharge value reported for the Uitkomst Compartment is attributed to the more rugged nature of the terrain that characterizes this compartment. These circumstances promote runoff in the incised drainages which, due to their geologic setting, are controlled by geologic structures (fracture and fault zones), and typically represent losing (influent) streams contributing autogenic recharge to the karst aquifer. These circumstances have been observed for the Grootvlei Spruit draining the Diepkloof Compartment (T. Abiye, personal communication).

The lower recharge value for the Zwartkrans Compartment possibly reflects the unaccounted for abstraction of groundwater primarily for agriculture in this compartment. Reported values in this regard vary from ~9 Mm^3/a (24.7 ML/d) to ~26 Mm^3/a (71.2 ML/d) (section 8.7). Assuming a use in the order of 15 Mm^3/a (41.1 ML/d) gives a total 'input' of 62.1 ML/d. It has been shown in section 4.2.2, however, that alloganic recharge via the Tweelopie Spruit and the Blougat Spruit amounts on average to between 15 and 20 ML/d in total. Accepting the lower (conservative) value reduces the 'natural' recharge to 47.1 ML/d, which is equivalent to a recharge value of ~17.5% of MAP over the ~9800 ha extent of the Zwartkrans Compartment. Whilst it is acknowledged that an assessment such as this is hypothetical and necessarily coarse, it does provide plausible order of magnitude volumes that offer a 'reality check'.

A second 'reality check' of the subcompartment definition in the south-western portion of the study area, based on a statistical analysis of groundwater rest level data, is presented in Table 61. The salient observations revealed by this analysis are summarized as follows:

- The difference in groundwater rest level depth and elevation between subcompartments 1a and 1b. Especially the difference of 35 to 40 m in terms of the mean and median elevation (absolute) values supports the observations documented in section 8.2.1.1 regarding the difference in groundwater rest level between these two subcompartments. [Note that it is shown in section 8.6 and Figure 73 that this difference reduces at the contiguous northern ends of these two subcompartments.]

- The difference in groundwater rest level depth and elevation between subcompartments 2a and 2b. Although the difference in mean and median elevation values is comparatively small (~3 m), the much shallower mean and median depth values that characterize subcompartment 2b reflect the association of this subcompartment with the valley of the Bloubank Spruit between the Zwartkrans Spring and Plover's Lake.

Table 61. Definition of groundwater rest level variables for the Bloubank Spruit system.

Subcompartment	Groundwater Rest Level Variable	Statistical Parameter					
		Count	25%ile	Mean	Median	75%ile	Inter-quartile Range (m)
1a (Vlakdrift)	Depth (m bs) Elevation (m amsl)	11	48 1461	63 1502	62 1503	75 1535	27 74
1b (Sterkfontein)	Depth (m bs) Elevation (m amsl)	16	20 1471	31 1536	28 1540	44 1570	24 99
1c (Zwartkrans)	Depth (m bs) Elevation (m amsl)	25	17 1439	28 1446	22 1444	30 1450	13 11
2a (Kromdraai)	Depth (m bs) Elevation (m amsl)	12	44 1418	60 1422	59 1420	74 1424	30 6
2b (Bloubank)	Depth (m bs) Elevation (m amsl)	14	6 1410	12 1419	11 1417	18 1420	12 10

8.3 Groundwater Level Behaviour

The behaviour of groundwater levels (the hydrostatic response) associated with the karst aquifer is reflected in the long-term water level records for the 15 DWA monitoring boreholes in the study area. An assessment of these data returns the statistics presented in Table 62. An analysis of the %ile Δh data yields a 25%ile value of 2.3 m, a median value of 3.6 m, and a 75%ile value of 6.1 m. A graphical representation of the information is shown in Figure 65.

The information presented in Table 62 and Figure 65 indicates that there is little correlation between the depth to groundwater rest level and the magnitude of variation evident in this parameter. For example, relatively small variations are associated with both 'deep' water levels (stations A2N0592 and A2N0594) and comparatively 'shallow' water levels (stations A2N0589 and A2N0600).

Table 62. Salient long-term groundwater level monitoring data statistics.

Station	Depth to Groundwater Rest Level (m bc)							Record Period(1)
	n	5%ile	Mean	Median	95%ile	Max Δh(2)	%ile Δh(3)	
A2N0580	252	51.00	54.83	54.59	59.96	11.13	8.96	05/1985 - 05/2010
A2N0582	206	35.73	40.10	40.12	42.91	8.53	7.18	05/1985 - 05/2010
A2N0583	200	44.42	45.01	45.06	45.56	1.84	1.14	05/1985 - 05/2010
A2N0584	233	22.14	26.17	26.55	28.13	7.91	6.00	05/1985 - 05/2010
A2N0586	249	22.85	26.99	27.29	28.72	8.21	5.87	05/1985 - 05/2010
A2N0589	170	27.93	28.97	29.02	30.08	6.15	2.16	05/1985 - 02/2010
A2N0590	146	34.16	35.37	35.41	36.50	4.52	2.33	05/1985 - 05/2010
A2N0592	236	76.25	77.42	77.45	78.58	4.71	2.33	06/1985 - 05/2010
A2N0594	187	70.84	72.80	72.83	74.42	5.80	3.58	01/1985 - 09/2008
A2N0598(4)	93	57.09	64.56	62.30	75.82	19.65	18.73	07/1985 - 02/2010
	93	52.75	58.49	58.67	63.28	12.17	10.54	
A2N0600	167	23.49	24.49	24.54	25.44	3.61	1.95	04/1989 - 05/2010
A2N0602	193	53.47	54.90	55.00	56.02	4.85	2.55	06/1987 - 05/2010
A2N0605	177	61.25	62.76	62.93	63.70	3.32	2.45	04/1989 - 05/2010
A2N0606	36	64.53	66.75	66.13	69.55	5.11	5.02	08/1989 - 11/2009
A2N0607	129	64.76	67.74	67.40	70.86	7.58	6.10	10/1993 - 02/2010

(1) Shaded rows denote stations no longer active and in service.
(2) Difference between minimum and maximum values (not shown in this table).
(3) Difference between the 5%ile and 95%ile values.
(4) Lower set of data incorporate the adjusted early records (see relevant hydrograph in Annexure B).

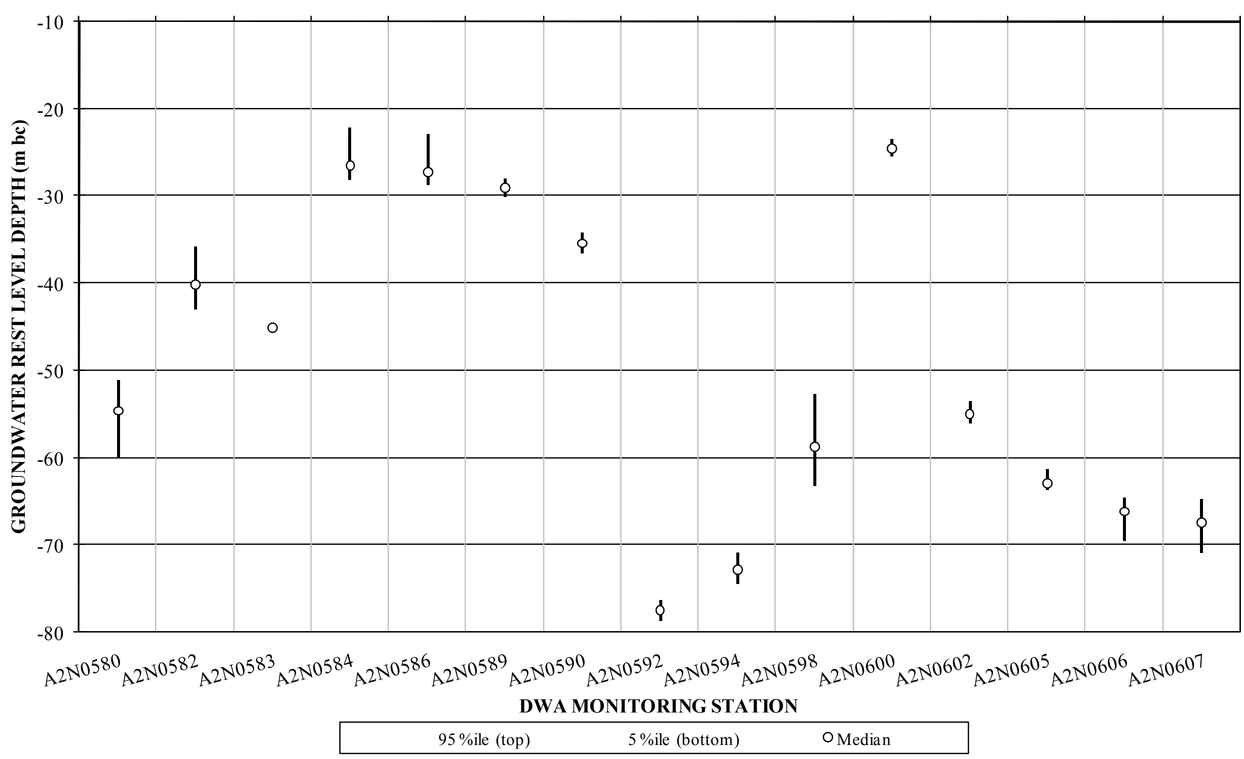

Figure 65. Graphical representation of the hydrographic response exhibited in DWA monitoring stations in the period *ca.* 1985 to *ca.* 2010.

The individual hydrographs associated with each monitoring station listed in Table 62, are presented in Annexure B. A selection of these graphs is compared in Figure 66, which indicates two distinct groupings of hydrograph, namely Group A occupying an elevation of >1530 m amsl, and Group B occupying an elevation <1490 m amsl. The elevation difference of >40 m indicates the location of these groupings in different compartments/subcompartments.

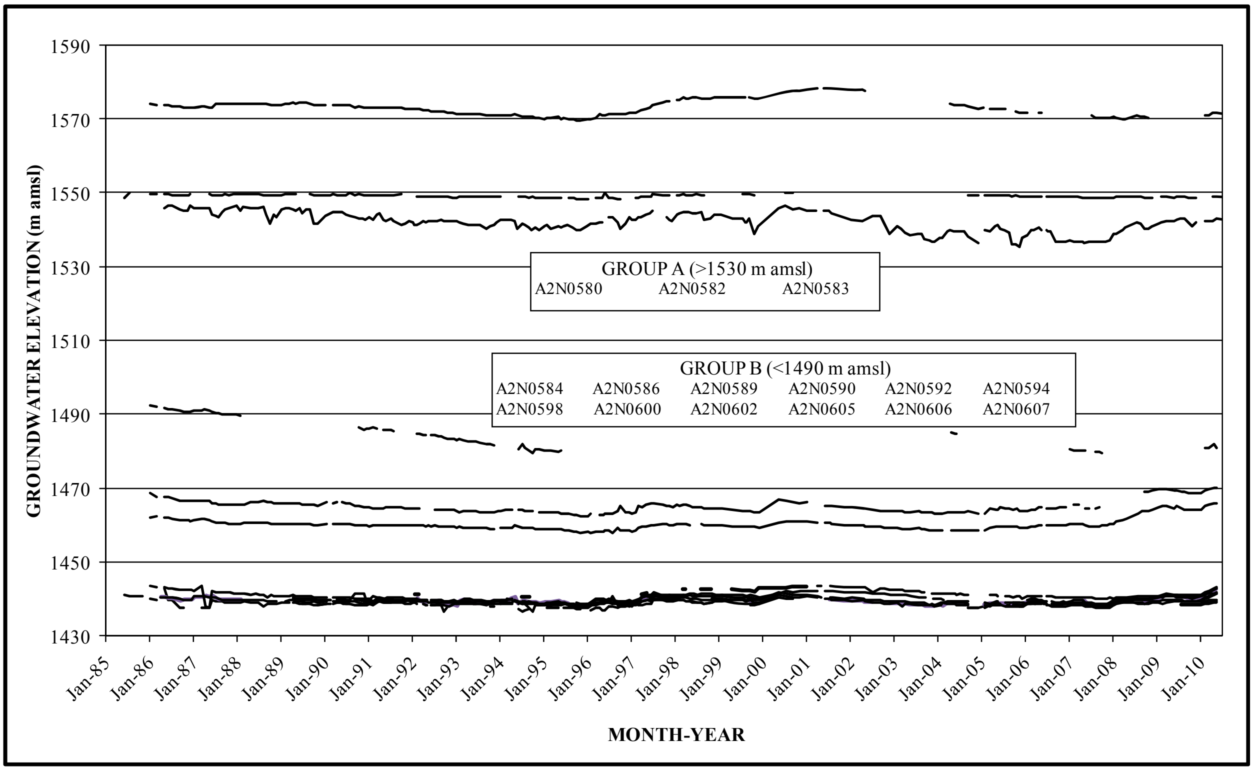

Figure 66. Long-term groundwater level response pattern in DWA monitoring boreholes.

It is evident from Table 62 that the maximum difference in groundwater rest level amounts to 12.2 m (station A2N0598), with a mean of 6.7 m and a median of 5.8 m. The slightly smaller differences between the 5 and 95%ile limits are characterized by a maximum value of 10.5 m (station A2N0598), and mean and median values of 4.9 and 3.6 m respectively. These results are in agreement with similar results obtained for the karst aquifer elsewhere in Gauteng Province, e.g. for the karst aquifer extending from south of Pretoria to Kempton Park, and from Rietvlei Dam in a south-easterly direction to Bapsfontein (Hobbs, 2004). Previous analyses of these data (Hobbs and Cobbing, 2007; Holland and Cobbing, 2008) indicate natural fluctuations in the order of 5 to 8 m manifested over a period of 2 to 5 years, i.e. not from season to season. In regard to the Sterkfontein Caves, Martini et al. (2003) report a gradual water level fluctuation in response to the preceding precipitation pattern in the range ~2 m. The CGS (undated) also reports that the water level in Sterkfontein Caves in 1982/1983 was 2 to 3 m higher than its current (presumably 2004) level.

The groupings shown in Figure 66 are produced separately in Figure 67 (Group A) and Figure 68 (Group B). The large measure of similarity in the hydrostatic response of the Group B stations is evident. By comparison, the Group A stations exhibit a poor correlation that is particularly evident in station A2N0583. An inspection of the original borehole drilling and test pumping records reported by Bredenkamp et al. (1986) provides a possible explanation for the observed response patterns. The data in Table 63 identify station A2N0580 as intersecting an unproductive aquifer (also reflected in the very low transmissivity (T) value of 1 m^2/d), which explains the more ‘ragged’ trace of this graph compared to the ‘smoother’ graphs of stations A2N0582 and A2N0583 (Figure 67). Especially the flat graph of station A2N0583 illustrates the capacity of the intersected groundwater resource to ‘absorb’ and ‘cushion’ the impact of recharge- or abstraction-induced stresses in the aquifer. This capacity derives from high transmissivity and/or storativity characteristics (Table 63). Similarly, the very productive aquifer(s) that support stations A2N0584 and A2N0586 (Figure 68) explain the relative smoothness of these graphical traces. It is probable that the other stations reflected in Figure 68 also penetrate productive groundwater systems.

Table 63. Salient hydrogeological attributes associated with selected DWA monitoring stations (from Bredenkamp, 1986).

Station	Blowout Yield (L/s)	Maximum Tested Yield (L/s)	Maximum Drawdown (m)	Transmissivity (m^2/d)	Comment by PSP
A2N0580	0	0.6	38.5	1	Unproductive aquifer
A2N0582	15	25.2	4.52	1600	Moderate to highly productive aquifer
A2N0583	>40	94.7	4.15	750	Extremely productive aquifer
A2N0584	>40	18	13.17	34	Moderately productive aquifer
A2N0586	>40	106.9	3.18	2100	Extremely productive aquifer

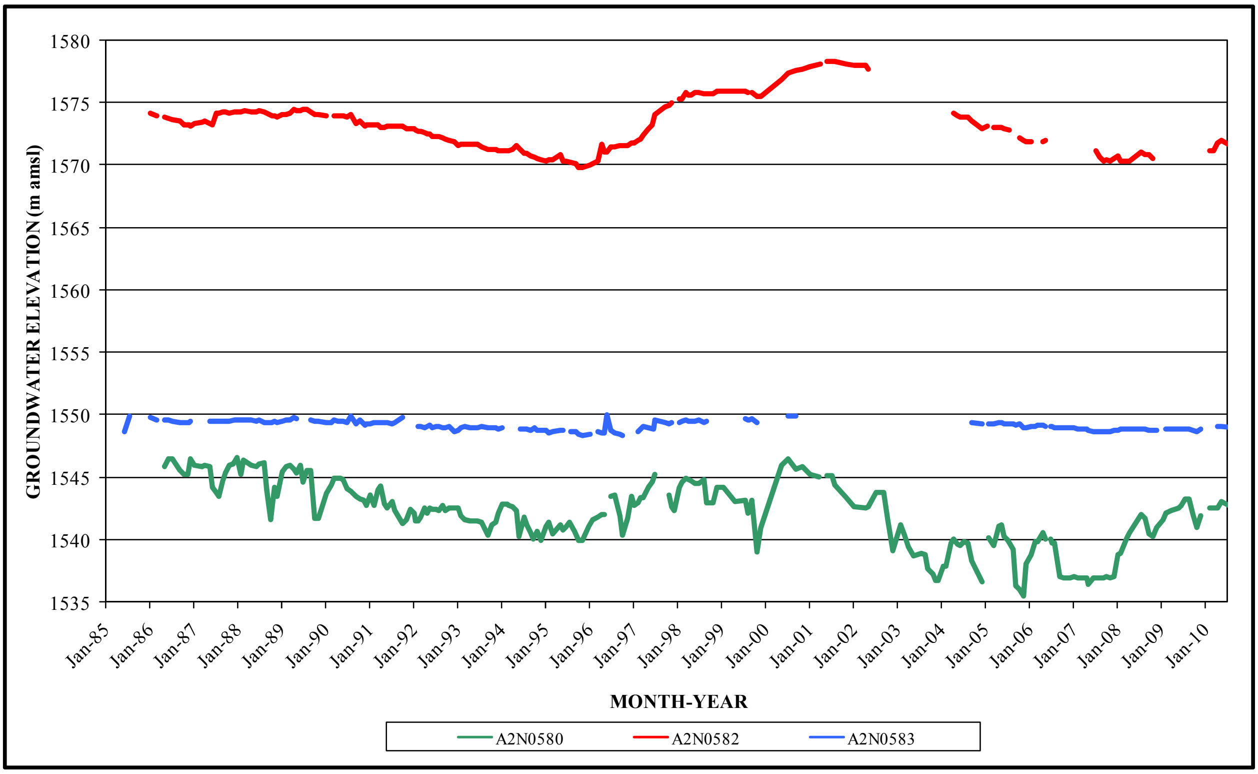

Figure 67. Long-term groundwater level response pattern in Group A boreholes from Figure 66.

The unprecedented rise in the groundwater level observed in stations A2N0584 and A2N0586 since late-2007 (Figure 68) reflects the impact of exceptional recharge associated with raw and/or treated mine water being lost from the lower reaches of the Tweelopie Spruit and its receiving main stem, the Riet Spruit (see Table 27). Both these stations are located in proximity to the Riet Spruit. These circumstances were precipitated by the abnormally wet summers experienced in the region starting with the 2007-'08 hydrological year, and resulting in treated mine water discharges in excess of 25 ML/d to the Tweelopie Spruit (see Figure 13). The additional contribution of raw mine water to this discharge has, on occasion, increased the flow in this drainage to >50 ML/d (see section 4.2.2).

A comparison of water level data sourced by the current study with historical values for the same sites is provided in Table 64. This reveals an unequivocal rise in water level in the recent past, which supports the above observation in regard to stations A2N0584 and A2N0586.

The greatest rises (>3 m) associated with boreholes located in the Riet Spruit valley upstream of Oaktree (CSIR57 and GB1) are again readily attributed to the ingress of surface water contributed primarily by the Tweelopie Spruit from the mining area. Further away from the Riet Spruit, the rise amounts to 0.5 to 1.5 m. Although the rise of ~0.6 m in the Danielsrust Compartment (sites DRGF1 and DRGF2) is similar to the 0.4 to 0.8 m observed nearby in the main karst aquifer (sites BolandB1, SF1 and MB1), these compartments are not in hydraulic continuity with each other.

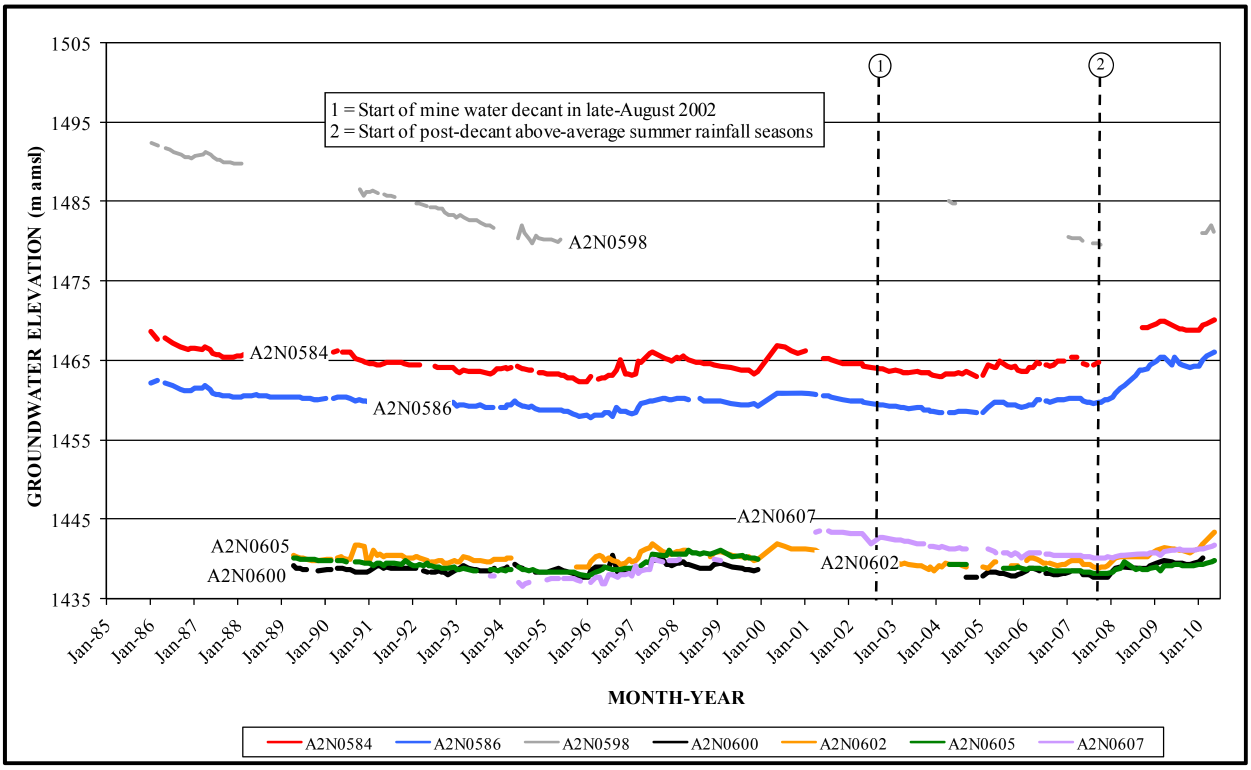

Figure 68. Long-term groundwater level response pattern in Group B boreholes from Figure 66.

Table 64. Comparison of historical and recent depth to groundwater level in the study area.

Station	Historic Water Level			Recent Water Level			Difference (m bc)
	Date	Depth (m bc)	Elevation (m amsl)	Date	Depth (m bc)	Elevation (m amsl)	
SW1	09/12/2005	18.00	1441	11/02/2010	11.36	1448	+6.64
A2N0594	25/01/2006	74.00	1439	08/02/2010	73.43	1440	+0.57
DRP15	30/07/2006	59.00	1416	02/12/2009	58.63	1417	+0.37
ZW1	30/07/2006	29.64	1438	17/02/2010	27.64	1440	+2.00
A2N0600	30/07/2006	25.06	1438	17/02/2010	23.03	1440	+2.03
DRGF1	30/07/2006	11.00	1486	11/02/2010	10.45	1487	+0.55
DRGF2	30/07/2006	26.93	1486	11/02/2010	26.30	1487	+0.63
BolandB1	30/07/2006	22.15	1438	17/02/2010	21.77	1438	+0.38
SF1	01/10/2007	17.43	1437	17/02/2010	16.13	1438	+1.30
				09/06/2010	15.54	1438	+1.89
GB1	30/07/2006	20.36	1444	11/02/2010	17.64	1447	+2.72
MB1	30/07/2006	15.07	1435	13/05/2010	13.79	1436	+1.28
VW1	30/07/2006	13.94	1445	06/05/2010	9.71	1449	+4.23
HW1	30/07/2006	8.00	1410	13/05/2010	6.09	1412	+2.09
SWBH1	30/07/2006	28.00	1417	13/05/2010	27.30	1418	+0.70
SBH1	30/07/2006	22.26	1415	13/05/2010	21.18	1416	+1.08
A2N0584	08/02/2007	25.71	1466	16/02/2010	21.78	1469	+3.93
CSIR34	13/02/2007	35.10	1470	14/04/2010	33.99	1471	+1.11
CSIR8	13/02/2007	28.42	1447	14/04/2010	24.28	1451	+4.14
A2N0586	08/03/2007	26.96	1460	16/02/2010	21.98	1465	+4.98
CSIR57	08/03/2007	12.32	1461	16/02/2010	7.06	1466	+5.26
A2N0598	16/05/2007	63.22	1480	09/06/2010	61.14	1482	+2.08
Statistical analysis (excluding stations DRGF1 and DRGF2)						n	19
						Minimum value	0.37
						5%ile value	0.38
						Mean value	2.42
						Median value	2.03
						95%ile value	5.40
						Maximum value	6.64

The resumption of mine water decant in late-January 2010, leading to elevated discharges via the Tweelopie Spruit into the Zwartkrans Compartment, and combined with the exceptionally high rainfall experienced in the 2009-'10 summer, precipitated exceptional recharge conditions. These conditions manifest as a rise in groundwater level of some 1 m within the space of only a few months in boreholes located next to the Riet Spruit, e.g. ≥0.86 m and ≥1.27 m in boreholes CSIR57 and GB1, respectively.

8.4 Sterkfontein Caves Water Level

8.4.1 General Discussion

It is known that the water level in the Sterkfontein Caves has been the subject of considerable debate and at least some confusion. A Western Basin Void Technical Group meeting held on 28/02/2007 at the Rand Uranium 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).

The above circumstances were put forward as evidence that the water level in the Sterkfontein Caves could not rise more than 3 m, i.e. up to the level at which the dolomitic compartment would overflow via the spring. The following circumstances, arrived at from an analysis of all relevant information, are considered to more closely reflect the true situation.

A re-survey on 12/12/2007 of the benchmark in Sterkfontein Caves from which the cave water level is derived, places it an elevation of 1437.94 m amsl compared to its previous elevation of 1452.37 as reported by JFA (2006). The difference of 14.43 m, when applied to the cave water level of 1450.88 reported by JFA (2006), returns a cave water level of 1436.5 m amsl, i.e. in agreement with that reported above. This compares favourably with both the reported groundwater level elevation of 1437.5 m amsl (JFA, 2006) in the nearby monitoring borehole SF1, and the elevation of the Zwartkrans Spring which the PSP places at ~1432 m amsl. A rest water level measurement in SF1 on 01/10/2007 by the PSP returned a value of 17.4 m bc which, for an interpolated surface elevation of 1454 m amsl, gives a potentiometric level of 1436.6 m amsl. This closely resembles that of the cave water level, and the PSP is of the opinion that the groundwater rest level in SF1 and the caves represents a single potentiometric surface. This opinion is shared by Krige (2009; 2010) following a revision of an earlier report by Krige and Van Biljon (2006; 2010). In practical terms, this indicates that the caves share the same aquifer as the nearby borehole SF1, and which is drained by the Zwartkrans Spring. Martini et al. (2003) report earlier similar discrepancies in elevation (up to 9 m) between various water bodies ('static' pools) inside the caves, but conclude that more recent measurements suggest elevation differences in the order of decimetres (tens of centimetres) rather than metres.

The above circumstances bring into question the relationship with the channel of the Bloubank Spruit north of (opposite) the Sterkfontein Caves, which the PSP places at ~1440 m amsl (compared to the 1445 m amsl attributed it by JFA, 2006). The elevation difference of ~3 m between the surface drainage and the October 2007 groundwater level does not necessarily imply that the surface and groundwater systems are in direct hydraulic continuity, since it has been shown by Hobbs and Cobbing (2007) that the potentiometric surface in the Riet Spruit upstream of the Oaktree area (and therefore the caves) was separated from the overlying surface drainage by 12 to 30 m. This difference has subsequently decreased significantly as a consequence of surface water inflow into the karst aquifer (see section 4.2.2). For example, by 09/06/2010 the water table in borehole SF1 had risen ~1.9 m from its 01/10/2007 depth of ~17.4 m bc (Table 64). This places the water table elevation in June 2010 at ~1438 m amsl, which is only some 2 m below the ~1440 m amsl of the Bloubank Spruit channel. The difference can be expected to reduce even more as the river elevation approaches that of the Zwartkrans Spring, these surfaces coinciding in proximity to the spring. Under these circumstances, it is probable that groundwater also 'resurfaces' in the channel of the Bloubank Spruit upstream of the Zwartkrans Spring. Observations that support this hypothesis are presented and discussed in section 4.2.2.3.

A further informative aspect of the cave water level reported by Martini et al. (2003) is the indication that the cave was already dewatered at 20 to 25 m above the present water level, i.e. between an elevation of 1456 and 1461 m amsl, some 3.3 Ma ago. In terms of the present landscape, this implies that the valley to the north of the caves would have been under water to a depth of 15 to 20 m. Martini et al. (2003) indicate further that the water level decline was irregular, being punctuated by temporary rises as indicated by re-solution of calcified deposits ~12 m above the current water level, and speleothems corroded up to 6 m above this level.

8.4.2 Potentiometric Response Pattern

The installation of a continuous water level monitoring device in the cave pool by the DWA in May 2005 yields information on the cave water level response pattern to July 2007. The recorded pattern is shown in Figure 69. It reveals an initial steady decline at an average rate of ~0.05 m per month, with an upward 'adjustment' of ~0.5 m in the 2006-'07 summer. In sympathy with the observed rise in water levels in the study area in the recent past (section 8.3 and Table 64), a similar response is observed in the Sterkfontein Caves. In mid-May 2010, guide K. Mangole (personal communication) estimated a rise of ~1 to 2 feet (0.3 to 0.6 m) since late-2009. This is in good agreement with the ~0.6 m rise observed in the nearby borehole SF1 between 17/02/2010 and 09/06/2010 (Table 64), and the ~0.4 m rise in borehole MB1 between 18/02/2010 and 13/05/2010. A water level measurement in borehole SF1 on 14/01/2011 indicated a further rise of ~0.7 m since 09/06/2010, for a total rise of ~2.6 m between October 2007 and January 2011. The rise of 1.3 m between 17/02/2010 and 14/01/2011 (11 months) equates to a rate of rise of ~0.12 m per month, yielding a groundwater (cave water) elevation of ~1439 m amsl in January 2011. This elevation is close to the ~1440 m amsl assigned to the Bloubank Spruit channel north of the site.

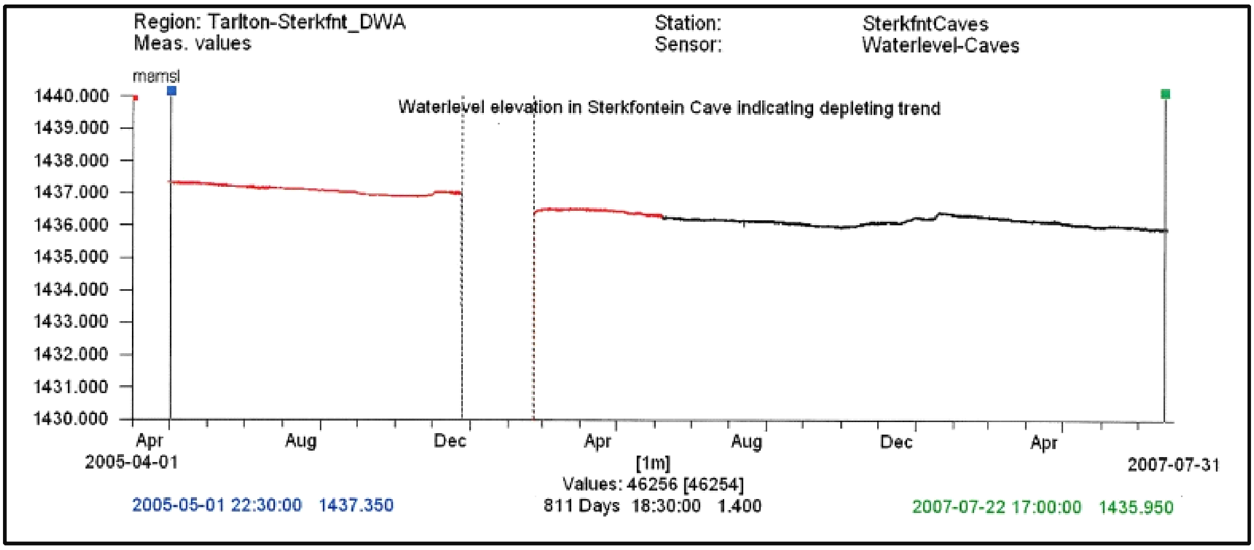

Figure 69. Continuous groundwater level response pattern in Sterkfontein Cave over a period of 27 months. (Use of image courtesy of E. van Wyk, DWA).

8.5 Springs

Springs (or 'eyes') are characteristic hydrogeologic features that mark the intersection of the potentiometric surface with the land surface. As such, they represent the lowest point in a groundwater basin to which flow converges (Quinlan and Ewers, 1986), and their flow behaviour, turbidity and chemistry reflect a composite of everything that has happened upstream (White, 2002). It is for this reason that Quinlan and Ewers (1985) stress that reliable monitoring in karst must involve springs, and not just boreholes. Bakalowicz (2005) goes as far as to state "*The spring is the only place where one can obtain information on the functioning of the whole system, …………..*" and "*Consequently, if the main spring cannot be monitored, ………. the system cannot be simulated nor managed properly.*" These circumstances define the recognition of springs as the most appropriate gauging points, sampling points and monitoring points also, and probably more particularly so, in a karst environment.

It is noted that Vegter (1995) lists 57 cold springs in South Africa yielding >1000 m^3/d (~11.6 L/s). An inspection of this list and its accompanying map suggests that only one of these springs, namely #13 (Kromdraai 520JO located at 25.969ºS/27.788ºE[39]) might form part of those enumerated in the COH WHS. However, the Kromdraai Spring enumerated in this study is located on the farm Kromdraai 520JQ at coordinates 25.98978°S/27.77551°E (Table 65 and Figure 58), which truncates to three decimals as 25.990°S/27.776°E. This equates to a linear disparity of ~2600 m, and elicits caution in the direct correlation based simply on the spring and topocadastral farm names. In any event, the Vegter (1995) list certainly includes only one of the more productive springs enumerated by this study in the COH WHS.

In view of the preceding discussion, it is encouraging that this study has enumerated eleven springs in the COH WHS. Some of these represent groups of springs (and seeps) located in close proximity to one another. However, the total number of such features in the study area is probably an order of magnitude greater, and only quantifiable following substantially greater investigative effort. Nonetheless, salient information pertaining to each of the enumerated springs is presented in Table 65.

Table 65. Salient information pertaining to enumerated springs in the COH WHS.

Spring	**Compartment**	**Coordinates (dd.ddddd)**	**Elevation (m amsl)**	**Discharge(1) (L/s)**	**(ML/d)**	**Type and Source Aquifer**
Zwartkrans	Zwartkrans	26.00822°S 27.74500°E	~1432	~100	~8.6	Barrier dyke contact : dolomite (Malmani Sbgp.)
Plover's Lake	Krombank	25.97786°S 27.77858°E	~1419	~60	~5.2	Barrier sill contact : dolomite (Malmani Sbgp.)
Kromdraai	Krombank	25.98978°S 27.77551°E	~1406	~279(2)	~24.1	Structural lineament : dolomite (Malmani Sbgp.)
Danielsrust	Danielsrust	25.97875°S 27.74322°E	~1486	~28	~2.4	Barrier sill contact : dolomite (Malmani Sbgp.)
Aquamine	Rietfontein	25.94681°S 27.81467°E	~1436	<2	<0.2	Lithologic contact : Shaly sandstone (Ventersdorp Spgp.)
Tweefontein	Tweefontein	25.90806°S 27.79755°E	~1450	~30	~2.6	Barrier dyke contact : dolomite (Malmani Sbgp.)
Nouklip	Diepkloof	25.87531°S 27.78589°E	~1330	~143(3)	~12.4	Lithologic contact : dolomite (Malmani Sbgp.)
Nash	Uitkomst	25.89417°S 27.76500°E	~1360	~130	~11.2	Lithologic contact : dolomite (Malmani Sbgp.)
Uitkomst	Not applicable	25.90949°S 27.73770°E	~1410	~2	~0.2	Lithologic contact : shale (Timeball Hill Fm.)
Cradle	Motsetse	25.91412°S 27.84978°E	~1405	~2	~0.2	Barrier sill contact : dolomite (Malmani Sbgp.)
Broederstroom	Broederstroom	25.81613°S 27.87049°E	~1281	~21	~1.8	Lithologic contact : dolomite (Malmani Sbgp.)
			TOTAL	797	68.9	

(1) Measured by the PSP using an OTT C20 current meter as described in footnote 20 (section 4.2.2.1).
(2) Excludes the autogenic recharge produced by the Danielsrust Spring.
(3) Excludes the autogenic recharge produced by the Tweefontein Spring.

The recognition by Vegter (1995) of ~11.6 L/s (1000 m^3/d) as a cutoff above which cold springs are listed, serves as 'benchmark' for the yield of the enumerated springs. Table 65 shows that eight of the eleven springs exceed a yield of 1000 m^3/d.

The position of springs in the landscape is determined by numerous geologic factors including structural features such as intrusive dykes and sills (where these serve as barriers to groundwater flow), and lithological contact zones between strata (where these possess different groundwater-bearing properties). These explanations serve as the main causative factors used to describe each of the enumerated springs in Table 65 as either (1) a barrier dyke, (2) a barrier sill or (3) a lithologic contact type, respectively. Ford and Williams (2007) simply refer to such springs by the collective term 'dammed springs'.

[39] Converted from the Cape Datum to the Hartebeesthoek94 Datum, although the accuracy of the conversion is limited by the coarse resolution of the original (Vegter, 1995) coordinates being reported to only three decimals.

8.5.1 Zwartkrans Spring

Located ~1.4 km north-east (downstream) of Sterkfontein Caves, this spring is the main outflow of the Zwartkrans Compartment, and drains the south-western dolomitic portion of quaternary basin A21D. It represents a typical barrier contact spring formed by the Zwartkrans Dyke at this position, which also explains a seepage area located on the opposite (north) bank of the Bloubank Spruit on the farm Boland. The spring occupies a position alongside the Bloubank Spruit at an elevation that is virtually the same as that of the streambed. Discharging directly into the stream, these features share a common water level elevation and, for all practical purposes, a surface elevation of ~1432 m amsl.

Flow measurements carried out on 27/07/2010 upstream and downstream of the Zwartkrans Spring provide an estimate of the spring discharge. The upstream measurement yielded a discharge of 442 L/s. The downstream discharge comprised the sum of the A-furrow discharge (154 L/s) and the Bloubank Spruit discharge (477 L/s) for a total of 631 L/s. The difference of 189 L/s (16.3 ML/d) might represent the discharge of the Zwartkrans Spring. However, the flow conditions and setting of the upstream and downstream measurement stations indicated that the calculated spring discharge value should be regarded as a relatively coarse approximation for the following reasons:

- the distance (~2450 m) of the river measurement station downstream of the Zwartkrans Spring;
- the shallow and turbulent flow conditions that characterized the culvert settings of the downstream river measurement station;
- the possibility of unaccounted-for abstraction from the A-furrow upstream of the canal measurement station; and
- the unaccounted flow through streambed vegetation at the upstream gauging site.

As a consequence, a second set of measurements was carried out closer to the Zwartkrans Spring on 13/08/2010. These returned a discharge of 535 L/s (46.2 ML/d) at the upstream station, and a total downstream discharge of 635 L/s (54.8 ML/d) comprising the sum of the A-furrow discharge (176 L/s) and the Bloubank Spruit discharge (459 L/s). It is encouraging that the downstream river and A-furrow discharges on the two measurement dates are similar, viz. 477 vs. 459 L/s, and 154 vs. 176 L/s, respectively. The total downstream discharges of 631 and 635 L/s on the two measurement dates differs by <1%. The 13/08/2010 set of measurements indicate a significantly lower yield of 100 L/s (8.64 ML/d) for the Zwartkrans Spring. These circumstances indicate the need to more accurately determine the discharge of the Zwartkrans Spring, perhaps focussing especially on the upstream measurement.

8.5.2 Plover's Lake Springs

Located on the Crab Farm and Plover's Lake Estates in the Kromdraai area of quaternary A21D, the features that comprise the group of springs and seeps collectively referred to as the Plover's Lake Springs produced combined yields of ~60 L/s (5.2 ML/d) in both September 2009 and May 2010. The excellent quality karst groundwater is channelled into a landscaped central drainage feature with canals and furrows on either side that deliver water to various downstream properties on the Plover's Lake and Crab Farm Estates before discharging into the Bloubank Spruit. These springs also provide a basis for the extrapolated elevation of the potentiometric surface associated with the Plover's Lake fossil site (Table 91 and section 14.1.7) located ~200 m upgradient (west) of these features.

8.5.3 Kromdraai Spring

Also located in quaternary catchment A21D, the Kromdraai Spring discharges into the Bloubank Spruit on the left bank of this drainage on Ptn. 35 (Ekuthuleni Estate) of the farm Kromdraai 520JQ. Its submerged discharge is distinguishable from that of the passing flow in the Bloubank Spruit on the basis of the following observations:

- displacement of floating particulate matter carried from upstream toward the opposite bank;
- a distinctive body of much clearer water in the receiving surface water body, together with a perceptibly perturbed flow environment directed at right-angles to the passing surface flow;

- a typical groundwater temperature of 19.4°C at the point of discharge in late winter[40], compared to the 13.3°C of the upstream river water (a differential of 6.1°C) at this time of year; and
- an EC value of 56 mS/m at the point of discharge, compared to an EC of 84 mS/m for the river water upstream of the spring.

An assessment of the spring discharge obtained from the difference between flow measurements made immediately upstream and downstream of the site (Table 66) returned a value of ~307 L/s (26.5 ML/d) on 13/08/2010. This is by far the highest discharge of the eleven springs enumerated in the study area (Table 65), which raised concern for the veracity of the measurements. A mass balance comparison of the spring water salt load ($Q_s \cdot C_s$) with the difference between the upstream ($Q_u \cdot C_u$) and downstream ($Q_d \cdot C_d$) surface water salt loads, using the measured field EC values as a proxy for TDS concentrations, offers a means to verify the result. This is demonstrated in Table 66 and Figure 70.

Table 66. Verification of the Kromdraai Spring discharge based on TDS load calculations.

Flow Location	Temp. (°C)	Field EC (mS/m)	TDS [C] (mg/L)	Discharge [Q] (L/s)	Discharge [Q] (ML/d)	Salt (TDS) Load mg/s [$=Q_x \cdot C_x$]	Salt (TDS) Load t/d
Downstream	14.8	74	481(1) [$=C_d$]	~773(2) [$=Q_d$]	66.8	371 813	31.2
Upstream	13.3	84	546(1) [$=C_u$]	~466(2) [$=Q_u$]	40.3	254 436	21.4
Calculated difference in salt load						117 377	9.9
Kromdraai Spring	19.4	56	364(1) [$=C_s$]	~307(3) [$=Q_s$]	26.5	111 748	9.4
(1) EC * 6.5	(2) Measured value.	(3) Derivative value from the difference of the measured values.					

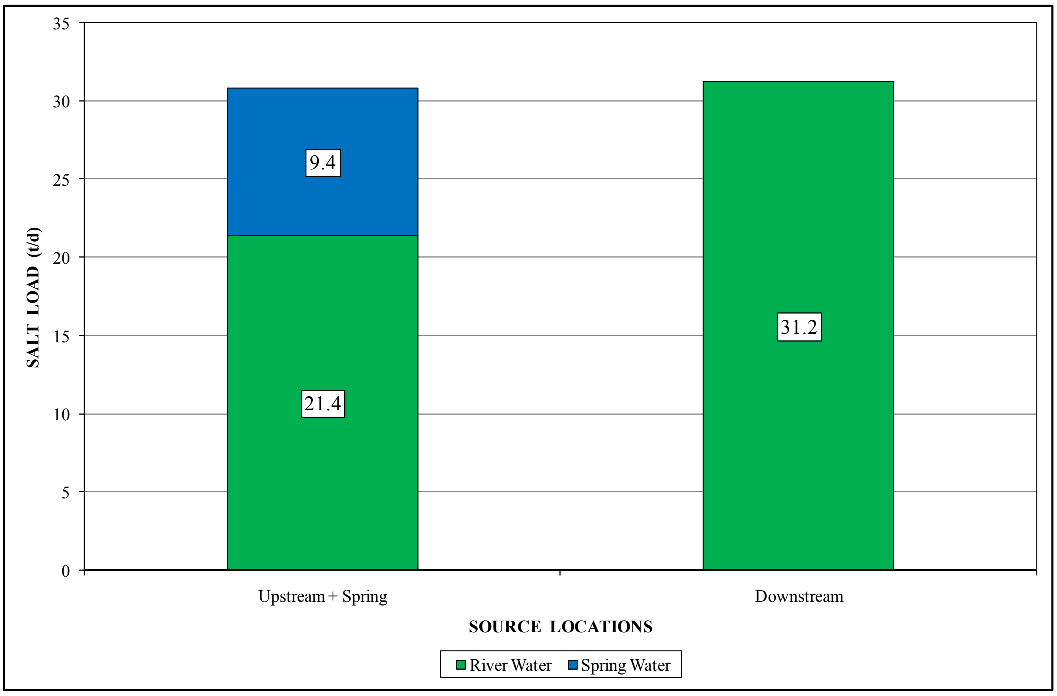

Figure 70. Verification of Kromdraai Spring flow based on mass balance calculations.

Accepting the margin of error associated with the flow measurements (possibly as much as ±10%), the result indicates that the Kromdraai Spring salt load closely approximates the difference between the upstream and downstream salt loads. Using the values in Table 66, the mass balance calculation

$$Q_s = [(Q_d \cdot C_d) - (Q_u \cdot C_u)]/C_s = [371813 - 254436]/364 = 322 \text{ L/s}$$

indicates that a spring discharge of 322 L/s would account exactly for the calculated difference in salt load of 9.9 t/d (Table 66) between the upstream and downstream flow locations. This result breeds confidence in the spring discharge value derived from the flow (synoptic discharge) measurements.

[40] The measurements were made on 13/08/2010.

Positioned on the intersection of a structural lineament with the Bloubank Spruit (Figure 58), the discharge values suggest that the Kromdraai Spring contributed ~40% of the flow in the Bloubank Spruit at this location on the day of measurement. The downstream discharge of 66.8 ML/d equates to 24.4 Mm^3/a, which is greater than the long-term median MAR value of 19.1 Mm^3/a recorded at gauging station A2H049 (Figure 11). Accepting the extreme coarseness of such an extrapolation, these circumstances reflect the abnormally high flow conditions experienced in the inter-connected surface water and groundwater components of the Bloubank Spruit system during the 2010 winter. More significantly, however, the Kromdraai Spring discharge of 26.5 ML/d (9.7 Mm^3/a) represents ~50% of the long-term median MAR at station A2H049. This contribution from karst groundwater increases to ~60% with the inclusion of the Plover's Lake Spring discharge of 60 L/s (5.2 ML/d).

8.5.4 Danielsrust Spring

The Danielsrust Spring drains the Danielsrust Compartment, a 'perched' karst aquifer ~740 ha in extent located within the Krombank Compartment, and which clearly exhibits hydraulic separation from the latter (section 8.2.3). The long-term discharge of 28 L/s (2.4 ML/d) is not used at present, and is lost to a combination of evaporation, evapotranspiration and infiltration into the Krombank Compartment. These circumstances simultaneously describe autogenic discharge of the Danielsrust and autogenic recharge of the Krombank compartments, both located in quaternary catchment A21D.

8.5.5 Aquamine Spring

The Aquamine Spring rises in the upper reaches of the Tweefontein Spruit on the contact between Ventersdorp Supergroup and Dominium Group strata, but is provisionally considered to include the ~725 ha Rietfontein Compartment in its catchment. However, the discharge of the spring (<2 L/s) is notably less than that of the karst springs draining dolomitic catchments of similar size, e.g. the 28 L/s Danielsrust Spring draining the ~740 ha Danielsrust Compartment. These circumstances might attract further investigation in future hydrogeologic studies.

8.5.6 Tweefontein Spring

Of the 11 karst springs surveyed, the Tweefontein Spring in the John Nash Nature Reserve (JNNR) occupies the second highest elevation after the Danielsrust Spring (Table 65). It also exhibits a similar discharge to that of the latter, namely ~30 L/s. As far as the PSP is aware, this is the first time the discharge of this feature has been measured and recorded. Although the spring is located in quaternary basin A21G, its catchment of ~1160 ha includes dolomitic portions of quaternary basins A21D and A21E. Rising in the Tweefontein Compartment at an elevation of ~1450 m amsl in the upper reaches of the Grootvlei Spruit, its discharge contributes autogenic recharge to the Diepkloof Compartment to the north and, therefore, also to the discharge of the Nouklip Spring. This is confirmed in a study carried out by the Wits School of Geosciences which reports the disappearance of the Tweefontein Spring flow some distance downstream of the spring (T. Abiye, personal communication).

8.5.7 Nouklip Spring

The Nouklip Spring (JNNR2) rises in the lower reach of the Grootvlei Spruit and is impounded in the so-called 'swimming pool' dam in the north-western portion of the JNNR. This impoundment also collects the discharges (<2 L/s each) of at least 11 other minor springs and seepages in the vicinity (T. Abiye, personal communication), and releases the aggregate flow (~173 L/s[41]) via the Grootvlei Spruit into the Skeerpoort River (Plate 12). Rising at an elevation of ~1330 m amsl at the contact between the Rooihoogte Formation and the overlying ferruginous shales of the Timeball Hill Formation (Pretoria Group), it drains the ~4125 ha Diepkloof Compartment catchment. This catchment includes part of the dolomitic portions of quaternary basins A21G and A21H.

[41] This does not include the contribution of minor springs that feed the Grootvlei Spruit downstream of the 'swimming pool' dam and before its confluence with the Skeerpoort River.

Plate 12. Discharge of the Grootvlei Spruit (centre right) into the Skeerpoort River (at left, looking downstream). The cascade occurs over part of an extensive travertine deposit formed by the deposition of calcium carbonate from the carbonate-saturated water discharged by the Nouklip Spring (T. Abiye, personal communication). Flow in the Skeerpoort River before this confluence derives mainly from the discharge (~130 L/s) of the Nash Spring. (Photo: Phil Hobbs).

The measured flow of ~173 L/s translates into a discharge of ~5.5 Mm^3/a, which is slightly greater than the long-term median discharge per hydrological year of ~3.5 Mm^3 reported in Figure 7 for gauging station A2H033. The difference falls within the standard deviation range of 2 Mm^3/a_h reported for this station (Figure 7). Subtracting the autogenic recharge delivered by the Tweefontein Spring (~30 L/s) from that of the aggregated Nouklip Spring discharge (~173 L/s) returns a value of ~143 L/s for this feature.

8.5.8 Nash Spring

The location of the Nash Spring (JNNR3) close to the contact between the dolomitic (Malmani Subgroup) and sedimentary (Timeball Hill Formation) strata in the north-western portion of the JNNR, together with the substantial discharge of ~130 L/s (Table 65), indicates that this feature represents the main outflow of the ~2750 ha Uitkomst Compartment north-westwards into the Skeerpoort River catchment (quaternary basin A21G). The catchment of this spring also includes a small dolomitic portion of quaternary catchment A21D.

8.5.9 Uitkomst Spring

This spring (JNNR4) issues from shale of the Timeball Hill Formation (Pretoria Group) in close proximity to the contact with the underlying older dolomite of the Eccles Formation, or possibly the Rooihoogte Formation, in the north-western portion of the JNNR. The discharge of ~2 L/s is similar to that of the Aquamine Spring which also issues from non-dolomitic strata (section 8.5.5). These circumstances again reflect the poorer water-bearing potential of the sedimentary rocks of the younger (overlying) Pretoria Group in quaternary basin A21G compared to the dolomitic formations.

8.5.10 Cradle Spring

Located in the Motsetse Nature Reserve (MNR), the Cradle Spring is another example of a barrier sill contact spring in the COH WHS. It drains the comparatively small (270 ha) Motsetse Compartment in quaternary basin A21E at an elevation of ~1405 m amsl. The groundwater level elevation of ~1432 m amsl determined for geosite MNR1, a borehole located ~1100 m upgradient of the spring, indicates a hydraulic gradient of 0.0245 between these two sources. This is 'normal' for a karst environment, and it is therefore surprising that the Cradle Spring delivers only ~2 L/s. This flow equates to a natural recharge of only ~3% of an MAP of 710 mm on the Motsetse Compartment (Table 60). A possible explanation for this low value (at least in part) is the comparatively shallow depth to groundwater level (~12 m bs) as observed in station MNR1, which circumstances promote groundwater loss through evapotranspiration.

8.5.11 Broederstroom Spring

Located on the Glen Afric Country Lodge property south of Broederstroom, this spring occupies an elevation of ~1281 m amsl in a northerly draining valley in quaternary basin A21H. It is another example of a lithologic contact spring in the COH WHS. Its measured yield of ~21 L/s equates to a natural recharge of only ~4% of an MAP of 710 mm on the 2050 ha Broederstroom Compartment (Table 60). The measured yield compares favourably with a reported maximum yield of 25 L/s (J. Brooker, personal communication).

8.5.12 Krugersdorp Game Reserve Springs

The Krugersdorp Game Reserve hosts at least eight springs, six of which are associated with dolomite and two with quartzitic strata. These features are described in Table 67.

Table 67. Description of springs enumerated in the Krugersdorp Game Reserve.

Spring	Alternative ID	Latitude(1) (dd.dddddºS)	Longitude(1) (dd.dddddºE)	Elevation (m amsl)	Source aquifer
CSIR30	Spring 2 @ cemetery	26.09808	27.71892	1641	Karst outlier
CSIR63	Spring 1 @ cemetery	26.09814	27.71958	1638	Karst outlier
Spring 1	F6S7 (Cemetery)	26.09694	27.71898	1637	Karst outlier
Spring 2	F8S9 (Poplar Grove)	26.09092	27.72011	1626	Karst outlier 'toe'
Lodge Spring	CSIR20	26.09044	27.71625	1600	Witwatersrand Spgp. quartzite
Aviary Spring	CSIR55	26.07753	27.70092	1530	Zwartkrans Compartment
Spring 3	Flip-se-Gat stream	26.08149(2)	27.69589(2)	1553	Zwartkrans Compartment

(1) Coordinates in accordance with the discussion put forward in section 3.5.
(2) Coordinates of the most westerly (highest) seepage described in Table 19 as contributing to the aggregate discharge measured and sampled at 26.07692ºS / 27.69928ºE.

It must be stressed that in a number of these instances, for example Spring 3, these features represent a group of distributed seeps rather than individually recognizable 'eyes'. In such instances, the discharge represents the aggregate flow of the contributing seeps.

Four of the six dolomitic springs drain the karst outlier that extends from the mining area located to the south into the southern portion of the KGR. The other two dolomitic springs are located in the Zwartkrans Compartment to the north of the quartzite ridge that strikes NE-SW diagonally through the centre of the KGR. The springs typically support discharges <5 L/s, although at least two (Spring 2 and Spring 3) yield >5 L/s. The yield of Spring 2 has not been measured, but that of Spring 3 amounts to ~8 L/s.

8.6 Groundwater Drainage Pattern

The groundwater drainage pattern in the study area is illustrated in Figure 71. This shows the conceptual principal flow vectors associated with each of the compartments/subcompartments, and recognizes the 'drain' function served by the enumerated springs. The drainage pattern is further illustrated in Figure 72, which presents a hydrogeologic profile along the section line A-B-C-D in Figure 71. The land surface profile is derived from the published 1:50 000 scale topocadastral maps, and the potentiometric surfaces from either groundwater rest level data obtained from boreholes or, in the case of springs, the respective surface elevations of these features.

Perhaps the most salient aspect revealed by the drainage pattern is the complete hydrogeologic separation of the groundwater systems either side of the Twin Dyke. This refutes previous contentions (e.g. Krige, 2010) that the Zwartkrans Compartment drains north-eastwards into the so-called Tweefontein Compartment[42].

The movement of groundwater northwards from the Sterkfontein Subcompartment into the Zwartkrans Subcompartment through/over/across the Sterkfontein Dyke is a particularly vexing question given the observed ~20 m step in groundwater rest level elevation that exists from south (~1465 m amsl) to north (~1445 m amsl) across this 'barrier' (Figure 73). Field observations at the four localities in this part of the study area shown in Figure 73 reveal the existence of grikes[43] with a distinct NW-SE orientation. These features are accessible to humans and features 'c' and 'd' extend many metres in depth into the subsurface. Some of these also demonstrate a significant visible linear length amounting to tens of metres, most notably the feature identified as 'b', which extends ~60 m north-westwards from the valley of the Riet Spruit near its confluence with the Blougat Spruit. It is reasonable to presume that features such as these represent an expression of similar sympathetic features that occur at depth, i.e. that intersect the water table of the karst aquifer. As such, they represent adequate conduits to establish a subsurface hydraulic connection through the Sterkfontein Dyke 'barrier', linking the Sterkfontein and Zwartkrans Subcompartments in this portion of the study area.

8.7 Groundwater Use

From an assessment of water use information sourced from the DWA Water Authorisation and Registration Management System (WARMS), Holland and Cobbing (2008) report a total groundwater use of 8.7 Mm^3/a as being registered for mainly agricultural use in the Zwartkrans Compartment. This figure contrasts sharply with those estimated by Schoeman and Associates (2006) of 14.1 Mm^3/a based on an interpretation of satellite imagery, and of 25.7 Mm^3/a estimated by JFA (2006) from a water balance calculation. The latter quantity is also reported by Krige (2009). A further measure of the variance in groundwater use figures for the Zwartkrans Compartment is provided by those of 15 and 18 Mm^3/a reported earlier by Bredenkamp et al. (1986) and Van Biljon (2006), respectively.

The Rhino and Lion Game Reserve maintains an excellent record of the abstraction from borehole RLGR4 which serves the chalets and Wonder Cave. An inspection of this record indicates that an average daily abstraction of 17 m^3/d (~6200 m^3/a) is made from this borehole. The occasional business opportunity where groundwater is bottled for wholesale distribution as 'mineral water' is also manifested in the study area. The number of such businesses and their combined annual 'consumption' is difficult to quantify. It is unlikely, however, that their combined groundwater use is sufficiently great to significantly impact on the groundwater resource supply potential of the karst aquifer(s) in the study area.

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[42] Term used in earlier studies (e.g. Holland, 2007; Holland and Cobbing, 2008; Holland et al., 2010) for the north-eastern expanse of karst formations extending to Broederstroom in the north-eastern corner of the COH WHS. Also referred to as the North Compartment by Krige (2010).

[43] See GLOSSARY OF SELECTED TERMS.

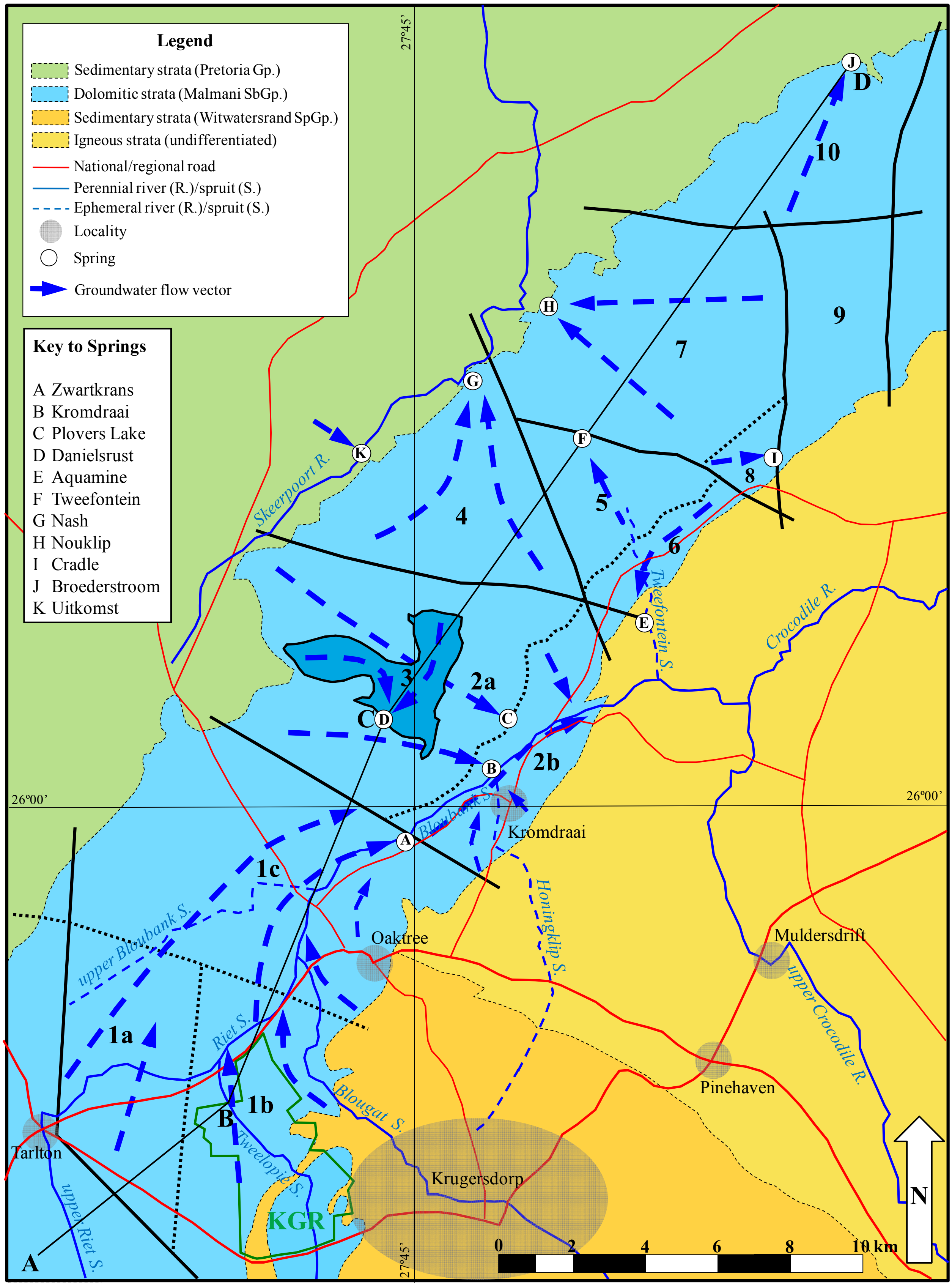


Figure 71. Groundwater drainage map illustrating the conceptual flow patterns associated with the compartments/subcompartments that build the karst aquifer in the study area. See Table 61 for statistical analysis of groundwater level data in the Bloubank Spruit system.

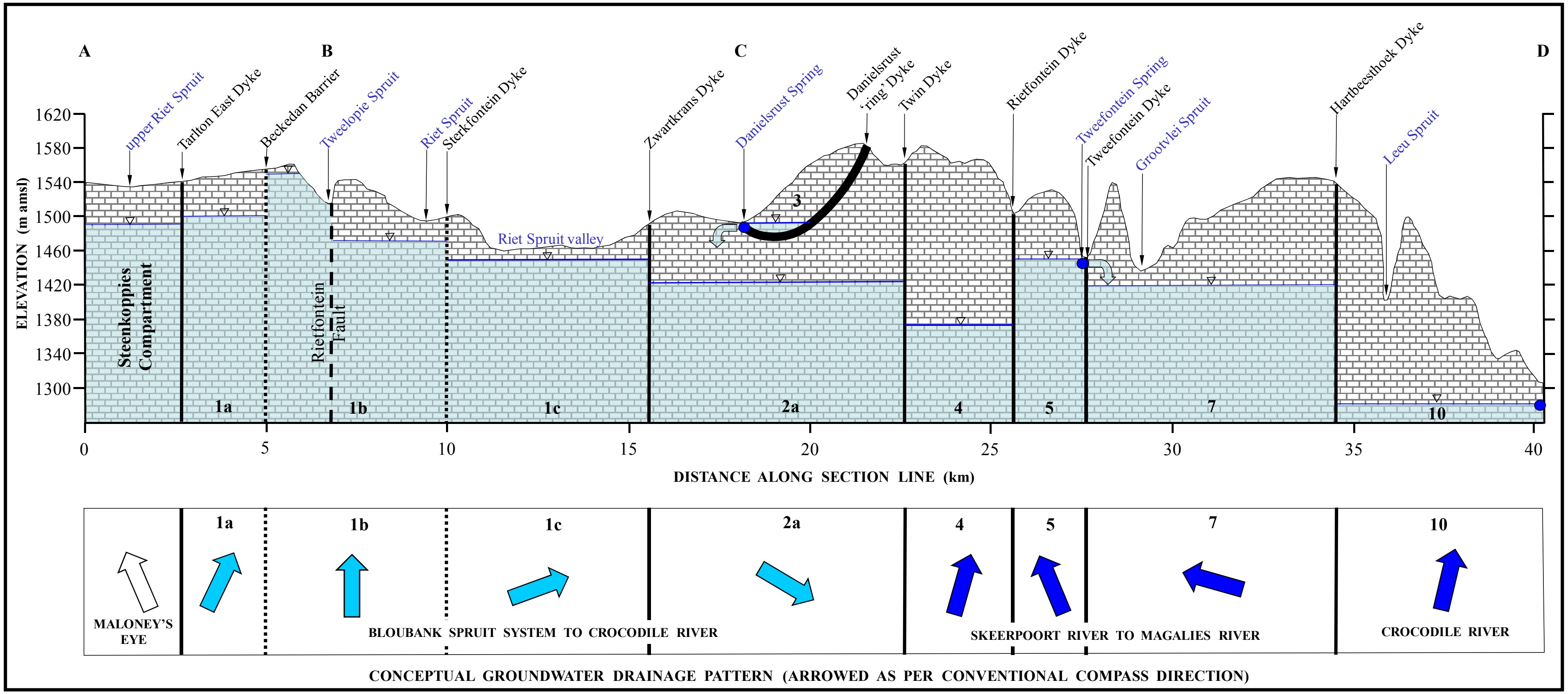


Figure 72. Hydrogeological cross-section (top) through the karst aquifer from south-west to north-east (see Figure 71) illustrating the differences in groundwater rest level between compartments/subcompartments, and plan view (bottom) illustrating the corresponding conceptual groundwater drainage pattern as per conventional compass direction. Note the autogenic recharge associated with the Danielsrust and Tweefontein Springs.

Key to compartments/subcompartments:

1a Vlakdrift Subcompartment	1b Sterkfontein Subcompartment	1c Zwartkrans Subcompartment
2a Kromdraai Subcompartment	3 Danielsrust Compartment	4 Uitkomst Compartment
5 Tweefontein Compartment	7 Diepkloof Compartment	10 Broederstroom Compartment

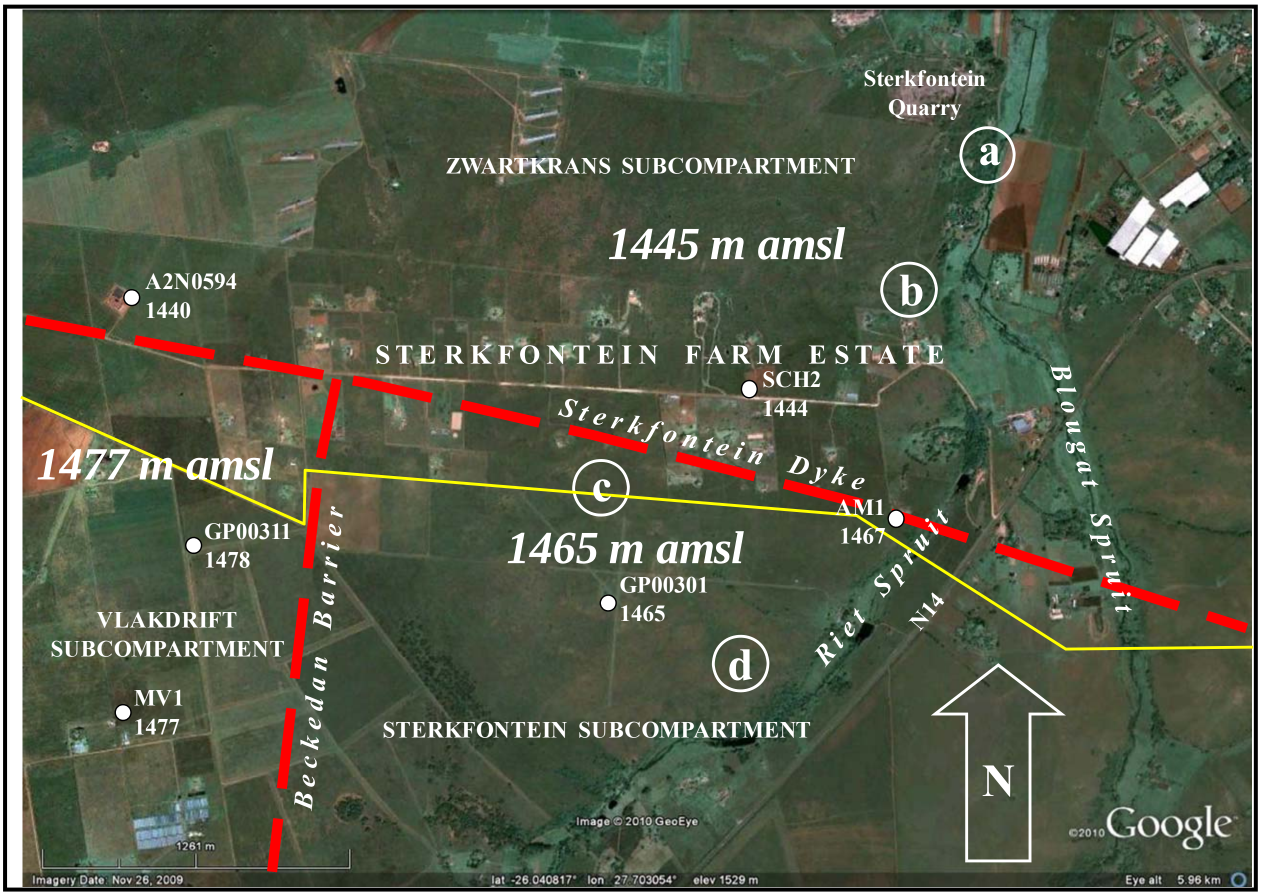


Figure 73. Elucidation of hydrological, geological and hydrogeological aspects along the southern boundary of the COH WHS (yellow line) south-west of Sterkfontein Quarry. Circled localities labelled 'a' to 'd' mark the position of significant grike features, and italicized values indicate the recent groundwater elevation as derived from the individual borehole measurements.

8.8 Closure of DWA Monitoring Stations

The recent closure of the DWA monitoring stations A2N0589, A2N0594, A2N0598 and A2N0606 is reported in Table 9 and Table 62. This circumstance was informed by the factors listed in Table 68.

Table 68. Assessment framework for the closure/recommissioniong of DWA water level monitoring stations.

Station	Record Length (months)	No. of Records	Record Frequency (per month)	Reason for Closure[(1)]	Additional information (provided by PSP)
A2N0589	285	170	0.60	Borehole collapsed	Redundant and expendable due to proximity to A2N0600 with record frequency of 0.66
A2N0594	288	187	0.65	Borehole equipped	Should be reopened due to strategic position in upper reaches of the Zwartkrans Compartment
A2N0598	283	93	0.33	Borehole equipped	Should be reopened due to strategic position adjacent to the losing middle reaches of the Riet Spruit; record frequency is easily improved
A2N0606	243	36	0.15	Borehole collapsed	Redundant and expendable due to proximity to A2N0594 with record frequency 0.65
(1) E. Bertram (personal communication).					

It is envisaged by the DWA (E. Bertram, personal communication) that in those instances where the stations have been equipped with pumps and serve an active water supply function, the landowners will be required to provide alternatives. This implies that the landowner(s) will establish a unique monitoring station that replaces the function of the original station. In both instances where this applies (stations

A2N0594 and A2N0598, Table 68), such an approach is considered to be unrealistic and therefore not workable. Further, if deemed necessary for reasons such as long record or strategic location, the collapsed boreholes (stations A2N0589 and A2N0606, Table 68) will be rehabilitated and returned to duty (E. Bertram, personal communication).

The closure of the stations must be assessed within the framework of the additional information presented in Table 68. This suggests that the closure of only two of the four stations is warranted and justifiable. It is recommended that the decision in regard to stations A2N0594 and A2N0598 be rescinded.

9 CHEMICAL HYDROGEOLOGY

9.1 Regional Groundwater Chemistry

The main lithostratigraphic units in the study area are identified as the younger units of the Witwatersrand Supergroup and the older units of the overlying Transvaal Supergroup (Table 4, section 2.4). Barnard (2000) provides information regarding the chemistry of groundwater regionally (and typically) associated with each of the relevant rock units. This information is summarized in Table 69, and illustrated in Figure 74. No groundwater chemistry data are available for the Rooihoogte Formation sandwiched between the Timeball Hill Formation and the Malmani Subgroup strata (Table 4, section 2.4).

Table 69. Groundwater chemistry characterization per lithostratigraphic unit in the COH WHS area (after Barnard, 2000).

Variable	Lithostratigraphic Unit					SANS 241: 2006 (Class 1)
	Hekpoort Fm.	Timeball Hill Fm.	Malmani Sbgp.	Black Reef Fm.	Central Rand Gp.	
pH	7.5	7.2	7.6	7.0	7.3	5.0 – 9.5
EC (mS/m)	52.0	34.0	62.9	34.3	29.3	<150
TDS (mg/L)	398.0	278.0	443.6	238.	207.0	<1000
Ca (mg/L)	44.0	29.0	52.7	28.0	17.6	<150
Mg (mg/L)	26.0	19.0	35.4	18.0	13.7	<70
Na (mg/L)	30.0	15.0	24.1	14.0	20.0	<200
K (mg/L)	2.0	1.6	2.3	1.7	2.6	<50
Cl (mg/L)	23.5	15.0	37.7	15.0	17.9	<200
SO_4 (mg/L)	79.0	26.0	70.5	36.0	33.5	<400
HCO_3 (mg/L)	190.2	152.4	216.2	119.5	103.6	n.s.
NO_3 (mg N/L)	3.5	2.9	5.6	2.8	2.0	<10
F (mg/L)	0.3	0.3	0.3	0.2	0.3	<1.0
Count (n)	41	81	223	52	18	

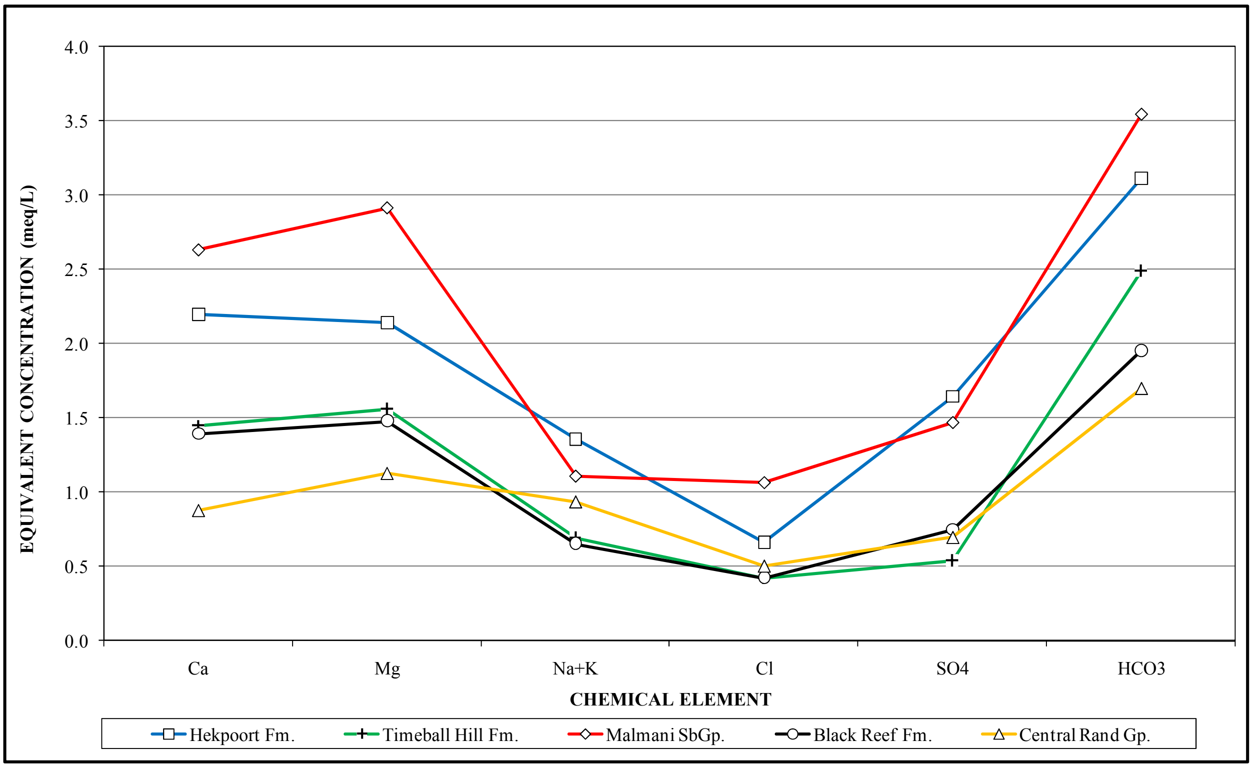


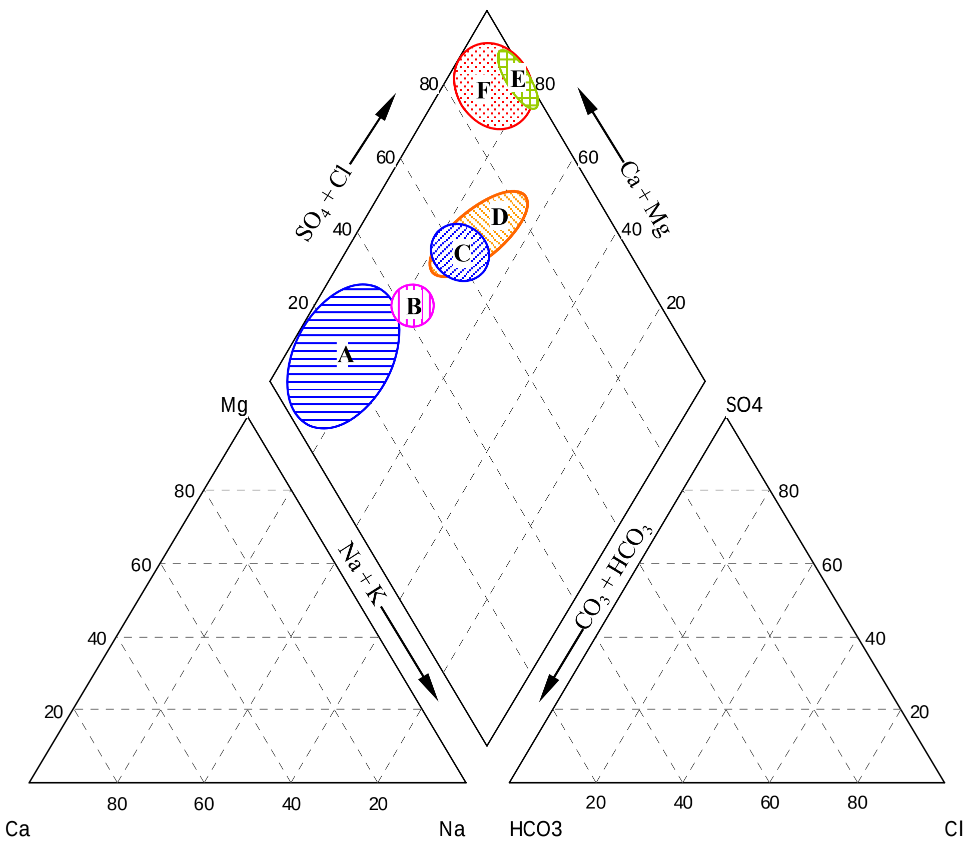
Figure 74. Schoeller graphical comparison of groundwater chemistry associated with the respective lithostratigraphic units represented in the study area.

Figure 74 reflects the similarity in chemical composition (MgCa-HCO_3) of groundwater associated with the Timeball Hill Formation, Black Reef Formation and, to a lesser extent, Central Rand Group strata. This is attributed to the similar rock type (mainly quartzite) that builds these formations. Although the volcanic rocks (lava) of the Hekpoort Formation also exhibit a MgCa-HCO_3 composition, they can be distinguished on the basis of generally higher element concentrations, especially SO_4 and Na, as well as higher salinity (EC) and TDS values (Table 69). The Malmani Subgroup dolomitic strata exhibit the most dominant MgCa-HCO_3 composition of all the formations represented. The higher Cl, SO_4 and N concentrations (Table 69) in the karst groundwater are, however, indicative of contamination (Barnard, 2000) and, as such, uncharacteristic of pristine karst groundwater as still occurs in much of the study area.

9.2 Subregional/Local Groundwater Chemistry

9.2.1 Background

Hobbs and Cobbing (2007) report 'ground'water (including raw and treated mine water) chemistry information for 42 sources enumerated in the south-western portion of the study area. Surface water chemistry was determined for a further seven sites mostly located on the Tweelopie Spruit, but including one Blougat Spruit sample. This information enabled the characterization of the hydrochemistry associated with the various water sources as shown in Figure 75. This characterization was also established by Holland and Witthüser (2009).



A Malmani SbGp. dolomite (largely natural)
B Black Reef Fm. quartzite
C Malmani SbGp. dolomite (lower Riet Spruit)
D West Rand Gp. quartzite
E Tweelopie Spruit surface water
F Acid mine drainage & associated

Figure 75. Piper diagram characterization of groundwater chemistry associated with various surface and groundwater sources in the south-western portion of the study area (from Hobbs and Cobbing, 2007).

9.2.1.1 West Rand Group (Witwatersrand Supergroup)

Groundwater from these strata is typically very weakly mineralized, as reflected in EC values <20 mS/m and TDS values <120 mg/L, and exhibit a low pH (≤6.0). The latter is attributed to the very low alkalinity of this groundwater, with total alkalinity typically <10 mg $CaCO_3$/L (Hobbs and Cobbing, 2007). This water is therefore also corrosive with a typical corrosion tendency ratio (CTR) of »1[44]. An example from this study is the water from station PS3, a borehole located on the quartzite ridge to the east of the Blougat Spruit, which reflects a Mg-HCO_3 composition and the following variable-specific values:

pH = 6.0 (field); EC = 4 mS/m (field); total alkalinity = 8 mg $CaCO_3$/L (laboratory)

9.2.1.2 Malmani Subgroup (Chuniespoort Group, Transvaal Supergroup)

Dolomitic groundwater is characterized by a CaMg-HCO_3 composition which, in its pristine state, also exhibits very low concentrations of Cl and SO_4 (generally <5 mg/L), a low salinity (EC <40 mS/m) and a typically alkaline pH (7.5 to 8.0). The water delivered by the Danielsrust, Nouklip and Nash Springs exemplifies this observtion. Anthropogenic impacts on this water quality are recognized on the basis of elevated Cl and SO_4 concentrations, higher salinity values (>60 mS/m) and lower pH values (<7.2).

9.2.1.3 Pretoria Group (Transvaal Supergroup)

The composition of groundwater associated with these strata is similar to that described for the Witwatersrand Supergroup strata (section 9.2.1.1). An example from this study is the analysis for spring JNNR4 draining interlayered shales and quartzites of the Timeball Hill Formation in the Skeerpoort River Valley, and which reflects a Mg-HCO_3 composition together with the following variable-specific values:

pH = 7.0 (field); EC = 1 mS/m (field); total alkalinity = 16 mg $CaCO_3$/L (laboratory)

This groundwater is generally distinguishable from that of the West Rand Group strata on the basis of a more neutral pH, a slightly greater salinity and detectable Fe and Mn concentrations which, in the case of JNNR4 spring water, amounted to ~0.3 and ~0.5 mg/L respectively.

9.2.2 Temporal Groundwater Chemistry Assessment

The DWA groundwater quality monitoring stations (Table 10) provide a longer term indication of groundwater chemistry changes in the southern portion of the study area. The trends are illustrated on the basis of the graphs presented in Annexure D. The results are summarized as follows.

- Station A2N0583 reveals an increase in the Ca, Mg and SO_4 concentrations in the recent past, giving a Ca-SO_4 character to this groundwater compared to the previous CaMg-HCO_3 character. This trend is unexpected, since the borehole is not in the expected path of mine water impact.

- Station A2N0584 similarly reveals a recent increase in the Ca, Mg and SO_4 concentrations, imparting a Mg-SO_4 character to this groundwater. It is also evident, however, that this chemistry does not differ significantly from the historical chemistry as observed in July 1985 and March 1989, which reflected even higher SO_4 concentrations than in August 2008. Both these circumstances indicate mine water infiltration into the karst aquifer in this vicinity.

- Station A2N0586 reveals a recent increase in Ca and Mg concentrations, and an elevated SO_4 concentration above historical levels, but which is still lower than a recent peak. The August 2008 chemistry is not too dissimilar from the historical chemistry observed in May 1985, the earlier Ca-SO_4 character being replaced by a Mg-SO_4 type water. These circumstances are again indicative of mine water infiltration into the karst aquifer in this vicinity.

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[44] For pH values in the range 7 to 8 and in the presence of dissolved oxygen, CTR values ≤0.1 indicate general freedom from corrosion, whereas higher values are indicative of more corrosive waters.

- Station A2N0590 yielded groundwater with a Mg-HCO_3 character in August 2008, which contrasts with the earliest Mg-SO_4 character exhibited in May 1985. For much of the observational record, however, this source produced a CaMg-HCO_3 type water that is typical of a karst aquifer. Whilst the Mg concentration indicates a mine water impact at this location, the recent comparatively low SO_4 concentrations are equivocal in this regard.

- Station A2N0600 has more recently exhibited a Mg-SO_4 type groundwater compared to the historical Ca-SO_4 character observed at this location. Nevertheless, the manifestation of SO_4 as the dominant anion throughout the observational record is out of character for karst groundwater, and not readily explained on the basis of available data.

The information shown in Figure 76 reflects the two most recently reported chemical analyses, those for May and August 2008, associated with each of the DWA groundwater monitoring stations. The graphs reveal that the August 2008 Ca, Mg, Cl and SO_4 concentrations are mostly higher than in May 2008, whereas the HCO_3 concentrations are invariably lower. With the exception of station A2N0584, the Na values show little variance. These trends account for the (SO_4+Cl):HCO_3 ratio trends shown in Figure 77. This ratio serves as an indicator of both the corrosion potential (CTR) of water and of possible anthropogenic impacts on water chemistry. The higher the ratio value, the more likely it is that poorer quality water has impacted on the natural water quality.

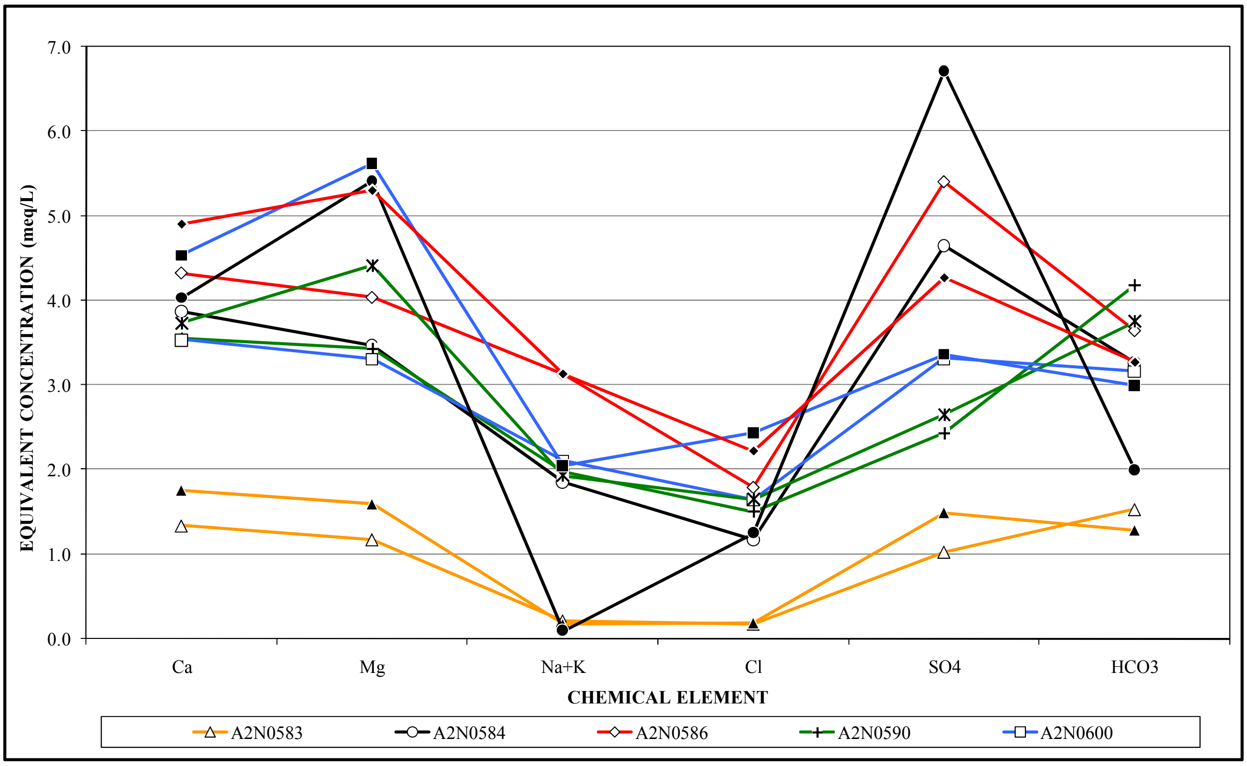

Figure 76. Comparison of the two most recently reported chemical analyses (open symbols = May 2008, solid symbols = August 2008) associated with the DWA groundwater monitoring stations.

With the exception of station A2N0590, Figure 77 shows that all the stations exhibit a gradually increasing (SO_4+Cl):HCO_3 ratio. The most marked increase is exhibited by station A2N0584, which is the station nearest to the initial infiltration of Tweelopie Spruit surface water. Other stations in this vicinity that similarly reflect the impact of mine water on the karst environment are the source-specific monitoring stations served by Rand Uranium as part of the DWA directive (section 3.3.1.2, Table 14), in particular stations WBD2, WBD3, WBD4 and WBD5. The response at these and other stations is discussed in section 9.2.3. Figure 77 also shows, however, that stations A2N0590 and A2N0600 located furthest downstream from the initial infiltration area exhibit the least obvious change in the

$(SO_4+Cl):HCO_3$ ratio. It should be noted that these responses were already manifested some 18 months before the recommencement of mine water decant in early-2010.

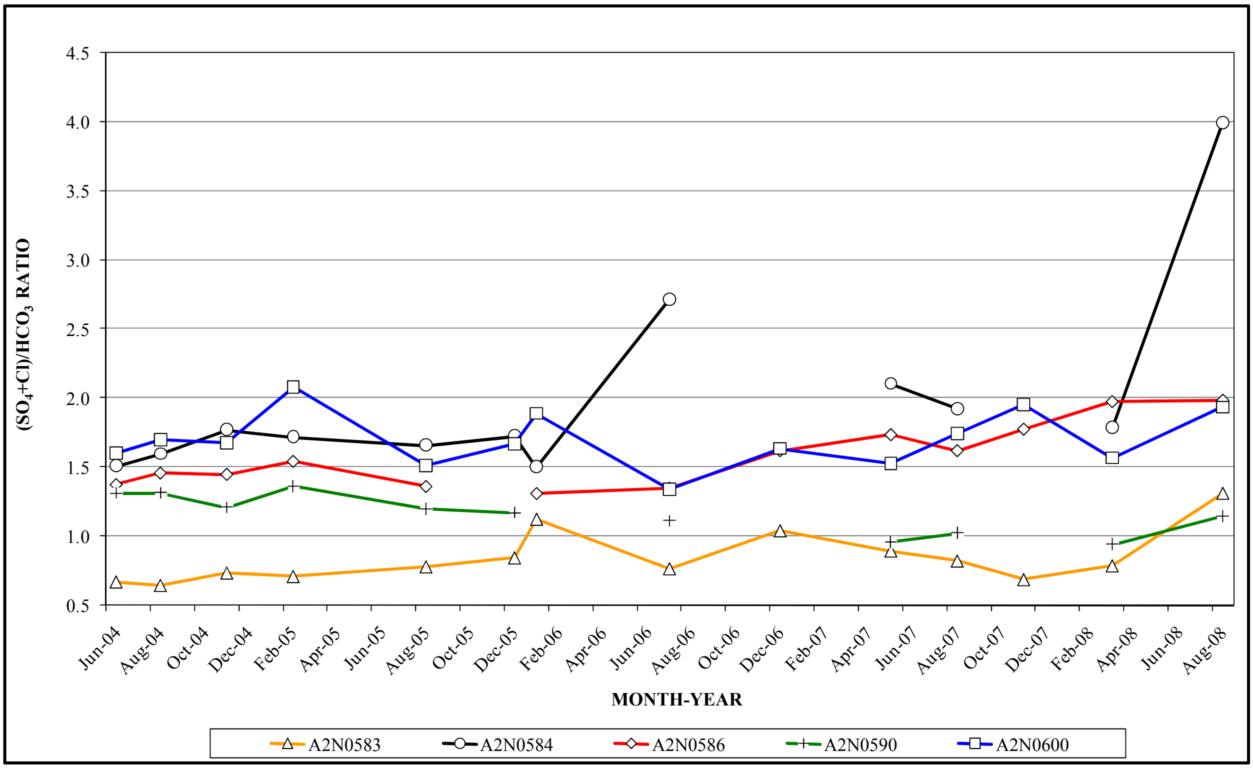

Figure 77. Comparison of $(SO_4+Cl):HCO_3$ ratio trend associated with the DWA groundwater quality monitoring stations.

9.2.3 Source-specific Temporal Assessment

9.2.3.1 Lower Riet Spruit

The groundwater quality monitoring programmes carried out by the mining houses (mainly Rand Uranium) and the DWA (sections 3.2.1.1 and 3.3.1.2) are focussed in the area most likely impacted by mine water. The footprint of this monitoring is, however, expanding to include areas adjacent to and further downstream of the focus area (S. du Toit, personal communication). These monitoring activities provide a record of the groundwater quality response for the variables measured (section 3.3.1.2). Since there is a fair degree of overlap between the Rand Uranium and DWA monitoring activities, the respective results are discussed jointly. This discussion, however, only considers those groundwater monitoring activities carried out to the north of the KGR, i.e. furthest removed from the area of mine water decant and its immediate downstream receiving environment. This approach is informed by the need to better understand the impact of mine water discharge on groundwater quality in closer proximity to the COH WHS, since the upstream impacts already receive considerable attention.

Routine sampling of the four geosites WBD2[45], WBD3[46], WBD4 and WBD5[47] (Table 14) reflect the SO_4 trends (and recent pH and EC values) shown in Figure 78. These are described as follows.

WBD2: The most upstream station where the water table occupies a depth of ~25 m below that of the nearby streambed, displays a gradual but comparatively linear increase. The SO_4 concentration has doubled in the last three years, although the most recent analysis shows a slight decrease. The latter observation might be explained by the decommissioning of the borehole following

[45] This geosite also carries the identifier CSIR34 from the Hobbs and Cobbing (2007) study.
[46] This geosite also carries the identifier CSIR32 from the Hobbs and Cobbing (2007) study.
[47] This geosite also carries the identifier CSIR57 from the Hobbs and Cobbing (2007) study.

closure of the business carried out on the property *ca.* April 2010, i.e. the cessation of abstraction no longer inducing flow from the nearby Tweelopie Spruit.

WBD3: The next station downstream a distance of ~880 m, displays a relatively uniform concentration of ~250 mg/L. This is a somewhat anomalous trend compared to that observed in the other stations. A 2007 water level measurement in this borehole placed the groundwater rest level at a depth of ~21 m below that of the nearby streambed (Hobbs and Cobbing, 2007). The water level has almost certainly risen since this measurement was made.

WBD4: Located ~550 m downstream of WBD3, a mid-2008 water level measurement in this borehole placed the groundwater rest level at a depth of ~12 m below that of the nearby streambed (Hobbs, 2008a). The groundwater chemistry shows an increase in SO_4 to a maximum of ~1750 mg/L in February 2009, followed by a rapid decline to a current level similar to that of station WBD3. The initial response is attributed to the damming up of the Riet Spruit on this property in early-2008, resulting in enhanced infiltration of poor quality surface water into the dolomitic aquifer at this location. Breaching of the impoundment in January 2009, following recommendations by Hobbs (2008a) to mitigate this impact, produced the decrease in SO_4 concentrations since February 2009.

WBD5: Located ~950 m downstream of WBD4 on the left bank of the Riet Spruit and adjacent to an impoundment. Although the water level in this borehole has risen ~5 m in the last three years (Table 64), its elevation in mid-2010 was still ~5 m below that of the streambed at this position. This station displays an elevated and slowly rising SO_4 concentration approaching 2000 mg/L. The extrapolation of the upward trend from the early-2007 value through the WBD4 data to the recent values observed at this station, although purely illustrative, is still informative. Perhaps even more informative is the measure of water quality deterioration reflected in the earliest and the most recent SO_4 levels of 125 and 1930 mg/L, respectively. It is likely that a similar intervention as was applied in the case of WBD4, namely breaching of the impoundment to establish the free-flow of surface water past this station, will most probably produce a similar result as observed at WBD4.

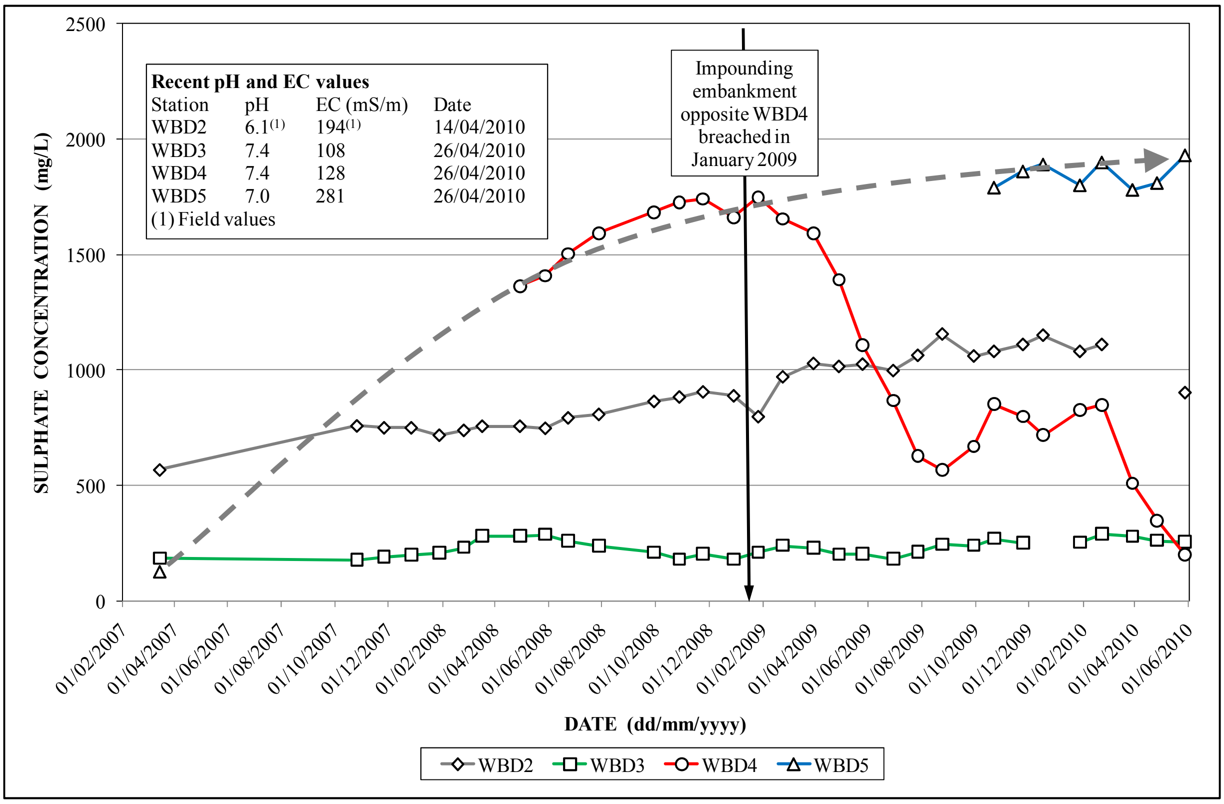

Figure 78. Observed SO_4 trend at four stations in the lower Riet Spruit valley.

The comparison of the most recent groundwater chemistry with similar earlier information for sites enumerated by Hobbs and Cobbing (2007) illustrates the change in groundwater chemistry in the recent past (Figure 79). Station CSIR57 reflects the greatest change with dramatic increases in Ca and SO_4 concentrations. This is also evident (albeit more muted) at station CSIR9 near the confluence of the Riet and Blougat spruits.

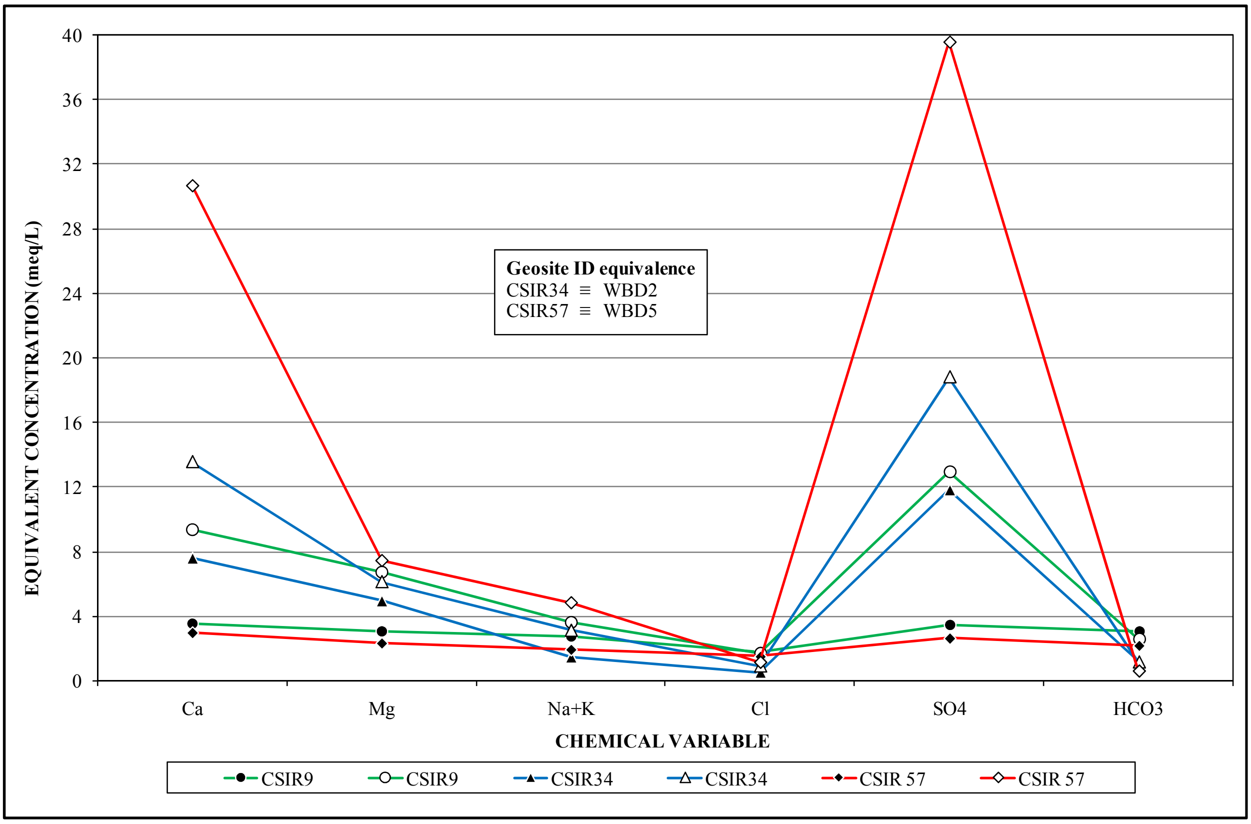

Figure 79. Change in groundwater chemistry from early-2007 (solid symbols) to early-2010 (open symbols) at selected stations in the lower reaches of the Riet Spruit.

9.2.3.2 Sterkfontein Caves

Holland et al. (2009) report comparatively recent SO_4 and Cl concentrations of 154 and 55 mg/L respectively for groundwater sourced from a borehole (presumably SF1) near the Sterkfontein Caves. This is put forward as "……… *undoubtedly indicating anthropogenic impacts*." These values agree with the averages of 147 mg SO_4/L and 66 mg Cl/L for three boreholes (CSIR7, CSIR8 and CSIR9) in the upstream Oaktree area reported by Hobbs and Cobbing (2007), and raise concern for the quality of the cave water.

A more complete comparison of earlier cave water chemistry with the present is provided by the analyses of April 2001 (from Harmony Gold/Rand Uranium records), 29/04/2005 (from DWA records) and 13/05/2010 (this project). This comparison is made in Figure 80, which also shows the 29/04/2005 analysis result for Koelenhof Cave groundwater. The similar chemical composition of the cave waters is readily apparent. Most notable and significant, however, is the very similar composition of the two more recent Sterkfontein Caves water samples, and the higher EC value of 74 mS/m associated with the 2001 water sample from this source.

The installation of a continuous electrical conductivity monitoring device in the cave pool by the DWA in May 2005 yields information on the cave water salinity response pattern to the present. This pattern is shown in Figure 81, and reveals an initial EC value of ~47 mS/m, followed after a hiatus of some 32 weeks by a notably higher value of ~60 mS/m. An analysis of the cave water sampled on 29/04/2005 (as sourced from the DWA records), i.e. within a month of installation of the monitoring device, returned an

EC value of 59 mS/m (see Figure 80). This suggests that the early salinity record is in error by an under-reading of ~12 mS/m. If so, then the salinity of the cave water has not changed much between mid-2005 and the present, a period of some five years. Recent field EC values for the cave water of 62 and 56 mS/m (in May 2010 and January 2011) confirm the pattern described by the continuous DWA record.

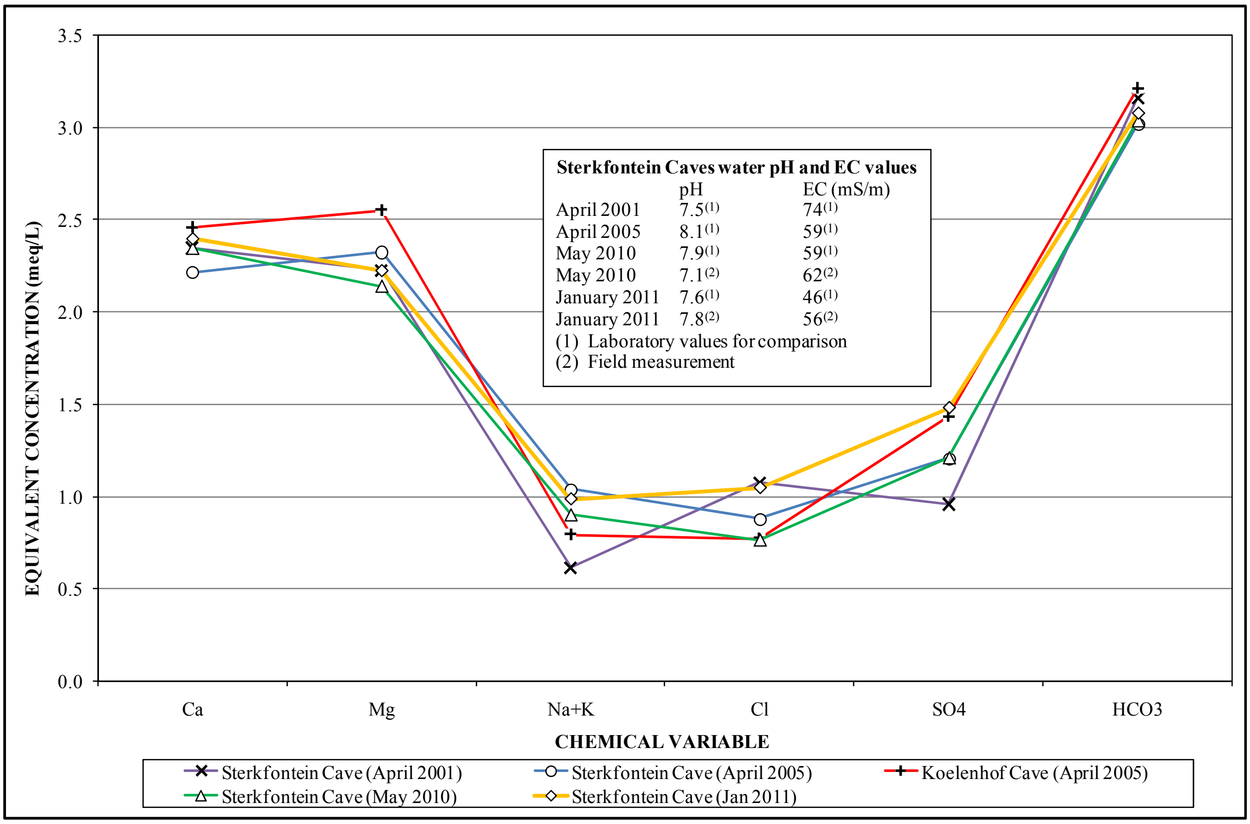

Figure 80. Comparison of historical and current Sterkfontein Caves groundwater chemistry.

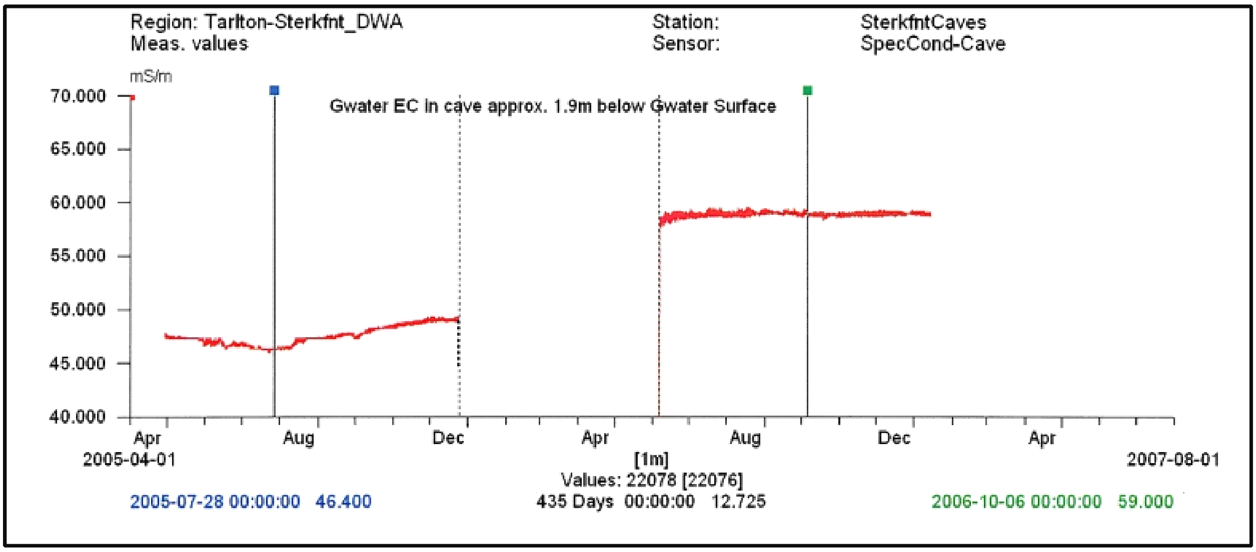

Figure 81. Continuous electrical conductivity response pattern in Sterkfontein Cave water over a period of 27 months (use of image courtesy of E. van Wyk, DWA).

The similar chemical composition of Sterkfontein Caves water reflected in Figure 80, despite the difference of five years between analyses, mimics the situation sketched by the near-continuous salinity record (Figure 81). This is very encouraging against the background of recent groundwater quality trends observed elsewhere in the Zwartkrans Compartment (sections 9.2.3.1 and 9.4). Equally encouraging are the results of stable isotope analyses carried out on cave water in the recent past. The comparative data tabulated hereunder indicate very little difference in the span of one year between analyses.

Date	δ^2H	$\delta^{18}O$	^3H
28/05/2009	−19.8‰	−3.53‰	1.3 ± 0.3 TU
13/05/2010	−20.3‰	−3.55‰	not analysed

A comparison of the May 2009 cave water tritium value with that obtained in July 2009 for the Zwartkrans Spring (section 9.7.1) reflects a significant difference of 1.1 ± 0.3 TU. The higher value associated with the spring water indicates that the source delivers a younger groundwater than that which is represented by the cave water. The most plausible explanation for this situation is that the Sterkfontein Caves does not lie in the main flowpath of groundwater discharge toward the Zwartkrans Spring. Similarly, Groenewald (2010) refers to the Sterkfontein Caves as occupying a low energy groundwater system. This possibility is discussed in greater detail in section 9.4.

9.3 Regional Groundwater Chemistry Assessment

Groundwater chemistry analyses generated by this study provide a comprehensive picture of groundwater quality distribution in the study area. The analyses reflect a combination of inorganic, organic, bacteriological and stable isotope results for groundwater sourced from boreholes and springs. The collection of a representative groundwater sample was facilitated by obtaining water only from equipped and active borehole installations, and as close to the installation as possible. The results of 48 chemical analyses performed on water sourced from 39 boreholes and nine springs (excluding the KGR springs, which are discussed separately in section 9.7.12) provide information on the spatial distribution of groundwater chemistry in the study area. The analyses are grouped geographically according to the compartments/subcompartments identified in section 8.2, and which are recognized as GRUs in section 11. The grouping of analyses on this basis, and taking the mean concentration of chemical variables per group, provides a measure of the current groundwater chemistry associated with these hydrogeologic units. This information is presented in Figure 82 and Figure 83, and discussed in the following sections.

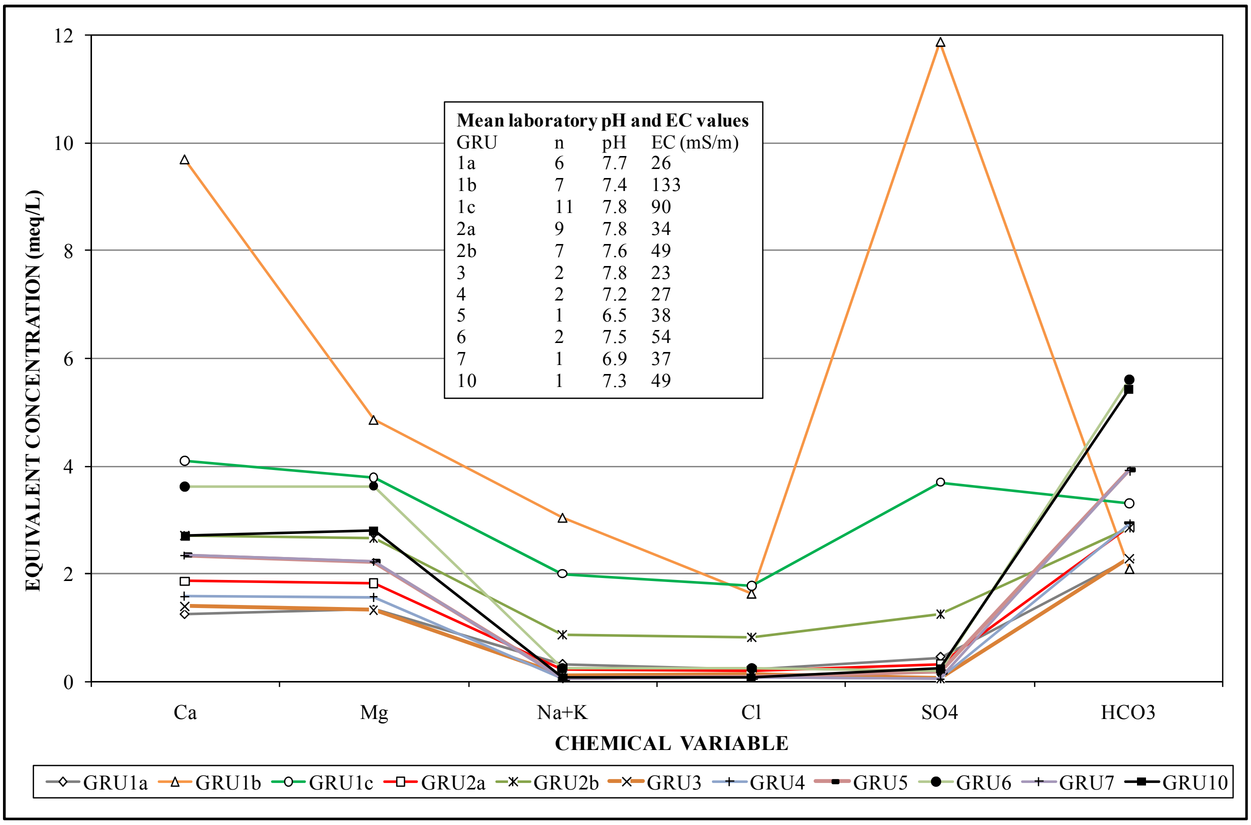

Figure 82. Chemical composition of groundwater per GRU based on available data.

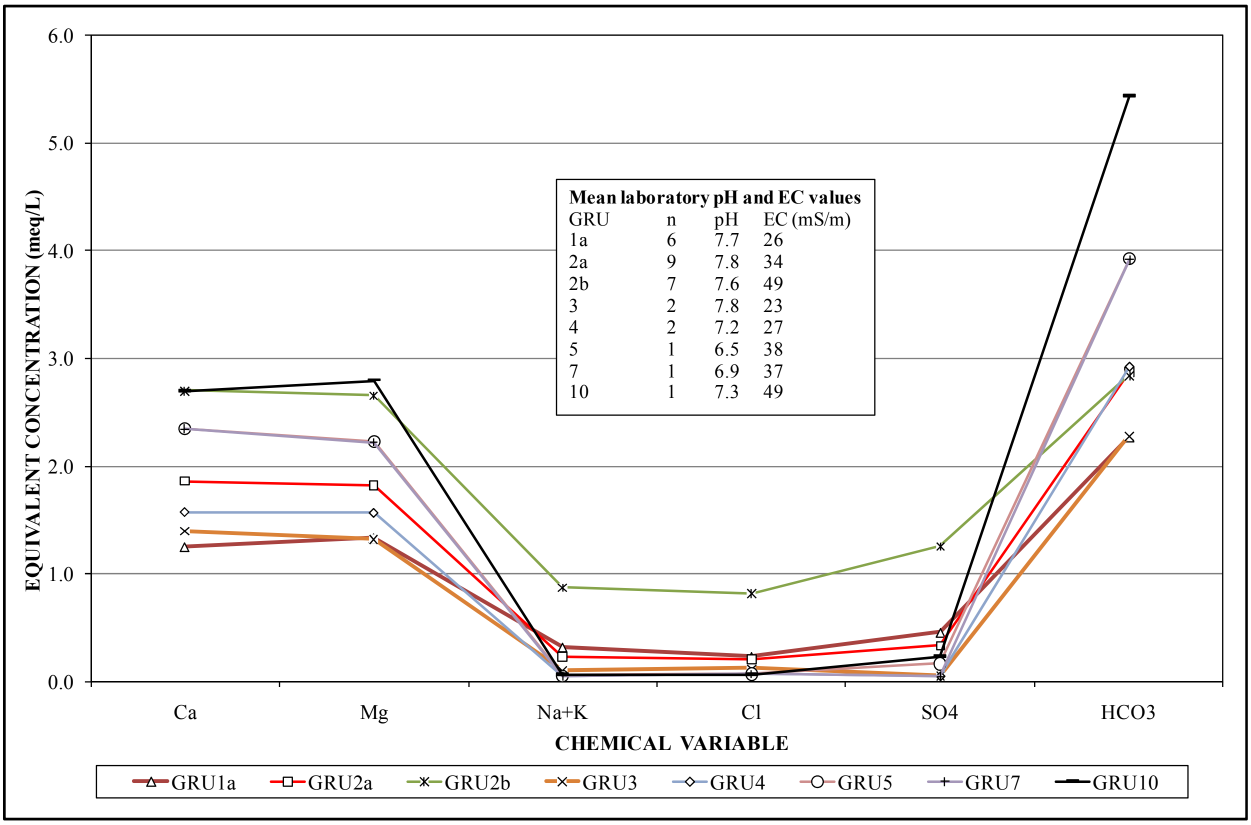

Figure 83. Chemical composition of groundwater for 'pristine' GRUs based on availale data.

9.3.1 Zwartkrans Compartment

9.3.1.1 Vlakdrift Subcompartment

It is evident from Figure 82 that the groundwater chemistry in this subcompartment (GRU1a) reflects a composition that is typical of a 'pristine' dolomite aquifer. The only concern is the indication of bacteriological contamination in the upper reaches of this subcompartment where it receives allogenic recharge via the Riet Spruit (sections 4.2.1 and 9.6).

9.3.1.2 Sterkfontein Subcompartment

Figure 82 shows the extent to which the groundwater chemistry in this subcompartment (GRU1b) differs from that in the other groundwater resource units. The Ca-SO_4 composition and mean EC of 133 mS/m of the groundwater reflects the impact of mine water on the karst groundwater in this GRU.

9.3.1.3 Zwartkrans Subcompartment

Albeit less pronounced compared to that of GRU1b, the Ca-SO4 composition of the GRU1c groundwater (Figure 82) still reflects the impact of mine water on the karst groundwater in this GRU. Figure 82 also shows that this subcompartment supports the highest mean Cl concentration, which circumstances reflect the additional impact associated with the ingress of treated municipal wastewater effluent from the Percy Stewart WWTW via the Blougat Spruit.

9.3.2 Krombank Compartment

9.3.2.1 Kromdraai Subcompartment

Figure 83 indicates that the groundwater chemistry in this subcompartment (GRU2a) is similar to that in the other 'pristine' dolomite compartments (e.g. GRUs 3, 4, 5 and 7). However, station RLGR5 located at the Kiosk and Camp Site in the Rhino and Lion Game Reserve in this subcompartment reflects slight bacteriological contamination (section 9.6 and Figure 88). Especially the *E. coli* concentration of 4 c/100 mL is cause for concern in the medium- to long-term.

9.3.2.2 Bloubank Subcompartment

The similarity in mean groundwater chemical composition between GRU2b and GRU1c is evident in Figure 82. The more muted composition associated with GRU2b groundwater reflects the situation where this unit is the main receiving groundwater resource for the discharge from GRU1c. It is therefore also not surprising that Figure 83 indicates that groundwater quality in the Bloubank Subcompartment is the 'poorest' of the 'pristine' dolomite compartments. This is also reflected in the mean EC value of 49 mS/m that characterizes this groundwater.

9.3.3 Danielsrust Compartment

Figure 83 shows that the groundwater chemistry in this compartment (GRU3) reflects a composition that is typical of a 'pristine' dolomite aquifer. Again the only concern is the indication of bacteriological contamination, albeit slight, in the water produced by the Danielsrust Spring (section 9.6 and Figure 88). A more complete discussion on the spring water chemistry is presented in section 9.7.4.

9.3.4 Uitkomst Compartment

The Uitkomst Compartment (GRU4) supports a pristine karst groundwater environment that is reflected in the chemical composition of the groundwater discharged from this compartment via the Nash Spring. The quality of this groundwater is described and discussed in section 9.7.8.

9.3.5 Tweefontein Compartment

The groundwater chemistry in GRU5 conforms to that associated with the more 'pristine' karst environments. Figure 83 indicates that the composition of this groundwater is virtually indistinguishable from that associated with GRU7 (the Diepkloof Compartment drained by the Nouklip Spring). These circumstances support the postulated autogenic recharge to GRU7 via the Tweefontein Spring discharge. Further information on the chemistry of this groundwater is provided in section 9.7.6.

9.3.6 Rietfontein Compartment

The Rietfontein Compartment (GRU6) produces a good quality groundwater (section 9.7.5) which reflects the different rock types (dolomite and undifferentiated igneous strata) that comprise this hydrogeologic unit. The influence of the non-karst groundwater on the mixture of karst and non-karst groundwater produced by GRU6 is evident in detectable concentrations of metals such as Fe (~2.6 mg/L) and Mn (~0.4 mg/L) (Table 71).

9.3.7 Diepkloof Compartment

The Diepkloof Compartment (GRU7) reflects a similar groundwater chemistry to that of GRU5, the Tweefontein Compartment (section 9.3.5). As such, it reflects a 'pristine' karst environment that produces a high quality groundwater (see section 9.7.7).

9.3.8 Motsetse Compartment

The groundwater chemistry associated with GRU8 is represented by the field variables listed in section 9.7.10. The salinity value of 64 mS/m is indicative of a slightly impacted karst groundwater chemistry.

9.3.9 Rhenosterspruit Compartment

There are no groundwater chemistry data available for this hydrogeologic unit (GRU9).

9.3.10 Broederstroom Compartment

The groundwater chemistry of this compartment (GRU10) is represented by that of the Broederstroom Spring as described in section 9.7.11. The composition of this groundwater again reflects that which characterizes the more 'pristine' karst environments (Figure 83).

9.4 Local Groundwater Chemistry Assessment

The recent chemical composition of groundwater in the Oaktree area is illustrated in Figure 84 and Figure 85. Figure 84 reveals the unequivocal CaMg-HCO_3 character of the NR1 and SC1 (Sterkfontein Caves) sources compared to the CaMg-SO_4HCO_3 character of the other sources. Of concern is the Ca-SO_4 character of the Zwartkrans Spring water, which clearly reflects the influence of upstream impacts on the chemistry of the dolomitic groundwater in the Zwartkrans Subcompartment as reflected at geosites MB1, CFM1 and PM1. As shown in Figure 85, a much more pronounced Ca-SO_4 composition is associated with sources CSIR8 and CSIR9 and, to a lesser extent, source SCH1. This is attributed to the location of this geosites near the confluence of the Riet and Blougat spruits. The observations also indicate that the Sterkfontein Cave water chemistry reflects the least impact of all the geosites sourced for groundwater samples in the Oaktree area.

A real and present concern is the result returned by a recent chemical analysis carried out on the groundwater produced by geosite WBD1, the recently established water supply borehole in the Krugersdorp Game Reserve. This analysis yielded a nitrate concentration of 51 mg N/L, a Cl value of 103 mg/L, a SO_4 value of 110 mg/L, a Na concentration of 82 mg/L and a laboratory EC value of 103 mS/m. All of these concentrations are anomalous for karst groundwater, and point to a significant impact on the karst groundwater produced by this borehole. The most likely source of this impact is the irrigation of ~65 ha of instant lawn with treated wastewater effluent obtained from the Percy Stewart WWTW as discussed in section 4.1.2.2 and illustrated in Plate 3.

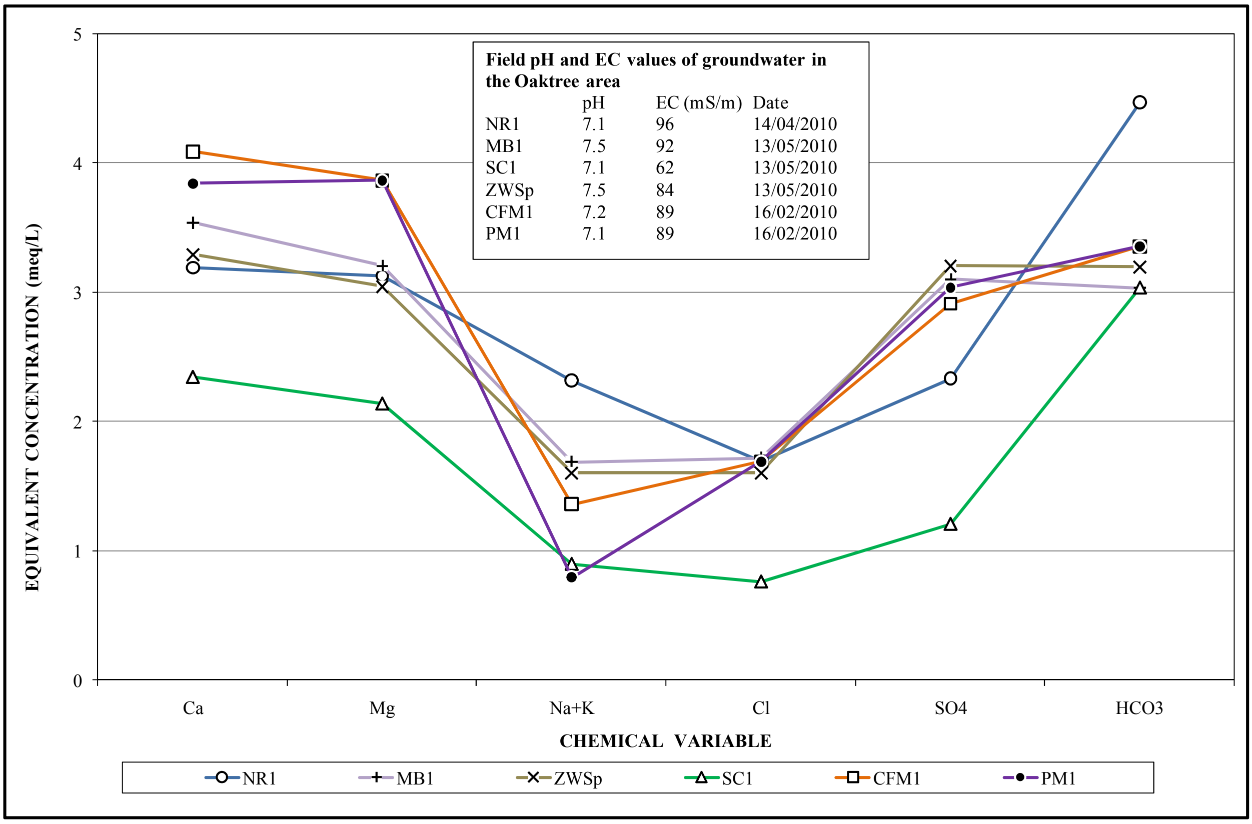

Figure 84. Comparison of moderately impacted groundwater chemistry in the Oaktree area.

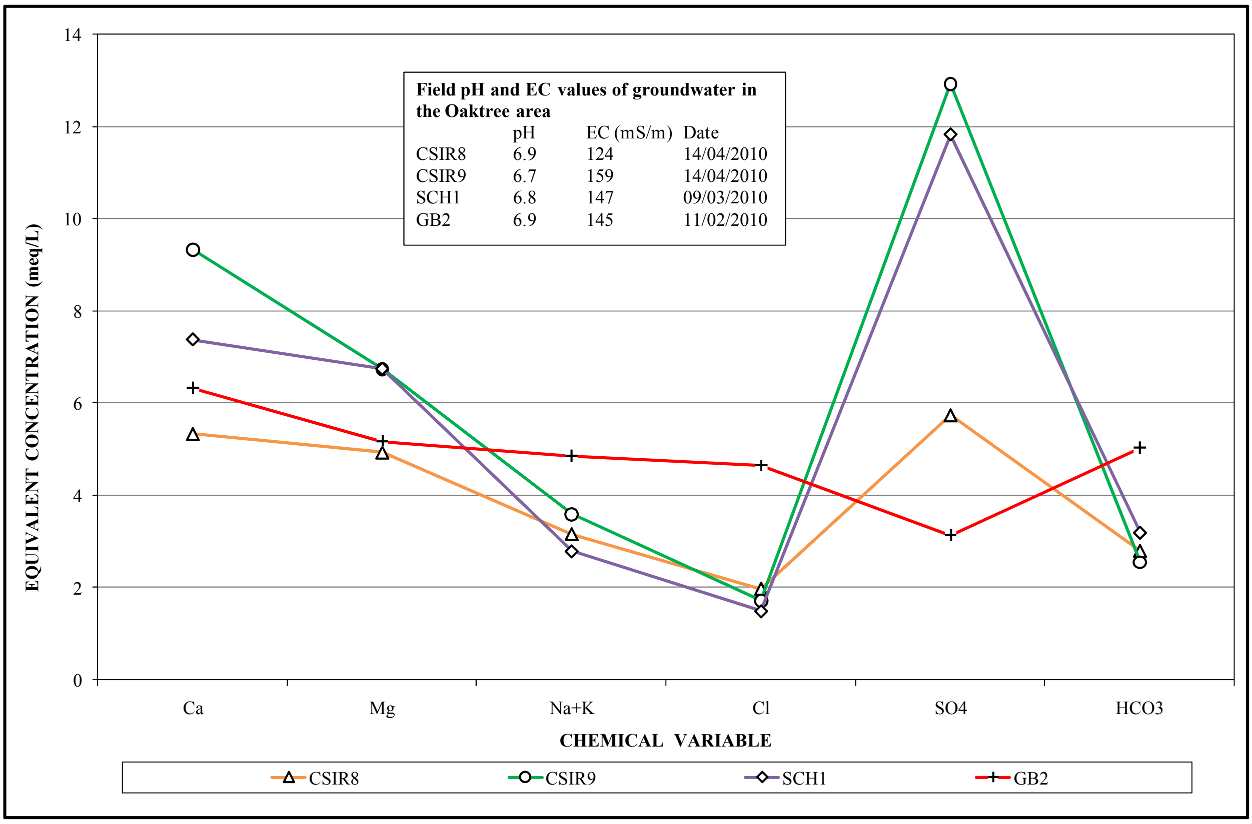

Figure 85. Comparison of severely impacted groundwater chemistry in the Oaktree area.

The above circumstances are not new, since a similar situation precipitated the study by Barnard (1996). The Barnard (1996) study found that the practice of flood irrigation in the Krugersdorp Game Reserve using wastewater effluent from the Percy Stewart WWTW was the most likely cause of elevated NO_3, SO_4 and Cl concentrations in the groundwater produced by the borehole WBD4 (section 9.2.3.1), as well as the source of bacteriological contamination of this groundwater. It is significant to note that the provision of wastewater to the KGR was terminated in September 2008 (section 4.1.2.2) on the presumption that this again was the cause for the observed deterioration in mid-2008 of the groundwater quality produced by borehole WBD4 (see Figure 78). The more probable cause, however, was the ingress of a mixture of raw and treated mine water (refer section 9.2.3.1) as discussed by Hobbs (2008a).

9.5 Isotope Chemistry

The study of isotope chemistry is a well established tool in both surface water and groundwater investigations (Cecil and Green, 2000; Osmond and Cowart, 2000; Wanty and Nordstrom, 1993). Ford and Williams (2007), however, caution that the use of stable isotopes in hydrogeology merely provides information on the general source of waters, and does not identify the exact source. This is seen as a significant limitation. The principal isotopes are those of hydrogen ^{2}H (deuterium) and ^{1}H, and oxygen ^{18}O and ^{16}O. These isotopes are not subjected to nuclear transformation, and are therefore also referred to as stable isotopes. The radioactive isotopes, of which ^{3}H (tritium) is one, are subject to decay over time. This also explains their use for age determination (dating).

It is standard practice to report stable isotope results as the ratio of the least abundant (heaviest) isotope to the most abundant (lightest) isotope (Kendall and Caldwell, 1998). For oxygen the ratio is $^{18}O/^{16}O$, and for hydrogen $^{2}H/^{1}H$. Since variations in the isotopic ratios are small, the δ (delta) notation is used to express the deviation of the isotopic ratio in the sample with respect to the ratio in the standard (e.g. $\delta^{18}O$) in units of parts per thousand (‰) relative to a standard of known composition represented by that of Standard Mean Ocean Water (SMOW).

9.5.1 Previous Studies

The use of isotopes in the study of water chemistry in the project area (primarily the area of mine water decant) has been documented, amongst others, by CGS (undated), Holland (2007), Hobbs and Cobbing (2007) and Hobbs et al. (2010). The CGS (undated) employed a variety of isotopes ($^{2}H/^{1}H$, $^{18}O/^{16}O$, $^{87}Sr/^{86}Sr$, $^{34}S/^{32}S$, $^{206}Pb/^{207}Pb$ and $^{208}Pb/^{207}Pb$) to investigate the chemical (isotopic) relationship between various water sources in the area of mine water decant and immediate downstream environment. In regard to the $\delta^{34}S$ data, this study reported interpretation difficulties associated with the available information, due mainly to a lack of background reference values. Nevertheless, the observed $\delta^{34}S$ values are ascribed to natural oxidative weathering of Witwatersrand sulphides (pyrite) interacting with and leached by the water. The $^{87}Sr/^{86}Sr$ data, viewed in conjunction with the $\delta^{34}S$ data, suggest that a gradual mixing between waters of probably dolomitic provenance and mine effluents is indicated. The lead isotope results, on the other hand, clearly reflect the difference between raw mine water and surface water and groundwater sources that exhibit a mine water impact (Figure 86).

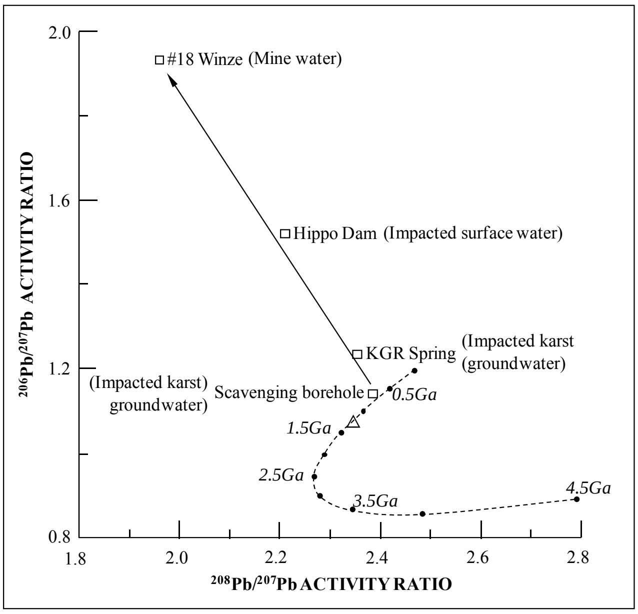

Figure 86. Relationship of lead isotopic ratios of water in the West Rand area to the Stacey-Kramers curve (pecked line). South African leaded petrol plots at Δ on this curve. Different stages of crustal evolution indicated by ages in billions of years (Ga) along the curve. Arrow shows the direction of deviation of the lead isotope signature associated with mine water impacts. (Modified from Coetzee and Rademeyer, 2006).

Both Holland (2007) and Hobbs and Cobbing (2007) used the stable isotope ratios $\delta^{2}H$ and $\delta^{18}O$ to distinguish between various natural and impacted water sources in the area (see section 9.5.2). In addition, Holland (2007) reports the results of 21 ^{3}H analyses for groundwater and spring water samples in the study area. Hobbs et al. (2010) report on the additional application of the radio-isotopes ^{222}Rn (radon), ^{226}Ra (radium) and ^{238}U as possible hydrological tracers in a natural and polluted environment (see section 9.5.2.2).

9.5.2 Recent Isotopic Information

9.5.2.1 Stable Isotopes

Isotope analyses performed on Sterkfontein Caves and Zwartkrans and Komdraai Springs groundwaters in mid-2009 are presented in Table 70. The more similar $\delta^{2}H$ and $\delta^{18}O$ values of the Sterkfontein Caves and Zwartkrans Spring groundwaters support the water level (section 8.4.1) and inorganic chemistry (section 9.2.3.2) data that indicate that the cave system penetrates and shares the karst aquifer drained by the spring. This observation also supports the use of these parameters to distinguish between various water sources (and mixture of sources) in the study area. Perhaps more significantly, however, is the difference in ^{3}H levels between the Sterkfontein Caves and Zwartkrans Spring groundwater. These values indicate that the spring water represents a younger water than that of the cave water. This observation supports the hypothesis, based on an assessment of the inorganic quality associated with moderately impacted groundwater in the Oaktree area (section 9.4 and Figure 84), that the Sterkfontein Caves does not lie in the main flowpath of groundwater discharge toward the Zwartkrans Spring.

Table 70. Comparison of recent isotope data for cave and spring water.

Variable	Sterkfontein Caves	Zwartkrans Spring	Plover's Lake Springs
Date	28/05/2009	17/07/2009	17/07/2009
δ^2H (‰ SMOW)	−19.8	−16.8	−28.9
$\delta^{18}O$ (‰ SMOW)	−3.53	−3.17	−5.01
^3H (TU)	1.3 ± 0.3	2.4 ± 0.3	1.6 ± 0.3
^{222}Rn (Bq/L)	n.a.	8.8	10.5

The tritium value of the cave water is closer to that of the pristine Plover's Lake Springs groundwater. The tritium value of 1.3 ± 0.3 TU is representative of groundwater that is several decades old[48], compared to the ostensibly 'younger' Zwartkrans Spring water with a tritium value of 2.4 ± 0.3 TU. The circumstances that give rise to these differences are important in evaluating the risk posed to the Sterkfontein Caves by poor quality groundwater in the Zwartkrans Compartment that originates from anthropogenic impacts. For example, Martini et al. (2003) report the development of a dolerite sill immediately below Sterkfontein, but which has not been observed in the cave. It is possible that the resistivity surveys reported in section 6.2.2 (in particular traverse R2) might have recognized this structure at the southern end of this traverse.

The stable isotope results generated by this study are illustrated in Figure 87. The comparatively close grouping of six of the spring water samples in the 'pristine' karst groundwater field is apparent. Further up the hypothetical 'local' evaporation line is the Sterkfontein Caves water sample, and beyond that the impacted Zwartkrans Spring groundwater. The elongated shape of the marginally impacted karst groundwater field reflects the wider mixture of isotopic composition associated with this groundwater, ranging from nearly pristine at the lower left ('heavier') end to moderately impacted at the upper right ('lighter') end as the evaporative water signature gains increasing dominance. Covering, amongst others, the same area investigated by Hobbs and Cobbing (2007), a Water Research Commission (WRC) study (Hobbs et al., 2010) that included $\delta^{18}O$ and δ^2H analyses associated with groundwater, mine water and surface water sources further established the use of these variables to distinguish between the various water sources as reflected in Figure 87.

9.5.2.2 Radioactive Isotopes

The study by Hobbs et al. (2010) investigated the use of ^{222}Rn as a hydrological tracer in natural and polluted environments, and added radioactive isotope data to the water quality data set generated by the Hobbs and Cobbing (2007) study. The data included ^{222}Rn (radon), ^{226}Ra (radium) and ^{238}U (uranium) analyses associated with groundwater, mine water and surface water sources collected on two occasions, once in early-2007 and again in early-2008. The radio-isotope data (^{222}Rn, ^{226}Ra and ^{238}U) proved less successful as hydrological tracers than $\delta^{18}O$ and δ^2H. For example, ^{222}Rn activity levels (concentrations) as high as 65 Bq/L were found in otherwise pristine groundwater issuing from quartzitic strata of the Witwatersrand Supergroup, whereas the median ^{222}Rn concentration associated with mine water sources was ~27 Bq/L. 'Pristine' karst groundwater returned a median ^{222}Rn concentration of ~7 Bq/L, which is in good agreement with the values reported in Table 70 for the Zwartkrans and Plover's Lake Springs.

The ^{226}Ra concentrations in mine water sources ranged from 0.12 to 1.38 Bq/L, the mean of 0.65 Bq/L exceeding the DWA (1999) target water quality range for domestic water use of 0.42 Bq/L. The comparatively low ^{226}Ra values of 0.029 and 0.002 Bq/L associated with a tailings dam source support findings by De Jesus (1985), that tailings dams do not represent a significant threat as a source of this radionuclide in the receiving surface and groundwater environments. The median ^{238}U concentration of 1.82 Bq/L (0.15 mg/L) associated with mine water sources exceeds the DWA (1996) target water quality range of 0.82 Bq/L (0.07 mg U/L) for domestic water use by a factor of ~2.

[48] Tritium values <2 TU are generally associated with groundwater residence times in the order of several decades, whereas higher values are indicative of more recent recharge and faster circulation (see for e.g. Hershey et al. (2010)).

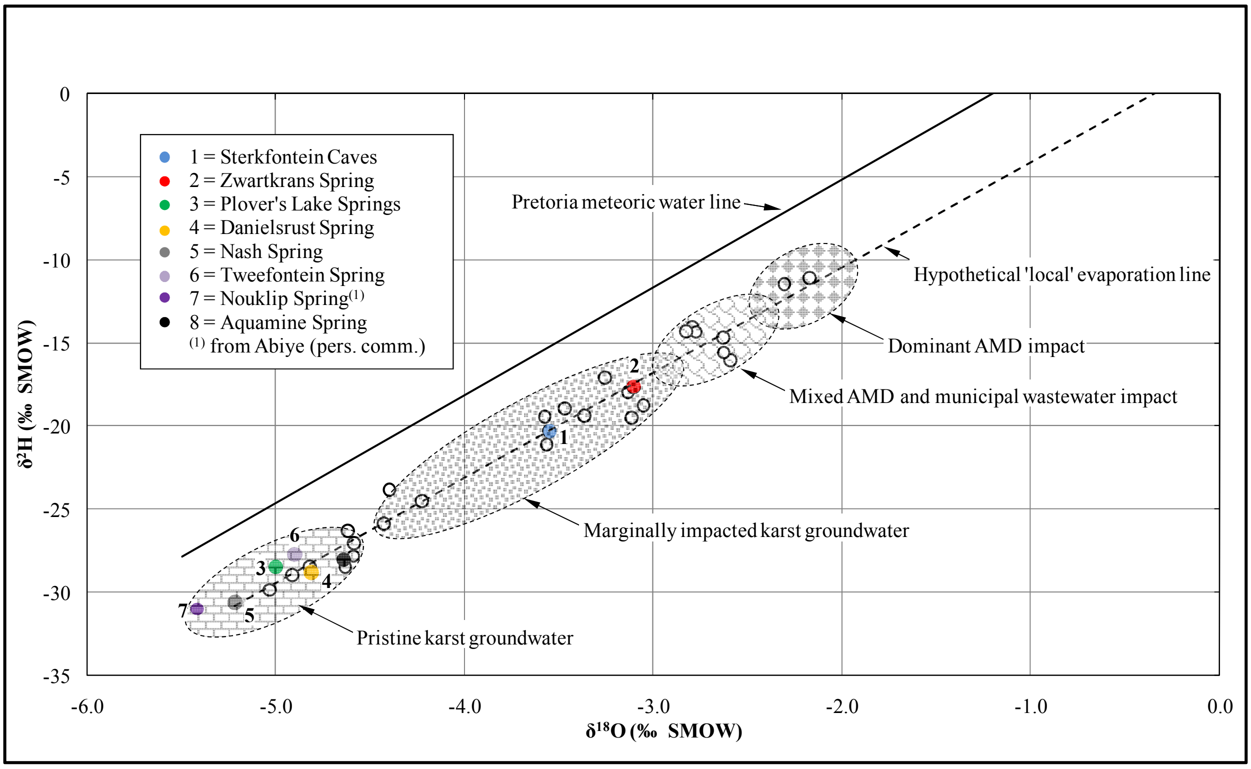

Figure 87. Recent stable isotope composition of groundwater in the study area, also showing the characteristic fields associated with various sources (modified from Hobbs and Cobbing, 2007).

The chemical analyses carried out as part of the current study in most instances included the determination of uranium (U) concentrations. Values in excess of the 0.001 mg/L detection limit were only observed in two surface water samples associated with mine water discharge in the Tweelopie/Riet Spruit system in mid-February 2010, when 0.026 mg U/L was recorded at stations F11S12 and MRd1.

Strachan et al. (2008) report that the Klip River Radioactivity Monitoring Programme found a good linear correlation between the U concentration in water and the total radiation dose from all radionuclides. This prompted these authors to suggest that the U concentration might serve as an indirect measure of the total radiation dose from all radionuclides for screening and routine monitoring purposes in a catchment.

9.6 Bacteriological Quality

The bacteriological quality of groundwater in terms of the microbiological parameters total coliform bacteria and *E. coli* has been determined for 16 sources (boreholes and springs) in the study area. Total coliforms and *E. coli* have traditionally been considered as the best faecal indicator bacteria (FIB) tracers of surface water and human faecal contamination in groundwater, respectively (Kozuskanich et al., 2010). Payment and Locus (2010) suggest that simple 'presence-absence' methods detecting both total coliforms and *E. coli* provide a reasonable approach, when combined with an appropriate sampling frequency, to establish the measure of risk from enteric pathogens in water. The presence of total coliforms in groundwater indicates that microorganisms in surface water have entered the aquifer, and a more rigorous monitoring should begin for pathogens which might also reach the aquifer (Payment and Locus, 2010).

Groundwater samples were collected from sources where the likelihood of bacteriological contamination was considered significant. The results are presented in Figure 88, and indicate the presence of bacteriological contamination at station A2N0598 in the upper reaches of the Zwartkrans Compartment, in the Oaktree area (stations CFM1, CSIR8, CSIR9 and NR1) and further downstream (stations MB1, BolandA, BolandC and ZWSp). Especially the presence of *E. coli* in some of the samples, notably the Zwartkrans Spring (ZWSp) and station OB1, is a concern. Station OB1, located the furthest downstream at Kromdraai, exhibits a surprising result given the following circumstances:

- the distance of ~870 m from the Bloubank Spruit with its elevated bacterial load (Table 39); and
- the groundwater rest elevation of ~1420 m amsl compared to that of ~1410 m amsl of the Bloubank Spruit, which indicates a groundwater gradient toward the river at this locality.

Although the above circumstances suggest the Bloubank Spruit is an unlikely source of this contamination, the use of the borehole for large-scale agricultural water supply might cause a reversal of the hydraulic gradient and draw in water from this source. Also anomalous is the bacteriological impact seen in the Danielsrust Spring (DRSp) water, which otherwise reflects a pristine dolomitic groundwater quality (section 9.7.4). The exposed and non-protected setting of the spring likely attracts a greater risk of bacteriological contamination from game such as Eland (*Taurotragus oryx*) that roam freely in this setting. Since it was not within the scope of this study to carry out site-specific instances of bacteriological contamination, these might attract further investigation in future hydrogeologic studies.

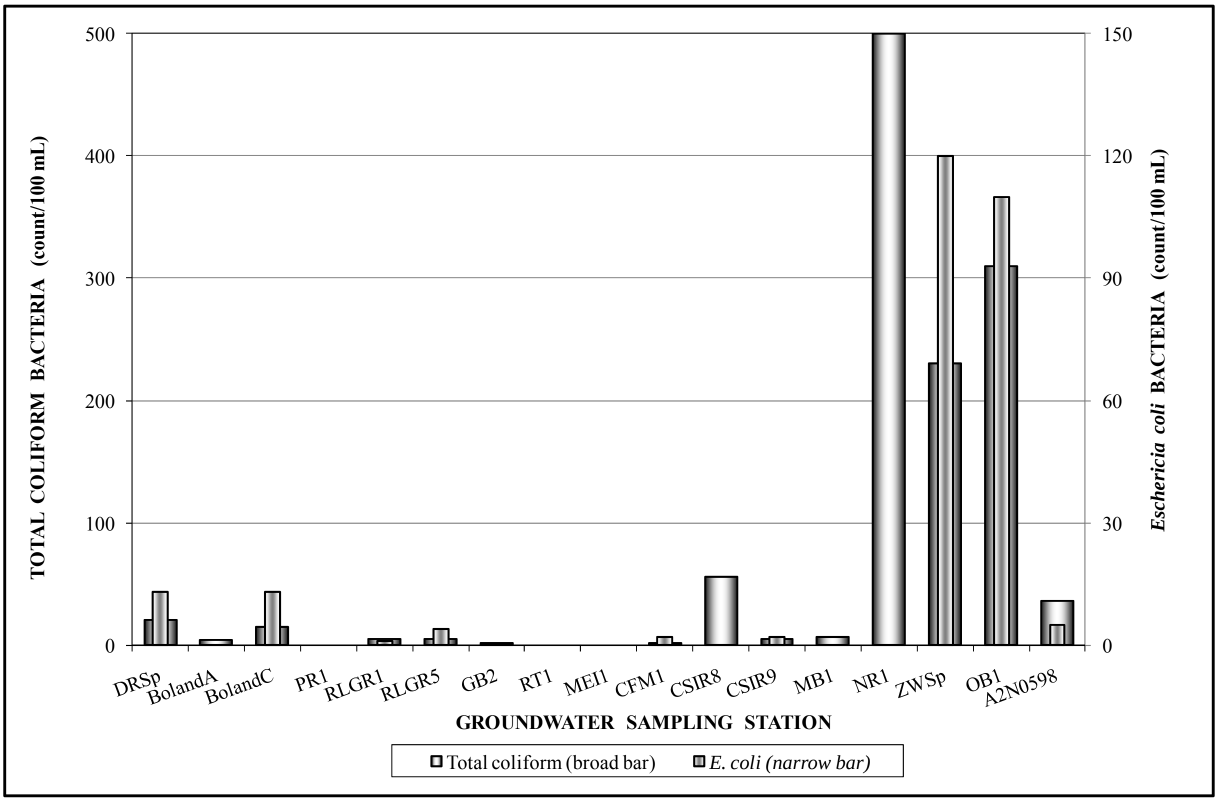

Figure 88. Graph of groundwater bacteriological quality in the study area. The ~3x difference in scale between the vertical axes explains those *E. coli* values that exceed Total coliform counts.

9.7 Spring Water Chemistry

The importance of springs in the study area warrants a separate discussion of the chemical composition of the groundwater[49] recently/currently produced by each of the enumerated features (section 8.5). The discussion is informed by the data presented in Table 71, which also form the basis for the stable isotope results (Figure 87) and the Schoeller graphs (Figure 89).

9.7.1 Zwartkrans Spring

As shown in Figure 90, the chemical composition of the spring water has not deteriorated much since May 2006. The principal change is the increase in SO_4 concentration from 123 to 154 mg/L. When compared to that of the other karst springs, the chemical composition (CaMg-SO_4HCO_3) of this spring water clearly exhibits the impact of poorer water quality sources (mainly mine water) on the karst groundwater of the Zwartkrans Compartment (section 8.2.1).

49 The terms groundwater and spring water are used synonamously.

Table 71. Recent spring water chemistry data.

Variable	Spring								
	ZWSp	**PLSp**	**DRSp**	**JNNR1**	**JNNR2**	**JNNR3**	**JNNR4**	**GSSp**	**BSp**
Date (dd/mm)(1)	13/05	13/05	10/02	19/05	19/05	19/05	19/05	10/02	21/12
pH (field value)	7.5	7.7	6.9	6.5	6.9	7.0	7.0	6.8	7.3
EC (mS/m) (field)	84	38	26	39	39	25	1	63	49
Ca (mg/L)	66	51	33	47	47	30	<2	87	54
Mg (mg/L)	37	29	18	27	27	18	3	48	34
Na (mg/L)	36	2	<2	<2	<2	<2	2	4	<2
K (mg/L)	1.5	<1	<1	<1	<1	<1	<1	<1	<1
Cl (mg/L)	57	<5	<5	<5	<5	<5	<5	10	<5
SO_4 (mg/L)	154	5	<5	8	<5	<5	<5	7	11
HCO_3 (mg/L)	195	234	156	239	239	161	20	390	332
F (mg/L)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
NO_3 (mg N/L)	12	0.9	0.7	0.8	0.6	0.5	0.4	<0.2	0.4
PO_4 (mg P/L)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Si (mg/L)	6.0	5.9	5.9	5.0	5.2	5.5	4.1	7.5	6.5
Fe (mg/L)	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	0.315	2.57	<0.02
Mn (mg/L)	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	0.466	0.38	<0.005
Al (mg/L)	0.116	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.128	<0.04
Sr (mg/L)	0.036	<0.025	<0.025	<0.025	<0.025	<0.025	<0.025	0.043	0.01
V (mg/L)	0.034	0.039	0.029	<0.025	<0.025	<0.025	<0.025	0.035	<0.005
Hg (mg/L)	<0.001	<0.001	<0.001	n.a.	n.a.	n.a.	n.a.	0.001	n.a.
U (mg/L)	<0.001	<0.001	<0.001	n.a.	n.a.	n.a.	n.a.	<0.001	n.a.
δ^2H (‰)	−17.6	−28.5	−28.8	−27.7	−31.0(2)	−30.6	n.a.	−28.0	n.a.
$\delta^{18}O$ (‰)	−3.11	−5.00	−4.81	−4.90	−5.42(2)	−5.22	n.a.	−4.64	n.a.
^3H (TU)	2.1±0.3	1.4±0.3	1.3±0.2	3.1±0.3	0.6±0.2(2)	0.1±0.2	n.a.	3.4±0.3	n.a.

(1) All dates are dd/mm/2010
(2) *ca.* 2009 data from Abiye (see footnote 59)
ZWSp = Zwartkrans; PLSp = Plover's Lake; DRSp = Danielsrust; JNNR1 = Tweefontein; JNNR2 = Nouklip; JNNR3 = Nash; JNNR4 = Uitkomst; GSSp = Aquamine BSp = Broederstroom

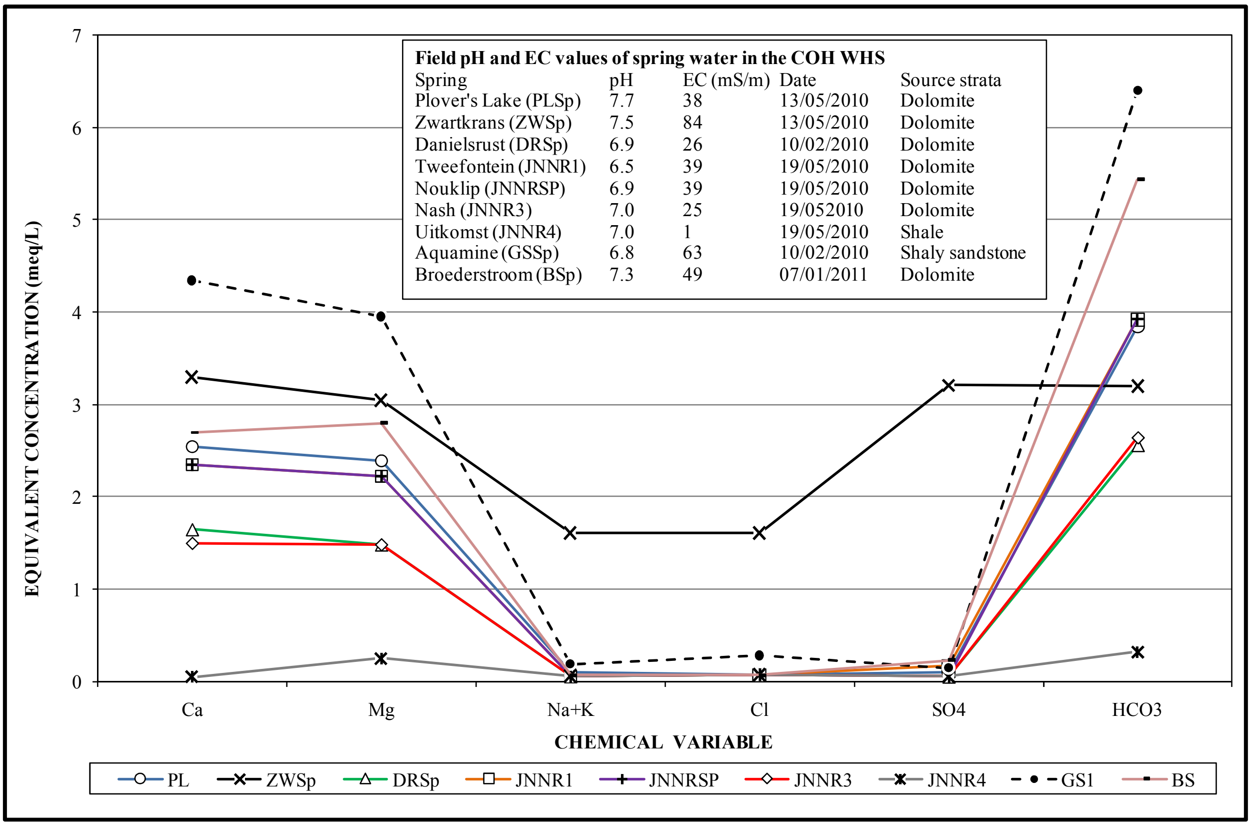

Figure 89. Comparison of spring water chemistry in the COH WHS.

The Zwartkrans Spring water chemistry represents the composition of the groundwater aggregated upstream thereof. It has previously been shown (sections 4.1.2 and 5.1.2) that the contributing sources include those of mine water with its very dominant Ca-SO_4 character, and treated wastewater with its Na-SO_4 character and elevated Cl levels, all of which are evident in this spring water. The stable isotope chemistry of this spring water is reflected in analyses dated July 2009 (Table 70) and May 2010 (Table 71). The results are compared hereunder, and reflect ostensibly small differences. The SI_c and SI_d values of 0.08 and 0.18 indicate saturation of the water with respect to calcite and dolomite, respectively.

Date	δ^2H	$\delta^{18}O$	^3H
17/07/2009	−16.8‰	−3.17‰	2.4 ± 0.3 TU
13/05/2010	−17.6‰	−3.11‰	2.1 ± 0.3 TU

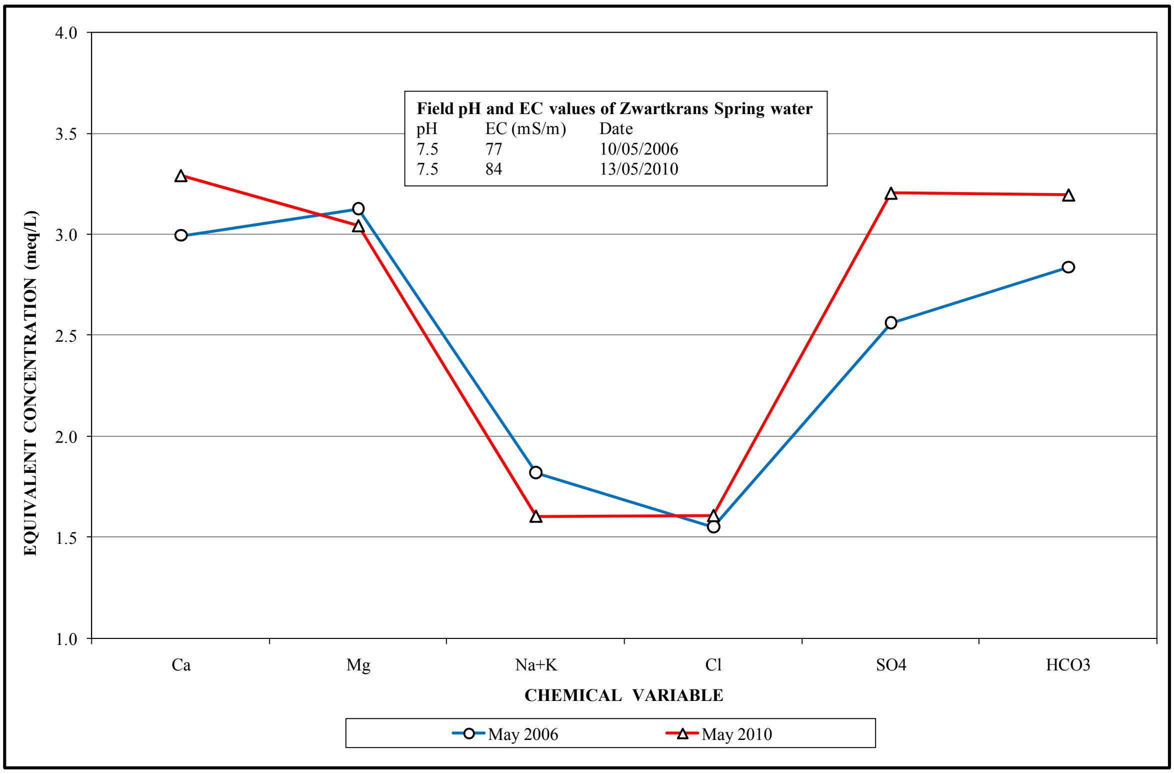

Figure 90. Comparison of Zwartkrans Spring water chemistry between 2006 and 2010.

9.7.2 Plover's Lake Springs

The chemistry of this spring water shows a close resemblance (virtually superimposed in Figure 89) to that produced by the Tweefontein (JNNR1) and Nouklip (JNNR2) Springs, all of which are representative of natural dolomitic groundwater with its typical CaMg-HCO_3 composition. These springs drain the Kromdraai Subcompartment of the Krombank Compartment (section 8.2.2). The stable isotope values of this spring water (compared hereunder) show very little difference between the two more recent sampling dates, but a significant difference compared to the earliest date. The heavier isotopic values of the two more recent analyses suggest that a greater component of recent recharge is manifested in these samples compared to the earlier sample. The SI_c and SI_d values of 0.25 and 0.53 indicate saturation of the water with respect to calcite and dolomite, respectively.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2006[50]	−30.3‰	−5.62‰	0.7[51] TU
17/07/2009	−28.9‰	−5.01‰	1.6 ± 0.3 TU
13/05/2010	−28.5‰	−5.00‰	1.4 ± 0.3 TU

50 Data from Holland (2007); no exact date of sampling readily discernible from source.
51 Data from Holland (2007); no error margin reported.

Figure 91 shows that the chemical composition of the spring water has changed very little since May 2006.

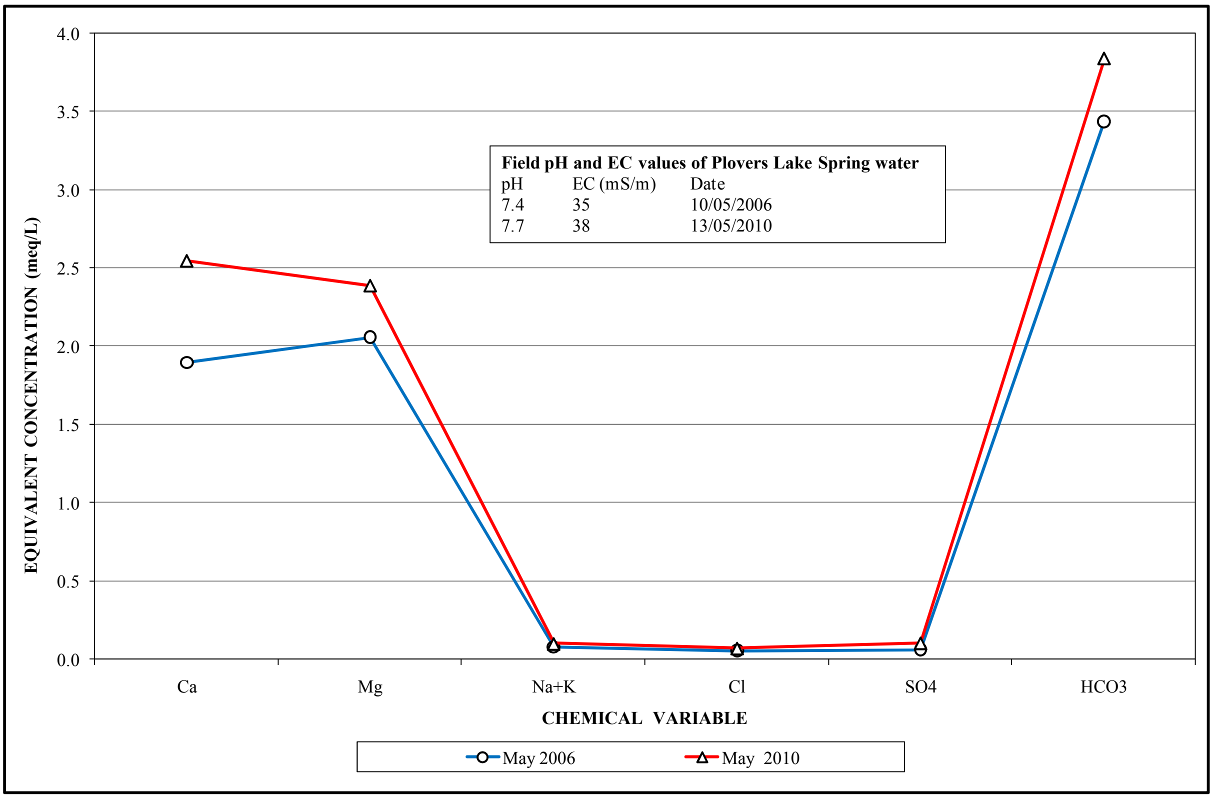

Figure 91. Comparison of Plover's Lake Springs water chemistry between 2006 and 2010.

9.7.3 Kromdraai Spring

The location of this source complicates the collection of a representative sample. In-situ measurements carried out from the riverbank at the locus of discharge returned an EC value of 56 mS/m, a pH value of 7.2 and a temperature of 19.4°C on 13/08/2010. A comparison of these values with those of river water upstream and downstream of the spring is presented in Table 66.

9.7.4 Danielsrust Spring

Together with that of the Nash Spring (JNNR3), the inorganic quality of the groundwater delivered by this spring is the best of any karst groundwater analysed in the COH WHS by this study. It drains the Danielsrust Compartment (section 8.2.3), producing the composition shown in Figure 92, which is virtually identical to that of the Nash Spring (JNNR3) water (Figure 89). The isotope chemistry of the spring water (see comparison hereunder) similarly reflects a current composition that differs only marginally from an earlier analysis. The observed difference of +0.38‰ in $\delta^{18}O$ (ignoring possible analytical error margins) reflects a shift toward a marginally heavier isotopic composition suggestive of either a slightly greater evaporative component in this groundwater, or a greater component of rainwater. Although the wetter than average past two summer rainfall seasons favours the rainfall hypothesis, a possible anthropogenic impact from immediate upstream landuse practices in the form of a commercial tourist lodge facility (section 8.2.3) cannot be ruled out.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2006[52]	−28.4‰	−5.19‰	1.2[53] TU
10/02/2010	−28.9‰	−4.81‰	1.3 ± 0.2 TU

52 See footnote 50.
53 See footnote 51.

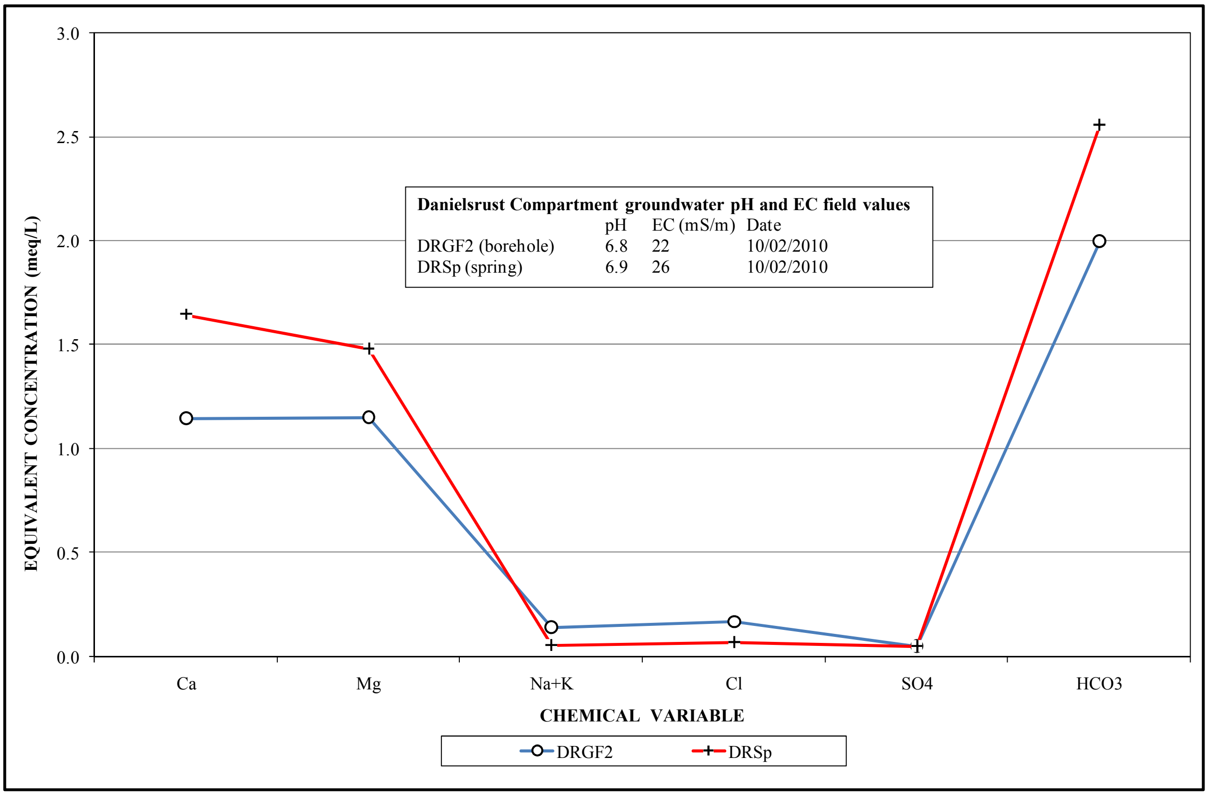

Figure 92. Comparison of Danielsrust Compartment groundwater produced by the spring and a borehole.

9.7.5 Aquamine Spring

The chemistry of the Aquamine Spring (GS1) water, although also reflecting a Ca-HCO_3 character, is clearly different from that of the karst groundwater. It is postulated that the upper reaches of the spring catchment comprise the dolomitic strata of the Rietfontein Compartment (section 8.2.6). The difference in chemistry is also evident in the detectable trace metal concentrations (Table 71) in this water, compared to the generally undetectable levels in many respects in a number of the other spring waters. A further difference is the elevated tritium level in the Aquamine Spring water (Table 71) compared to that of some of the karst spring waters. This indicates the comparatively recent age, possibly coupled with a shallow circulation pattern, associated with this groundwater system.

9.7.6 Tweefontein Spring

This spring drains the Tweefontein Compartment (section 8.2.5). Its water chemistry is virtually identical in inorganic composition to that of the Nouklip Spring (JNNR2) water (Figure 89), and very similar to that produced by the Plover's Lake Springs. The SI_c and SI_d values of −0.96 and −1.86 indicate under-saturation of the water with respect to calcite and dolomite, respectively. The stable isotope composition of this water, as sampled on various dates reported hereunder, reflects a trace from a lighter to a heavier δ^2H and $\delta^{18}O$ isotopic ratio. This is interpreted as reflecting a greater proportion of younger rainwater recharge in the more recent spring discharge. The shift in ^3H values supports this interpretation.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2006[54]	−29.2‰	−5.52‰	2.1[55] TU
ca. 2009[56]	−29.0‰	−5.17‰	2.9 ± 0.3 TU
19/05/2010	−27.7‰	−4.90‰	3.1 ± 0.3 TU

[54] See footnote 50.
[55] See footnote 51.
[56] Data from T. Abiye (personal communication).

Figure 93 shows that the chemical composition of the spring water has remained largely unchanged since May 2006.

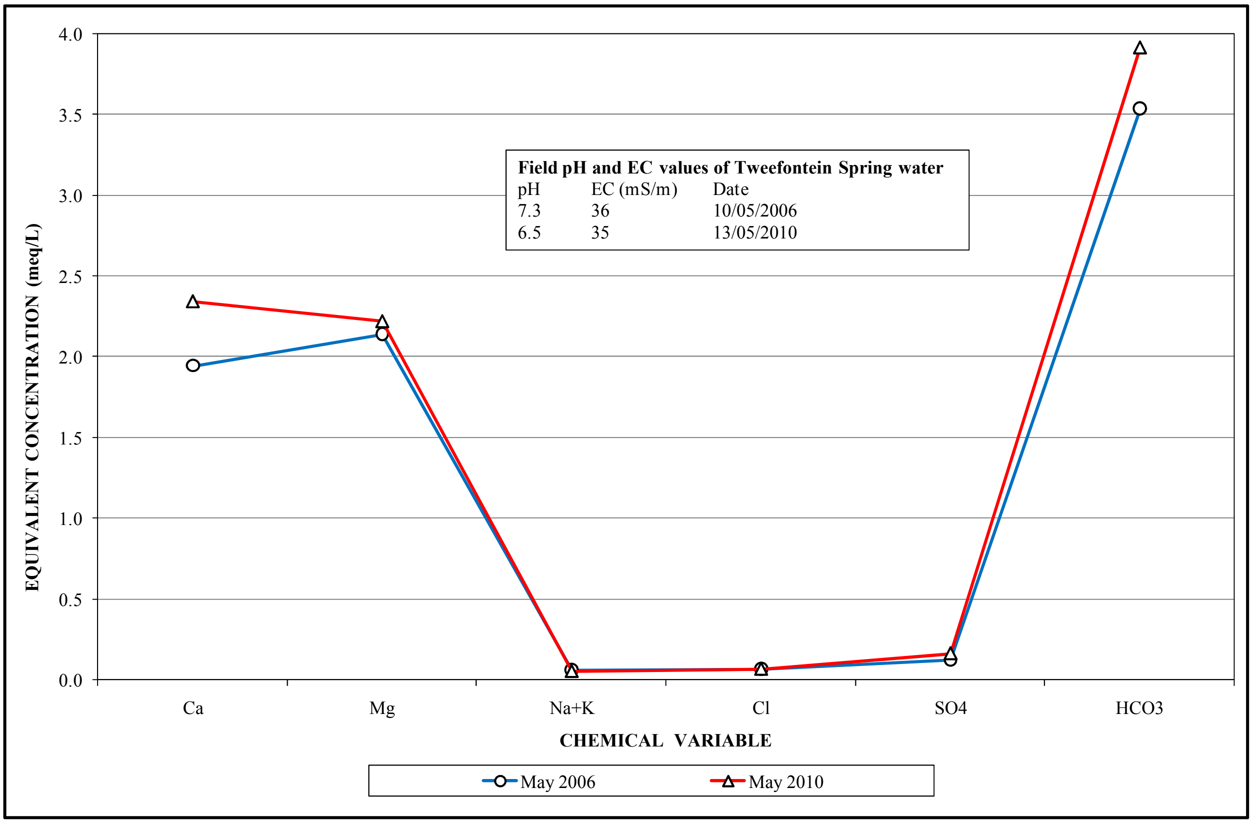

Figure 93. Comparison of Tweefontein Spring water chemistry between 2006 and 2010.

9.7.7 Nouklip Spring

This water is of excellent quality in respect of all the elements included in the analytical suite. The spring drains the Diepkloof Compartment (section 8.2.7) and, as stated in section 9.7.6, produces water that is virtually identical in composition to that produced by the Tweefontein Spring (Figure 89). It is therefore reasonable to presume that the May 2006 composition of the Tweefontein Spring water (Figure 93) also reflects that of the Nouklip Spring at the time. However, the similarity is not reflected in the isotope results as shown hereunder. These results, and in particular the tritium values, indicate a large proportion of substantially older groundwater in the discharge of the Nouklip Spring compared to the Tweefontein Spring. The SI_c and SI_d values of −0.53 and −0.97 indicate slight under-saturation of the water with respect to calcite and dolomite, respectively.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2006[57]	−32.1‰	−5.78‰	0.6[58] TU
ca. 2009[59]	−31.0‰	−5.42‰	0.6 ± 0.2 TU

9.7.8 Nash Spring

The quality of the typically CaMg-HCO_3 dolomitic groundwater produced by this spring (JNNR3) reflects a pristine condition (Figure 89). This is unlikely to deteriorate for as long as the largely 'wilderness' character of the Uitkomst Compartment (section 8.2.4) is maintained. The isotope results presented hereunder reflect similar circumstances to those associated with the similarly high-yielding

[57] See footnote 50.
[58] See footnote 51.
[59] See footnote 56.

Nouklip Spring (section 9.7.7). The SI_c and SI_d values of −0.77 and −1.47 indicate slight under-saturation of the water with respect to calcite and dolomite, respectively.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2009[60]	−32.4‰	−5.64‰	0.2 ± 0.2 TU
19/05/2010	−30.6‰	−5.22‰	0.1 ± 0.2 TU

The virtually identical inorganic chemical composition to that of the Danielsrust Spring water (Figure 89) is not, however, matched by the respective tritium (^3H) values (Table 71). These reveal a distinct difference in the relative age of the two spring waters. The smaller ^3H concentration of the Nash Spring water suggests a comparatively older water that accords with larger and almost certainly much deeper groundwater circulation pattern in the Uitkomst Compartment compared to that of the Danielsrust Compartment.

9.7.9 Uitkomst Spring

The spring water chemistry reflects an extremely fresh character with a field EC of 1 mS/m. Together with the Mg-HCO_3 composition of this water, these characteristics help to distinguish groundwater associated with the Pretoria Group sedimentary strata from that of the Malmani Subgroup dolomitic strata.

9.7.10 Cradle Spring

The Cradle Spring drains the Motsetse Compartment (section 8.2.8). Its chemistry is characterized by the field variables listed hereunder. The salinity value of 64 mS/m is indicative of a slightly impacted karst groundwater chemistry.

Date	pH	EC	Eh	Temperature
21/12/2010	7.7	64 mS/m	–35 mV	21.0°C

9.7.11 Broederstroom Spring

The Broederstroom Spring water chemistry is characterized by the following field variables.

Date	pH	EC	Eh	Temperature
21/12/2010	7.3	49 mS/m	–13 mV	22.8°C

Holland (2007) reports the following values for the listed isotope variables. The tritium value of 5.2 TU is the greatest of any spring water in the COH WHS for which a ^3H value is known. It indicates a relatively young groundwater that is probably associated with a shallow groundwater system. This observation finds support in the higher than normal ambient spring water temperature of ~23°C as indicated above.

Date	δ^2H	$\delta^{18}O$	^3H
ca. 2006[61]	−29.2‰	−5.37‰	5.2 TU

9.7.12 Krugersdorp Game Reserve Springs

A description of the springs enumerated in the Krugersdorp Game Reserve (KGR) is given in section 8.5.12 and Table 67. These springs are important for the reason that they reflect the chemistry of groundwater in the receiving subsurface environment located immediately downstream of the locus of decant. This was recognized as early as mid-2003, when the DWA commenced water quality monitoring at some of these sources (Table 8 and Table 11).

[60] See footnote 56.
[61] See footnote 50

The results of recent field variable measurements carried out at the springs are reported in Table 72. Especially the elevated EC values distinguish those springs which deliver a compromised groundwater quality (indicative of an impacted resource) from those that drain an unimpacted resource.

Table 72. Recent field water chemistry parameters of springs in the KGR.

Spring	Date (dd/mm/yyy)	EC (mS/m)	pH	Eh (mV)	Temperature (ºC)	Source aquifer
Spring 1/SP1/F6S7	24/11/2010	79.4	6.1	48.4	18.2	Karst outlier
CSIR30/Spring 2	24/11/2010	90.2	6.0	55.0	17.9	Karst outlier
CSIR63/Spring 3	24/11/2010	101.2	5.9	58.3	17.7	Karst outlier
Poplar Spring/SP2/F8S9	24/11/2010	90.9	5.4	85.2	17.6	Karst outlier
Lodge Spring	24/11/2010	12.6	5.3	92.2	19.2	Wits quartzite
Aviary Spring	24/11/2010	201	7.3	–16.5	17.2	Zwartkrans Compartment
Flip-se-Gat Spring/SP3	24/11/2010	21.5	8.2	–61.3	19.1	Zwartkrans Compartment

It is shown in Table 7, Table 11 and Table 14 that the groundwater produced by the spring sources SP1 and SP2 is subject to routine chemical analysis by various parties. Further, the spring SP3 is included in this programme as per the current DWA directive (Table 14). The results of the RU monitoring are reflected in Figure 94, which shows the mean inorganic chemical composition of the groundwater produced by these sources in the period September 2009 to May 2010.

It is evident that the source SP2 delivers the most impacted groundwater with a distinctive Ca-SO_4 composition that reflects the 'strong' mine water influence at this location. This is also reflected in the surprisingly low pH value of 5.1 associated with this water. A possible explanation for such a low pH is that the source aquifer includes quartzitic strata which have been shown to produce low pH groundwater with a very low total alkalinity (section 9.2.1.1). A similar but more muted impact is reflected in the chemical composition of the SP1 groundwater chemistry. By comparison, the source SP3 produces typical fresh (unimpacted) CaMg-HCO_3 composition dolomitic water draining from the largely unimpacted area of smallholdings to the west.

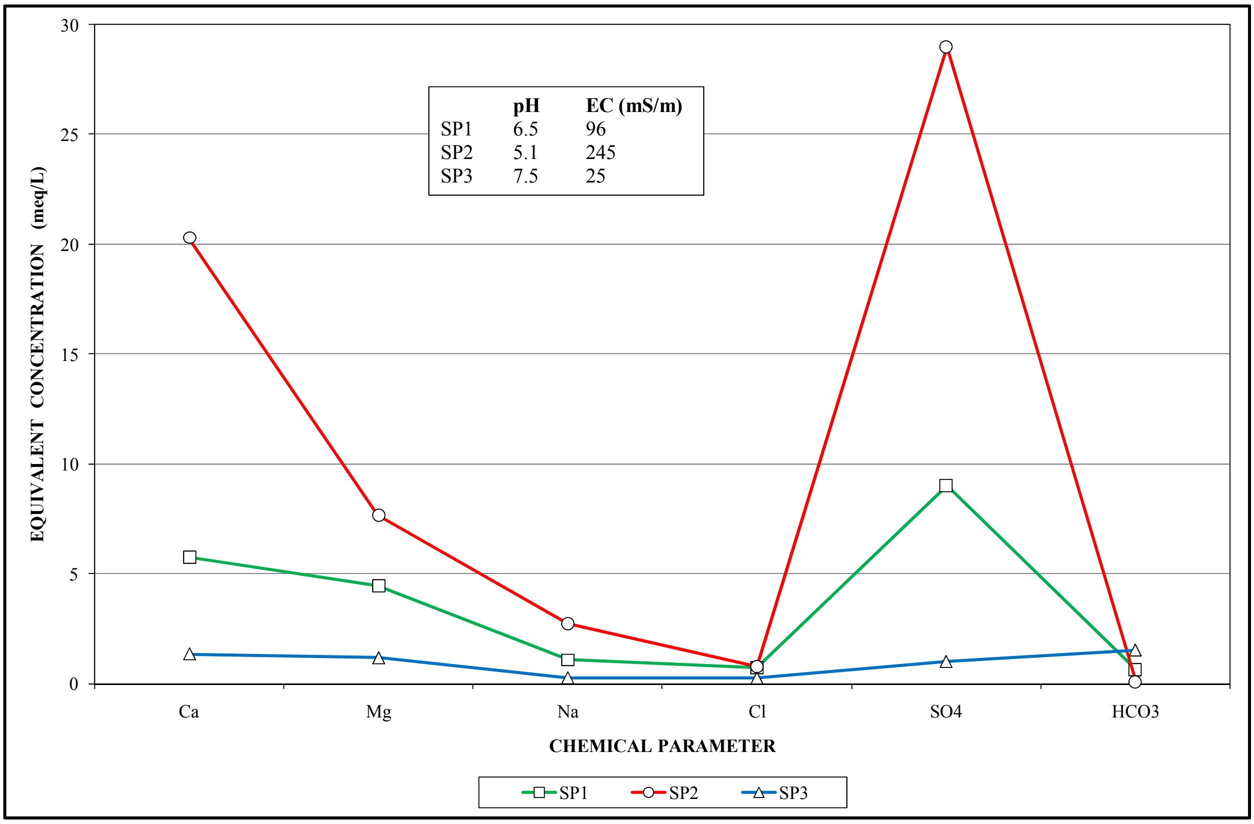

Figure 94. Comparison of water chemistry associated with monitored springs in the KGR.

The salinity (EC) and SO_4 trends associated with the water recently produced by the three monitored springs in the Krugersdorp Game Reserve are shown in Figure 95 and Figure 96 respectively. Whereas spring source SP1 shows no trend in these variables, the source SP2 reflects similar trends that are not readily explained in terms of the measure of variability exhibited.

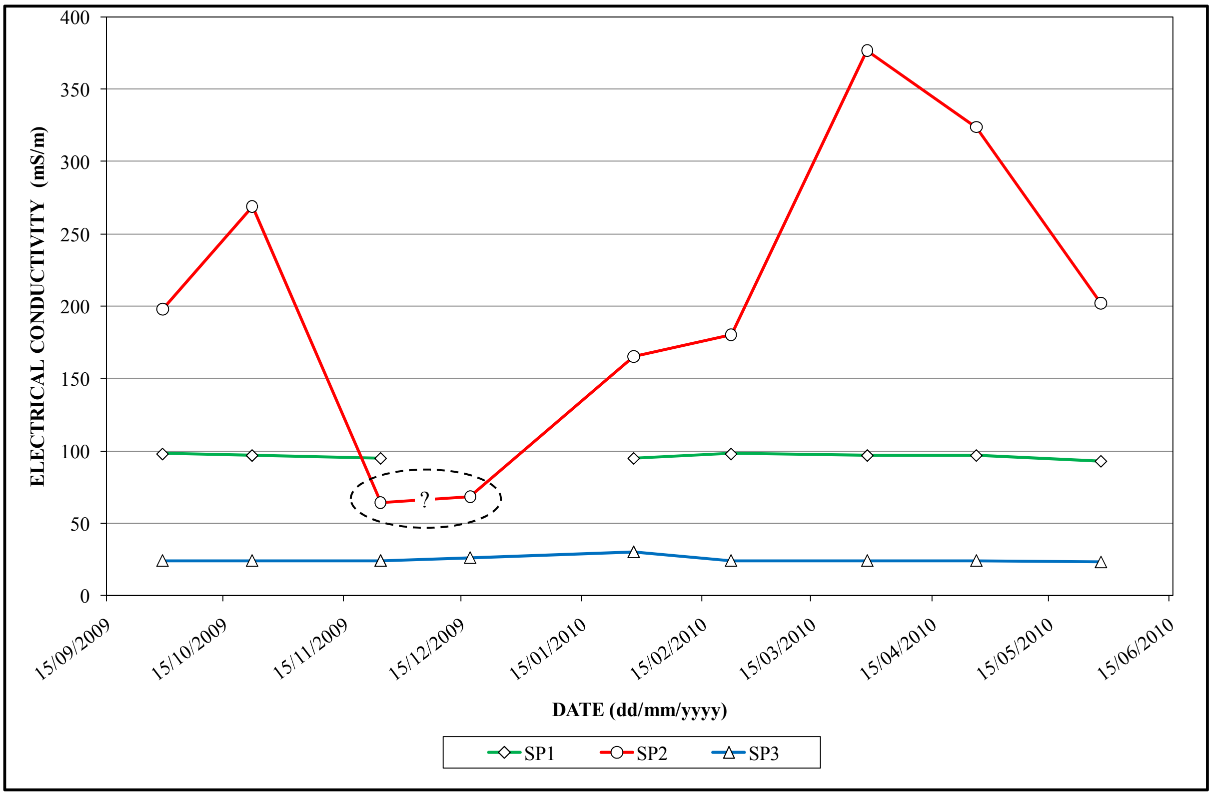

Figure 95. Salinity trend observed in water produced by monitored springs in the KGR.

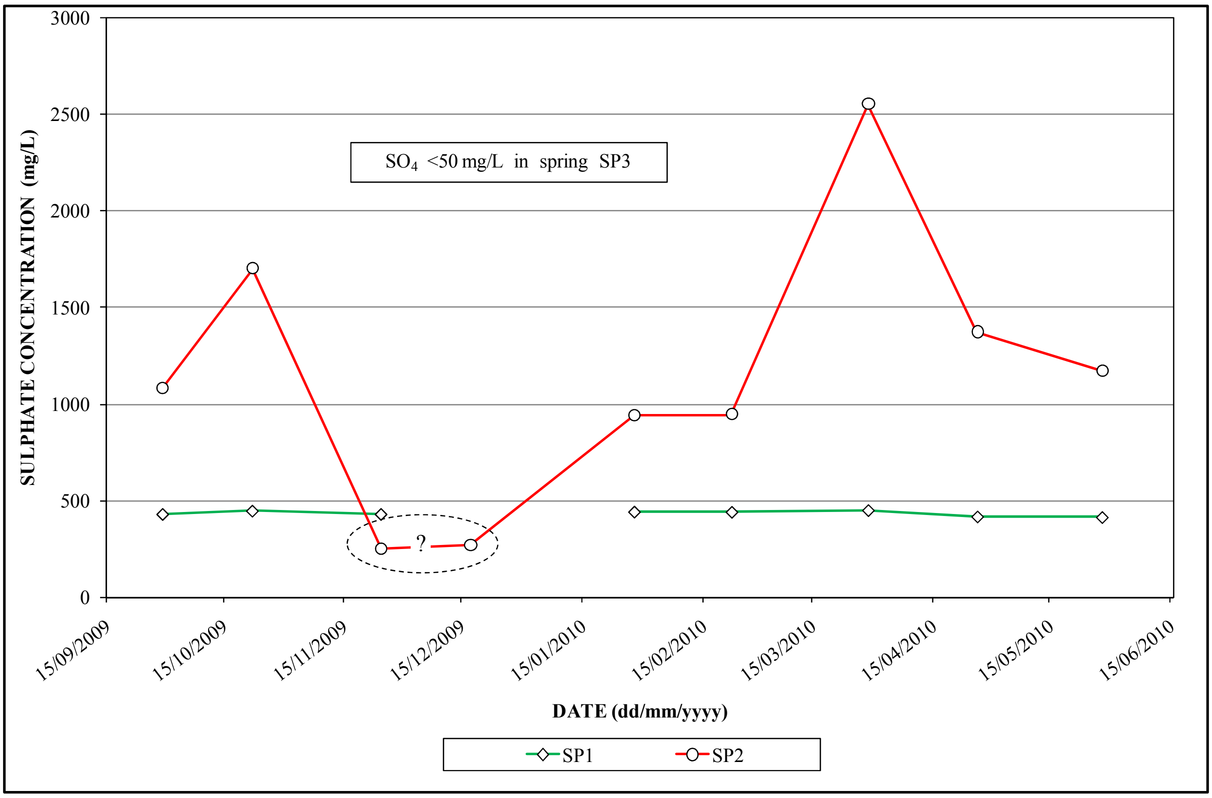

Figure 96. Sulphate trend observed in water produced by monitored springs in the KGR.

9.8 Agricultural Impacts

The impact of agriculture on the quality of groundwater resources is assessed on the basis of analytical results for pesticide residues in water. Groundwater samples collected from two boreholes (CSIR8 and CFM1) in the Oaktree area were subjected to multi-residue pesticide analysis by the South African Bureau of Standards (SABS) Chromatographic Services. These sources were selected for their position in proximity to and down-gradient of intensive agricultural activity including the tunnel farming of flowers for export (Figure 97). The results are presented in Supplementary Report C appended to this document. These show that no residues were detected in either of the samples. Similarly, Groenewald (2010) reports that no knowledge of pesticide contamination is currently available. Although these circumstances suggest that no impact is present, future groundwater quality studies might further inform this aspect.

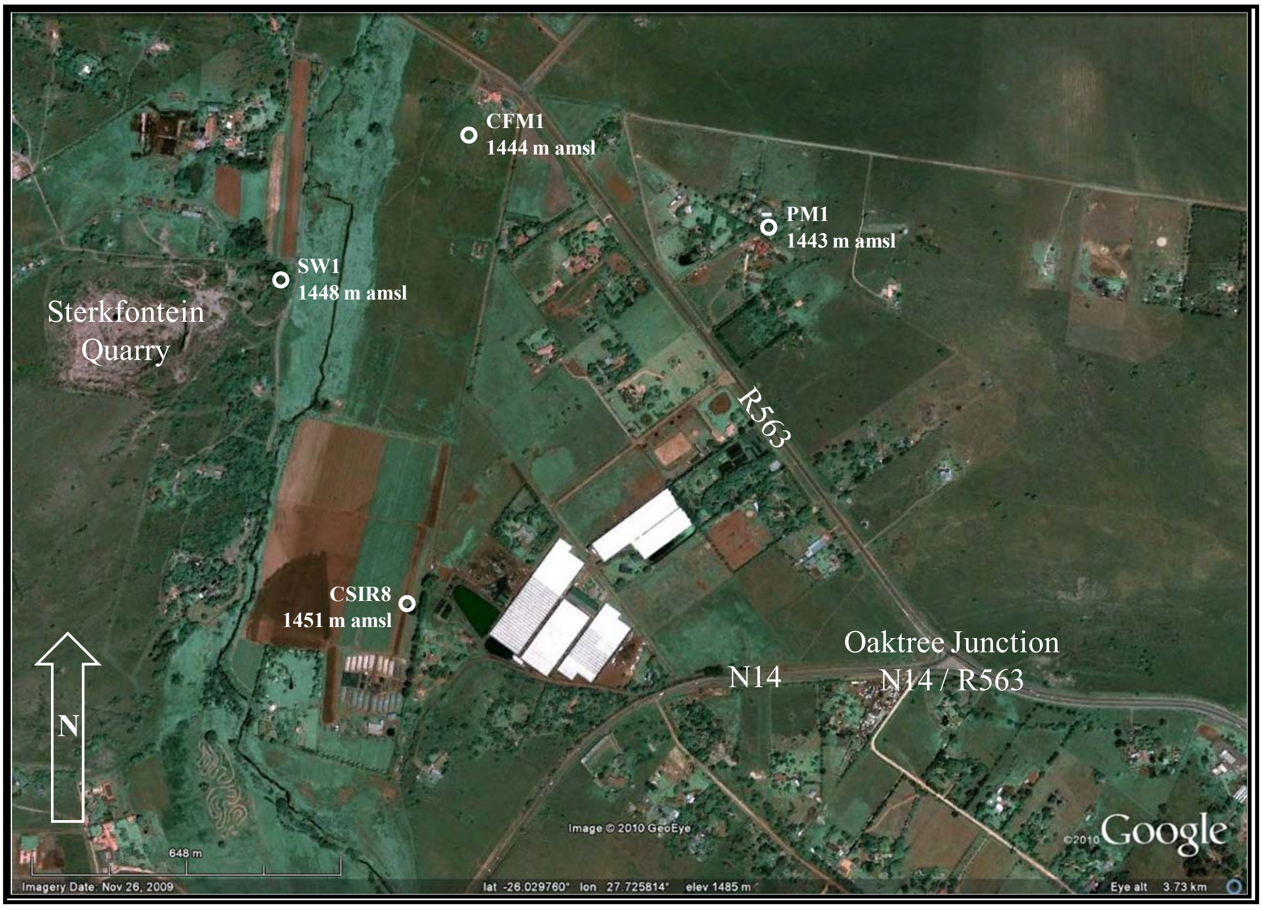

Figure 97. Locality map of pesticide residue sample sources CSIR8 and CFM1.

9.9 Groundwater Fitness

9.9.1 Potable Use

The project has defined the quality of groundwater resources in by far the greater portion of the study area as being suitable for human consumption in terms of the SANS 241 (2006) standard for drinking water quality. This does not, of course, provide solace to those groundwater users who have experienced a compromized quality of groundwater due to extraneous impacts associated with mine water and municipal wastewater effluent. The extent to which these impacts will extend into the broader hydrogeologic environment will be described by the water resources monitoring programme established as an outcome of this project.

At present, the impacts would appear to be reasonably well restricted to the area defined by the congruence of the mine water and wastewater effluent sources in the Sterkfontein Subcompartment and south-eastern portion of the Zwartkrans Subcompartment, respectively. In these areas, the groundwater chemistry reflects electrical conductivity values >100 mS/m, SO_4 concentrations >150 mg/L, and Cl concentrations >50 mg/L. However, the levels of the variables EC and SO_4 exceed their respective SANS 241 (2006) Class 1 drinking water limits of 150 mS/m and 400 mg/L, respectively, in only four of the 51 sampled groundwater sources. All four of these sources are located in proximity to the Riet Spruit upstream of Oaktree.

The presence of heavy metals in both the mine wastewater and the municipal sewage wastewater also raises a concern for the potability of groundwater resources in the study area. As shown in section 10.2, the presence of heavy metals such as Al, Co, Mn, Ni and Zn could not be detected (for the specified detecton limits reported in section 9.9.3) in the groundwater from sources otherwise reflecting the most impacted quality in terms of EC and SO_4. The association of radionuclides with mine water raises a further concern. However, it is shown in section 9.5.2.2 that none of the groundwater samples exhibited a U concentration greater than the detection limit of 0.001 mg/L.

The above observations suggest that the fitness of groundwater in the study area for potable use is not unduly compromized by inorganic elements, trace/heavy metals or radionuclides. However, the observed presence of bacteriological contamination in some sources (refer section 9.6) cautions against the unqualified use of groundwater for drinking water purposes.

9.9.2 Agricultural Use

9.9.2.1 Livestock Watering

Guidelines in this regard are provided in the DWAF (1996b) publication. The target water quality range (TWQR) limits for the major inorganic variables are typically less strict than for human consumption. For example, the TWQR for SO_4 (a variable that effects the palatability of water also for livestock) is 1000 mg/L compared to the 400 mg/L for humans. This is also true for trace/heavy metals, e.g. Mn and Fe <10 mg/L for livestock compared to <0.1 and <0.2 mg/L, respectively, for humans. Even the observed presence of bacteriological contamination in some groundwater sources (refer section 9.6) is mitigated by the faecal coliforms TWQR of <1000 c/100 mL in 20% of samples, compared to the <10 c/100 mL in 1% of samples for humans. Under circumstances where the highest total coliform count (which includes faecal coliforms) recorded in this study for groundwater amounted to 500 c/100 mL, the fitness of groundwater in the study area for livestock watering is not unduly compromized by inorganic elements, trace/heavy metals or bacteriological considerations.

9.9.2.2 Irrigation

An analysis of the 51 groundwater chemistry analyses generated by this study returned mean and median SAR values of 0.52 and 0.27, respectively. The Wilcox diagram reflecting the classification of all 51 analyses is presented in Figure 98. It is evident from Table 73 that the mean value is matched or exceeded in only three compartments/subcompartments. Significantly, these are the compartments that receive allogenic recharge from the poorest quality surface water sources (sections 4.2.2 and 5.1.2).

Table 73. Range of SAR values for compartments/subcompartments in the study area.

Compartment/ Subcompartment	Range of SAR Values				Classification per Mean(1)
	n	Minimum	Mean	Maximum	
1a	6	0.07	0.27	0.65	C2-S1
1b	7	0.78	1.10	1.78	C3-S1
1c	11	0.40	0.99	1.99	C3-S1
2a	9	0.04	0.16	0.27	C2-S1
2b	7	0.11	0.50	0.91	C2-S1
3	2	0.03	0.07	0.12	C1-S1
4	2	0.03	0.03	0.04	C2-S1
5	1	0.03			C2-S1
6	2	0.09	0.10	0.12	C2-S1
7	1	0.03			C2-S1
(1) Where applicable.					

Nevertheless, the classification of the groundwater for irrigation use (refer section 5.4.2.2) is no worse than a C3-S1 quality class rating as illustrated in Figure 99. More typically, however, it exhibits a C2-S1 rating, which allows its use for the irrigation of crops with a moderate salt tolerance on soils where a moderate amount of leaching occurs.

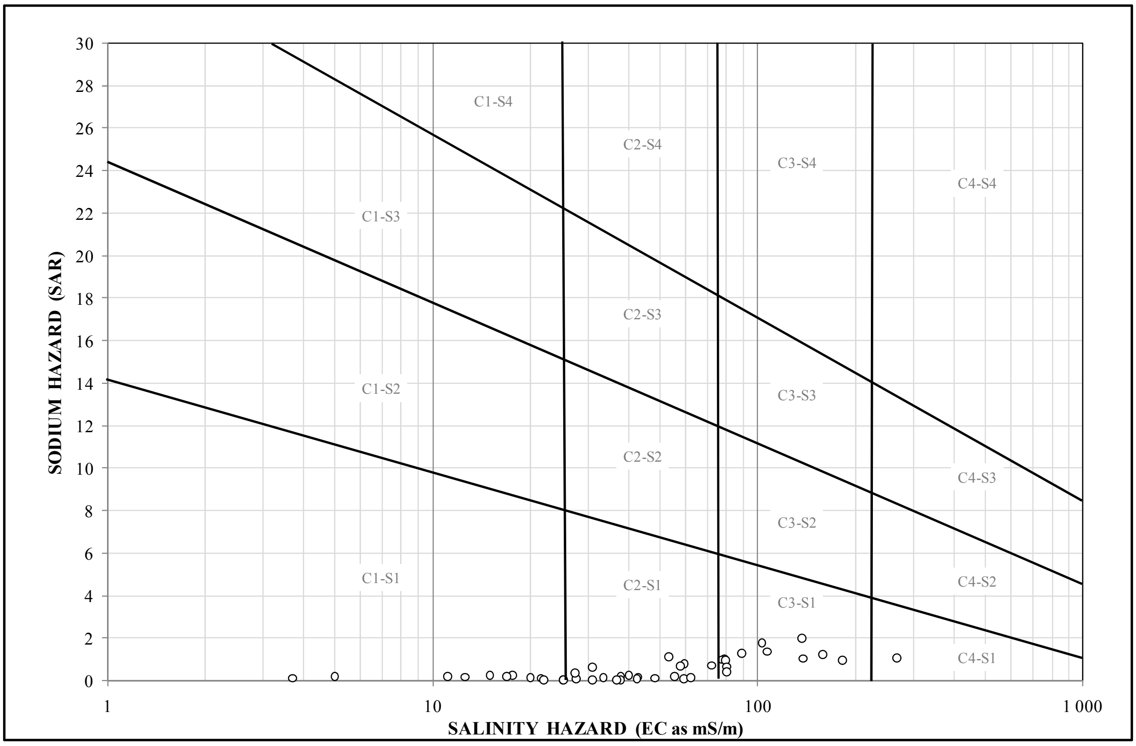

Figure 98. Wilcox diagram illustrating the classification of groundwater chemistry in the study area for irrigation purposes.

Figure 99. Wilcox diagram illustrating the classification of groundwater chemistry per GRU for irrigation purposes.

9.9.3 Cave Ecosystems

The fitness of groundwater quality in regard to cave ecosystems is important where the latter intersect the water table and provide refugia for stygobitic (groundwater) fauna (Tasaki, 2006), also referred to as stygobionts or stygofauna (aquatic species) by Culver and Sket (2000; 2002). As far as could be established, such biota (typically blind amphipods) have been found in Sterkfontein Caves and two other caves (Koelenhof and Yom Tov) in the study area (Tasaki, 2006). Durand and Peinke (2010) indicate that certain amphipod species (notably *Sternophysinx transvaalensis*) are also associated with springs in the John Nash Nature Reserve. Since this report is concerned with water resources, the consideration of subterranean (cave-dwelling) terrestrial species (troglobitic fauna or troglobionts) is not considered. However, Durand and Peinke (2010) indicate that the humidity levels associated with 'wet' caves might be an important environmental factor for resident bat colonies.

The impact of pollution effects on cave systems is related to the same factors that inform the contamination of surface water and/or groundwater resources. These have previously been recognized as elevated nutrients (nitrate and phosphorus) associated with municipal wastewater effluent and agricultural return flows, and trace metals associated with wastewater effluent and mine water. The treated wastewater and/or agriculturally derived nutrients promote eutrophication in surface water systems through photosynthesis. However, the absence of sunlight in cave ecosystems precludes the excessive growth of aquatic vegetation in the subterranean environment (Graening and Brown, 2000; Boulton et al., 2003). These authors recognize the negative impacts of organic pollution on cave ecosystems as being related to the following:

- alteration of the community assemblage;
- impoverishment of biodiversity; and
- increased risk of predation from surface fauna.

Culver and Sket (2002) identify the usual sequence of eutrophic impacts in caves as an initial increased population size of stygobites, followed by increased population sizes of non-specialized species usually accompanied by a decline in population sizes of stygobites, and culminating in the extirpation of the latter. Since population increases in the food-poor environment of caves usually means an increase in available food (typically associated with eutrophication), observations of such a trend through routine biomonitoring activities offers an early warning of potentially catastrophic longer term impacts on stygobitic fauna (Culver and Sket, 2002).

Graening and Brown (2000) recognize that increased concentrations of Pb and Zn in cave water are manifested in the accumulation of these trace metals in cave sediments and the tissues of cave organisms rather than in their biomagification in the food chain. This is identified as a concern under circumstances where heavy metals might be present in concentrations that are acutely toxic to aquatic organisms.

The chemical analysis of a Sterkfontein Caves water sample collected on 13/05/2010 (section 9.2.3.2) returned a NO_3-N concentration of 8.2 mg/L and a PO_4-P concentration of <0.2 mg/L, but revealed no concentrations of the following trace metals above the specified detection limits.

Detection limit	Variable
≥0.100 mg/L	Al
≥0.025 mg/L	Ag, B, Ba, Be, Bi, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Sn, Sr, Ti, V, W, Zn, Zr
≥0.020 mg/L	Pb, Se
≥0.010 mg/L	As, Sb
≥0.005 mg/L	Cd

Whether the detection limits mask the possible presence of trace metals that at lower concentrations might still constitute a threat to the continued existence of stygobionts in the Sterkfontein Cave system is beyond the scope of this study. Further, it is important to note that single measurements of inorganic nitrogen (NH_3, NH_4, NO_2 and NO_3) are a poor basis for assessment (DWAF, 1996a). The likely biological consequences (at least in surface water systems) are best estimated from average summer inorganic nitrogen concentrations. Nevertheless, the concurrently low PO_4 concentration and the absence of sunlight suggest that the trophic status of the Sterkfontein Caves water system is unlikely to change despite the elevated NO_3+NO_2 concentration, provided the current hydrochemical conditions prevail. Assurance in this regard can be obtained from regular biomonitoring programmes (as described by Culver and Sket, 2002) that target stygobitic fauna. Schneider and Culver (2004) have shown that focussing on the largest caves improves sampling efficiency for both terrestrial and aquatic underground species.

In support of Kenyon and Ellis (2010), it is also recommended that any cave biomonitoring programme that is implemented in the COH WHS area includes the participation of recognized caving associations and their members. The contribution of such I&APs, especially if these include knowledgeable and experienced local 'cavers', will extend the benefit of biomonitoring activities to less well-known and frequented caves.

In conclusion, it is acknowledged that cave ecosystem monitoring extends well beyond the water resource environment alone. In the interests of 'integrated monitoring' across a broad spectrum of disciplines and environments, the PSP therefore supports the monitoring requirements put forward by Durand and Peinke (2010) in regard to the karst ecology of the COH WHS.

10 ASSESSMENT OF MINE WATER IMPACT ON DOLOMITE

The dissolution of dolomitic strata (carbonate rocks) is a naturally occurring phenomenon. Brink (1996) reports AL du Toit's (1954) calculation that the Gerhardminnebron Eye draining the Gerhardminnebron Compartment in the Lower Wonderfontein Spruit at a rate of 57 ML/d as removing over 10 tons of dolomite in solution daily. Given the density of dolomite as 2850 kg/m^3 (Ford and Williams, 2007), this represents the creation of a void volume at a rate of ~3.5 m^3/d (~1280 m^3/a). Similarly, Swart et al. (2002) report the De Kock (1964) analyses of spring water draining the Wonderfontein Valley as containing ~200 kg of dissolved limestone per million litres (200 mg/L $CaCO_3$). For a discharge of 200 ML/d, this implies the removal of >40 tons of limestone daily from this karst system. At a rate of ~14 m^3/d, this represents the development of a void volume of ~5110 m^3/a. A comparison with the Du Toit (1954) calculation reveals a similar dissolution-to-flow rate ratio of ~0.2 t/ML indicative of, amongst other factors, similar groundwater chemistry.

In light of the above, the geochemical interaction between acidic mine water and the dolomitic strata that build the receiving karst aquifer in the study area is the subject of much conjecture. The two main hypotheses are summarized as follows:

- The possible dissolution of the dolomitic strata (carbonate rocks) by low pH mine water, and the associated potential risk of increased subsurface instability and land subsidence. This process adds alkalinity to the groundwater system through the release of bicarbonate (HCO_3) according to the reaction

  $$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^{-}$$

  Scott (1995) reports the 'consumption' (dissolution) of dolomite in the East Rand Basin as ranging from ~0.9 t/d (321 t/a) to ~18 t/d (~6400 t/a) for 'flow' rates of 1 ML/d (most realistic) and 20 ML/d (worst case scenario), respectively, for 'modelled' East Rand Basin water. These values represent void volumes of ~115 to ~2250 m^3 being created annually, i.e. at a rate of ~0.3 to ~6 m^3/d. They also represent a dissolution-to-flow rate ratio of ~0.9 t/ML, which is nearly five times the value associated with 'pristine' karst groundwater.

- The precipitation of oxyhydroxides on the surface of the dolomite within fractures and karst features according to the reaction

  $$4Fe^{2+} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^{+}$$

  which results in armouring of the strata, inhibiting any further dissolution and reaction(s) that lead to neutralising acidity in the water.

Apart from the dissolution of carbonate rocks, however, a second main source of positive alkalinity in mine drainage is SO_4 reduction / organic matter oxidation (Kirby and Cravotta, 2005). This releases HCO_3 to solution according to the reaction

$$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^{-}$$

where $2CH_2O$ represents organic matter.

It has previously been reported (section 5.1.2.2) that the treated effluent discharged from the Percy Stewart WWTW carries an elevated bacteriological and nutrient (N, P and COD) load (see Table 33, Table 35 and Table 36). Further, that this water also enters the karst aquifer at a rate of ~7 ML/d (section 4.2.2.2). This water mixes in the subsurface with the similarly infiltrating mine water (section 4.2.2.1) in the area around the confluence of the Riet and Blougat spruits upstream (west) of Oaktree. These circumstances reflect the addition of an organic matter component that potentially promotes the in situ process of 'natural' bioremediation associated with the generation of alkalinity through bacteriological (dissimilatory) sulphate reduction (Knoeller et al., 2004) in this portion of the karst aquifer.

10.1 Dolomite Leaching/Armouring Studies

10.1.1 Previous Work

Krige (2009) reports on studies carried out by DD Science Laboratory cc., using the acid-base titration method employed in standard acid base accounting (ABA) determinations, to establish the neutralization potential of dolomite ($CaCO_3$) toward raw mine water from the decant area. The outcome suggested that 1 ML of mine water would dissolve 900 kg of $CaCO_3$, in the process creating a void of ~0.32 m^3. By extrapolation of the volume of mine water that had entered the karst aquifer since the commencement of decant in August 2002 up until the 'capture-and-control' of this discharge *ca.* February 2005, Krige (2009) reports a total void volume of ~4500 m^3 that potentially had developed in the karst aquifer in this time Further, it was suggested by Krige (2009) that this volume could be doubled (i.e. to ~9000 m^3) due to the additional carbonic acid (H_2CO_3) generated by the reaction between mine water and dolomite creating an equivalent volume of karst dissolution. These figures, and even more recently a figure of 16 700 m^3 (Liefferink, 2010), have been reported in the public domain. Establishing the veracity of these figures is therefore crucial to arrive at an informed assessment of this phenomenon.

As indicated, the procedure followed in the above-mentioned assessment used raw mine water in the calculation. The karst aquifer that receives this water is, however, located north of the Krugersdorp Game Reserve a distance of some 4.9 km from where the mine water enters the environment (Table 50 and Table 51). In the course of its flow down the Tweelopie Spruit, this water cascades over a number of 'obstacles', e.g. the waterfall over the quartzite ridge to the south of the Ngonyama Lion Lodge in the KGR, the overflow of the Charles Fourie Dam at the lodge, the overflow of the Aviary Dam where this water leaves the KGR, and the causeway at station F11S12 (Plate 13). The cascading action serves to thoroughly aerate the water, which causes iron to precipitate out of solution. As a consequence, the chemical composition of the mine water has changed significantly by the time it reaches the area where it drains into the karst aquifer of the Zwartkrans Compartment. The nature of this change is shown by comparison of the long-term median concentration of elements monitored at the BRI (representative of raw mine water chemistry), with that of these elements monitored at station F11S12 for both the entire record and the early record. This is shown in Figure 100 (see Table 74 for data), which reflects the very different SO_4 and Fe concentrations in the water at the two monitoring stations.

Plate 13. Cascade and aeration of water over the causeway at station F11S12 (see Plate 4 for scale of monitoring station). (Photo: Phil Hobbs).

The procedure described by Krige (2009) also indicates the use of hydrochloric acid (HCl) to determine the mass of dolomite involved in a reaction between the mine void water and the acid according to the reaction $2HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O$. The appropriate acid to use would be sulphuric acid (H_2SO_4). It is suggested, therefore, that the use of raw mine water and HCl in the acid-base titration exercise does not reflect the 'real-world' situation. This exercise would need to be repeated with H_2SO_4 and surface water having a composition similar to that recently obtained at stations F11S12 and MRd1 (see Table 39) in order to have more direct and current relevance to the study area.

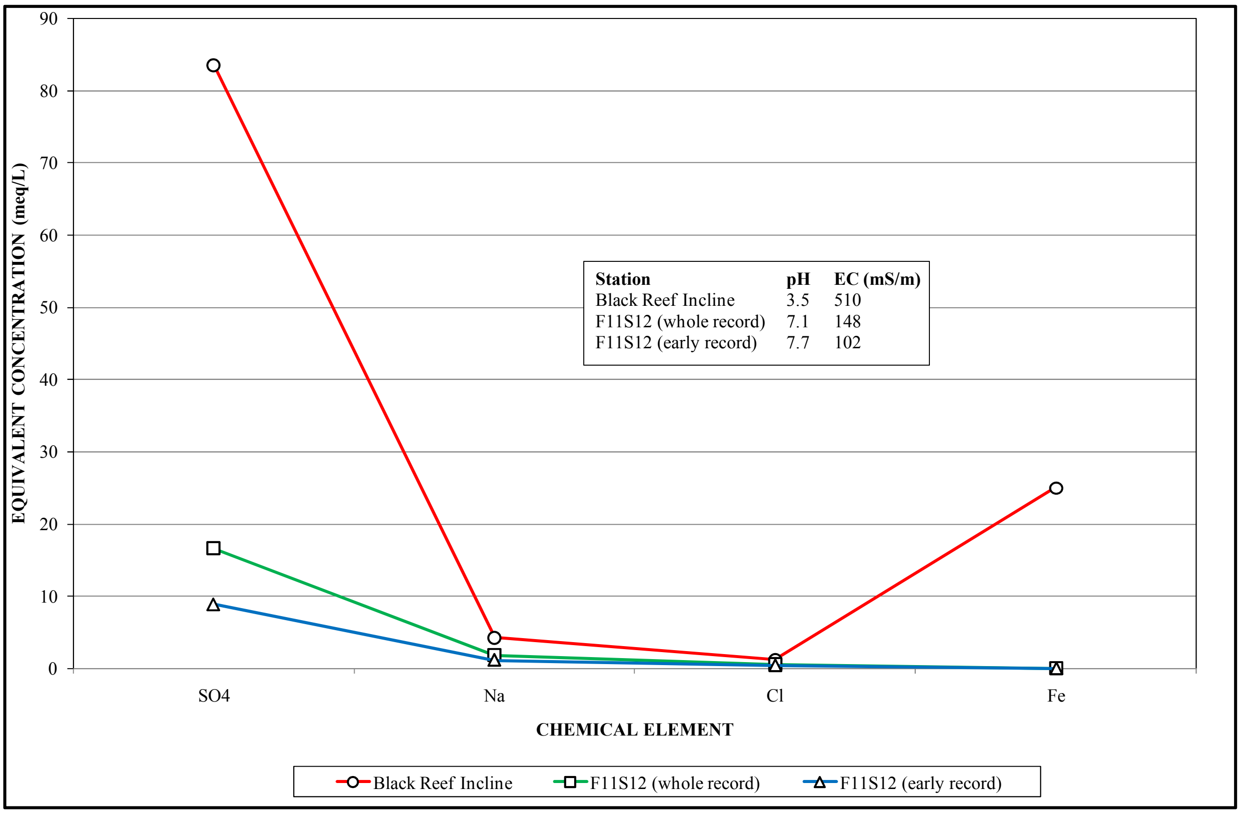

Figure 100. Comparison of raw mine water and downstream surface water chemistry.

Table 74. Water chemistry data used in Figure 100 to compare raw mine water from station BRI with Tweelopie Spruit surface water at station F11S12.

Station	**Variable Median Value and Count (n)**					
	pH	**EC (mS/m)**	**Na (mg/L)**	**SO_4 (mg/L)**	**Cl (mg/L)**	**Fe (mg/L)**
Black Reef Incline(1)	3.5	510	97	4010	40	697
	n = 231	n = 231	n = 222	n = 231	n = 223	n = 231
F11S12 (whole record)(2)	7.2	148	44	797	21	0.014
	n = 53	n = 52	n = 53	n = 52	n = 53	n = 53
F11S12 (early record)(3)	7.7	102	27	425	15	0.014
	n = 16	n = 16	n = 16	n = 16	n = 16	n = 16

(1) Covers the period 04/2005 to 09/2009.
(2) Covers the period 11/2003 to 08/2008.
(3) Covers the period 11/2003 to 01/2005.

10.1.2 Results of this Study

In order to further inform the topic of dolomite dissolution in regard to the potential impact on the karst environment of the COH WHS, various studies were carried out by the Council for Geoscience (CGS). These entailed a comparative petrographic study, as well as laboratory-based column leaching tests. The outcome of these studies is reported in the following sections.

10.1.2.1 Petrographic Study

A comparative study of dolomite samples before and after exposure to acid mine drainage (AMD) was carried out by the Petrographic Laboratory of the CGS. The outcome is documented in Supplementary Report D appended to this document.

Portions of two polished thin sections of a sample of dolomite were photographed under magnification before and after being exposed to acid mine water. Any changes associated with the exposure to the mine water were studied petrographically under a microscope using both plane polarized light (PPL) and cross polarized light (XPL). A comparison of the ‘before’ and ‘after’ photomicrographs allowed for a qualitative assessment of observed changes/differences. Based on the following observations, it appears that partial dissolution of the dolomite occurred on exposure to acid mine water.

- A lower apparent birefringence after exposure compared to before exposure. This is most likely attributable to a loss of thin section thickness during exposure.

- Greater definition (under magnification) of carbonate grain boundaries after exposure.

- Preferential exploitation of cleavages within carbonate grains, resulting in greater definition of cleavage patterns in the post-exposure image.

- In some instances, a decrease in carbonate grain size following exposure.

Scanning electron microscopy (SEM) is recommended to identify any reaction products or precipitates present within or coating the thin sections following exposure.

10.1.2.2 Laboratory Kinetic Testing

A kinetic (column leaching) experiment was devised by the CGS using synthetic AMD prepared in the laboratory as a leachant to closely mimic the bulk composition of Western Basin AMD while maintaining the iron in a dissolved state. The composition of this leachant is reported in Supplementary Report E appended to this document. The pH was adjusted to a value of 3.6 using H_2SO_4. The leachant was passed through five columns packed with dolomite of different size fractions (refer Table 3 in appended Supplementary Report E) at a slow rate (0.1 L/kg/d) to simulate that of groundwater flow through a dolomitic aquifer.

The kinetic tests revealed the following processes occurred during the interaction between dolomite and synthetic AMD solutions:

- dissolution of the dolomite as indicated by the neutralisation of the AMD at sufficiently high solid to liquid ratios; whether this will lead to the development of new cavities (or the enlargement of existing cavities) within the affected dolomitic areas cannot be determined, as this will be influenced by a combination of the flow rate, the surface area exposed and the rate at which mineral precipitation armours the reactive surface of the dolomite within the aquifer;
- precipitation of new minerals as identified at both macro- and micro-scales using optical and scanning electron microscopy respectively; the minerals that precipitate will depend on the chemistry of the input solutions as well as the Eh-pH conditions under which precipitation occurs;
- armouring of the dolomite surface with reaction products, reducing the quantity of reactive material exposed;
- an increase in the pH of the solution, reducing the solubility of a number of its components; iron and aluminium are almost completely attenuated, manganese is partially attenuated with an apparent strong dependence on the available reactive surface area, while sodium and sulphate are not attenuated significantly; and
- increased concentrations of calcium and magnesium as a result of the dissolution of dolomite, with an apparent preferential dissolution of calcium over magnesium, in the final solutions produced by the tests.

10.1.2.3 Conclusions

The likely effects of AMD ingress into the karst aquifer(s) of the COH WHS will be a rise in the pH of the influent mine water (as a result of the dissolution of dolomite) to a value comparable to that of the ambient karst groundwater. This might lead to a structural weakening of the subsurface formation if the process continued over a long period of time without the dolomite surfaces becoming armoured. The rise in pH would result in the reduction of the solubility of some of the contaminant species in the mine water, significantly removing iron and aluminium from solution, partially removing manganese and not having a significant effect on the sodium or sulphate concentration. The metal precipitates, which would include gypsum, goethite and crystalline and amorphous (botryoidal) aluminium oxy-hydroxide species, are likely to form on the reactive surfaces of the dolomite, preventing further neutralisation reactions from taking place. Influent mine water would therefore tend to react at the point of first contact with the dolomite, resulting in both neutralisation of the mine water and the prevention of further neutralisation from taking place. Over time the mine water would migrate further and further into the karst aquifer, and the buffering capacity of the aquifer would reduce progressively.

In conclusion, natural attenuation of AMD by allowing it to enter dolomitic aquifer systems is not regarded as an appropriate or sustainable management strategy.

10.2 Bacterial Sulphate Reduction

The possibility that this process might be occurring in that portion of the karst aquifer where mine water entering the groundwater environment encounters infiltrating wastewater effluent must be considered. The organic matter associated with the latter might serve as the driving reductant, and positive indications in this regard are the comparatively low SO_4 and trace metal concentrations in groundwater in this portion of the Zwartkrans Compartment. The process reduces SO_4 to H_2S (hydrogen sulphide), which in turn reacts with metal ions such as Pb, Cu, Hg and As to form metal sulphides. The availability of excess Fe-oxide may consume all H_2S present in the groundwater (Appelo and Postma, 2009). The precipitation of metal sulphides out of solution in a reducing (anaerobic) environment leads to a reduction in the concentrations of these metals in the groundwater. This possibility is demonstrated in Figure 101.

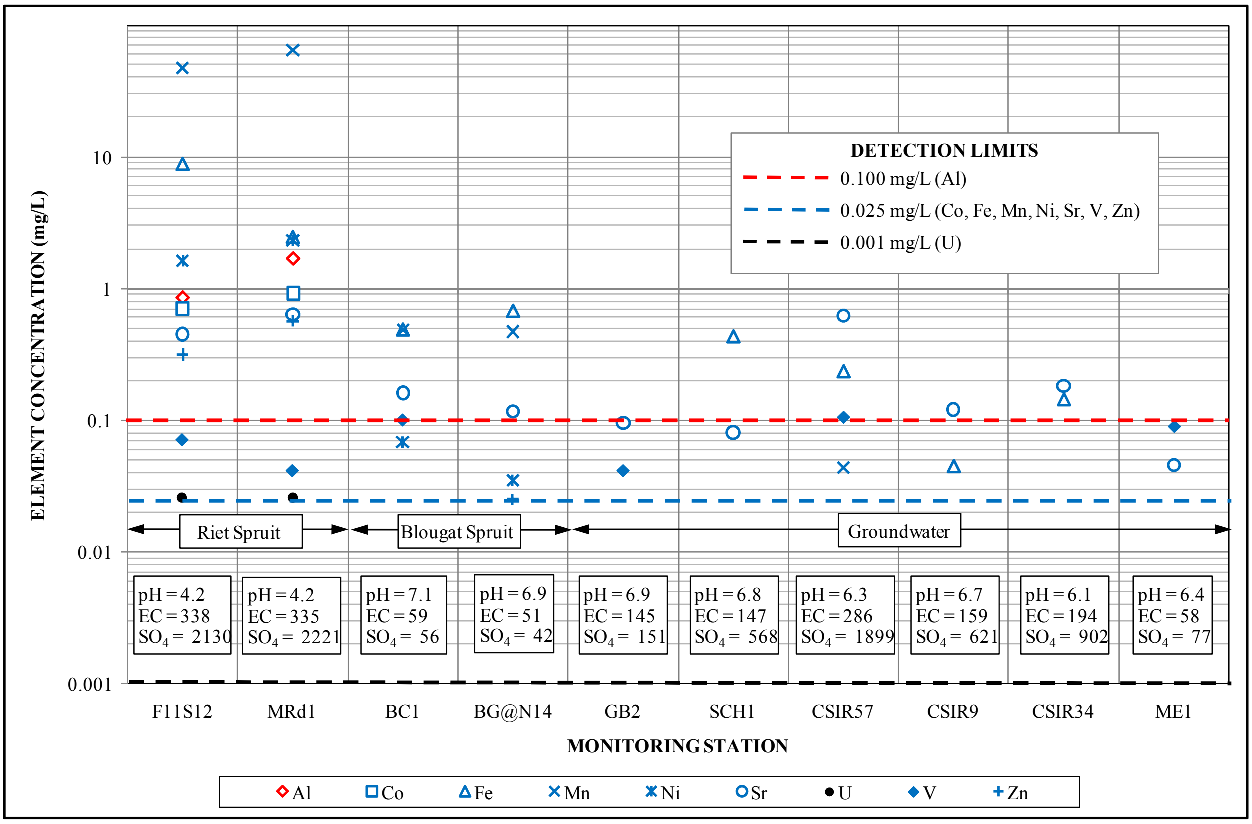

Figure 101. Comparison of trace metal and other parameter concentrations in surface water and adjacent groundwater sources (EC values as mS/m; SO_4 values as mg/L).

Figure 101 shows the larger number of trace metals exhibiting elevated concentrations in the Riet Spruit surface water compared to those in the Blougat Spruit. Significant in the latter regard are Fe, Mn and Ni. A further observation is the ubiquitous presence of Sr and, to a lesser extent Fe and V, in both surface water and groundwater sources.

Perhaps most significantly, however, is the indication of the undetectable presence (for the specified detection limits) of metals such as Al, Co, Mn, Ni, U and Zn in the groundwater. This observation lends support for the possible manifestation of BSR in the karst aquifer.

The above discussion finds support in a study by Strosnider and Nairn (2010), who demonstrated that concentrations of various trace metals including Al, As, Cd, Cr, Fe, Pb, V and Zn reduced significantly when incubated in a mixture of acid mine water and municipal wastewater (see also Omoike and Vanloon, 1999; Johnson and Younger, 2006). In essence, the mixing of these two environmental 'liabilities' is likely to generate beneficial reactions such as the following:

- the dilution of AMD hydrogen ion concentrations leading to reduced solubility of many metals at higher pH;
- the reaction of phosphate with dissolved Al and Fe in AMD resulting in precipitation;
- the binding of many metals to organic ligands present in the municipal wastewater; and
- the organic matter present in the municipal wastewater providing a source of carbon that sulphate reducing bacteria can utilize to generate alkalinity and precipitate metals as sulphides.

It has similarly been demonstrated by Winfrey et al. (2010) that faecal indicator bacteria (FIB) counts reduced significantly when subjected to co-treatment with municipal wastewater and acid mine drainage in an engineered laboratory-scale passive system. Tutu et al. (2008) also attribute the observed increase in pH of AMD-related water in wetlands in the Central Rand Gold Field to desulfurization by bacteria.

10.3 Natural Solutional Denudation

The neutralization of low pH water by the dissolution of carbonate strata has been described at the start of this section. This phenomenon, however, is a natural process in all karst systems, and it is therefore appropriate to examine the phenomenon also in regard to those portions of the study area unaffected by the impact of low pH mine water.

The Corbel formula (reported in Ford and Williams, 2007) is the best known (and simplest) equation for calculating the solutional denudation rate. The equation describes limestone solution (X) according to the formula:

$$X = 4ET/100$$

where E is runoff (dm) and T is the mean $CaCO_3$ concentration (mg/L) of the water.

The application of this formula to the autogenic Danielsrust Compartment (~740 ha), drained at a rate of 28 L/s by the Danielsrust Spring producing water with a $CaCO_3$ concentration of 128 mg/L, returns a solutional denudation rate of ~6.2 $m^3/km^2/a \equiv 6.2$ mm/Ka. The result might be questioned on the basis that the Corbel formula assumes, amongst others but mainly, that all carbonate rocks have a density of 2.5 kg/m^3, whereas dolomite has a density of 2.85 kg/m^3 (Ford and Williams, 2007). Although the formula also incorporates surface denudation, the above result reflects primarily in situ dissolution since in this instance the T value represents the $CaCO_3$ concentration in the 100% autogenic spring water.

11 RESOURCE QUALITY OBJECTIVES

11.1 Introduction

The National Water Act (NWA, 1998) recognizes groundwater resource directed measures (GRDM) as an integral component of water resources assessment. The purpose of GRDM is the evaluation of the importance of groundwater variables in determining the capacity of groundwater resources to maintain a potable water supply function for basic human needs and the environmental sustainability of ecosystems that are dependant on this resource. This relates as much to the status of the groundwater rest level over time, as it does to the quality (chemical composition) of the groundwater. Whereas depressed (lowered) groundwater rest levels are indicative of an over-stressed groundwater resource, regressive (deteriorating) water quality variable values are indicative of contaminating impacts. The study by Holland (2007) represents the application of the GRDM concept in the karst environment of the COH WHS.

A further development regarding the GRDM concept applied to the study area, amongst others, is represented by the published West Rand Dolomite Compartments map at scale 1:85 000 (DWA, 2010b). This map subdivides the study area into groundwater management units[62] (GMUs) and groundwater resource units[63] (GRUs) along much the same lines as defined in section 8.2. However, a flaw of this map is the lack of hydrogeologic support given for the definition of GRUs in the Tweefontein Compartment, which is identified as a groundwater management area[64] (GMA). For example, it reflects the 'Nash Farm Eye' (identified as the Tweefontein Spring in this study with a discharge of ~30 L/s as per section 8.5.6) as representing the outflow from GRU05 in GMU A21G-01, but does not show the much higher yielding Nouklip (~173 L/s, section 8.5.7) and Nash (~130 L/s, section 8.5.8) springs as discharge loci for other GRUs in the north-eastern portion of the map area.

The rationale for including GRDM in this study is the incorporation of this concept in the objective assessment of water resources monitoring in the interests of sustainable basic human needs and ecological water supply requirements. It is **not** considered or presented as a fully-fledged GRDM assessment. It does, however, attempt to provide more quantifiable criteria against which to measure the successful implementation of groundwater resource directed measures than are available from the limited available literature. This is given effect on the basis of resource quality objectives (RQOs) set for both groundwater quantity and quality in regard to identified groundwater resource units (GRUs).

11.2 Groundwater Resource Units

The basic 'building block' of a GRDM assessment is a groundwater resource unit (GRU). The compartments (and subcompartments) identified in section 8.2 represent suitable candidates for recognition as GRUs. A comparison of the extent of the GRUs recognized in this study with those recognized on the DWA (2010b) map is provided in Table 75. The comparison is only made in regard to those GRUs for which an area is reported on the DWA (2010b) map. This excludes the GRUs associated with the DWA (2010b) GMU A21G-01 which encompasses GRUs 4, 5 and 6 of this study, GMU A21G-02 encompassing GRUs 7 and 8 of this study, and GMU A21H-02 encompassing GRUs 9 and 10 of this study. Nevertheless, the comparison made in Table 75 shows a reasonable correlation (within ±6%).

Table 75. Area-based comparative analysis of GRU definition by this study and DWA (2010b).

Definition by this Study			Area (km^2)		DWA (2010b) Definition		Area (km^2)	Difference (%)
Compartment	Subcompartment	GRU			GMU	GRU(s)		
Zwartkrans	Vlakdrift	1a	23.6		A21D-01	01 + 02	22.9	+3
	Sterkfontein	1b	24.5		A21D-02	08 + 10 + 11	24.4	~0
	Zwartkrans	1c	49.9		A21D-03	02 + 04	47.2	+6
Krombank	Kromdraai	2a	34.7	50.8	A21D-04	04 + 07	52.1	–3
	Bloubank	2b	16.1					

62 See GLOSSARY OF SELECTED TERMS.
63 See GLOSSARY OF SELECTED TERMS.
64 See GLOSSARY OF SELECTED TERMS

11.3 Groundwater Quantity

In the context of GRDM, this component of the hydrogeologic regime is represented by the status of groundwater levels as measured against historical values for this parameter. Following the above average precipitation experienced in the region in the last two summer rainfall seasons, groundwater levels reflect a rebound (section 8.3 and Table 64) that largely negates any prior depletion due to increased abstraction. These circumstances are further enhanced by the following:

- the excessive discharge entering the COH WHS from the Riet Spruit via the mine water contribution into the Tweelopie Spruit (section 4.1.2.1); and
- the significant discharge entering the COH WHS via the treated municipal wastewater effluent contribution into the Blougat Spruit (section 4.1.2.2).

It has also been shown in section 8.3 that the difference between the long-term 5%ile and 95%ile groundwater rest level elevations, as recorded in 15 DWA monitoring boreholes in the study area, amounts to only ~4.5 m on average, with a maximum of ~10.5 m. Similarly, the discussion of the Sterkfontein Caves water level (section 8.4) describes a fluctuation that does not exceed 3 m in the last 30 years. This observation does not, however, consider the recent and current abnormally high ingress of mine water into the Sterkfontein Subcompartment as described in sections 4.2.2.1 and 8.4. A measure of concern must therefore exist for the groundwater quantity aspect of the hydrogeologic regime at least in the short- to medium-term. Ironically, this concern pertains to a situation that under natural circumstances would be described as a positive impact. Continued monitoring of this aspect will provide sufficient warning of negative impacts (including an unprecedented rise and/or fall in water table) in this regard.

In light of the above, it is recommended that a gradational permissible change (understood as either a rise or fall) in the water table elevation in each dolomitic compartment be used to quantify this hydrogeologic parameter of the GRDM assessment. Serving the purpose of a resource quality objective[65] (RQO), the gradational change is defined per zone of a compartment as follows:

- ≤2.3 m (the 25%ile value of the data presented in Table 62) for the lower third;
- ≤3.6 m (the median value of the data presented in Table 62) for the middle third; and
- ≤6.1 m (the 75%ile value of the data presented in Table 62) for the upper third.

The 'permissible' changes in groundwater rest level listed above derive from the statistical assessment of long-term groundwater rest level trends in the Zwartkrans Compartment (section 8.3), where the upper third comprises the Vlakdrift Subcompartment, the middle third the Sterkfontein Subcompartment, and the lower third the Zwartkrans Subcompartment. The zonation-based 'permissible' change in water table elevation simplifies the adjudication of this parameter, whilst simultaneously recognising a greater tolerance in the upper reaches of a compartment, and a lesser tolerance in the lower reaches closer to the compartment outlet.

The remaining nine dolomitic compartments represent a natural environment that remains largely unaffected by changes in land use activities and practices. As such, the setting of RQOs as above is not an imperative at this stage. Further, it would be required that a better understanding of groundwater rest level trends in these groundwater resource units is developed before RQOs can be set with the necessary statistical support to generate confidence.

11.4 Groundwater Quality

The impact of mine water and municipal wastewater sources on the quality of groundwater resources in particularly the south-western portion of the study area is a real concern. Surface water of poor quality (section 5.1.2.1) is entering the karst aquifer at rates in excess of 20 ML/d (section 4.2.2.1). Recent attempts to ameliorate the quality of mine water being discharged into the Tweelopie Spruit through the

[65] See GLOSSARY OF SELECTED TERMS.

addition of lime were largely negated by hydrolysis reactions that lower the pH of surface water in the downstream receiving reaches of the Tweelopie and Riet Spruit drainages (section 5.5). Except for these intervention measures, nothing is being done at present to mitigate this impact. Similarly, the treated wastewater discharged from the Percy Stewart WWTW continues to carry an elevated bacteriological load (section 5.1.2.2) which also finds its way into the karst aquifer immediately upstream of the Oaktree area.

The groundwater chemistry data sourced by this project, synthesized for each GRU in Table 76, provide the basis for determining the groundwater quality component of a GRDM assessment. The latter is presented in the standard DWA format for each GRU in Table 77. The following aspects related to the tabulated information bear mention.

- The GRUs relate explicitly to the karst formations that underlie ~45% of the study area (section 2.4). The adjacent formations are not considered.

- The groundwater chemistry data presented for the Zwartkrans and Krombank compartments and their respective subcompartments are based on recent analytical results of water sourced mainly from boreholes located in these GRUs.

- The groundwater chemistry data presented for the Tweefontein, Diepkloof and Broederstroom compartments are based on recent analytical results of water sourced from the springs that drain these GRUs. It is acknowledged that in each of these instances, the analyses represent a single recent result. Nevertheless, the representivity of these results as an accurate reflection of the groundwater chemistry in these GRUs has been discussed and described at length in this report.

- Similarly, the groundwater chemistry data presented for the Danielsrust, Uitkomst and Rietfontein compartments are based on only two recent analytical results of water sourced, in each instance, from a spring and a borehole. The statistical relevance of the data will improve as more results become available in the course of routine monitoring activities.

Table 76. Synthesis of baseline groundwater chemistry data for the derivation of a groundwater quality RQO per GRU in the study area.

Compartment	Subcompartment	GRU	DWA[1] GMU #	Variable											
				n	pH	EC	Ca	Mg	Na	K	Cl	SO_4	T. Alk.	N	F
Zwartkrans	Vlakdrift	GRU1a	A21D-01	6	7.7	26	25	16	7	0.5	8	22	113	1.2	0.2
	Sterkfontein	GRU1b	A21D-02	7	7.4	133	194	59	68	3.2	58	570	104	13.7	0.2
	Zwartkrans	GRU1c	A21D-03	11	7.8	90	82	46	45	2.0	63	178	165	11.1	0.2
Krombank	Kromdraai	GRU2a	A21D-04	9	7.8	34	37	22	5	1.0	7	16	144	2.8	0.2
	Bloubank	GRU2b		7	7.6	49	54	32	19	2.0	29	60	142	6.8	0.2
Danielsrust		GRU3		2	7.8	23	28	16	2	0.5	4	2.5	114	0.8	0.2
Uitkomst		GRU4	A21G-01	2	7.2	27	32	19	1	0.5	2.5	2.5	146	0.5	0.2
Tweefontein		GRU5		1	6.5	38	47	27	1	0.5	2.5	8	196	0.8	0.2
Rietfontein		GRU6		2	7.5	54	73	44	5	2.0	9	9.5	280	0.4	0.2
Diepkloof		GRU7	A21G-02	1	6.9	37	47	27	1	0.5	2.5	2.5	196	0.6	0.2
Motsetse		GRU8		1[2]	7.7[2]	64[2]	*73*	*44*	*5*	*2.0*	*9*	*9.5*	*280*	*0.4*	*0.2*
Rhenosterspruit		GRU9	A21H-02	*0*	*7.5*	*54*	*73*	*44*	*5*	*2.0*	*9*	*9.5*	*280*	*0.4*	*0.2*
Broederstroom		GRU10		1	7.3	49	54	34	<2	0.85	<5	11	272	0.4	0.2

(1) From DWA (2010b). (2) Single field measurement Units as follows; n = count; pH = pH units EC = mS/m Other variables = mg/L

Table 77. Synthesis of proposed groundwater quality RQOs for each GRU in the study area.

Compartment	Subcompartment	GRU	DWA[1] GMU #	Variable											
				pH	EC	Ca	Mg	Na	K	Cl	SO_4	T. Alk.	N	F	EB (%)
Zwartkrans	Vlakdrift	GRU1a	A21D-01	6.5-9.5	29	28	18	8	1	9	24	124	1.3	0.2	–1.2
	Sterkfontein	GRU1b	A21D-02	6.5-9.5	146	213	65	75	4	64	627	114	15.1	0.2	5.3
	Zwartkrans	GRU1c	A21D-03	6.5-9.5	99	90	51	50	2	69	196	182	12.2	0.2	4.9
Krombank	Kromdraai	GRU2a	A21D-04	6.5-9.5	37	41	24	6	1	8	18	158	3.1	0.2	6.3
	Bloubank	GRU2b		6.5-9.5	54	59	35	21	2	32	66	156	7.5	0.2	10.8
Danielsrust		GRU3		6.5-9.5	25	31	18	2	1	4	3	125	0.9	0.2	6.7
Uitkomst		GRU4	A21G-01	6.5-9.5	30	35	21	1	1	3	3	161	0.6	0.2	2.3
Tweefontein		GRU5		6.5-9.5	42	52	30	1	1	3	9	216	0.9	0.2	5.2
Rietfontein		GRU6		6.5-9.5	59	80	48	6	2	10	10	308	0.4	0.2	10.6
Diepkloof		GRU7	A21G-02	6.5-9.5	41	52	30	1	1	3	3	216	0.7	0.2	6.6
Motsetse		GRU8		6.5-9.5	70	*80*	*48*	*6*	*2*	*10*	*10*	*308*	*0.4*	*0.2*	*10.6*
Rhenosterspruit		GRU9	A21H-02	*6.5-9.5*	*59*	*80*	*48*	*6*	*2*	*10*	*10*	*308*	*0.4*	*0.2*	*10.6*
Broederstroom		GRU10		6.5-9.5	54	59	37	2	1	5	12	299	0.4	0.2	–1.6

(1) From DWA (2010b). Units as follows; pH = pH units EC = mS/m Other variables = mg/L

[Note: Italicized values for GRUs 8 and 9 derive from GRU6 under circumstances where a complete water chemistry analysis is not available for these GRUs. The selection of GRU6 as a proxy for GRUs 8 and 9 is premised on their similar SoE classification as presented in section 12.2 and Table 85.]

12 STATE OF THE ENVIRONMENT ASSESSMENT

A full state of the environment (SoE) assessment encompasses a myriad of aspects that this study cannot replicate within its limited (and strictly water resources) scope. Nevertheless, the following discussion presents a synthesis of existing information that provides an informed indication of the 'health' of water resources in the COH WHS.

12.1 Surface Water Resources

12.1.1 Regional Assessments

The state-of-rivers report series generated by the river health programme[66] (RHP) provides a considered synopsis of the ecological importance and sensitivity (EI&S) associated with rivers and streams in the various Water Management Areas (WMAs) of South Africa. The EI&S of major drainages in the COH WHS is assessed in the RHP (2005) report for the Upper Crocodile Sub-management Area of the Crocodile (West) Marico WMA.

The RHP (2005) assessment considered only the Skeerpoort (quaternary catchment A21G) and the Crocodile Highveld (quaternary catchment A21E) ecological study units in this sub-management area (see Figure 1 for the location of these quaternary catchments). Although the Bloubank Spruit system (quaternary catchment A21D) did not receive attention in this assessment, it is reasonable to presume that it would attract a similar classification to that of the Crocodile Highveld ecological study unit. The outcome of the RHP (2005) assessment is shown in Table 78.

Table 78. Classification of surface water resources in the study area.

Quaternary Catchment	Main Drainage	Classification[(1)]	Comment (by PSP)
A21D	Bloubank Spruit	Poor	Does not distinguish between the severely impacted condition of upstream tributaries such as the Tweelopie, Riet and Blougat spruits, and the less impacted downstream reaches
A21E	Crocodile River (upper)	Poor	Represents only a small portion of the COH WHS footprint, and encroaches minimally on the sensitive karst environment of the study area
A21G	Skeerpoort River	Natural/good	For the most part a remarkably pristine karst environment that supports major springs critical to maintaining the ecological importance and sensitivity of the catchment
A21H	Crocodile River (lower)	Poor	The portion of this catchment located within the COH WHS footprint drains a largely natural subcatchment which would probably attract a better classification at sub-catchment level
(1) Interpreted by Brown (2009) after RHP (2005).			

As reported by Brown (2009), although the overall ecological status of the Crocodile (West) and Marico catchment is poor with 13 of the 23 units classified as poor (RHP, 2005), there are some sub-management areas where water quality and ecological status is relatively good at the local level. This is even more likely for localized portions within sub-management areas, where water quality and ecological status might even be classified as natural. Excellent examples hereof are the Danielsrust, Tweefontein, Uitkomst and Diepkloof compartments (sections 8.2 and 9.3).

The National Freshwater Ecosystem Priority Areas (NFEPA, 2010) project provides a more recent perspective on the 'state' (condition) of rivers. This project assigns a **'natural' condition (class AB)** to the Skeerpoort River, and a **'largely modified' condition (class D)** to the Bloubank Spruit system and the Crocodile River upstream of its confluence with the Klein Jukskei River. Downstream of this confluence, into and beyond Hartbeespoort Dam, the Crocodile River is assigned a **'modified' (class C) condition.**

[66] Renamed the National Aquatic Ecosystem Health Monitoring Programme (NAEHMP) *ca.* 2006.

12.1.2 Local Assessments

The Tweelopie Spruit was subjected to a SASS4[67] assessment at the Kemp's Cave locality (Figure 102) in the Krugersdorp Game Reserve on 30/08/2000 (Du Toit, 2000). The assessment of the biotic condition of the Tweelopie Spruit at the survey site in regard to aquatic invertebrate species scored the results presented in Table 79. Whilst the EC value is representative of a reasonably good quality water, the comparatively low pH value is uncharacteristic for water originating from dolomitic springs in the upstream reaches. Given that the survey was carried out two years prior to the manifestation of AMD on surface, it is possible that these parameters already reflected the impact of mine water collecting in and filling up the dolomitic outlier and discharging first from a spring located at a lower surface elevation (~1626 m amsl) than that of the later active AMD decant position (~1661 m amsl). This possibility finds support in the observation that recent EC and pH values of 100 mS/m and 5.6, respectively, for the karst spring are not greatly different from the 30/08/2000 surface water values, especially when compared to the raw mine water EC and pH values of ~400 mS/m and <5.0, respectively.

Table 79. Biotic condition of the Tweelopie Spruit at Kemp's Cave in the KGR on 30/08/2000 (from Du Toit, 2000).

Biotope	South African Scoring System (SASS4)		Average Score per Taxon (ASPT)	
	Score	Condition Class	Score	Condition Class
Stones in current	79	Fair	4.65	Good
Mud	74	Fair	5.29	Good
Aquatic vegetation	35	Poor	3.50	Poor
Water quality parameters	EC = 58 mS/m	pH = 6.4	Dissolved oxygen = 6.7 mg/L	

The outcome of SASS5 surveys carried out on 04/06/2005 at two sites, one each in the Tweelopie Spruit and the Wonderfontein Spruit, are reported by Krige and Du Toit (2005). The surveys included toxicity assessments by Rand Water. The site on the Tweelopie Spruit corresponds to the Rand Uranium end-of-pipe (RU EoP) discharge position (Figure 102). The results obtained for this site are presented in Table 80. The water toxicity assessment returned 0% survival rates for *Daphnia pulex* and *Poecilia reticulate*.

Table 80. Biotic condition of the Tweelopie Spruit at the Rand Uranium EoP on 04/06/2005 (from Krige and Du Toit, 2005).

Biotope	South African Scoring System (SASS5)			Average Score per Taxon (ASPT)	
	Score	Overall	Condition Class	Score	Condition Class
Stone & rock	25	35	Poor = seriously modified	3.89	Poor = seriously modified
Sand, mud & gravel	14				
Vegetation	15				
Water quality parameters	EC = 71 mS/m		pH = 8.5	Dissolved oxygen = 9.5 mg/L	

Eight water samples collected in February 2007 were similarly subjected to toxicity testing by the CSIR's Toxicity Testing Laboratory (Slabbert, 2007). The sample sites (Figure 102) are described in Table 81.

Table 81. Description of sample localities sourced for water toxicity evaluation by the CSIR.

Station	Sampling Date	Site Description	Most Probable Water Source
CSIR19	07/02/2007	Robinson Lake	Occasional mine process water repository
CSIR22	07/02/2007	Decanting mine shaft	Defunct underground mine workings
CSIR39	15/02/2007	Outlet of Hippo Dam in KGR	Harmony Gold Mine treatment plant effluent
CSIR40	15/02/2007	Outlet of Aviary Dam in KGR	Surface water in Tweelopie Spruit
CSIR41	15/02/2007	'Flip-se-Gat' stream	Dolomitic groundwater
CSIR44	20/02/2007	Weir on Blougat Spruit	Effluent discharge from the Percy Stewart WWTW
CSIR50	21/02/2007	Valley Spring	Valley slimes dam
CSIR51	21/02/2007	Battery Spring	Quartzitic groundwater

[67] The South African Scoring System Version 4 (SASS4), a systematic and uniform protocol for assessing the condition of aquatic ecosystems in the dry winter months, was replaced by the updated SASS5 protocol *ca.* 2002 (Dickens and Graham, 2002).

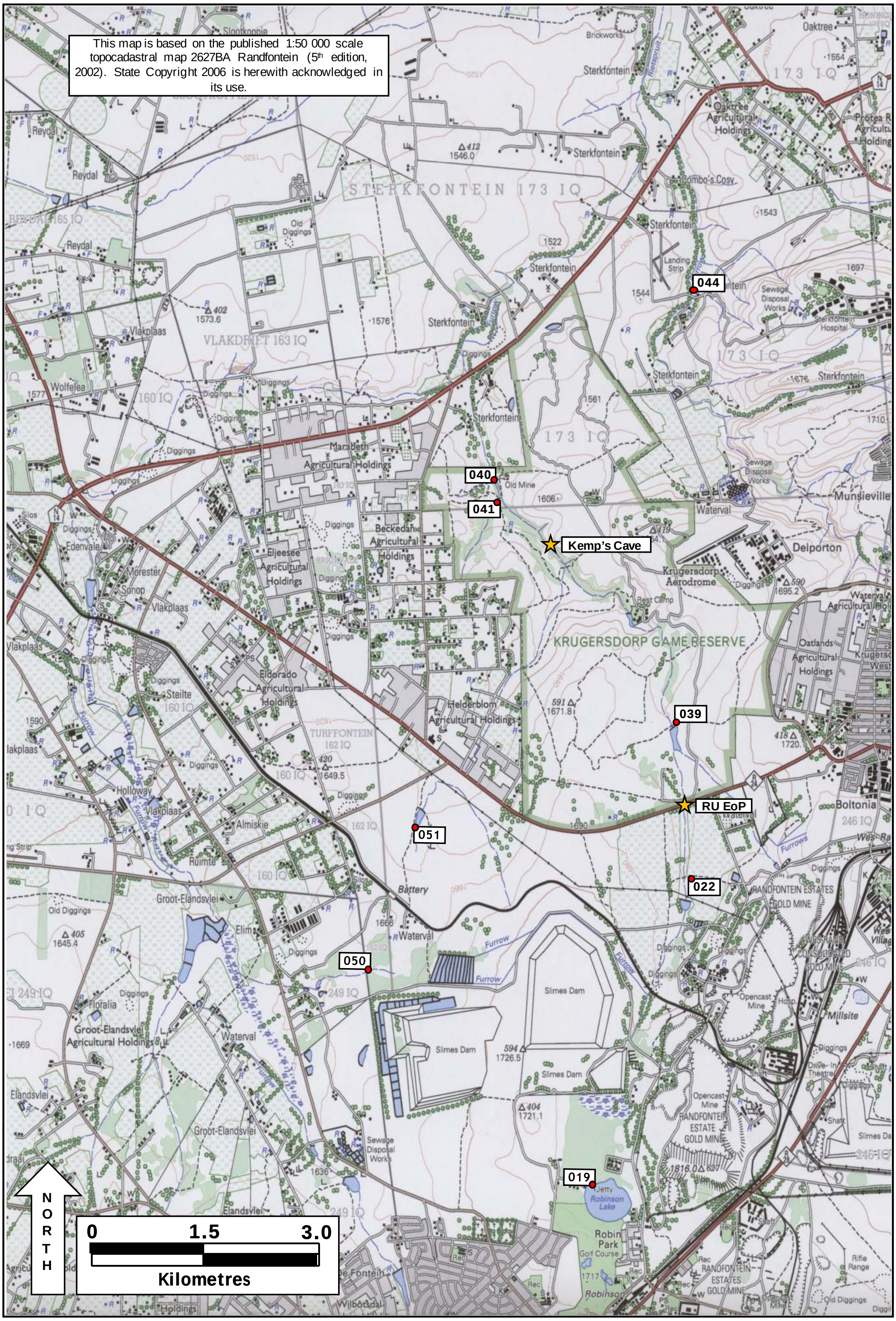

Figure 102. Locality map of February 2007 toxicity testing sampling sites (from Hobbs and Cobbing, 2007).

The results of direct tests (no sample dilution) on all samples are presented in Table 82. Samples CSIR19, CSIR22, CSIR44 and CSIR50 caused 100% lethality after 24 hours. The optimum pH range for *Daphnia pulex* is 6.0 to 8.5. The pH values of samples CSIR19, CSIR22 and CSIR50 were low and are suspected to have played a role in the observed lethality. Sample CSIR44, 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 CSIR39, CSIR40, CSIR41 and CSIR51; lethality values of <10% indicate an absence of toxicity.

Table 82. Effect of water samples on *Daphnia pulex*.

Station	pH	% Lethality after time	
		24 hours	48 hours
CSIR19	2.1	100	100
CSIR22	3.7	100	100
CSIR39	7.3	0	0
CSIR40	7.3	0	0
CSIR41	7.9	0	0
CSIR44	7.6	100	100
CSIR50	4.1	100	100
CSIR51	6.2	0	5

Table 83 shows the results obtained when *Daphnia p.* were exposed to 10-fold dilutions (range-finding tests) of the samples exhibiting low pH values (CSIR19, CSIR22 and CSIR50). Samples CSIR19 and CSIR22 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 CSIR50 during 24 h exposure. In all instances, except in the case of the 10% concentration of sample CSIR19 (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 CSIR19 and CSIR22 turned yellow and dark orange, respectively, upon dilution with moderately hard water (increased pH), indicating the presence of dissolved iron in the samples.

Table 83. Effect of 10-fold dilutions of samples on *Daphnia pulex*.

Station	Concentration (%)	pH	% Lethality after Time	
			24 hours	48 hours
CSIR19	10	3.4	100	100
	1	6.5	15	15
CSIR22	10	5.9	60	100
	1	6.5	15	15
CSIR50	10	7.2	0	not recorded
	1	7.6	0	not recorded

Definitive tests on serial dilutions were carried out on samples CSIR19, CSIR22, CSIR44 and CSIR50 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 84.

Table 84. 48-h *Daphnia p.* LC_{10} and LC_{50} values for samples 019, 022, 044 and 050.

Station	Statistical Programme	LC_{10}		LC_{50}		95% Confidence Limits	
		%	Dilution factor(1)	%	Dilution factor(1)	Lower limit	Upper limit
CSIR19	Spearman-Karber	2.5	40	3.3	30	3.0	3.6
CSIR22	Probit	1.3	77	2.3	43	1.8	2.8
CSIR44	Probit	28.7	3.5	43.5	2.3	36.6	51.6
CSIR50	Spearman-Karber	50.0	2	66.0	1.5	60.1	72.4
(1) Dilution factor denotes the number of times the water needs to be diluted in order to meet the respective lethality concentration.							

Samples CSIR19 and CSIR22 exhibited the highest toxicity (low LC_{50} values), followed in order of magnitude by samples CSIR44 and CSIR50. The results obtained for samples CSIR19 and CSIR50, 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. The toxicity evaluation produced the following conclusions.

- Samples CSIR39 and CSIR40 (surface water) and CSIR41 and CSIR51 (groundwater) were non-toxic.

- Samples CSIR19 (Robinson Lake), CSIR22 (Black Reef Incline), CSIR44 (Blougat Spruit) and CSIR50 (Valley Spring) were toxic.

- pH played a major role in the lethalities exhibited by samples CSIR19 (Robinson Lake) and CSIR50 (Valley Spring).

- Sample CSIR19 was highly toxic with an LC_{50} of 3.3%.

- Compared to sample CSIR19, the toxicity of sample CSIR50 was low (LC_{50} = 66%).

- The toxicity of sample CSIR44, strongly influenced by sewage effluent, was slightly higher than that of sample CSIR50 (LC_{50} = 43.5%). The adverse activity was most probably due to free chlorine and toxic pollutants.

- Sample CSIR22 (raw mine water from the 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.

12.1.3 Discussion

The following factors, in order of decreasing significance, militate against a rigid comparison between the results of the 2000 and 2005 SASS surveys:

- the different localities (separation distance ~4000 m) at which the two surveys were carried out;
- the difference, albeit small, between the procedures that describe a SASS4 versus a SASS5 survey; and
- the slight difference in the time of year (late-August versus early-June) that the surveys were carried out, although both took place in winter.

With due recognition of the above militating factors, the results nevertheless clearly indicate the measure of aquatic habitat degradation that occurred in this drainage in the period between the pre-decant (2000) and post-decant (2005) assessments. The toxicity testing results similarly reveal the toxicity of especially the raw mine water.

The value of both SASS-type and toxicity assessment exercises in gauging the ‘health’ of aquatic ecosystems and water as a measure of the state of the environment is clear. It is recommended that such assessments and tests be carried out regularly at selected sites in accordance with the necessary guidelines and protocols in order to generate temporally comparative data. In this regard, it is considered that the Skeerpoort River in the John Nash Nature Reserve represents a natural river system that will provide a benchmark against which to gauge the measure of deterioration established for other drainages in the study area.

12.2 Groundwater Resources

The state of the groundwater environment in the COH WHS cannot be described in the comparatively simple terms that inform surface water assessments (section 12.1). Under these circumstances, it is considered that the study area must be assessed on the basis of the GRUs (compartments and subcompartments) that facilitate a more local assessment which more closely approaches reality than can be achieved from a regional perspective.

12.2.1 Zwartkrans Compartment

It has repeatedly been shown that the Zwartkrans Compartment bears the brunt of the mine water and treated wastewater effluent impacts. These impacts, however, are not manifested to the same degree everywhere in this compartment. It is also apparent that human habitation and associated land use and economic activities are extensively developed in this compartment, more so than in any other part of the study area. These factors dictate that a SoE assessment be made for each of the three subcompartments that build this compartment (section 8.2.1).

12.2.1.1 Vlakdrift Subcompartment

Located in the headwaters of the Zwartkrans Compartment, this subcompartment reflects relatively minor impacts compared to the 'middle' Sterkfontein and 'lower' Zwartkrans Subcompartments. The long-term groundwater level response patterns exhibited in the DWA monitoring boreholes A2N0594 and A2N0598 (Annexure B) do not reflect an excessive impact from groundwater abstraction in this subcompartment. Although groundwater quality impacts are not seen in a chemical analysis of water drawn from borehole A2N0594, the bacteriological quality at station A2N0598 does reveal the presence of total coliform and *E. coli* contamination with values of 36 and 5 c/100mL, respectively. The latter might reflect the circumstances where A2N0598 is ideally placed to reveal the impact from the irregular ingress of municipal wastewater from the Randfontein WWTW (section 4.2.1). Whilst the depth to groundwater level in this subcompartment (typically >50 m bs) might otherwise constitute a risk reduction factor in this regard, it would seem not to in the presence of a swallow hole in the streambed. Under these circumstances, the groundwater SoE condition of this subcompartment is assigned a **'modified' class C** classification. This might seem harsh under circumstances where the northernmost portion of this subcompartment reflects a more 'pristine' karst groundwater quality warranting a **'slightly modified' class B** condition.

12.2.1.2 Sterkfontein Subcompartment

This subcompartment reflects the combined impact of mine water discharge and municipal wastewater discharge from the Percy Stewart WWTW. These impacts are reflected in anomalously rapid rising groundwater levels and groundwater qualities that reveal elevated salinity values (>100 mS/m) and SO_4 concentrations (>250 mg/L) compared to natural dolomitic groundwater. The wastewater impact is revealed in microbiological analyses that reflect *E. coli* values of 2 c/100 mL at geosites CSIR9 and CFM1. It is also apparent, however, that the presence of *E. coli* bacteria in groundwater encompasses a limited area as shown by the nil count/100 mL at station NR1, despite the total coliform value of 500 c/100 mL at this station. The groundwater SoE condition of this subcompartment is assigned a **'largely modified' class D** condition.

12.2.1.3 Zwartkrans Subcompartment

The Zwartkrans Subcompartment receives the aggregate discharge of the Sterkfontein and Vlakdrift Subcompartments. Groundwater quality in this subcompartment is represented by that of the Zwartkrans Spring, which exhibits an impacted character compared to that of natural dolomitic groundwater. The chemistry of the spring water has been discussed at length in section 9.7.1. It is on this basis that the groundwater SoE condition of this subcompartment is assigned a **'largely modified' class D** condition.

12.2.2 Krombank Compartment

The Krombank Compartment encompasses a distributed mixture of land uses from largely natural (for example the Savannah Nature Reserve, the Danielsrust Game Farm, the Ekutheni Estate and the Rhino and Lion Game Reserve) to intensively developed (for example the agricultural activity along the Bloubank Spruit, particularly between Zwartkrans and Kromdraai).

12.2.2.1 Kromdraai Subcompartment

The Kromdraai Subcompartment represents the more natural environment in the Krombank Compartment. If the quality of the Plover's Lake and Kromdraai Springs water (discussed at length in sections 9.7.2 and 9.7.3) is taken as a measure of that of the subcompartment, then the groundwater SoE condition of this subcompartment is assigned a **'slightly modified' class B** condition.

12.2.2.2 Bloubank Subcompartment

Closely associated with the course of the Bloubank Spruit, the groundwater resources in this subcompartment reflect the surface water / groundwater interaction in the form of impacted groundwater quality. This is represented by the chemistry of the groundwater sourced from boreholes SBH1 and SWB2 with EC values of ~75 mS/m, SO_4 concentrations of ~125 mg/L, NO_3 levels of 10 mg N/L, and Fe concentrations of ~0.03 mg/L. These circumstances suggest that a **'modified' class C** condition suitably describes the groundwater SoE condition associated with this subcompartment.

12.2.3 Danielsrust Compartment

The Danielsrust Compartment represents a 'pristine' dolomitic compartment that currently supports some human development in its eastern portion. The latter takes the form of a tourist lodge and camp. The PSP is aware of three water supply boreholes within this compartment. Two of these (located on Danielsrust Game Farm) are subject to very low use, whilst the third provides a water supply for the tourist lodge and camp. The relatively shallow depth to groundwater level (maximum ~50 m bs) and the existence of sinkhole features represents a karst environment that is vulnerable to impacts from improperly designed on-site sanitation structures and waste disposal facilities.

The excellent inorganic quality of the Danielsrust Spring water is compromized by the presence of *E. coli* bacteria (section 9.6) which, as has already been mentioned in section 9.7.4, might be attributed to upstream land use activities. Against this background, the groundwater SoE condition of this compartment must unfortunately (and perhaps rather harshly) be assigned a **'slightly modified' class B** condition.

12.2.4 Uitkomst Compartment

The Uitkomst Compartment represents a 'pristine' dolomitic compartment that currently supports very little human development. The latter takes the form of a handful of farmhouses in the southern headwater portion of the compartment. The scarcity of boreholes in this compartment (the PSP is aware of only three) and the minimal use of groundwater (mainly for domestic purposes) implies an insignificant impact on the quantity of this resource. Further, the considerable depth to groundwater level (>150 m bs) affords the resource better protection from surface-based quality impacts than where the water table is shallower. The excellent quality of the MVR1 borehole water and the Nash Spring water testifies to this. The groundwater SoE condition of this compartment is therefore assigned as **'natural' class AB**.

12.2.5 Tweefontein Compartment

The Tweefontein Spring water is virtually identical in inorganic composition to that of the Nouklip Spring (section 9.7.6). Together with the largely 'protected' nature of this compartment in terms of land use, these circumstances suggest that a **'natural' class AB** condition suitably describes the groundwater SoE condition associated with this compartment.

12.2.6 Rietfontein Compartment

The Rietfontein Compartment is traversed by the D540 secondary road (Figure 64) and, together with its position along the south-eastern margin of the karst environment, is therefore more vulnerable to potentially negative anthropogenic impacts. It also evident from Table 76 that the groundwater associated with this compartment exhibits a slightly poorer quality than that associated with the more pristine compartments. Accordingly, the groundwater SoE condition of this compartment is assigned as 'slightly modified' class BC condition.

12.2.7 Diepkloof Compartment

The Diepkloof Compartment similarly represents a 'pristine' dolomitic compartment that currently supports very little human development. The scarcity of boreholes in this compartment (the PSP is not aware of any) and the absence of groundwater use implies an insignificant impact on the quantity of this resource. The postulated substantial depth to groundwater level (>75 m bs) and lack of human impacts again afford the resource better protection from quality impacts. The excellent quality of the Nouklip Spring water testifies to this. Accordingly, the groundwater SoE condition of this compartment is assigned a **'natural' class AB** condition.

12.2.8 Motsetse Compartment

The Motsetse Compartment and its associated Motsetse Nature Reserve for the most part represents a 'pristine' dolomitic compartment. The Cradle restaurant represents the most significant human development in this compartment. These circumstances suggest that a **'slightly modified' class BC** condition suitably describes the groundwater SoE condition associated with this compartment.

12.2.9 Rhenosterspruit Compartment

The Rhenosterspruit Compartment is the least studied compartment in the study area. The project has not enumerated any springs that might serve as discharge features draining this compartment. Amongst other conference venues straddling the R512 road north of Lanseria, it also hosts the Lesedi Cultural Village. Application of the precautionary principle under these circumstances suggests that a **'slightly modified' class BC** condition suitably describes the groundwater SoE condition associated with this compartment.

12.2.10 Broederstroom Compartment

The Broederstroom Compartment similarly supports a substantial expanse of undeveloped dolomitic terrain. However, the presence of numerous residences, lodges and smallholdings along the northern margin south of Broederstroom suggest that a **'slightly modified' class BC** condition is an appropriate description of the groundwater SoE condition associated with this compartment.

12.3 Synthesis of SoE Classification per GRU

The state of the environment assessment results for the various GRUs are summarized in Table 85.

Table 85. Summary of SoE classification per GRU.

Compartment	Subcompartment	GRU	DWA GMU #(1)	SoE	Description	Type
Zwartkrans	Vlakdrift	1a	A21D-01	C	Modified	Karst
	Sterkfontein	1b	A21D-02	D	Largely modified	Karst
	Zwartkrans	1c	A21D-03	D	Largely modified	Karst
Krombank	Kromdraai	2a	A21D-04	B	Slightly modified	Karst
	Bloubank	2b		C	Modified	Karst
Danielsrust		3		B	Slightly modified	Karst
Uitkomst		4	A21G-01	AB	Natural	Karst
Tweefontein		5		AB	Natural	Karst
Rietfontein		6		BC	Slightly modified	Karst
Diepkloof		7	A21G-02	AB	Natural	Karst
Motsetse		8		AB	Natural	Karst
Rhenosterspruit		9	A21H-02	BC	Slightly modified	Karst
Broederstroom		10		BC	Slightly modified	Karst
Pretoria Group strata		11	Not assigned	B	Slightly modified	Non-karst
Witwatersrand Supergroup & older strata		12	Various(2)	C	Modified	Non-karst
(1) From DWA (2010b). (2) Grouped with adjoining dolomitic strata in DWA (2010b).						

The summary shows that two of the 15 GRUs are assigned a **'largely modified' class D** condition, and a further three a **'modified' class C** condition. The remainder are assigned either a **'slightly modified' class B/BC** or a **'natural' class AB** condition. These circumstances reflect the generally good to excellent state of the groundwater environment in two-thirds of the study area.

A closer inspection of the spatial representation of the karst GRUs according to their SoE classification is presented in Table 86. This shows that 59% of the karst area supports a **'slightly modified' class B/BC** or better condition. Further, that only 27% supports a **'largely modified' class D** condition.

Table 86. Spatial representation of karst GRU by SoE classification.

Compartment	Subcompartment	GRU	SoE	Description	Area (km^2)	Total (km^2)	% of Total
Uitkomst		4	AB	Natural	28.6	80.9	29
Tweefontein		5			11.6		
Diepkloof		7			38.0		
Motsetse		8			2.7		
Krombank	Kromdraai	2a	B/BC	Slightly modified	34.7	83.5	30
Danielsrust		3			7.4		
Rietfontein		6			5.4		
Rhenosterspruit		9			15.5		
Broederstroom		10			20.5		
Krombank	Bloubank	2b	C	Modified	16.1	39.7	14
Zwartkrans	Vlakdrift	1a			23.6		
	Sterkfontein	1b	D	Largely modified	24.5	74.4	27
	Zwartkrans	1c			49.9		
				TOTAL	278.5	278.5	100

13 GROUNDWATER RESOURCE RISK ASSESSMENT

The aquifer vulnerability study by Leyland et al. (2008) generated the first assessment of this kind for a karst aquifer in South Africa. A subsequent refinement of the algorithm (Leyland, 2010) has incorporated the concepts of hazard and risk. Hazards are recognized as activities and land use practices that pose a threat to groundwater resources. Risks are determined from a synthesis of the information provided by hazard and vulnerability maps. The application of hazard and risk mapping procedures in the COH WHS expands on the aquifer vulnerability study by Leyland et al. (2008) to produce a risk management tool for this sensitive environment.

13.1 Hazard Mapping

13.1.1 Methodology and Approach

The 7-step approach developed by the Cooperation in Science and Technology (COST) Action 620 Working Group 3 (Zwahlen, 2003) set up by the European Commission was followed in the hazard assessment. The approach requires the sequential execution of the following components:

- inventory and definition;
- data compilation;
- rating and weighting;
- graphical interpretation;
- mapping technique;
- data evaluation; and
- map production.

13.1.1.1 Inventory and Definition

A hazard assessment must consider both the potential degree of harmfulness for each type of hazard and the likelihood of a contamination event (actual release into the environment) occurring. The former is determined by both the toxicity and the quantity of harmful substances that may be released as a result of a contamination event. Zwahlen (2003) recognizes three main categories, namely infrastructure, industry and agriculture, as Level 1 hazard categories in the Hazard Inventory (Table 87). A second tier (Level 2) of category distinguishes between hazards according to the main source (solid or liquid contaminants) of contamination or the types of industrial or agricultural activity with the corresponding spectrum of possible pollutants. A further subdivision into Level 3 categories (Annexure E) provides even greater definition of hazards that facilitates the assignment of a weighting value to each.

Table 87. Definition of Level 1 and Level 2 hazard categories (after Zwahlen, 2003).

No.	Level 1 Hazard Category	Level 2 Hazard Category	
1	Infrastructural development	1.1	Wastewater
		1.2	Municipal waste
		1.3	Fules
		1.4	Transport and traffic
		1.5	Recreational activities
		1.6	Diverse hazards
2	Industrial activities	2.1	Mining (active and abandoned)
		2.2	Excavations
		2.3	Oil and gas exploration
		2.4	Industrial plants (non-mining)
		2.5	Power plants
		2.6	Industrial storage
		2.7	Diversion and treatment of wastewater
3	Agricultural activites	3.1	Livestock
		3.1	Agriculture

The main aim of the inventory is to consider all the various hazards considered relevant to groundwater and to inform the mapping, evaluation and assessment of the hazards in an economically feasible and practical manner. Hazards that pose a threat to karst systems result in the following principal impacts (Zwahlen, 2003):

- emission of air pollution;
- discharge of wastewater and non-aqueous organic liquids;
- storage and disposal of solid waste;
- excavations in connection with mining, foundation and construction work; and
- distribution of fertilizers and pesticides.

13.1.1.2 Data Compilation

Data are required on the process or nature of activity (production, storage, etc.), type of harmful substances present, amount of substances which can be released and the age and status of installations and plants. Zwahlen (2003) suggests that topographic maps, aerial photos, archives and agencies, field surveying and direct inquiries with companies represent primary sources of data. The use of geographic information systems (GIS) requires that only georeferencable hazards be taken into consideration.

13.1.1.3 Rating and Weighting

Hazard assessment requires that all the necessary detail of influencing factors (e.g. the amount and harmfulness or toxicity of the possibly involved substances, based on factors such as the state of preservation, maintenance or security measures of a hazard) have to be determined for the likelihood that a release may occur. Since not all these data are directly available, the collection of all the data needed for a quantitative and systematic evaluation and assessment of different hazards requires substantial effort and manpower to achieve. To simplify this process, a series of steps was devised to arrive at a classification of the hazards (Zwahlen, 2003).

The first step employs a weighting system that allows for comparison between the different types of hazards within a relative assessment scheme, and is suitable for the formulation of possible groundwater protection zones or measures. Recognising that it is essentially impossible to establish quantitative methods to arrive at an absolute measure of the degree of harmfulness, it was concluded that the main criteria for weighting different hazards was the toxicity of relevant substances associated with each type of hazard, as well as their properties regarding solubility and mobility (Zwahlen, 2003). Cost 620 employed multiple methods to arrive at a final weighting system for different hazards (Annexure E). The list serves as a general recommendation for judging the potential degree of harmfulness of different types of hazards.

Following the weighting of hazards, it is necessary to establish a ranking procedure for hazards of the same type/weighting. Again factors influencing the degree of harmfulness have to be considered, and since toxicity has been accounted for in the weighting system, the ranking procedure is based mainly on the variable quantity of harmful substances which can be released. The ranking procedure should neither lead to a drastic minimization nor excess overvaluing within a category of hazards, as this will negate the effects of the weighting system (Zwahlen, 2003). By implication, a comparatively small amount of highly toxic substances, or alternatively a high amount of low toxic substances, should not lead to wide deviation from the average weighting value previously assigned to a particular hazard. The ranking procedure therefore involves multiplying the weighting values by a ranking factor of between 0.8 and 1.2 (with values below and above 1 for low and high amounts respectively). A gradual variation between 0.8 and 1.2 or a limited subdivision of three classes, namely low (0.8), medium (1.0) and high (1.2) can be used.

A hazard that has been assigned a weighting and ranking factor then needs to be assessed with respect to the likelihood that a release of contaminant may take place. Factors considered for this assessment include technical status, level of maintenance, surrounding conditions and security measures.

The application of a reduction factor (R^f) reduces the possible expenditure of time and effort in achieving a questionable quantitative result. If no information on the above-mentioned factors is available, then an $R^f = 1$ (worst case) factor is appropriate. Positive information indicating the increasingly less likelihood of a contaminant release peaks at an $R^f = 0$ (no risk of groundwater contamination).

The hazard index (H_i) is calculated from the weighting value (H), ranking factor (Q^n) and reduction factor (R^f) according to the formula (Zwahlen, 2003):

$$H_i = H \bullet Q^n \bullet R^f$$

where H_i = hazard index,
H = weighting value,
Q^n = ranking factor (0.8 to 1.2), and
R^f = reduction factor.

The possible range of H_i values (0 to 120) is subdivided into five classes (Table 88) to simplify and facilitate interpretation and application of this index (Zwahlen, 2003).

Table 88. Hazard index classes proposed by Zwahlen (2003).

Hazard Index	Hazard Index Class	Hazard Level	Hazard Map Colour
0 – 24	1	None / very low	Blue
>24 – 48	2	Low	Green
>49 – 72	3	Moderate	Yellow
>72 – 96	4	High	Orange
>96 –120	5	Very high	Red

13.1.1.4 Graphical Interpretation

The accuracy of the hazard locality map depends on the quality of the original sources used to determine their positional information. Whilst the scale of the hazard map is dependent on the size of the area under investigation, it should also match that of other maps, e.g. vulnerability maps, to ensure compatibility of information exchange (Zwahlen, 2003).

13.1.1.5 Mapping Technique

Whereas data may be acquired from various sources, their integration is best performed using a geographic information system (GIS). The eventual production of high quality output maps is provided by computer aided cartographic software (Zwahlen, 2003).

13.1.1.6 Data Evaluation

Any map is only as good as the data used for its compilation, and potential sources of error are equally relevant to the production of hazard maps. The introduction of hazard attributes to exercise rigorous data quality control and assurance is strongly recommended, especially if such attributes distinguish between measured, statistical, extrapolated and estimated hazard data, and also help appraise the spatial and temporal variability of each hazard (Zwahlen, 2003).

13.1.1.7 Map Production

Hazard maps are either produced to be 'unclassified' (showing only the relevant geographical location) or 'classified' (based on a hazard index computation). At very small scales there exists a high possibility that different hazards will plot at the same location on a map. Wherever such overlap occurs, it is recommended that the activity with the greatest hazard index be shown.

13.1.2 Application

Data collection employed an aerial photograph interpretation of the study area to identify and map potential hazards in a GIS environment. This allowed many features to be easily identified and their spatial extent mapped. However, numerous potential hazards could be seen but not identified. Additional field work was undertaken to correctly identify such features. Critically, the field work also served to identify hazards that post-dated the photographic coverage, i.e. were not evident in the latter. Further, the aerial photograph interpretation benefitted from the good general knowledge of the study area possessed by the interpreter, thus maximising the use of this technique. Since no detailed determination of the potential amounts of pollutants associated with each hazard or the technical status thereof was undertaken (as would be the case for a comprehensive study), ranking and reduction factors of 1 were applied. Nevertheless, an excellent first assessment of hazards was obtained. Hazards were recorded within a GIS as point (e.g. buildings), linear (e.g. roads, railways, runways) or polygon (e.g. cultivated or urbanised areas) features.

The linear and point features required further GIS buffering (a buffer zone of 25 m was applied to all point and linear features) to accurately reflect their zone of influence. Structures on the numerous poultry farms in the study area were assigned a buffer zone of 50 m to cover the active working area around them. The buffering exercise translated all hazards into polygonal features to which a hazard weighting could be assigned according to Annexure E. The hazards identified within the study area, and the weightings assigned to these, are shown in Table 89. This table includes additional and modified hazard numbers (when compared to Annexure E) used for hazard types unique to the study area.

Table 89. Identified hazards and associated weighting values for the COH WHS.

No.	Hazard Description	Weighting Value
1.1.2	Urbanization without sewer systems	70
1.1.3a	Detached houses without sewer systems	45
1.1.3b	Semi-informal housing	55
1.1.3c	Informal housing	60
1.1.4	Septic tank, cesspool, latrine	45
1.3.6a	Petrol station	60
1.3.6b	Car workshops	50
1.4.1	Road, unsecured	40
1.4.4	Car parking area (incl. boat, and airplane storage)	35
1.4.9	Runway	35
1.5.1	Tourist urbanization	30
1.6.4	Transformer station (incl. cell towers)	30
2.2.3	Quarry	25
2.4.7	Rubber & tyre industry (& asphalt plants)	65
2.4.11	Light industries	40
3.1.1	Animal barn (shed, cote, sty)	30
3.1.2	Feedlot	30
3.1.3	Factory farm	30
3.1.4	Manure heap	45
3.2.1	Open silage	25
3.2.2	Closed silage	20
3.2.3	Stockpiles of fertilisers & pesticides	40

13.1.3 Result

The result of the hazard mapping exercise as described above is presented in Figure 103. This indicates the greater hazard present in the south-western corner of the COH WHS in the Oaktree area, as well as the elevated hazard rating associated with the surface water drainages. Whereas the former is directly related to the intensity of agricultural activity mainly in the form of cut flower production for the export market, the latter is informed by the intrinsically close hydraulic relationship that exists between surface water and groundwater resources in a karst environment.

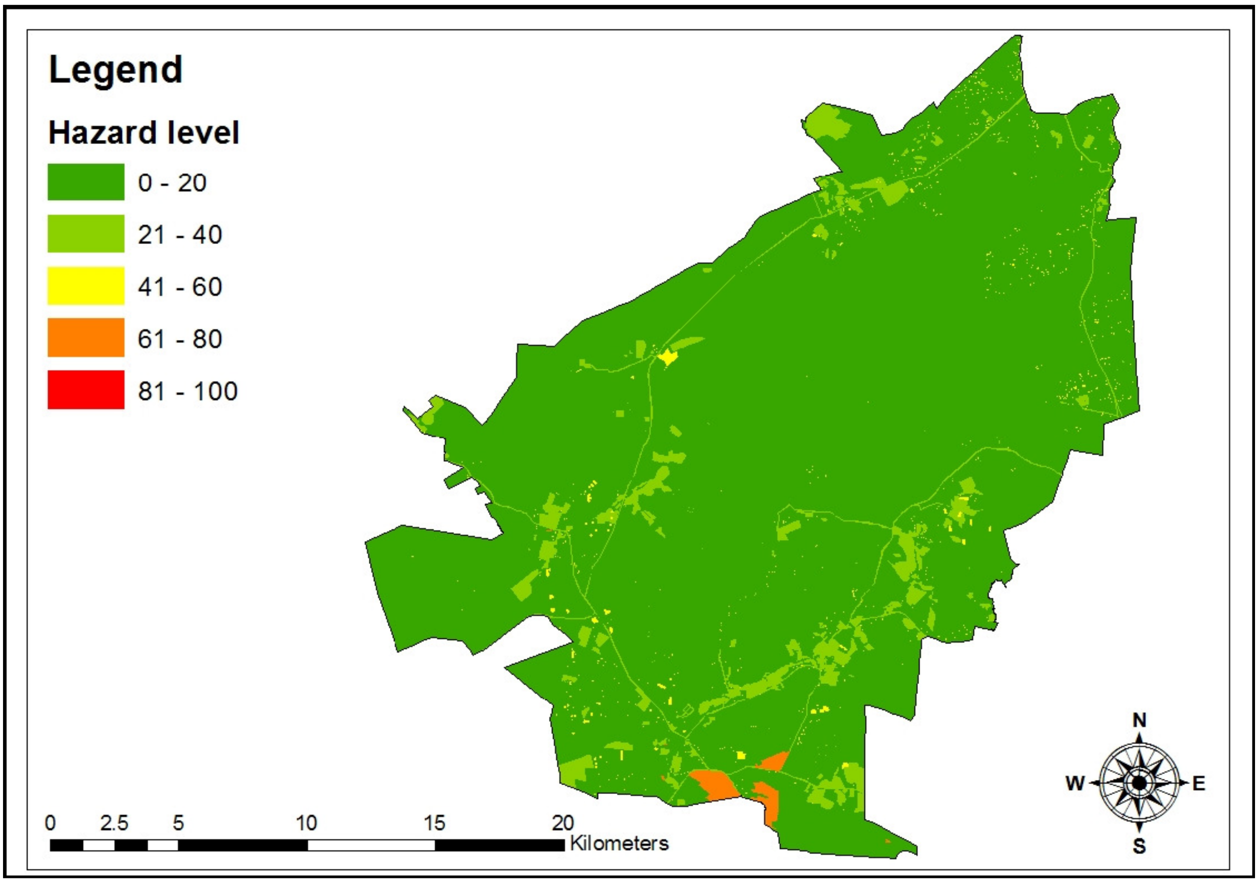

Figure 103. Groundwater hazard map of the COH WHS generated from field data (from Leyland, 2010).

13.2 Risk Mapping

13.2.1 Methodology and Approach

Risk is defined as a term used to denote the probability of suffering harm from a hazard. With regard to groundwater, it refers to possible contamination resulting from a hazardous event. It embodies both probability and consequences, defined as the likelihood or expected frequency of a specified adverse consequence on groundwater. Risk is not intended as an absolute measure but as a means of relative measure or comparison. This relative measure can be defined by the product of the probability of an event occurring and the consequential damage caused. Following the origin-pathway-target model, the risk of contamination of groundwater depends on three elements, namely the hazard posed by a potential polluting activity (origin), the intrinsic vulnerability of a groundwater resource to contamination (pathway) and the potential consequences of a contamination event (in the groundwater environment).

A full (total) risk assessment consists of a risk intensity assessment (likelihood and intensity of a potential impact) and a risk sensitivity assessment (sensitivity of groundwater to impact). The conceptual questions that inform the different components of a risk assessment are presented in Table 90. Although in most risk analyses only the risk intensity assessment is carried out, it should be understood that for further application, particularly with regard to risk management, a complete risk assessment including risk sensitivity assessment is necessary. A risk intensity assessment ultimately produces a risk intensity map (a combination of the hazard map and the vulnerability map) that reflects the distribution of the risk intensity index (RI_i) within the area of interest. Risk sensitivity assessments produce risk sensitivity maps which depict spatial variations of the risk sensitivity index (RS_i), a relative measure of the sensitivity with which the groundwater environment reacts to the impact and the resulting damage expressed in terms of ecological and economical values.

Table 90. Conceptual questions that inform risk analyses (after Zwahlen, 2003).

Assessment Aspect	Questions	Result
Risk intensity	What can go wrong?	Hazard identification and identification of outcomes
	How likely is it to go wrong?	Estimation of probability of outcomes
	How far can the hazardous impact reach target?	Estimation of possible impact reduction (or estimation of vulnerability)
Risk sensitivity	What would happen to the target if it does go wrong?	Evaluation of the sensitivity of the target against the impact (consequence analysis)
	Is the risk acceptable and can it be reduced?	Evaluation of the damage with regard to environmental and economic value
Total risk	What decisions arise from risk assessment?	Risk management
	What control measures are needed to minimize the risk?	

Risk sensitivity assessments produce risk sensitivity maps which depict spatial variations of the risk sensitivity index (RS_i), a relative measure of the sensitivity with which the groundwater environment reacts to the impact and the resulting damage expressed in terms of ecological and economical values. Zwahlen (2003) emphasizes that risk sensitivity and total risk assessments are essential for sustainable groundwater management based on risk evaluations that include such processes. The production of the final risk map (total risk map or ecological risk map) requires the combination of the risk intensity index and risk sensitivity index to arrive at a total risk index (TR_i) (Zwahlen, 2003).

The risk intensity index (RI_i) is calculated from the hazard index (H_i) and the vulnerability index (V_i) according to the formula:

$$RI_i = [1/H_i] \bullet [(V_i/15)\bullet 100]$$

where RI_i = risk intensity index,
H_i = hazard index, and
V_i = vulnerability index

13.2.2 Application

A risk intensity map was created using the formula presented in section 13.2.1 employing the vulnerability index (VUKA) spatial data generated in the Leyland et al. (2008) study and the hazard index spatial data used in the creation of the hazard maps described in sections 13.1.1 and 13.1.2. The VUKA data were normalized to facilitate combination of vulnerability index values (in the range 0 to 15) and hazard index values (in the range 0 to 100).

13.2.3 Result

The risk map developed by combining the aquifer vulnerability map and the hazard map is shown in Figure 104. The map clearly reveals the elevated risk associated with the roads running through the area.

13.3 Historical Mining Activity

The COH WHS and surrounding area is witness to numerous forms of mining activity at various scales. These vary from artisanal gold mine workings represented by stopes in the Black Reef Formation such as are seen in the Krugersdorp Game Reserve (KGR), to opencast workings for limestone, for example the Aviary Quarry in the KGR, and dolomite, e.g. the large Sterkfontein Quarry at Bolt's Farm near Oaktree. The (often destructive) exploitation of numerous caves (including Sterkfontein) in the study area for limestone at the end of the 19th and beginning of the 20th centuries is also well documented (e.g. McCarthy and Rubidge, 2005).

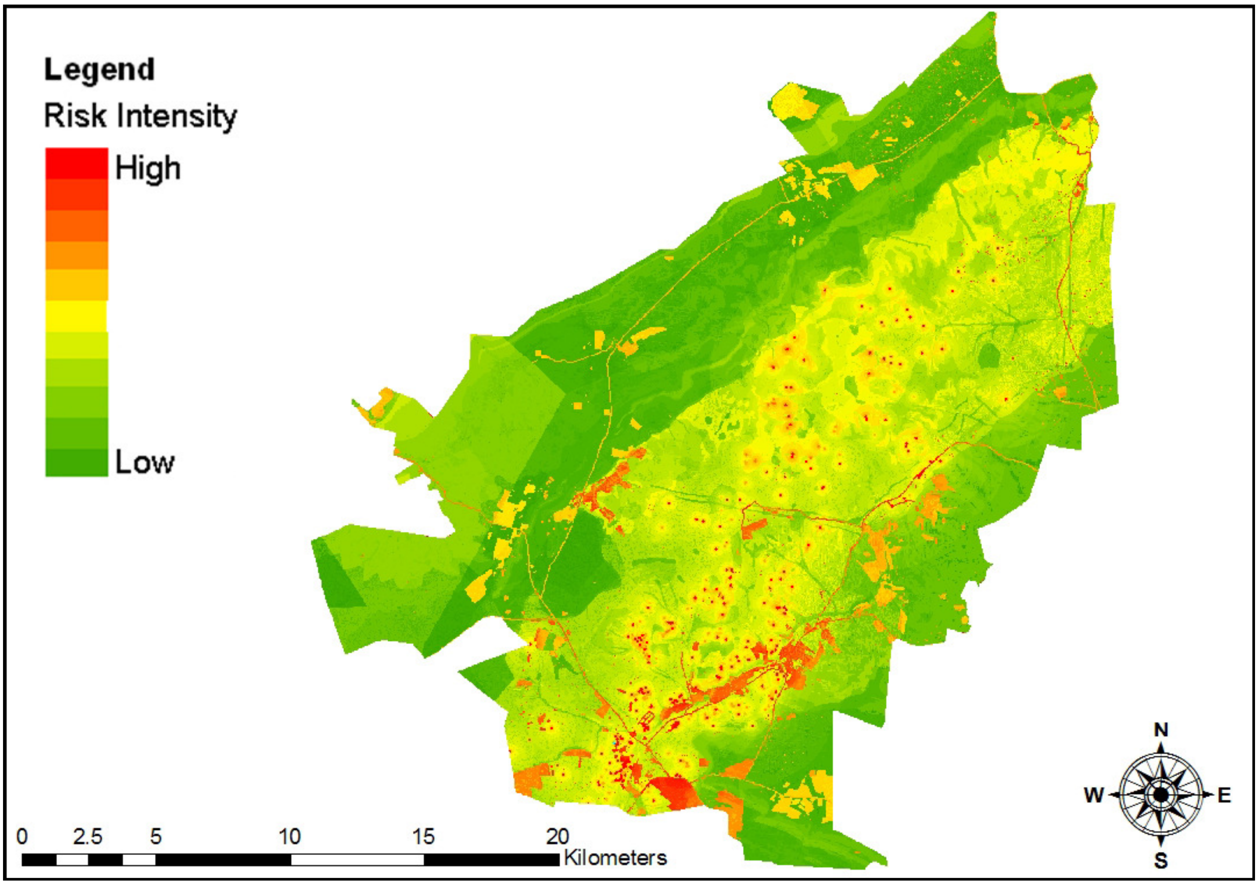

Figure 104. Groundwater risk map of the COH WHS (from Leyland, 2010).

The COH WHS area hosts the earliest proclaimed gold mine on the Witwatersrand. The Kromdraai Gold Mine located on Ptn. 43 (Ibis Ridge Farm) of the farm Kromdraai 520JQ commenced operations in 1881, and closed down in 1914 (G. Whatley, personal communication). In an article titled 'The Kromdraai Gold Field', The Star newspaper of 07/10/1893 reports on a substantial quantity of water encountered in the mine workings. As was common to many of the early Witwatersrand gold mines, the Kromdraai Gold Mine exploited gold-bearing horizons in the Black Reef Formation at the base of the Malmani Subgroup dolomite succession. Only one of the original three adits to the Kromdraai Gold Mine still allows risk-free access to the underground workings, which comprise at least three levels linked by winzes. The water level in the mine fluctuates in the interval defined by the 3rd (deepest known) and the 2nd levels, and reached a maximum elevation just above the 2nd Level (G. Whatley, personal communication) in the year 2000 (which happened to be an extremely wet year).

The current water level occupies an elevation of ~1420 m amsl, as inferred from the depth to groundwater rest level of ~12 m below surface measured in a water supply borehole (geosite KGM1) on the property in May 2010. The quality of the groundwater produced by this borehole (EC = 18 mS/m, pH = 5.6) does not reflect an acid mine water signature. The low EC and pH values are characteristic of groundwater associated with quartzitic strata of the Witwatersrand Supergroup (section 9.2.1.1). The absence of an acid mine water signature is supported by 'in-mine' water EC, pH and temperature measurements that reveal even lower EC values (in the range 10 to 13 mS/m) but slightly higher pH values (in the range 6.1 to 6.4), at two localities within the partially flooded mine workings. The differences with the borehole KGM1 groundwater might be attributed to the depth from which the latter is drawn; the pump is installed a depth of ~55 m below surface (G. Whatley, personal communication). This would indicate that the borehole penetrates some distance into the underlying Witwaterstrand Supergroup quartzites. Figure 105 provides a comparison of the mine water and groundwater in the vicinity of the mine with that of surface water in the nearby Honingklip Spruit. Despite the ostensible similarity of chemical composition reflected in the graphs, a distinctive grouping of 'mine' water (samples KGM1 and KGM-MW) on the one hand, and groundwater (OB1) and surface water (HS1) on the other, is also apparent. Nevertheless, the absence of acid mine water development in the mine workings after more than a century of 'flooding' is considered significant.

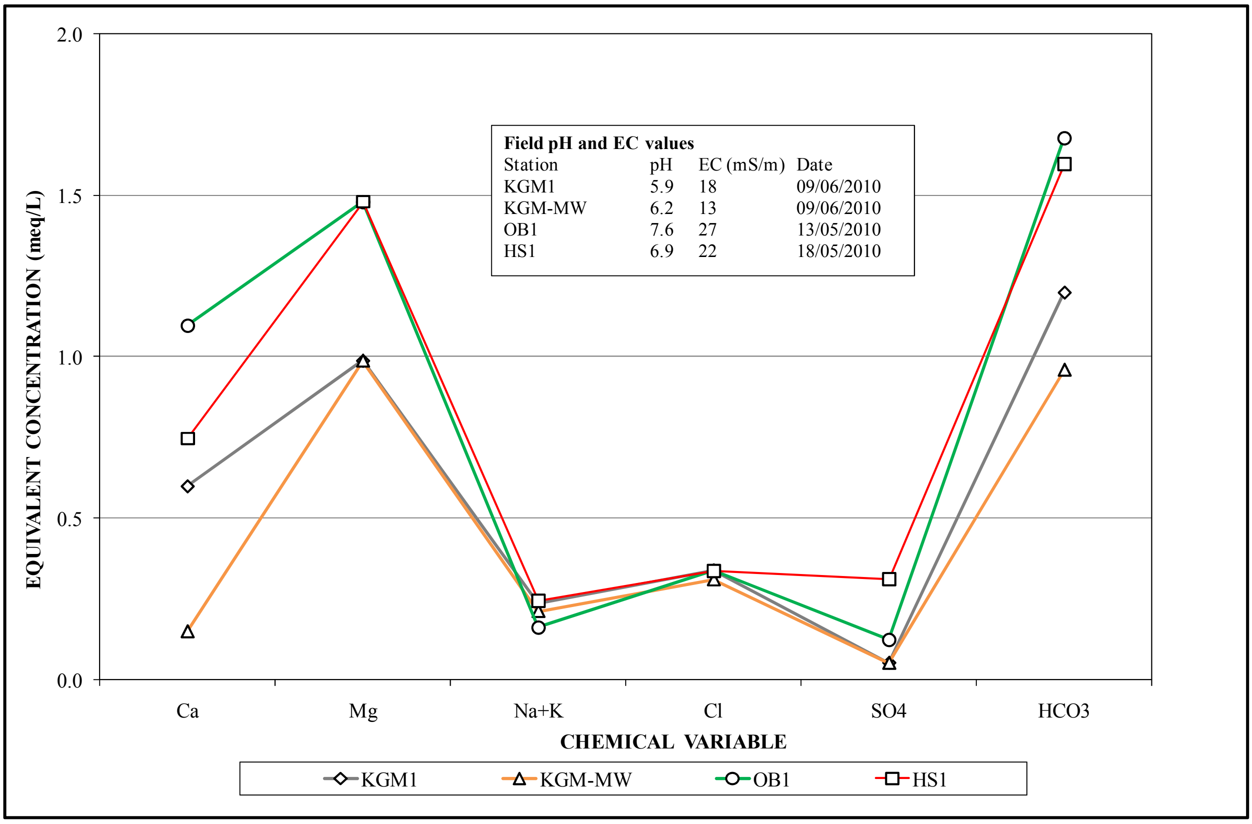

Figure 105. Comparison of surface water and groundwater chemistry in the vicinity of the historic Kromdraai Gold Mine.

The groundwater elevation of ~1420 m amsl is slightly lower than the streambed elevation of the nearby Honingklip Spruit, which is interpolated at ~1423 m amsl. Circumstances where the water level in the mine workings is partly informed by discharge in the Honingklip Spruit can therefore not be discounted. The mine water level would need to rise more than ~3 m above its current level before a reverse of the hydraulic gradient between the mine and the Honingklip Spruit is established. Although two of the adits that provide access to the mine workings (one risk-free and the other hazardous) occupy a similar elevation of ~1435 m amsl, the third so-called 'lost adit' (G. Whatley, personal communication) was uncovered during earthworks along the regional road that passes the property. This adit occupies a lower surface elevation of ~1425 m amsl, which is only some 2 m above the level of the nearby Honingklip Spruit, and 5 m above the current mine water level elevation. It is probable that the highest recorded mine water level (in 2000) approached this elevation. If the Kromdraai Gold Mine is therefore to decant, it will be via this adit. Based on the present quality of the mine water, however, such decant is unlikely to contribute acid mine drainage (AMD) into the receiving surface and groundwater environments.

It bears mention that the historical Kromdraai Gold Mine shares the ecological significance associated with many of the natural cave features in the study area, namely that of providing a habitat and breeding ground for bats (G. Whatley, personal communication).

13.4 Human Settlement

The issue of informal housing developments in the COH WHS reached disturbing proportions recently when a community at Kromdraai resorted to civil unrest in order to air grievances they felt toward the West Rand District Municipality as responsible authority for the area (Damons, 2010). The geo-environmental factors that inform the situation are summarized as follows:

- location of the settlement on 'untested'[68] dolomitic ground;
- location of the settlement on undermined ground associated with the historical Kromdraai Gold Mine workings, the entrance to which is located on the adjoining property; and
- a comparatively shallow (<20 m) depth to groundwater rest level.

The combination of these factors creates understandably significant concern for a variety of reasons that include the compromize of human health and safety and water resource quality. It is therefore imperative that provincial government and district/local authorities are equally aware of the sensitivity and value of the COH WHS environment.

A further concern associated with both informal and formal low-cost residential areas is the proliferation of refuse disposal sites associated with these areas. Examples hereof are the refuse sites centred on the coordinates 26.07385°S/27.65700°E and 26.07073°S/27.65820°E to the north-east of the informal residential settlement located on Ptn. 6 of Vlakplaats 160IQ in the south-eastern quadrant of the N14/R24 junction at Tarlton. Both sites are readily identifiable on the Google Earth® image of the area, which also reveals their location in the middle reaches of the Riet Spruit valley. This segment of the drainage only carries surface water into the Zwartkrans Compartment during periods of excessive rainfall and runoff from the Randfontein area. This is impounded in several dams, notably one located at 26.06515°S/27.66104°E. However, no surface water flow passes the downstream (eastern) boundary, located at 26.06436°S/27.66960°E, of the Jomajoco Farms property (J. van den Bosch, personal communication). Although the depth to groundwater rest level along this segment of the Riet Spruit channel is ~60 m bs (DWA monitoring station A2N0598, Table 64), this otherwise substantial separation with the surface is short-circuited by swallow holes in the river bed that allow poorer quality surface water more rapid access to the groundwater resource. This might explain the total coliform and *E. coli* values of 36 and 5 c/100 mL, respectively, detected in the chemical analysis of a groundwater sample from station A2N0598 collected on 09/06/2010.

The provision of suitably adequate refuse/waste removal facilities for the low-cost and/or informal residential areas that have been developed on dolomitic ground in the COH WHS and surrounds, is no less important than the provision of water and sanitation facilities to these communities. These represent opportunities for integrated land use development between local (MCLM) and district (WRDM) municipal authorities. The illegal dumping of refuse in the COH WHS is, however, not limited to areas of low-cost and/or informal housing. The image in Plate 14 shows an illegal dumpsite located immediately downstream of where the Malmani Road leading to the Sterkfontein Farm Estate crosses the Riet Spruit. The refuse covers the entire drainage channel, including the active flow section. Exercising control over such practices is extremely difficult, and must rely as much on pride in a 'sense of place' as it does on community 'policing'.

Plate 14. View on 27/07/2010 of an 'illegal' refuse disposal site in the drainage channel of the Riet Spruit near its confluence with the Blougat Spruit. (Photo: Phil Hobbs).

[68] The development of dolomitic terrain is subject to prior geotechnical investigation and assessment in accordance with guidelines put forward in the CGS/SAIEEG (2003) publication.

14 FOSSIL SITE HYDROVULNERABILITY ASSESSMENT

The vulnerability of the fossil sites (and their associated cave systems) in the COH WHS (section 2.5) is a particular concern in regard to their hydrologic and hydrogeologic settings. A description of each fossil site, including a synoptic description of the cave morphology in terms of geometry relative to the landscape setting, is provided in Table 5. The hydrovulnerability of each site is examined and discussed in the context of its hydrologic and hydrogeologic settings in the sections hereunder. The assessment considers both the physical (e.g. surface water/groundwater interaction, groundwater rest level, etc.) and chemical (mainly water quality) components associated with the respective fossil site settings. The outcome is summarized in Table 91, and illustrated schematically in Figure 106.

Table 91. Analysis of the hydrovulnerability of fossil sites in the COH WHS.

Fossil Site	Groundwater Compartment	Surface Elevation (m amsl)	Cave Base Elevation (m amsl)	Groundwater Elevation (m amsl)	Separation Distance[(1)] (m)	Hydrovulnerability
Bolt's Farm	Zwartkrans	~1480 – 1505	<1448[(2)]	~1448	0	Very high
Swartkrans		~1470 – 1480	<1465	~1440	<25	Moderate
Sterkfontein		~1470 – 1485	<1437	~1437	0	High
Coopers		~1465 – 1475	~1460	~1435	<30	Low
Kromdraai		~1470 – 1475	~1465	~1432	<35	Low
Minnaars		~1455 – 1460	<1450	~1437	<20	Moderate
Plover's Lake	Krombank	~1430 – 1440	<1425	~1420	<5	Moderate
Wonder Cave		~1500 – 1510	~1440	~1422	>20	Low
Drimolen	Danielsrust	~1545 – 1555	~1540	~1490	~50	Very low
Gladysvale	Uitkomst	~1415 – 1425	~1370	~1362	~10	Low
Motsetse	Motsetse	~1495 – 1505	~1490	~1415	>80	Very low
Haasgat	Diepkloof	~1470 – 1480	~1465	~1420	~45	Very low
Gondolin	Broederstroom	~1385 – 1395	~1380	~1340	~40	Very low
Malapa	Diepkloof	~1435 – 1445	~1430	~1375	~55	Very low

(1) Approximate distance between lowest surface elevation and current groundwater elevation.
(2) Associated with cave accessed from entrance in the western sidewall of Sterkfontein Quarry.

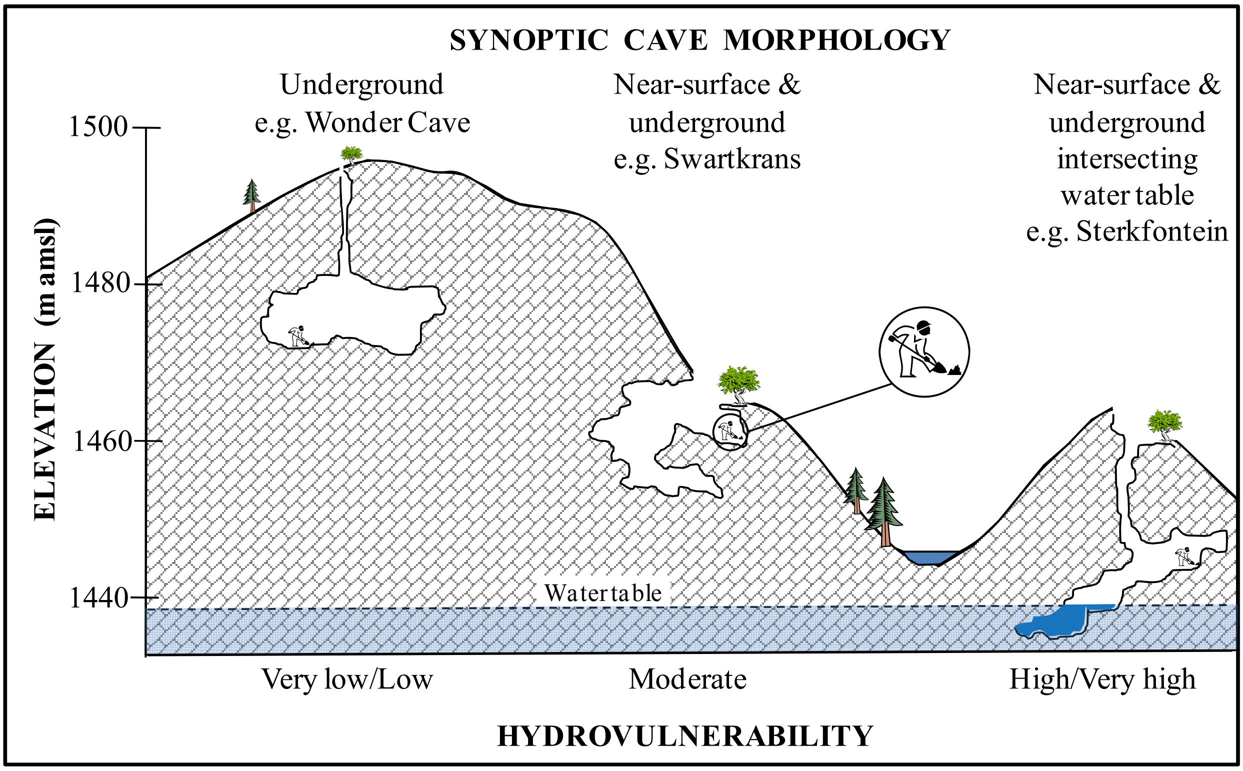

Figure 106. Schematic diagram illustrating the link between synoptic cave morphology and hydrovulnerability as applied to fossil sites in the COH WHS.

The fossil site hydrovulnerability assessment is further illustrated in Figure 107 and Figure 108, which show the fossil site locations in relation to the hydrologic and hydrogeologic frameworks as defined earlier in this report (section 8). It is important to note that the assessment does not consider the numerous other cave features in the study area, and in particular those such as Yom Tov, Fulton's, Grobler's, Koelenhof and Kemp's Caves that are known to intersect the water table. It is considered, however, that this report provides sufficient information for such an assessment to be made independently of this study.

14.1 Fossil Site Hydrovulnerability

14.1.1 Bolt's Farm

Located immediately to the north of the Riet Spruit in the Oaktree Agricultural Holdings area, the caves in this system either intersect the water table or are located immediately above it. It has been shown in section 4.2.2 that the Riet Spruit upstream of this fossil site loses as much as 32 ML/d of poor quality surface water to the karst environment under extreme flow conditions. These circumstances have precipitated a rise of at least 4 m in the groundwater rest level in the recent past (section 8.3 and Table 62). The contiguous nature of the water table suggests that a water level rise of similar magnitude has occurred in those caves of the Bolt's Farm system that extend below an elevation of ~1448 m amsl. The potentiometric surface in this area currently occupies an elevation of ~1450 m amsl, which is still ~10 m below the streambed elevation of ~1460 m amsl. Theoretically, it is therefore possible that the potentiometric surface could rise a further 10 m to intersect the streambed. This is unlikely, however, since discharge from the Zwartkrans Compartment would increase significantly to counteract a buildup in potentiometric head of this magnitude.

Of equal concern is the quality of the groundwater encountered in this portion of the karst aquifer. Groundwater samples obtained recently from geosites CSIR8, CSIR9, GB2 and SCH1 (all boreholes) located immediately upstream of this fossil site reflect elevated EC, SO_4 and Cl concentrations indicative of both a mine water and a municipal wastewater impact (Figure 85). Under the above circumstances the cave systems that form part of the Bolt's Farm fossil site, and in particular those that extend below an elevation of ~1450 m amsl [this includes Aladdin's Cave as described by Kenyon and Ellis (2010)], exhibit a **very high vulnerability** to both groundwater level fluctuations and water quality. Mitigation measures that may be implemented upstream to lessen water quality impacts might include the following:

- the selective placement of limestone in the channels of the Tweelopie and Riet spruits to counteract the hydrolysis reactions that lower the pH of the mine water in its passage through the Krugersdorp Game Reserve and beyond into the COH WHS – this is a short-term (emergency) measure for implementation under excessive decant and flow conditions, and
- the effective containment and treatment of raw mine water in the headwaters of the Tweelopie Spruit – this is a short- to medium-term measure.

14.1.2 Swartkrans

Located to the north of the Bloubank Spruit upstream of the Sterkfontein Caves, the potentiometric surface (water table) at this position has an interpolated elevation of ~1440 m amsl. Positioned near the downstream (overflow) boundary of the Zwartkrans Compartment, it is unlikely that the magnitude of groundwater level fluctuation in such settings will be excessive (Hobbs, 2008b). It would appear from section 11.3 that a maximum long-term fluctuation of <3 m might be expected.

The current quality of the groundwater passing beneath this fossil site is represented by that obtained from stations NR1, MB1, SC1 (Sterkfontein Caves) and ZWSp (Zwartkrans Spring) (Figure 84). As described in section 9.4 and illustrated in Figure 84, this groundwater reflects a varied composition. Although the elevated EC values (80 to 100 mS/m) reveal the impact of poorer quality surface water on the karst groundwater, the slightly alkaline pH values (7.1 to 7.5) reflect the continuing neutralising capacity of the carbonate strata. A **moderate vulnerability** is assigned to this fossil site (Table 91).

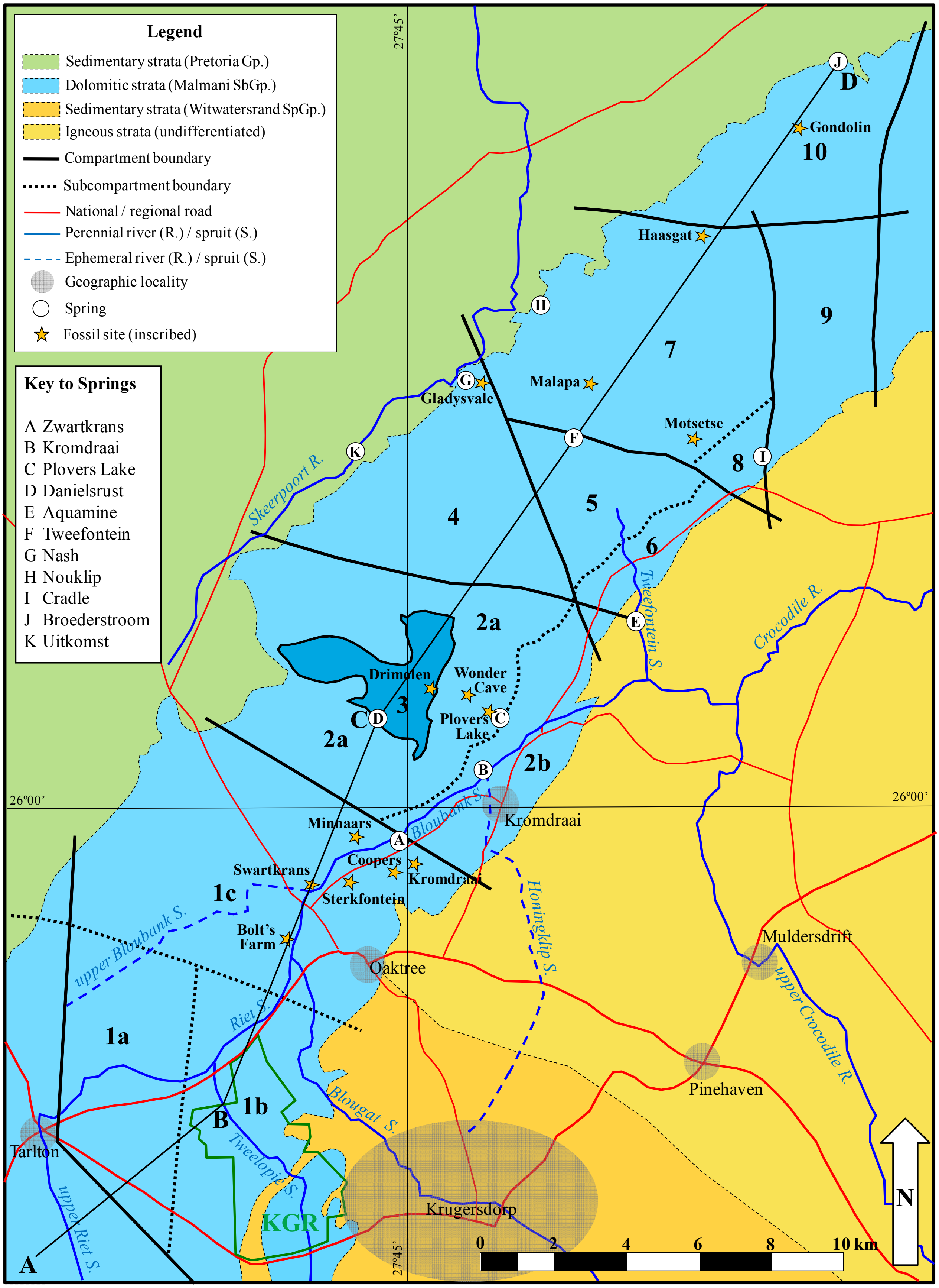

Figure 107. Definition of fossil site localities in relation to the dolomitic springs and compartments/subcompartments in the study area.

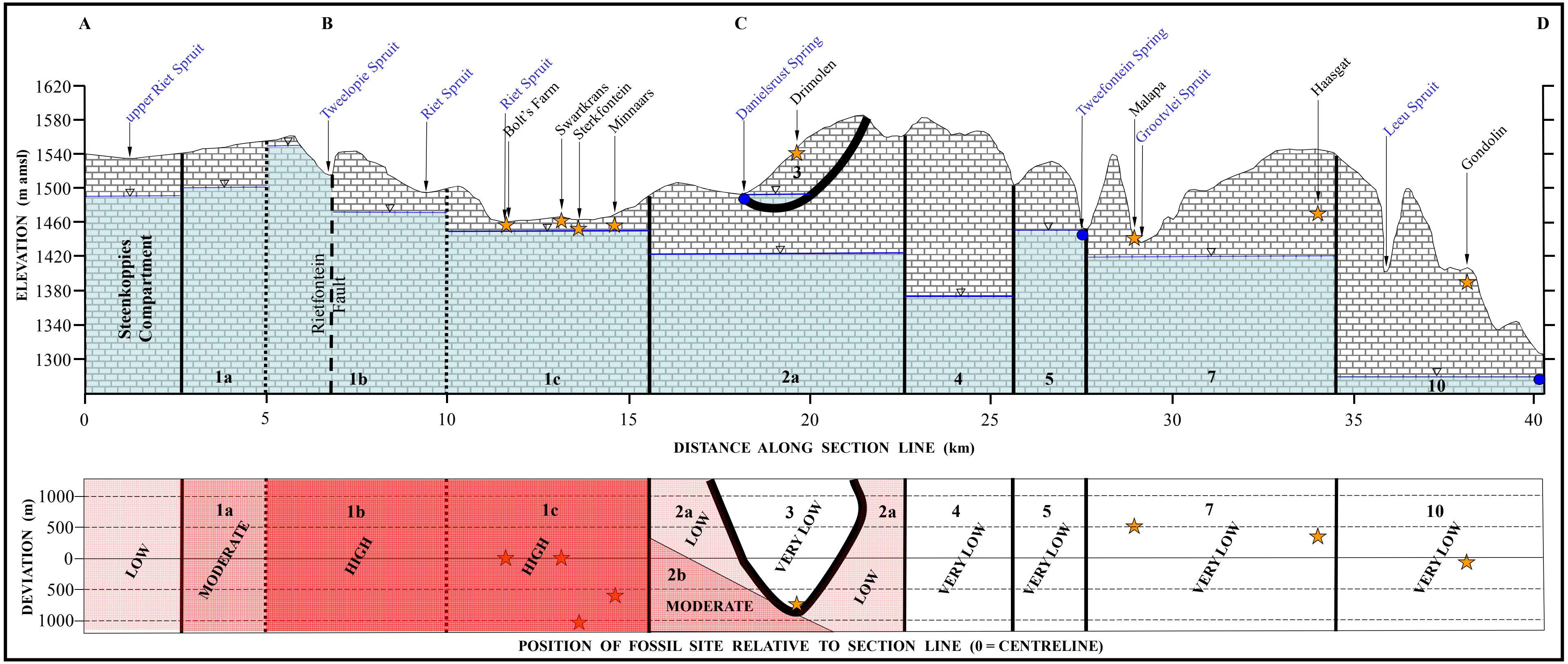

Figure 108. Cross-section (top) through the karst aquifer from south-west to north-east (see Figure 107) illustrating the position of fossil sites within ~1 km of the section line in relation to the hydrogeology at each site, and plan view (bottom) showing the measure of fossil site deviation from the centreline (expressed as metres normal to the latter) and the relative risk to the compartment/subcompartment from contaminated water.

[Note: The fossil site elevations shown in the cross-section reflect approximately the surface elevations given in Table 91, namely at the site itself, and therefore do not necessarily match the surface elevation of the profile. Observed differences are a function of the ruggedness of the terrain and the distance of the sites from the actual line of section as shown in the plan view.]

<u>Key to compartments/subcompartments:</u>

1a Vlakdrift Subcompartment	1b Sterkfontein Subcompartment	1c Zwartkrans Subcompartment	
2a Kromdraai Subcompartment	2b Bloubank Spruit Compartment	3 Danielsrust Compartment	4 Uitkomst Compartment
5 Tweefontein Compartment	7 Diepkloof Compartment	10 Broederstroom Compartment	

14.1.3 Sterkfontein

The lake in the Sterkfontein Caves represents the water table in the karst aquifer of the Zwartkrans Compartment close to its downstream boundary. The potentiometric surface (water table) in the Bloubank Spruit valley in this vicinity lies at an elevation of ~1438 m amsl, some 2 m below the 1440 m amsl of the streambed opposite the caves (section 8.4.1). These circumstances reflect the close hydraulic continuity that exists between the surface and groundwater environments in this portion of the study area. Positioned even nearer this boundary than the Swartkrans fossil site, it is probable that the magnitude of groundwater level fluctuation will be even less than that postulated for Swartkrans. This would represent a maximum fluctuation of <2 m, which is in agreement with the historical observations described in section 8.4.2. It is also reasonable to expect that the magnitude of groundwater level fluctuation in the valley will be tempered by the largely uniform flow in the perennial Bloubank Spruit derived mainly from Percy Stewart WWTW effluent discharge and, more recently, the excess mine water discharge via the Riet Spruit.

The chemistry of the cave water reflects a composition that is similar to that determined for station NR1 (Figure 84). As such, it represents the situation already described for the Swartkrans fossil site (section 14.1.2). Although the municipal wastewater contribution raises concern for the bacteriological quality of the groundwater and its suitability as a potable supply, this should not represent a risk to the fossil site *per se*. It is also observed that the cave water quality reflects the least impact of all the geosites sourced for groundwater samples in the Oaktree area (Figure 84). This observation suggests that the Sterkfontein Caves does not lie in the main flowpath (thalweg) of groundwater discharge toward the Zwartkrans Spring. Nevertheless, a **high vulnerability** is assigned to this fossil site (Table 91).

In addition to the afore-mentioned considerations, it is also important to note that the elevation of the 'Little Foot' find, the deepest fossil find so far discovered in the Sterkfontein Cave system, itself lies at an elevation of ~1460 m amsl (section 2.5). This is ~22 m above the current cave water level elevation of ~1438 m amsl. Despite the high vulnerability assigned to this fossil site, this specific find is therefore considered to be at a comparatively low risk from the threat of any hydrogeologic impact associated with a rising water table. The latter is a necessary pre-requisite for the manifestation of any threat associated with a compromized groundwater quality. Factors such as these provide a more objective perspective than does a statement such as "*The place is riddled with fossils in direct line of the AMD*." (Béga, 2010), which conjures up the perception of fossil treasures at direct risk from the impact of acid mine drainage. The associated threat posed by enhanced dissolution leading to subsidence and slumping of overlying potentially fossil-bearing strata has been discussed in section 10.1.

14.1.4 Coopers

The Coopers fossil site is located to the south of Zwartkrans Spring, which places it in the Zwartkrans Compartment. Its position on a hillside puts it some distance above both the ambient groundwater level (~1435 m amsl) and the streambed level (~1430 m amsl). These circumstances, as well as the near-surface nature of the workings, provide this fossil site with a fair measure of protection against hydrogeologic risks, and explain the **low vulnerability** assigned to this site.

14.1.5 Kromdraai

Also located in the Zwartkrans Compartment to the south-east of the Zwartkrans Spring, this fossil site with its near-surface workings occupies an even higher elevation on the south flank of the Bloubank Spruit valley than Coopers. It therefore has a similar measure of protection against hydrogeologic risks as Coopers, and accordingly exhibits a similarly **low vulnerability**.

14.1.6 Minnaars

This fossil site is located to the north of the Bloubank Spruit upstream of the Zwartkrans Dyke, and therefore within the Zwartkrans Compartment. It exhibits an underground cave morphology (Table 5) with an interpolated groundwater level located <20 m from surface in this vicinity. As such, it reflects a slightly greater hydrogeologic vulnerability than does Swartkrans, especially if the cave system extends to <1437 m amsl, and material of archaeological and/or palaeontological and/or mineralogical significance occurs below this elevation. In all other respects, this site shares the potentiometric and groundwater quality characteristics of the Swartkrans and Sterkfontein fossil sites. These circumstances underpin the **moderate vulnerability** assigned to this site.

14.1.7 Plover's Lake

Occupying a lowest surface elevation of ~1430 m amsl, the proximity of this fossil site to the Plover's Lake Springs located at an elevation of ~1419 m amsl suggests that this fossil site probably intersects the water table if it extends to a depth below ~1420 m amsl. A cave system further up the valley from the fossil site [possibly site SAAN 0026 (Bones Cave) of Berger and Brink (undated)] is reported to extend sufficiently far down to intersect the water table (G. Doyle, personal communication). A number of factors, identified as the following, serve as mitigation for these circumstances and the **moderate vulnerability** assigned to this site:

- the springs drain a dolomitic compartment (the Kromdraai Subcompartment of the Krombank Compartment) that is dominated by natural veld and vegetation which typifies the natural Carletonville Dolomite Grassland vegetation unit (section 2.3);
- located near the discharge (overflow) boundary of the compartment, the fossil site will experience the muted groundwater rest level behaviour that typifies these hydrogeologic settings;
- the quality of the groundwater discharged at the springs (section 9.7.2) represents a typically pristine karst water chemistry; and
- the largely natural landscape and low risk land use activities that characterize the Kromdraai Subcompartment provide good assurance against the deterioration of groundwater quality.

14.1.8 Wonder Cave

The groundwater rest level in the vicinity of this site occupies an elevation of ~1422 m amsl, some 80 m below the surface elevation (~1500 m amsl) at the cave entrance. At an elevation of ~1440 m amsl (the cave is some 60 m deep[69]), the accessible base of the cave lies ~20 m above the water table. This is a reasonable separation that ensures the immunity of this fossil site from changes in the ambient groundwater environment due to either anthropogenic or natural factors. Accordingly, this site is assigned a **low vulnerability**.

14.1.9 Drimolen

The groundwater level elevation at the Drimolen fossil site is placed at ~1490 m amsl, some 50 m below the postulated cave base elevation of ~1540 m amsl. These circumstances, together with the location of this site in the 'perched' Danielsrust Compartment (Figure 107 and Figure 108), indicate that the site is at very little, if any, risk from changes in the groundwater environment. It is therefore assigned a **very low vulnerability**.

14.1.10 Gladysvale

The Gladysvale fossil site in the John Nash Nature Reserve has been 'probed' to a depth of ~45 m below surface[70] at the cave location, which equates to an elevation of ~1370 m amsl. This is above the ~1360 m amsl of the Nash Spring (Table 65). The fossil site and spring are located a distance of ~800 m apart in the Uitkomst Compartment. The water table at the Gladysvale location is therefore placed at ~1362 m amsl, i.e. 8 m below the deepest surveyed portion of the cave system.

[69] Sourced 28/06/2010 at http://www.southafrica.net/sat/content/en/us/full-article?oid=10034&sn=Detail&pid=7014.
[70] Based on a Jpeg image sourced at http://en.wikipedia.org/wiki/File:Gladysvale4.jpg on 17/05/2010.

The substantial discharge rate of the Nash Spring (~130 L/s on 19/05/2010) is indicative of a highly transmissive karst system, which suggests in turn that increases in the potentiometric head will readily translate into a higher spring flow. The counter-balance generated by these circumstances at the discharge end of the aquifer system should serve to mitigate the risk to the cave system/fossil site from excessive groundwater level fluctuations.

The quality of the groundwater discharged at the Nash Spring is excellent in respect of all the parameters analysed (section 9.7.8). Further, the largely natural landscape and low risk land use activities that characterize the Uitkomst Compartment provide excellent assurance against the deterioration of groundwater quality. The cave system is therefore not considered to be at risk from groundwater quality threats as long as the landscape in this compartment remains in its current state (section 12.2.4). Accordingly, this fossil site is assigned a **low vulnerability**.

14.1.11 Motsetse

Located in the Motsetse Nature Reserve and groundwater compartment, this fossil site occupies a position >80 m above the ambient groundwater level. Further, the largely natural landscape and low risk land use activities that characterize the compartment provide assurance against negative impacts on groundwater quantity and quality. This fossil site is therefore not considered to be at risk from changes in the ambient groundwater environment as long as the landscape in this compartment remains in its current state (section 12.2.8). Accordingly, this fossil site is assigned a **very low vulnerability**.

14.1.12 Haasgat

The paucity of groundwater rest level data in the Diepkloof Compartment limits a rigorous evaluation of the hydrogeologic vulnerability of this site. The elevation of the Nouklip Spring (~1330 m amsl) provides a lower bound for the potentiometric surface in this compartment. This is some 135 m below the cave base elevation of ~1465 m amsl. The distance between the fossil site and the Nouklip Spring is ~4.8 km, which indicates a maximum hydraulic gradient of ~0.03. Since this approaches the maximum gradient in a productive karst aquifer, it is probable that the depth to groundwater level beneath the fossil site is significantly less than 135 m. It is proposed that a depth of 45 m, which translates into a gradient of ~0.02, is a more likely value. Accordingly, this fossil site is assigned a **very low vulnerability**.

14.1.13 Gondolin

This fossil site is located near the north-eastern extremity of the COH WHS (Figure 107). Situated in the Broederstroom Compartment, it occupies an elevation that is placed >40 m above the ambient groundwater rest level. Identified as a near-surface feature (Table 5), this site is assigned a **very low vulnerability**.

14.1.14 Malapa

The Malapa Cave system occupies a surface elevation of 1442 m amsl (Dirks et al., 2010), and a postulated base elevation of ~1430 m amsl. Again, the paucity of groundwater rest level data in the Diepkloof Compartment limits a rigorous evaluation of the hydrogeologic vulnerability of this site. As in the case of Haasgat, the elevation of the Nouklip Spring (~1330 m amsl) provides a lower bound for the potentiometric surface in this compartment. The distance between the Malapa site and the Nouklip Spring is ~2.4 km, which indicates a maximum hydraulic gradient of ~0.04. Applying the same argument as in the case of Haasgat suggests that a more probable depth to groundwater level beneath the fossil site is in the order of 55 m, again yielding a gradient of ~0.02. Dirks et al. (2010) report that the Malapa site lies 85 m above the bedrock channel of the ephemeral Grootvlei Spruit to the west-north-west. This observation matches field observations by T. Abiye and P. Dirks (T. Abiye, personal communication) regarding the depth of a vertical shaft (aven) located in proximity to the Malapa fossil site. Accordingly, this fossil site is assigned a **very low vulnerability**.

14.2 Discussion

As far as can be established, the COH WHS is the only protected karst landscape in the world that is ostensibly threatened by acid mine drainage (AMD). The perceived threat of AMD to the area has generated wide and considerable concern for the preservation of the UNESCO-inscribed fossil sites. Against this background, the fossil site hydrovulnerability assessment represents a first attempt to evaluate the threat on the basis of a better understanding of the physical and chemical hydrologic and hydrogeologic frameworks that describe the receiving aquatic environment as both a pathway for and receptor of AMD.

14.3 Conclusions

It is concluded that nine of the 14 inscribed fossil sites in the COH WHS exhibit a very low or low hydrovulnerability. This is attributed to their location (a) in groundwater compartments that are hydrogeologically separate from those where the contaminated water impact is manifested, and (b) at substantial elevations above the ambient groundwater level.

Only the Bolt's Farm site exhibits a very high hydrovulnerability. This is due to its position immediately down-gradient of the two main sources of poor quality surface water, namely mine water via the Riet Spruit and treated municipal wastewater via the Blougat Spruit. This is compounded by the fact that (a) both these drainages lose water to the karst aquifer, and (b) at least one cave system is known to intersect the water table. Nevertheless, the very high vulnerability rating is mitigated to some extent in those instances where fossil sites in this area occupy surface elevations >40 m above the ambient water table.

The Sterkfontein site is assigned a high hydrovulnerability. The fact that this cave system intersects the water table is mitigated by the observed long-term cave water quality record and other hydrochemical data. These reflect circumstances where the cave water does not exhibit the measure of impact observed in the Zwartkrans Subcompartment as is recorded for the Zwartkrans Spring.

The Swartkrans, Minnaars and Plover's Lake sites exhibit a moderate hydrovulnerability. This is mainly due to a relatively shallow (5 to 25 m bs) water table.

In conclusion, therefore, it is apparent that the majority of the inscribed fossil sites in the COH WHS are not under threat from either changes in surface water or groundwater levels and/or changes in surface water or groundwater chemistry (quality), whether due to mine water or treated sewage effluent ingress, or from agriculture. The sites that are the most vulnerable have been identified and are earmarked for specific monitoring activities.

14.4 Recommendations

It is recommended that the fossil sites assigned a very high (Bolt's Farm) or high (Sterkfontein Caves) vulnerability be monitored closely by means of either indirect or direct means. The Bolt's Farm fossil site lends itself to indirect monitoring via the recently established DWA monitoring station GP00311 located at 26.04455°S/27.68438°E. It is recommended that this borehole be equipped with an automatic recording device (data logger) that measures and stores EC, temperature and water level depth readings at a pre-set 6-hourly interval.

The Sterkfontein Caves site lends itself to direct monitoring by tourist guides. Such 'self-monitoring' can be implemented if the tour guides are tasked to routinely record the following:

- the cave water level by measured and documented observation of a water level gauge in the cave lake that can be easily and routinely read and recorded by a tourist guide — to start with, these measurements need only be relative to a local datum, although their translation into absolute values will be required sooner or later; and
- field water chemistry variables (e.g. EC-pH-temperature) using a handheld multi-parameter probe to establish the trend of these variables associated with the cave water.

The 'self-monitoring' programme not only serves the monitoring requirements, but also empowers the tour guides with the additional competence of being able to measure basic field hydrogeologic and hydrochemical variables. This will also provide the guides with additional first-hand and current information that can be communicated to visitors as part of the standard tour guide 'script'.

In addition, however, a more complete quarterly water chemistry analysis incorporating major anions and cations together with nitrate (NO_3+NO_2, as N), ortho-phosphate (PO_4 as P) and the trace metals Al, Fe, Mn, Ni and U will be required. It is also recommended that the borehole SF1 located in the north-eastern corner of the Sterkfontein Caves site be incorporated in a monthly groundwater level monitoring programme.

Finally, it is also recommended that biomonitoring activities targeting the stygobitic fauna in the Sterkfontein Caves be carried out regularly and routinely (at least annually) to establish the cave ecosystem integrity. The purpose of these activities aims to establish the population dynamics of these fauna, since population increases in the food-poor environment of caves usually means an increase in available food (typically associated with eutrophication), and therefore observation of such a trend offers an early warning of potentially severe (or even catastrophic) longer term impacts on stygobitic fauna.

15 CONCLUSIONS

The understanding of the surface water and groundwater environments in the COH WHS area, also in regard to their inter-relationship, is considerably expanded by the current study. This understanding extends as much to the water chemistry aspect as it does to the water quantity aspect. Outcomes of the study that are considered especially significant are summarized as follows:

- the quantification of surface water flow losses in the lower Riet Spruit valley;
- the quantification of spring discharges;
- the definition of compartments/subcompartments and corresponding groundwater resource units associated with the karst formations in the study area;
- the evaluation of the geochemical interaction between acidic mine water and the dolomitic strata that form the receiving karst aquifer in the study area;
- the development of semi-quantitative resource quality objectives (RQOs) to inform groundwater resource directed measures for the karst portions of the study area;
- the derivation of a fossil site risk assessment that informs the vulnerability of each declared fossil site and its associated cave system in the context of its hydrogeologic setting; and
- the development of a monitoring programme for the COH WHS.

The platform built from historical data integrated with a wide range of rigorous and defensible newly generated and interpreted hydrologic and hydrogeologic data and information, underpins the situation assessment of the surface water and groundwater environments. This, in turn, has provided the means to objectively gauge the impact of varied and numerous threats on the water resources in the study area. The salient conclusions drawn from the study are summarized in the following sections.

15.1 Surface Water Resources

15.1.1 Quantity

The Skeerpoort River system fed by dolomitic springs remains in a near pristine condition. The Bloubank Spruit system, on the other hand, has experienced above average discharges in its upper reaches via the Tweelopie Spruit and the Riet Spruit since the resumption of mine water decant in late-January 2010. Together with the treated sewage effluent discharged from the Percy Stewart WWTW via the Blougat Spruit, these circumstances have resulted in an unprecedented volume and duration of surface water flow in the Bloubank Spruit system through the 2010 winter. Further, the combined discharge of raw and treated mine water witnessed surface water losses of between 20 and 32 ML/d to the dolomitic aquifer in the lower Riet Spruit, equating to an infiltration rate of as much as ~90 L/s/km.

15.1.2 Quality

The Skeerpoort River system continues to reflect a karst-dominated water composition of excellent quality. Up until mid-2010, the impact of the poor quality associated with the recent abnormal combined discharge of treated and raw mine water in the upper reaches of the Bloubank Spruit system was mitigated by (a) the contribution of treated wastewater effluent discharged by the Percy Stewart WWTW and (b) the above average surface water runoff associated with the extremely wet 2009-'10 summer. Since mid-2010, the increase in salinity of Bloubank Spruit water from ~50 to >100 mS/m, together with a decrease in pH from 7.2 to 6.9 at the downstream boundary of the Zwartkrans Compartment, is considered to reflect an increasing contribution of mine water to the middle reaches of this drainage. This impact is less evident in the Zwartkrans Spring water, which as recently as August 2010 still reflected a field salinity of ~77 mS/m. Similarly, the water in the Sterkfontein Caves continues to reflect a salinity of ~60 mS/m as it did in June 2006, a year after the start of monitoring of this variable by the DWA.

The quality of surface water resources in the Bloubank Spruit system is further compromized by bacterial contamination derived from wastewater effluent. These circumstances also make it difficult to assess agricultural impacts on the surface water resources, since these impacts are similarly associated with nutrient inputs.

15.2 Groundwater Resources

15.2.1 Quantity

The very wet 2009-'10 and 2010-'11 summers precipitated an exceptional recharge of groundwater resources in the study area. A rise in groundwater rest levels by at least ~1 m is testimony to these circumstances. Greater water level recoveries of as much as ~5 m are attributed to allogenic recharge associated with the infiltration of surface water contributed from extraneous sources including mining and municipal wastewater effluent. This infiltration has amounted to as much as 32 ML/d in the case of mine water, and a more modest 7 ML/d in the case of municipal wastewater effluent. It is concluded, therefore, that the aspect of groundwater quantity as represented by recent/current groundwater rest levels compared to historical levels, reflects an extremely positive outlook.

15.2.2 Quality

As might be expected, the chemistry of groundwater in the study area reflects the greatest spatial variation depending on the position in the physical hydrogeologic environment. For instance, the subcompartments receiving water of compromized quality in terms of either trace/heavy metals and elevated salt loads associated with mine water, and/or elevated bacterial loads associated with municipal wastewater (both representing allogenic recharge), reflect the poorest groundwater chemical composition. In contrast, compartments/subcompartments receiving only autogenic recharge remain largely unaffected in terms of groundwater chemistry (and quality).

15.3 Sediment Chemistry

Sediment samples collected at eight localities in the southern portion of the study area provided information on the chemical composition of streambed material at various positions along the Tweelopie Spruit, the Riet Spruit, the Blougat Spruit and the Bloubank Spruit. These drainages receive either raw and/or treated mine water via the Tweelopie Spruit, and treated municipal wastewater effluent via the Blougat Spruit. The 'once-off' sampling campaign took the form of a screening level reconnaissance survey, and facilitated a Tier 1 risk assessment comparing measured concentrations of U and Ni to a regulatory standard using values from the European Union (EU) and the National Nuclear Regulator (NNR), since South Africa does not yet have freshwater sediment guidelines or legislated limits for most contaminants in soil. The outcome identified the two most upstream localities, namely the Hippo Dam and the Lion Camp Dam on the Tweelopie Spruit in the KGR, as definitely posing a risk in regard to both U and Ni. The next two localities downstream were identified as definitely posing a risk in regard to Ni only.

Three different leach tests were carried out to determine the extractable (mobile) fraction of the total concentration of elements measured by XRF. None of the leach tests extracted a U concentration higher than the regulatory limit of 16 mg/kg as proposed by the NNR. A highest U concentration of ~5% of the total U concentration was extracted. A highest Ni concentration of ~12% was extracted from one sample, the extractable fraction of ~71 mg/kg exceeding the regulatory limit of 35 mg/kg proposed by the EU. These results put those of the Tier 1 risk assessment into perspective, since it is probable that a Tier 1 risk assessment based on extractable concentrations (as opposed to total concentrations) would return a greater number of lower risk quotient values. Although these circumstances mitigate the risk associated with the mobilization/remobilization of sediment-bound trace/heavy metals, the cumulative mass/volume of sediment contained in the various impoundments cautions against minimization or downplaying of the associated risk.

15.4 Mine Water Impact on Dolomite

A comparative petrographic study together with laboratory-based column leaching tests carried out by the CGS further informed the potential impact on the karst environment of the COH WHS dolomite by infiltrating mine water.

The likely effects of AMD ingress into the karst aquifer(s) will be a rise in the pH of the influent mine water (as a result of the dissolution of dolomite) to a value comparable to that of the ambient karst groundwater. The rise in pH would result in the reduction of the solubility of some of the contaminant species in the mine water, significantly removing iron and aluminium from solution, partially removing manganese and not having a significant effect on the sodium or sulphate concentration. The metal precipitates, which would include gypsum, goethite and crystalline and amorphous (botryoidal) aluminium oxy-hydroxide species, are likely to form on the reactive surfaces of the dolomite, preventing further neutralisation reactions from taking place. Influent mine water would therefore tend to react at the point of first contact with the dolomite, resulting in both neutralisation of the mine water and the prevention of further neutralisation from taking place. Over time the mine water would migrate further and further into the karst aquifer, and the buffering capacity of the aquifer would reduce progressively.

It is concluded, however, that natural attenuation of AMD by allowing it to enter dolomitic aquifer systems is not regarded as an appropriate or sustainable management strategy.

15.5 Resource Quality Objectives

The setting of resource quality objectives (RQOs) for groundwater quantity and quality in the COH WHS expands the impact of the study.

15.5.1 Quantity

The statistical assessment of long-term groundwater rest level trends provides a means to quantify the setting of RQOs for groundwater quantity in a part of the study area. The proposed RQOs recognize 'permissible' changes in groundwater rest level that vary across a compartment. Although the proposed RQOs do not find a priori support in the DWA library of existing RQOs in this regard, they are nevertheless put forward for consideration as advancing the knowledge base in regard to this GRDM component.

Long-term groundwater level monitoring data are only available for the Zwartkrans Compartment. The proposed RQO for the upper reaches represented by the Vlakdrift Subcompartment, assigned a **'modified' class C** SoE condition, is a change in groundwater rest level of ≤6.1 m. The middle reaches represented by the Sterkfontein Subcompartment, assigned a **'largely modified' class D** SoE condition, is set a change in groundwater rest level of ≤3.6 m, and the Zwartkrans Subcompartment in the lower reaches, assigned a **'largely modified' class D** SoE condition, is set a value of ≤2.3 m.

The remaining nine dolomitic compartments, which are either assigned a **'slightly modified' class B/BC** or a **'natural' class AB** SoE condition, represent a natural environment that remains largely unaffected by changes in land use activities and practices. As such, the setting of RQOs as above is not an imperative at this stage. Further, it would be required that a better understanding of groundwater rest level trends in these groundwater resource units is developed before RQOs can be set with the necessary statistical support to generate confidence.

15.5.2 Quality

The setting of RQOs in regard to groundwater chemistry (quality) is a comparatively much simpler exercise given the relationship of analytical groundwater chemistry data with the discharge(s) of associated groundwater compartments, especially where these are coupled with spring water chemistries. The springs draining the largely pristine Danielsrust, Tweefontein, Uitkomst and Diepkloof compartments do not reflect anthropogenic impacts on the chemistry (quality) of the groundwater produced by these hydrogeologic environments, compared to the chemistry of groundwater produced by the Zwartkrans Spring. The latter drains the most severely compromized hydrogeologic regime in terms of groundwater quality in the study area, with groundwater analyses typically exhibiting electrical conductivity values >100 mS/m, SO_4 concentrations >150 mg/L, and Cl concentrations >50 mg/L. The geographic extent of this footprint in the host aquifer is still comparatively limited.

15.6 State of the Environment

The state of the environment assessment shows that two of the 15 groundwater resource units (GRUs) are assigned a **'largely modified' class D** condition, and a further three a **'modified' class C** condition. The remainder are assigned either a **'slightly modified' class B/BC** or a **'natural' class AB** condition. These circumstances reflect the good, and in some instances even excellent, state of the groundwater environment associated with two-thirds of the GRUs study area. A closer inspection of the spatial representation of the karst GRUs according to their SoE classification shows that 59% of the karst area supports a **'slightly modified' class B/BC** or better condition. Further, that only 27% of this area supports a **'largely modified' class D** condition.

15.7 Groundwater Resource Risk

The application of hazard and risk mapping procedures in the COH WHS expanded on a 2008 aquifer vulnerability study to produce a more realistic risk management tool for this sensitive environment.

The outcome of the hazard mapping exercise indicates the greater hazard present in the south-western corner of the COH WHS in the Oaktree area, as well as the elevated hazard rating associated with the surface water drainages. Whereas the former is directly related to the intensity of agricultural activity mainly in the form of cut flower production for the export market, the latter is informed by the intrinsically close hydraulic relationship that exists between surface water and groundwater resources in a karst environment. The risk map developed by combining the aquifer vulnerability map and the hazard map, clearly reveals the elevated risk associated with the roads running through the area.

The proliferation of 'illegal' refuse disposal sites associated with both informal and formal low-cost residential areas is further cause for concern. This is especially relevant in instances where the disposal sites occupy positions close to or even within surface drainages that traverse dolomite. The provision of suitably adequate refuse/waste removal facilities for the low-cost and/or informal residential areas that have been developed on dolomitic ground in the COH WHS and surrounds, is no less important than the provision of water and sanitation facilities to these communities. This represents an opportunity for integrated land use development between local and district municipal authorities.

15.8 Fossil Site Hydrovulnerability

It is concluded that nine of the 14 fossil sites in the COH WHS exhibit a **very low** or **low vulnerability**. This is attributed to their location (a) in groundwater compartments that are hydrogeologically separate from those where the contaminated water impact is manifested, and (b) at substantial elevations above the ambient groundwater level. Only the Bolt's Farm site exhibits a **very high vulnerability**. This is due to its position immediately down-gradient of the two main sources of poor quality surface water, namely mine water via the Riet Spruit and treated municipal wastewater via the Blougat Spruit. This is compounded by the fact that (a) both these drainages lose water to the karst aquifer, and (b) at least one cave system in this area is known to intersect the water table. The Sterkfontein site is assigned a **high vulnerability**. The fact that this cave system intersects the water table is mitigated by the observed long-term cave water quality record and other hydrochemical data. These reflect circumstances where the cave water does not exhibit the measure of impact observed in the Zwartkrans Subcompartment as is recorded for the Zwartkrans Spring. The Swartkrans, Minnaars and Plover's Lake sites exhibit a **moderate vulnerability**. This is mainly due to a relatively shallow (5 to 25 m bs) water table. In conclusion, therefore, it is apparent that the majority of the fossil sites in the COH WHS are not under threat from either changes in surface water or groundwater levels and/or changes in surface water or groundwater chemistry (quality), whether due to mine water or treated sewage effluent ingress, or from agricultural land use practices. The sites that are the most vulnerable have been identified and are earmarked for specific monitoring activities.

16 RECOMMENDATIONS

Recommendations that address aspects specific to the water resources and ancilliary aspects such as sediment chemistry, fossil site hydrovulnerability and cave ecosystem integrity have been put forward in the body of the report. They are not repeated in this section. The following recommendations are of a more general nature. They are put forward for consideration

16.1 Hydrovulnerability Assessment

It is advisable to extend the hydrovulnerability assessment to other cave systems in the study area. These will comprise those non-inscribed sites that researchers and cavers are familiar with, and therefore can be recommended for such attention.

16.2 Gravimetric Survey

It is advisable to carry out a gravimetric survey in the lower Riet Spruit valley extending from the confluence of the Tweelopie Spruit and the Riet Spruit down to the confluence of the Blougat Spruit and the Riet Spruit. The results of such a survey will indicate the measure of karst dissolution present in this important E-W corridor that hosts the N14 national road.

16.3 Mine Water Treatment

The Inter-Ministerial Committee (IMC) on AMD, in its recently released report (IMC, 2010), recommends (amongst others) that the mine water treatment capacity in the headwaters of the Tweelopie Spruit be increased to accommodate a decant volume of 40 ML/d. This recommendation is supported unequivocally. It is recognized, however, that the implementation of this recommendation lies outside the jurisdiction of the Management Authority of the COH WHS.

It is further recommended that additional mine water treatment facilities be established in the headwaters of the Tweelopie Spruit to further 'polish' the treated mine water that is generated by the expanded mine water treatment capacity and released into the environment.

16.4 Monitoring Committee

It is recommended that a monitoring committee comprising a core of key stakeholder groupings (e.g. national, provincial and local government, environment and tourism, agriculture) be established. This committee, chaired by the Management Authority, should function in cooperation with the similar committee established within the Team of Experts that advises the IMC on AMD.

16.5 Workshop

It is recommended that the Management Authority hosts a workshop or seminar to communicate the outcomes of the study to as wide an audience of stakeholders and interested and affected parties as might be interested. The facilities at the Sterkfontein Caves provide a suitable and appropriate venue for such an event. Holding the event on a Saturday should ensure as large an audience as possible.

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GLOSSARY OF SELECTED TERMS

allogenic Describes a system that derives its water entirely from that running off a neighbouring non-karst catchment area (Ford and Williams, 2007).

anion An ion (atom or complex of atoms) that has gained one or more electrons to exhibit a negative electric charge, e.g. Cl^-, SO_4^{2-}.

aquifer A stratum of water-bearing rock that has the ability to both store and transmit groundwater in quantities that are sufficient to sustain the long-term water-yielding properties of a borehole that intersects such stratum, for the water supply purposes required of the borehole. For example, a low-yielding aquifer that can sustain a sufficient groundwater yield to meet a comparatively low-demand domestic supply is as "good" as a high-yielding aquifer that can sustain a groundwater yield capable of supplying water for large-scale irrigation or municipal water supply purposes.

autogenic Describes a system composed entirely of **karst** strata, and which derives its water only from rainfall on such a system (Ford and Williams, 2007).

aven A vertical or highly inclined shaft extending upward from a cave passage, generally to the surface. May equally be described as a shaft when seen from above. Commonly related to enlarged vertical joints.
[http://network.speleogenesis.info/directory/glossary/term.php?gloss_id=161]

cation An ion (atom or complex of atoms) that has lost one or more electrons to be left with a positive electric charge, e.g. Na^+, Mg^{2+}.

confined aquifer An **aquifer** in which the **hydrostatic head** (pressure) is greater than that of atmospheric pressure, generally due to the load exerted on the aquifer by overlying impervious (confining) strata, and therefore supports a **potentiometric surface** that is located above the 'roof' of the **aquifer**. This is typically represented by a groundwater level that stands at a shallower depth than that at which water was first encountered in a borehole penetrating the confined aquifer, and which phenomenon finds ultimate expression in the form of an artesian or free-flowing borehole.

doline An enclosed topographic depression, basin or typically grassy hollow caused by direct solution and subsidence of the dolomite/limestone surface zone (solution doline), or formed by collapse over a cave (collapse doline) (Field, 2002); a collapse doline more readily conforms to the generally deeper funnel or shaft geometry with rocky cliff-bounded sides typical of a **sinkhole**.

electrical balance A measure of the accuracy of a chemical analysis determined by the formula $(\sum\text{Cations} - \sum\text{Anions}) \div (\sum\text{Cations} + \sum\text{Anions}) \times 100$, which expresses the difference between the sum of the major positively charged **cations** and that of the major negatively charged **anions** as a percentage. Whereas a value of 0% denotes a perfect balance, an error margin of ±5% is generally considered acceptable for fresh water (Hem, 1985; Appelo and Postma, 2009). The calculation of this parameter in this study has considered only analyses which are complete for their reported sampling date, i.e. are not missing any major anion or cation. Where significant, the calculation has also included elements such as NO_3, PO_4, Fe and Mn which might materially influence the electrical balance.

epikarst The zone of highly weathered strata that occupies the top of the **vadose zone** and might or might not be covered with soil, and gradually grades downward into largely unweathered bedrock that forms the main body of the **vadose zone** (Ford and Williams, 2007). Also referred to in some **karst** texts as the subcutaneous zone.

gaining stream A river or stream that receives groundwater discharge; also referred to as an effluent drainage (stream).

grike A vertical or sub-vertical cleft in a limestone pavement developed by solution along a joint or system of crisscrossing joints (UNESCO, 1972).

groundwater management unit An area of a catchment that requires consistent management actions to maintain the desired level of use or protection of groundwater; delineation is based on management considerations rather than geohydrological criteria (Parsons and Wentzel, 2007).

groundwater resource unit A groundwater body that has been delineated or grouped into a single significant water resource based on one or more characteristics that are similar across that unit (Parsons and Wentzel, 2007).

hydraulic conductivity The rate of flow (m^3/d) of water through a 1 m^2 cross section of **aquifer** under a **hydraulic gradient** of 1 (Driscoll, 1986). Typically expressed as "k" with the unit m/d ≡ $m^3/d/m^2$.

hydraulic gradient The slope of the **potentiometric surface** that also describes the direction of groundwater movement in an **aquifer**.

hydrophobic Lacking an affinity for water.

hydrostatic head Describes the water table in a phreatic aquifer, or the potentiometric head in a **confined aquifer**, that represents the elevation of the groundwater rest level which, in turn, determines the direction of groundwater flow. For example, in a **phreatic aquifer**, groundwater drainage is from a higher elevation to a lower elevation, i.e. driven by gravity drainage. In a **confined aquifer**, groundwater drainage is from an area of a greater head (hydrostatic pressure) to an area of lower head, i.e. driven by differences in pressure (from higher to lower).

inlier An area (usually of limited extent) of older strata completely surrounded by younger strata.

karst The type of landscape that develops on carbonate rocks such as dolomite and limestone, and is formed principally by the dissolving of rock, giving rise to a landscape characterized by sinkholes and ground subsidence, losing drainages, a well-developed subsurface drainage system, strong interaction between the circulation of surface water and groundwater, and caves (Ford and Williams, 2007). Often also supports **aquifers** capable of storing and transmitting substantial quantities of groundwater typically drained by springs or 'eyes'.

karst barré An isolated **karst** that is impounded by impermeable strata (Ford and Williams, 2007), examples of which in the study area are represented by the Danielsrust Compartment and the dolomitic **outlier** that hosts the locus of mine water decant. Note that the definition makes no reference to the age of the impounded strata relative to the impounding strata, as is the case in the distinction between **outlier** and **inlier**.

losing drainage A river or stream that loses some or all of its water into the subsurface, where it becomes groundwater; also referred to as an influent drainage (stream); in a karst environment, such loss typically occurs through a stream sink, swallet or swallow hole.

median Statistical parameter that defines the value which is exceeded 50% of the time in a data set, the remaining 50% of values being below this value, and which means that this value is not unduly influenced (skewed) by anomalously high or low values in the data set.

occurrence survey The first phase of study of trace elements and **hydrophobic** organic contaminants in streambed sediment and tissues of aquatic organisms. The primary objective is to determine which target constituents are common and important to water quality conditions in each study unit (Shelton and Capel, 1994).

outlier An area (usually of limited extent) of younger strata completely surrounded by older strata.

phreatic aquifer An **aquifer** in which the hydrostatic pressure is equal or similar to that of atmospheric pressure, and therefore supports a **potentiometric surface** that is equivalent to a **water table**. Also referred to as an unconfined **aquifer**.

phreatic surface The surface defined by the **potentiometric surface** in a **phreatic aquifer**, and which is equivalent to the **water table**.

potentiometric surface The theoretical surface fitted to the groundwater level elevation, in layman's terms often referred to as the **water table**, and which represents the spatial dimensions of the **hydrostatic** (pressure) **head** in a **confined aquifer** (Freeze and Cherry, 1979; Domenico and Schwartz, 1998; Ford and Williams, 2007).

resource quality objective The measure(s) that must be imposed to ensure that the Class that has been assigned to a groundwater resource as part of a Groundwater Resource Directed Measures assessment is met. The measure(s) might for example consider the maximum allowable lowering and/or fluctuation of groundwater rest level, and the maximum allowable deterioration of groundwater quality. In the absence of data, the measure(s) generally take the form of qualitative descriptions, whereas semi-quantitative or even quantitative measures can be derived from long-term data records.

salt load The mass of dissolved salts carried by a water body per unit time (typically expressed as t/d or t/a), calculated as the product of the flow volume (typically expressed as ML/d, where 1 ML/d ≡ 1000 m^3/d) and the salt concentration (typically expressed as mg/L, where 1 mg/L ≡ 0.001 kg/m^3).

sinkhole An engineering/engineering geology term of North American origin (Ford and Williams, 2007) for a collapse **doline** forming a hole on surface (WRC/IUCN/SAKWG, 2010); synonymous terms are closed depression, **doline**, ponor, stream sink, sumidero, swallet and swallow hole (Field, 2002).

stygobite A form of aquatic fauna that completes its entire life cycle in a cave environment.

thalweg Hydrological term that describes the deepest part of a watercourse and, as such, generally the path of fastest flow in a river or stream.

transmissivity The rate at which water is transmitted through a vertical section of an **aquifer** 1 m wide and extending the full saturated height (depth "d") of the aquifer under a **hydraulic gradient** of 1 (Driscoll, 1986). Typically expressed as "T" with the unsual unit m^2/d, derived from its association with the product of **hydraulic conductivity** "k" with units m/d and "d" (as previously defined) with units m, i.e. T= kd.

troglobite A form of terrestrial fauna that completes its entire life cycle in a cave environment.

vadose zone The unsaturated zone between the land surface and the **water table**.

VUKA An intrinsic aquifer vulnerability mapping method developed by Leyland et al. (2008) for use in karst terrains in South Africa.

water table The surface represented by the groundwater level in a **phreatic aquifer**.

winze A steep (not vertical) shaft which joins different levels in an underground mine. In the strictest sense, a winze has its entrance below surface within the mine, and not at surface as is the case with a shaft.

Unnumbered plate.
Surface expression of the epikarst at the Swartkrans Cave fossil site.
(Photo: Phil Hobbs).

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Unnumbered plate.
Surface expression of the epikarst at the Swartkrans Cave fossil site.
(Photo: Phil Hobbs).

TABLE OF CONTENTS : ANNEXURES

Unnumbered plate.
The ~21 L/s Broederstroom Spring that rises under the concrete slab (at feet of seated figure) which forms part of the spring protection measures.
(Photo: Phil Hobbs).

ANNEXURE A : HYDROCHEMICAL MONITORING METADATA

A.1 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION A2N034 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
ASAR-Diss-Water	Adjusted SAR	Null	63	04/10/1999	15/01/2001
CORR-Diss-Water	Corrosivity index	Null	262	04/10/1999	08/10/2008
Ca-Diss-Water	Calcium	mg/L Ca	1300	21/01/1976	08/10/2008
Cl-Diss-Water	Chloride	mg/L Cl	1300	21/01/1976	08/10/2008
DMS-Tot-Water	Total dissolved salts	mg/L	1279	02/06/1976	23/04/2008
EC-Phys-Water	Electrical conductivity	Null	1497	21/01/1976	23/04/2008
F-Diss-Water	Fluoride	mg/L F	1299	21/01/1976	23/04/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	70	03/08/2005	08/10/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	262	04/10/1999	08/10/2008
K-Diss-Water	Potassium	mg/L K	1299	21/01/1976	23/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	1	30/07/1985	30/07/1985
LANGL-Index-Water	Langelier saturation index	Null	261	04/10/1999	23/04/2008
Mg-Diss-Water	Magnesium	mg/L Mg	1300	21/01/1976	08/10/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	533	02/01/1995	23/04/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	1353	02/06/1976	08/10/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	1380	21/01/1976	08/10/2008
Na-Diss-Water	Sodium	mg/L Na	1299	21/01/1976	23/04/2008
P-Tot-Water	Total phosphorus	mg/L P	1	30/07/1985	30/07/1985
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	1370	21/01/1976	08/10/2008
RYZNAR-Index-Water	Ryznar stability index	Null	261	04/10/1999	23/04/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	1279	21/01/1976	23/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	1300	21/01/1976	08/10/2008
Si-Diss-Water	Silicon	mg/L Si	1353	02/06/1976	08/10/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	1310	21/01/1976	08/10/2008
TEMP-Phys-Water	Temperature	°C	490	04/08/1980	07/10/1991
TURB-Phys-Water	Turbidity	NTU	10	21/06/1993	15/08/1994
pH-Diss-Water	pH	pH units	1408	21/01/1976	23/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	69	03/08/2005	23/04/2008

A.2 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION A2N049 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
ASAR-Diss-Water	Adjusted SAR	null	66	05/07/1999	22/01/2001
Al-Diss-Water	Aluminium	mg/L Al	51	24/06/2004	02/06/2008
As-Diss-Water	Arsenic	mg/L As	51	24/06/2004	02/06/2008
B-Diss-Water	Boron	mg/L B	51	24/06/2004	02/06/2008
Ba-Diss-Water	Barium	mg/L Ba	51	24/06/2004	02/06/2008
CORR-Diss-Water	Corrosivity index	Null	270	05/07/1999	19/05/2008
Ca-Diss-Water	Calcium	mg/L Ca	784	23/05/1979	19/05/2008
Cd-Diss-Water	Cadmium	mg/L Cd	51	24/06/2004	02/06/2008
Cl-Diss-Water	Chloride	mg/L Cl	784	23/05/1979	19/05/2008
Cr-Diss-Water	Chrome	mg/L Cr	51	24/06/2004	02/06/2008
Cu-Diss-Water	Copper	mg/L Cu	51	24/06/2004	02/06/2008
DMS-Tot-Water	Total dissolved salts	mg/L	781	23/05/1979	19/05/2008
EC-Phys-Water	Electrical conductivity	mS/m	963	23/05/1979	19/05/2008
F-Diss-Water	Fluoride	mg/L F	784	23/05/1979	19/05/2008
Fe-Diss-Water	Iron	mg/L Fe	51	24/06/2004	02/06/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	72	15/08/2005	19/05/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	270	05/07/1999	19/05/2008
K-Diss-Water	Potassium	mg/L K	784	23/05/1979	19/05/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	51	22/11/1993	21/04/2008
LANGL-Index-Water	Langelier saturation index	Null	268	05/07/1999	19/05/2008
Mg-Diss-Water	Magnesium	mg/L Mg	784	23/05/1979	19/05/2008
Mn-Diss-Water	Manganese	mg/L Mn	51	24/06/2004	02/06/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	51	24/06/2004	02/06/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	544	02/01/1995	19/05/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	856	23/05/1979	19/05/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	856	23/05/1979	19/05/2008
Na-Diss-Water	Sodium	mg/L Na	784	23/05/1979	19/05/2008
Ni-Diss-Water	Nickel	mg/L Ni	51	24/06/2004	02/06/2008
P-Tot-Water	Total phosphorus	mg/L P	50	22/11/1993	19/05/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	856	23/05/1979	19/05/2008
Pb-Diss-Water	Lead	mg/L Pb	51	24/06/2004	02/06/2008
RYZNAR-Index-Water	Ryznar stability index	Null	268	05/07/1999	19/05/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	771	23/05/1979	19/05/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	784	23/05/1979	19/05/2008
Si-Diss-Water	Silicon	mg/L Si	856	23/05/1979	19/05/2008
Sr-Diss-Water	Strontium	mg/L Sr	51	24/06/2004	02/06/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	786	23/05/1979	19/05/2008
TEMP-Phys-Water	Temperature	°C	190	01/12/1981	07/10/1991
V-Diss-Water	Vanadium	mg/L V	51	24/06/2004	02/06/2008
Zn-Diss-Water	Zinc	mg/L Zn	51	24/06/2004	02/06/2008
pH-Diss-Water	pH	pH units	858	23/05/1979	19/05/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	72	15/08/2005	19/05/2008

A.3 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION A2N050 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
ASAR-Diss-Water	Adjusted SAR	null	66	19/04/1999	15/01/2001
Al-Diss-Water	Aluminium	mg/L Al	52	24/06/2004	02/06/2008
As-Diss-Water	Arsenic	mg/L As	52	24/06/2004	02/06/2008
B-Diss-Water	Boron	mg/L B	52	24/06/2004	02/06/2008
Ba-Diss-Water	Barium	mg/L Ba	52	24/06/2004	02/06/2008
CORR-Diss-Water	Corrosivity index	Null	268	19/04/1999	22/09/2008
Ca-Diss-Water	Calcium	mg/L Ca	790	02/05/1979	22/09/2008
Cd-Diss-Water	Cadmium	mg/L Cd	52	24/06/2004	02/06/2008
Cl-Diss-Water	Chloride	mg/L Cl	789	02/05/1979	22/09/2008
Cr-Diss-Water	Chrome	mg/L Cr	52	24/06/2004	02/06/2008
Cu-Diss-Water	Copper	mg/L Cu	52	24/06/2004	02/06/2008
DMS-Tot-Water	Total dissolved salts	mg/L	787	02/05/1979	28/07/2008
EC-Phys-Water	Electrical conductivity	mS/m	968	02/05/1979	28/07/2008
F-Diss-Water	Fluoride	mg/L F	789	02/05/1979	28/07/2008
Fe-Diss-Water	Iron	mg/L Fe	52	24/06/2004	02/06/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	75	18/07/2005	22/09/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	269	19/04/1999	22/09/2008
K-Diss-Water	Potassium	mg/L K	789	02/05/1979	28/07/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	51	22/11/1993	21/04/2008
LANGL-Index-Water	Langelier saturation index	Null	267	19/04/1999	28/07/2008
Mg-Diss-Water	Magnesium	mg/L Mg	790	02/05/1979	22/09/2008
Mn-Diss-Water	Manganese	mg/L Mn	52	24/06/2004	02/06/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	52	24/06/2004	02/06/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	546	24/05/1983	28/07/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	862	02/05/1979	22/09/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	863	02/05/1979	22/09/2008
Na-Diss-Water	Sodium	mg/L Na	789	02/05/1979	28/07/2008
Ni-Diss-Water	Nickel	mg/L Ni	52	24/06/2004	02/06/2008
P-Tot-Water	Total phosphorus	mg/L P	50	22/11/1993	21/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	862	02/05/1979	22/09/2008
Pb-Diss-Water	Lead	mg/L Pb	52	24/06/2004	02/06/2008
RYZNAR-Index-Water	Ryznar stability index	Null	267	19/04/1999	28/07/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	774	02/05/1979	28/07/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	790	02/05/1979	22/09/2008
Si-Diss-Water	Silicon	mg/L Si	862	02/05/1979	22/09/2008
Sr-Diss-Water	Strontium	mg/L Sr	52	24/06/2004	02/06/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	791	02/05/1979	22/09/2008
TEMP-Phys-Water	Temperature	°C	191	20/04/1981	07/10/1991
V-Diss-Water	Vanadium	mg/L V	52	24/06/2004	02/06/2008
Zn-Diss-Water	Zinc	mg/L Zn	52	24/06/2004	02/06/2008
pH-Diss-Water	pH	pH units	862	02/05/1979	28/07/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	73	18/07/2005	28/07/2008

A.4 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F1S1 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	47	13/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	47	13/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	47	13/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	47	13/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	30	13/11/2003	27/03/2008
Ca-Diss-Water	Calcium	mg/L Ca	47	13/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	47	13/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	47	13/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	47	13/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	47	13/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	25	13/11/2003	27/03/2008
EC-Phys-Water	Electrical conductivity	mS/m	47	13/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	30	13/11/2003	27/03/2008
Fe-Diss-Water	Iron	mg/L Fe	47	13/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	25	16/01/2006	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	46	13/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	46	13/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	33	13/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	25	13/11/2003	27/03/2008
Mg-Diss-Water	Magnesium	mg/L Mg	46	13/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	47	13/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	47	13/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	27	13/11/2003	27/03/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	27	13/11/2003	27/03/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	29	13/11/2003	27/03/2008
Na-Diss-Water	Sodium	mg/L Na	47	13/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	47	13/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	32	13/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	28	13/11/2003	27/03/2008
Pb-Diss-Water	Lead	mg/L Pb	47	13/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	25	13/11/2003	27/03/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	46	13/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	47	13/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	28	13/11/2003	27/03/2008
Sr-Diss-Water	Strontium	mg/L Sr	47	13/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	30	13/11/2003	27/03/2008
V-Diss-Water	Vanadium	mg/L V	47	13/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	47	13/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	47	13/11/2003	30/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	16	16/01/2006	27/03/2008

A.5 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F2S2 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	47	13/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	47	13/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	47	13/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	47	13/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	26	13/11/2003	13/11/2007
Ca-Diss-Water	Calcium	mg/L Ca	42	13/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	47	13/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	41	13/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	47	13/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	47	13/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	25	13/11/2003	13/11/2007
EC-Phys-Water	Electrical conductivity	mS/m	42	13/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	28	13/11/2003	12/02/2008
Fe-Diss-Water	Iron	mg/L Fe	47	13/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	22	16/01/2006	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	42	13/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	41	13/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	30	13/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	25	13/11/2003	13/11/2007
Mg-Diss-Water	Magnesium	mg/L Mg	42	13/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	47	13/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	47	13/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	27	13/11/2003	13/11/2007
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	27	13/11/2003	13/11/2007
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	27	13/11/2003	13/11/2007
Na-Diss-Water	Sodium	mg/L Na	41	13/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	47	13/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	27	13/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	26	13/11/2003	13/11/2007
Pb-Diss-Water	Lead	mg/L Pb	47	13/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	25	13/11/2003	13/11/2007
SAR-Diss-Water	Sodium adsorption ratio	Null	41	13/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	42	13/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	27	13/11/2003	13/11/2007
Sr-Diss-Water	Strontium	mg/L Sr	47	13/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	27	13/11/2003	12/02/2008
V-Diss-Water	Vanadium	mg/L V	47	13/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	47	13/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	42	13/11/2003	30/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	15	14/02/2006	13/11/2007

A.6 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION W1S1 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	53	13/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	53	13/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	53	13/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	53	13/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	30	20/11/2003	12/02/2008
Ca-Diss-Water	Calcium	mg/L Ca	51	13/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	53	13/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	52	13/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	53	13/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	53	13/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	28	20/11/2003	12/01/2008
EC-Phys-Water	Electrical conductivity	mS/m	52	13/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	31	20/11/2003	12/02/2008
Fe-Diss-Water	Iron	mg/L Fe	53	13/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	31	29/06/2005	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	51	13/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	52	13/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	38	20/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	28	20/11/2003	12/01/2008
Mg-Diss-Water	Magnesium	mg/L Mg	52	13/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	53	13/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	53	13/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	29	20/11/2003	12/01/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	29	20/11/2003	12/01/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	30	20/11/2003	12/01/2008
Na-Diss-Water	Sodium	mg/L Na	52	13/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	53	13/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	36	20/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	29	20/11/2003	12/01/2008
Pb-Diss-Water	Lead	mg/L Pb	53	13/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	28	20/11/2003	12/01/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	51	13/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	51	13/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	31	20/11/2003	12/01/2008
Sr-Diss-Water	Strontium	mg/L Sr	53	13/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	30	20/11/2003	12/02/2008
V-Diss-Water	Vanadium	mg/L V	1	23/02/2007	23/02/2007
Zn-Diss-Water	Zinc	mg/L Zn	1	23/02/2007	23/02/2007
pH-Diss-Water	pH	pH units	1	23/02/2007	23/02/2007
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	1	23/02/2007	23/02/2007

A.7 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION BGS1 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
COD	Chemical oxygen demand	mg/L	23	21/11/2002	28/10/2008
CORR-Diss-Water	Corrosivity index	Null	19	21/11/2002	22/09/2008
Ca-Diss-Water	Calcium	mg/L Ca	1	14/08/2007	14/08/2007
Cl-Diss-Water	Chloride	mg/L Cl	22	21/11/2002	22/09/2008
E.COLI-Susp-Water	*E. coli* bacteria	count/100 mL	12	07/07/2005	28/10/2008
EC-Phys-Water	Electrical conductivity	mS/m	23	21/11/2002	28/10/2008
F-Diss-Water	Fluoride	mg/L F	22	21/11/2002	22/09/2008
FC-Susp-Water	Faecal coliform bacteria	count/100 mL	23	21/11/2002	28/10/2008
Fe-Diss-Water	Iron	mg/L Fe	1	07/07/2005	07/07/2005
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	16	21/11/2002	25/06/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	23	21/11/2002	28/10/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	23	21/11/2002	28/10/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	23	21/11/2002	28/10/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	23	21/11/2002	28/10/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	10	14/08/2007	28/10/2008
SOLIDS-Susp-Water	Suspended solids	mg/L	21	21/11/2002	22/09/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	11	21/11/2002	29/09/2004
TC-Susp-Water	Total coliform bacteria	count / 100 mL	23	21/11/2002	28/10/2008
pH-Diss-Water	pH	pH units	23	21/11/2002	28/10/2008

A.8 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION BGS2 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
COD	Chemical oxygen demand	mg/L	23	21/11/2002	28/10/2008
CORR-Diss-Water	Corrosivity index	Null	19	21/11/2002	22/09/2008
Ca-Diss-Water	Calcium	mg/L Ca	1	14/08/2007	14/08/2007
Cl-Diss-Water	Chloride	mg/L Cl	22	21/11/2002	22/09/2008
E.COLI-Susp-Water	*E. coli* bacteria	count/100 mL	12	07/07/2005	28/10/2008
EC-Phys-Water	Electrical conductivity	mS/m	23	21/11/2002	28/10/2008
F-Diss-Water	Fluoride	mg/L F	22	21/11/2002	22/09/2008
FC-Susp-Water	Faecal coliform bacteria	count/100 mL	23	21/11/2002	28/10/2008
Fe-Diss-Water	Iron	mg/L Fe	1	07/07/2005	07/07/2005
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	16	21/11/2002	25/06/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	23	21/11/2002	28/10/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	23	21/11/2002	28/10/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	23	21/11/2002	28/10/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	23	21/11/2002	28/10/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	10	14/08/2007	28/10/2008
SOLIDS-Susp-Water	Suspended solids	mg/L	21	21/11/2002	22/09/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	11	21/11/2002	29/09/2004
TC-Susp-Water	Total coliform bacteria	count / 100 mL	23	21/11/2002	28/10/2008
pH-Diss-Water	pH	pH units	23	21/11/2002	28/10/2008

A.9 : SUMMARY OF WASTEWATER EFFLUENT QUALITY MONITORING METADATA FOR STATION PSFE (Percy Stewart Final Effluent) [SOURCE = DWA]

Monitoring Variable (after DWA)	**Description**	**Measuring Unit**	**Number of Analyses**	**First Analysis**	**Last Analysis**
COD	Chemical oxygen demand	mg/L	21	21/11/2002	28/10/2008
CORR-Diss-Water	Corrosivity index	Null	18	21/11/2002	22/09/2008
Ca-Diss-Water	Calcium	mg/L Ca	1	14/08/2007	14/08/2007
Cl-Diss-Water	Chloride	mg/L Cl	20	21/11/2002	22/09/2008
E.COLI-Susp-Water	*E. coli* bacteria	count/100 mL	14	25/01/2005	29/10/2008
EC-Phys-Water	Electrical conductivity	mS/m	21	21/11/2002	28/10/2008
F-Diss-Water	Fluoride	mg/L F	20	21/11/2002	22/09/2008
FC-Susp-Water	Faecal coliform bacteria	count/100 mL	25	21/11/2002	29/10/2008
Fe-Diss-Water	Iron	mg/L Fe	4	25/05/2004	26/08/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	1	07/07/2005	07/07/2005
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	14	21/11/2002	07/05/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	21	21/11/2002	28/10/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	20	21/11/2002	28/10/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	21	21/11/2002	28/10/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	21	21/11/2002	28/10/2008
SOLIDS-Susp-Water	Suspended solids	mg/L	22	21/11/2002	28/10/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	19	21/11/2002	22/09/2008
TC-Susp-Water	Total coliform bacteria	count / 100 mL	11	21/11/2002	29/09/2004
pH-Diss-Water	pH	pH units	21	21/11/2002	28/10/2008

A.10 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F6S7 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	52	13/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	52	13/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	52	13/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	52	13/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	37	13/11/2003	12/02/2008
Ca-Diss-Water	Calcium	mg/L Ca	50	13/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	52	13/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	51	13/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	52	13/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	52	13/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	34	13/11/2003	17/01/2008
EC-Phys-Water	Electrical conductivity	mS/m	50	13/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	37	13/11/2003	12/02/2008
Fe-Diss-Water	Iron	mg/L Fe	52	13/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	30	29/06/2005	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	50	13/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	50	13/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	36	13/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	34	13/11/2003	17/01/2008
Mg-Diss-Water	Magnesium	mg/L Mg	51	13/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	52	13/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	52	13/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	37	13/11/2003	17/01/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	37	13/11/2003	17/01/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	37	13/11/2003	17/01/2008
Na-Diss-Water	Sodium	mg/L Na	51	13/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	52	13/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	40	13/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	37	13/11/2003	17/01/2008
Pb-Diss-Water	Lead	mg/L Pb	52	13/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	34	13/11/2003	17/01/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	50	13/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	50	13/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	37	13/11/2003	17/01/2008
Sr-Diss-Water	Strontium	mg/L Sr	52	13/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	37	13/11/2003	12/02/2008
V-Diss-Water	Vanadium	mg/L V	52	13/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	52	13/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	51	13/11/2003	30/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	20	29/06/2005	17/01/2008

A.11 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F8S9 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	53	14/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	53	14/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	53	14/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	53	14/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	42	14/11/2003	12/02/2008
Ca-Diss-Water	Calcium	mg/L Ca	52	14/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	53	14/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	53	14/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	53	14/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	53	14/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	40	14/11/2003	19/01/2008
EC-Phys-Water	Electrical conductivity	mS/m	53	14/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	42	14/11/2003	12/02/2008
Fe-Diss-Water	Iron	mg/L Fe	53	14/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	33	29/06/2005	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	52	14/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	53	14/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	41	14/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	40	14/11/2003	19/01/2008
Mg-Diss-Water	Magnesium	mg/L Mg	53	14/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	53	14/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	53	14/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	40	14/11/2003	19/01/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	40	14/11/2003	19/01/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	41	14/11/2003	19/01/2008
Na-Diss-Water	Sodium	mg/L Na	53	14/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	53	14/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	47	14/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	40	14/11/2003	19/01/2008
Pb-Diss-Water	Lead	mg/L Pb	53	14/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	40	14/11/2003	19/01/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	52	14/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	53	14/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	41	14/11/2003	19/01/2008
Sr-Diss-Water	Strontium	mg/L Sr	53	14/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	42	14/11/2003	12/02/2008
V-Diss-Water	Vanadium	mg/L V	53	14/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	53	14/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	53	14/11/2003	30/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	24	29/06/2005	19/01/2008

A.12 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F10S11 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	53	14/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	53	14/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	53	14/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	53	14/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	46	14/11/2003	27/03/2008
Ca-Diss-Water	Calcium	mg/L Ca	52	14/11/2003	30/04/2008
Cd-Diss-Water	Cadmium	mg/L Cd	53	14/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	52	14/11/2003	30/04/2008
Cr-Diss-Water	Chrome	mg/L Cr	53	14/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	53	14/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	45	14/11/2003	27/03/2008
EC-Phys-Water	Electrical conductivity	mS/m	52	14/11/2003	30/04/2008
F-Diss-Water	Fluoride	mg/L F	47	14/11/2003	27/03/2008
Fe-Diss-Water	Iron	mg/L Fe	53	14/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	30	29/07/2005	30/04/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	52	14/11/2003	30/04/2008
K-Diss-Water	Potassium	mg/L K	52	14/11/2003	30/04/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	39	14/11/2003	30/04/2008
LANGL-Index-Water	Langelier saturation index	Null	45	14/11/2003	27/03/2008
Mg-Diss-Water	Magnesium	mg/L Mg	52	14/11/2003	30/04/2008
Mn-Diss-Water	Manganese	mg/L Mn	53	14/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	53	14/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	46	14/11/2003	27/03/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	46	14/11/2003	27/03/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	46	14/11/2003	27/03/2008
Na-Diss-Water	Sodium	mg/L Na	52	14/11/2003	30/04/2008
Ni-Diss-Water	Nickel	mg/L Ni	53	14/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	36	14/11/2003	30/04/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	46	14/11/2003	27/03/2008
Pb-Diss-Water	Lead	mg/L Pb	53	14/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	45	14/11/2003	27/03/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	52	14/11/2003	30/04/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	51	14/11/2003	30/04/2008
Si-Diss-Water	Silicon	mg/L Si	46	14/11/2003	27/03/2008
Sr-Diss-Water	Strontium	mg/L Sr	53	14/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	47	14/11/2003	27/03/2008
V-Diss-Water	Vanadium	mg/L V	53	14/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	53	14/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	52	14/11/2003	30/04/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	27	29/07/2005	27/03/2008

A.13 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F11S12 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
ASAR-Diss-Water	Adjusted SAR	null	1	29/08/2008	29/08/2008
Al-Diss-Water	Aluminium	mg/L Al	53	14/11/2003	23/05/2008
As-Diss-Water	Arsenic	mg/L As	53	14/11/2003	23/05/2008
B-Diss-Water	Boron	mg/L B	53	14/11/2003	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	53	14/11/2003	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	47	14/11/2003	29/08/2008
Ca-Diss-Water	Calcium	mg/L Ca	54	14/11/2003	29/08/2008
Cd-Diss-Water	Cadmium	mg/L Cd	53	14/11/2003	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	54	14/11/2003	29/08/2008
Cr-Diss-Water	Chrome	mg/L Cr	53	14/11/2003	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	53	14/11/2003	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	46	14/11/2003	23/05/2008
EC-Phys-Water	Electrical conductivity	mS/m	54	14/11/2003	29/08/2008
F-Diss-Water	Fluoride	mg/L F	48	14/11/2003	23/05/2008
Fe-Diss-Water	Iron	mg/L Fe	53	14/11/2003	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	35	29/06/2005	29/08/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	54	14/11/2003	29/08/2008
K-Diss-Water	Potassium	mg/L K	54	14/11/2003	29/08/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	37	14/11/2003	12/02/2008
LANGL-Index-Water	Langelier saturation index	Null	46	14/11/2003	23/05/2008
Mg-Diss-Water	Magnesium	mg/L Mg	54	14/11/2003	29/08/2008
Mn-Diss-Water	Manganese	mg/L Mn	53	14/11/2003	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	53	14/11/2003	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	49	14/11/2003	29/08/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	49	14/11/2003	29/08/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	48	14/11/2003	23/05/2008
Na-Diss-Water	Sodium	mg/L Na	54	14/11/2003	29/08/2008
Ni-Diss-Water	Nickel	mg/L Ni	53	14/11/2003	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	41	14/11/2003	29/08/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	50	14/11/2003	29/08/2008
Pb-Diss-Water	Lead	mg/L Pb	53	14/11/2003	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	46	14/11/2003	23/05/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	54	14/11/2003	29/08/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	53	14/11/2003	29/08/2008
Si-Diss-Water	Silicon	mg/L Si	49	14/11/2003	29/08/2008
Sr-Diss-Water	Strontium	mg/L Sr	53	14/11/2003	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	48	14/11/2003	29/08/2008
V-Diss-Water	Vanadium	mg/L V	53	14/11/2003	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	53	14/11/2003	23/05/2008
pH-Diss-Water	pH	pH units	54	14/11/2003	29/08/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	29	29/07/2005	23/05/2008

A.14 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION 188048 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	44	24/06/2004	23/05/2008
As-Diss-Water	Arsenic	mg/L As	44	24/06/2004	23/05/2008
B-Diss-Water	Boron	mg/L B	44	24/06/2004	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	44	24/06/2004	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	41	24/06/2004	27/03/2008
Ca-Diss-Water	Calcium	mg/L Ca	42	24/06/2004	27/03/2008
Cd-Diss-Water	Cadmium	mg/L Cd	44	24/06/2004	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	42	24/06/2004	27/03/2008
Cr-Diss-Water	Chrome	mg/L Cr	44	24/06/2004	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	44	24/06/2004	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	41	24/06/2004	27/03/2008
EC-Phys-Water	Electrical conductivity	mS/m	42	24/06/2004	27/03/2008
F-Diss-Water	Fluoride	mg/L F	41	24/06/2004	27/03/2008
Fe-Diss-Water	Iron	mg/L Fe	44	24/06/2004	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	30	29/06/2005	27/03/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	42	24/06/2004	27/03/2008
K-Diss-Water	Potassium	mg/L K	42	24/06/2004	27/03/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	38	04/08/2004	27/03/2008
LANGL-Index-Water	Langelier saturation index	Null	41	24/06/2004	27/03/2008
Mg-Diss-Water	Magnesium	mg/L Mg	42	24/06/2004	27/03/2008
Mn-Diss-Water	Manganese	mg/L Mn	44	24/06/2004	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	44	24/06/2004	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	41	24/06/2004	27/03/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	41	24/06/2004	27/03/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	41	24/06/2004	27/03/2008
Na-Diss-Water	Sodium	mg/L Na	42	24/06/2004	27/03/2008
Ni-Diss-Water	Nickel	mg/L Ni	44	24/06/2004	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	36	04/08/2004	27/03/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	41	24/06/2004	27/03/2008
Pb-Diss-Water	Lead	mg/L Pb	44	24/06/2004	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	41	24/06/2004	27/03/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	42	24/06/2004	27/03/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	42	24/06/2004	27/03/2008
Si-Diss-Water	Silicon	mg/L Si	41	24/06/2004	27/03/2008
Sr-Diss-Water	Strontium	mg/L Sr	44	24/06/2004	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	41	24/06/2004	27/03/2008
V-Diss-Water	Vanadium	mg/L V	44	24/06/2004	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	44	24/06/2004	23/05/2008
pH-Diss-Water	pH	pH units	42	24/06/2004	27/03/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	30	29/06/2005	27/03/2008

A.15 : SUMMARY OF SURFACE WATER QUALITY MONITORING METADATA FOR STATION F14S15 [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
Al-Diss-Water	Aluminium	mg/L Al	45	24/06/2004	23/05/2008
As-Diss-Water	Arsenic	mg/L As	45	24/06/2004	23/05/2008
B-Diss-Water	Boron	mg/L B	45	24/06/2004	23/05/2008
Ba-Diss-Water	Barium	mg/L Ba	45	24/06/2004	23/05/2008
CORR-Diss-Water	Corrosivity index	Null	42	24/06/2004	23/05/2008
Ca-Diss-Water	Calcium	mg/L Ca	42	24/06/2004	23/05/2008
Cd-Diss-Water	Cadmium	mg/L Cd	45	24/06/2004	23/05/2008
Cl-Diss-Water	Chloride	mg/L Cl	42	24/06/2004	23/05/2008
Cr-Diss-Water	Chrome	mg/L Cr	45	24/06/2004	23/05/2008
Cu-Diss-Water	Copper	mg/L Cu	45	24/06/2004	23/05/2008
DMS-Tot-Water	Total dissolved salts	mg/L	42	24/06/2004	23/05/2008
EC-Phys-Water	Electrical conductivity	mS/m	42	24/06/2004	23/05/2008
F-Diss-Water	Fluoride	mg/L F	42	24/06/2004	23/05/2008
Fe-Diss-Water	Iron	mg/L Fe	45	24/06/2004	23/05/2008
HARD-Mg-Calc-Water	Magnesium hardness	mg/L	30	29/07/2005	23/05/2008
HARD-Tot-Water	Total hardness	mg/L $CaCO_3$	42	24/06/2004	23/05/2008
K-Diss-Water	Potassium	mg/L K	42	24/06/2004	23/05/2008
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	37	24/06/2004	23/05/2008
LANGL-Index-Water	Langelier saturation index	Null	42	24/06/2004	23/05/2008
Mg-Diss-Water	Magnesium	mg/L Mg	42	24/06/2004	23/05/2008
Mn-Diss-Water	Manganese	mg/L Mn	45	24/06/2004	23/05/2008
Mo-Diss-Water	Molybdenum	mg/L Mo	45	24/06/2004	23/05/2008
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	42	24/06/2004	23/05/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	42	24/06/2004	23/05/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	42	24/06/2004	23/05/2008
Na-Diss-Water	Sodium	mg/L Na	42	24/06/2004	23/05/2008
Ni-Diss-Water	Nickel	mg/L Ni	45	24/06/2004	23/05/2008
P-Tot-Water	Total phosphorus	mg/L P	37	24/06/2004	23/05/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	42	24/06/2004	23/05/2008
Pb-Diss-Water	Lead	mg/L Pb	45	24/06/2004	23/05/2008
RYZNAR-Index-Water	Ryznar stability index	Null	42	24/06/2004	23/05/2008
SAR-Diss-Water	Sodium adsorption ratio	Null	42	24/06/2004	23/05/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	42	24/06/2004	23/05/2008
Si-Diss-Water	Silicon	mg/L Si	42	24/06/2004	23/05/2008
Sr-Diss-Water	Strontium	mg/L Sr	45	24/06/2004	23/05/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	42	24/06/2004	23/05/2008
V-Diss-Water	Vanadium	mg/L V	45	24/06/2004	23/05/2008
Zn-Diss-Water	Zinc	mg/L Zn	45	24/06/2004	23/05/2008
pH-Diss-Water	pH	pH units	42	24/06/2004	23/05/2008
pHs-Calc-Water	pH @ saturation re $CaCO_3$	Null	30	29/07/2005	23/05/2008

A.16 : SUMMARY OF WASTEWATER EFFLUENT QUALITY MONITORING METADATA FOR STATION DFE (Driefontein Final Effluent) [SOURCE = DWA]

Monitoring Variable (after DWA)	Description	Measuring Unit	Number of Analyses	First Analysis	Last Analysis
COD	Chemical oxygen demand	mg/L	22	21/11/2002	28/10/2008
CORR-Diss-Water	Corrosivity index	Null	19	21/11/2002	22/09/2008
Ca-Diss-Water	Calcium	mg/L Ca	1	14/08/2007	14/08/2007
Cl-Diss-Water	Chloride	mg/L Cl	21	21/11/2002	22/09/2008
E.COLI-Susp-Water	*E. coli* bacteria	count/100 mL	11	25/01/2005	28/10/2008
EC-Phys-Water	Electrical conductivity	mS/m	22	21/11/2002	28/10/2008
F-Diss-Water	Fluoride	mg/L F	21	21/11/2002	22/09/2008
FC-Susp-Water	Faecal coliform bacteria	count/100 mL	21	21/11/2002	28/10/2008
Fe-Diss-Water	Iron	mg/L Fe	1	25/05/2004	25/05/2004
KJEL N-Tot-Water	Kjeldal nitrogen	mg/L N	1	07/07/2005	07/07/2005
NH_3(25)-Union-Diss-W	Ammonia	mg/L N	16	21/11/2002	31/07/2008
NH_4-N-Diss-Water	Ammonium nitrogen	mg/L N	22	21/11/2002	28/10/2008
NO_3+NO_2-N-Diss-Water	Nitrate + nitrite nitrogen	mg/L N	22	21/11/2002	28/10/2008
PO_4-P-Diss-Water	Ortho-phosphate	mg/L P	22	21/11/2002	28/10/2008
SO_4-Diss-Water	Sulphate	mg/L SO_4	22	21/11/2002	28/10/2008
SOLIDS-Susp-Water	Suspended solids	mg/L	20	21/11/2002	28/10/2008
TAL-Diss-Water	Total alkalinity	mg/L $CaCO_3$	20	21/11/2002	22/09/2008
TC-Susp-Water	Total coliform bacteria	count / 100 mL	10	21/11/2002	29/09/2004
pH-Diss-Water	pH	pH units	22	21/11/2002	28/10/2008

A.17 : SUMMARY OF WASTEWATER QUALITY MONITORING METADATA FOR THE PERCY STEWART WWTW [SOURCE = MOGALE CITY LOCAL MUNICIPALITY]

Monitoring Variable	Description	Measuring Unit	Number of Analyses	First Analysis(1)	Last Analysis(1)
EC	Electrical conductivity	mS/m	24	07/2007	06/2009
SS	Suspended Solids	mg/L	24	07/2007	06/2009
TDS	Total dissolved salts	mg/L	24	07/2007	06/2009
NH_3-N	Ammonia	mg/L N	24	07/2007	06/2009
NO_3-N	Nitrate	mg/L N	24	07/2007	06/2009
Cl	Chloride	mg/L Cl	24	07/2007	06/2009
Chlorine (Residual)	Chlorine (residual)	mg/L Cl	13	07/2007	06/2009
O-PO_4	Ortho-phosphate	mg/L P	24	07/2007	06/2009
pH	pH	pH units	24	07/2007	06/2009
Talk	Total alkalinity	mg/L $CaCO_3$	16	07/2007	06/2009
Cd	Cadmium	mg/L Cd	19	07/2007	06/2009
Cr	Chromium	mg/L Cr	19	07/2007	06/2009
Cu	Copper	Mg/L Cu	19	07/2007	06/2009
Pb	Lead	mg/L Pb	19	07/2007	06/2009
Mn	Manganese	mg/L Mn	19	07/2007	06/2009
Na	Sodium	mg/L Na	19	07/2007	06/2009
Zn	Zinc	mg/L Zn	19	07/2007	06/2009
COD	Chemical oxygen demand	mg/L	24	07/2007	06/2009
Soap, oil or grease	Soap, oil or grease	mg/L	16	07/2007	06/2009
Faecal Coliforms	Faecal coliform bacteria	count/100 mL	22	07/2007	06/2009
E Coliforms	*E. coli* bacteria	count/100 mL	6	07/2007	06/2009

(1) As provided by the Mogale City Local Municipality

A.18 : SUMMARY OF GROUNDWATER QUALITY MONITORING METADATA FOR THE PERCY STEWART WWTW [SOURCE = MOGALE CITY LOCAL MUNICIPALITY]

Monitoring Variable	**Description**	**Measuring Unit**	**Number of Analyses**	**First Analysis(1)**	**Last Analysis(1)**
Color	Apparent colour	Hazen units (Hz)	4	17/02/2009	03/11/2009
pH	pH	pH units	4	17/02/2009	03/11/2009
EC	Electrical conductivity	mS/m	4	17/02/2009	03/11/2009
Ca	Calcium	mg/L Ca	4	17/02/2009	03/11/2009
Mg	Magnesium	mg/L Mg	4	17/02/2009	03/11/2009
Na	Sodium	mg/L Na	4	17/02/2009	03/11/2009
K	Potassium	mg/L K	4	17/02/2009	03/11/2009
Cl	Chloride	mg/L Cl	4	17/02/2009	03/11/2009
SO_4	Sulphate	mg/L SO_4	4	17/02/2009	03/11/2009
NH_3	Ammonia	mg/L N	4	17/02/2009	03/11/2009
NO_3	Nitrate	mg/L N	4	17/02/2009	03/11/2009
PO_4	Ortho-phosphate	mg/L P	4	17/02/2009	03/11/2009
SS	Suspended solids	mg/L	4	17/02/2009	03/11/2009
Mg. hard.	Magnesium hardness	mg/L $CaCO_3$	4	17/02/2009	03/11/2009
Ca Hard.	Calcium hardness	mg/L $CaCO_3$	4	17/02/2009	03/11/2009
Tot. Hard.	Total hardness	mg/L $CaCO_3$	4	17/02/2009	03/11/2009
Odor	Odour	TON	4	17/02/2009	03/11/2009
Temperature	Temperature	°C	4	17/02/2009	03/11/2009
T. Alk.	Total alkalinity	mg/L $CaCO_3$	4	17/02/2009	03/11/2009
TDS	Total dissolved salts	mg/L	4	17/02/2009	03/11/2009
Turb.	Turbidity	NTU	4	17/02/2009	03/11/2009
Cd	Cadmium	mg/L Cd	4	17/02/2009	03/11/2009
Cr	Chromium	mg/L Cr	4	17/02/2009	03/11/2009
Co	Cobalt	mg/L Co	4	17/02/2009	03/11/2009
Cu	Copper	mg/L Cu	4	17/02/2009	03/11/2009
Fe	Iron	mg/L Fe	4	17/02/2009	03/11/2009
Pb	Lead	mg/L Pb	4	17/02/2009	03/11/2009
Mn	Manganese	mg/L Mn	4	17/02/2009	03/11/2009
Ni	Nickel	mg/L Ni	4	17/02/2009	03/11/2009
Zn	Zinc	mg/L Zn	4	17/02/2009	03/11/2009
HPC	Heterotrophic plate count	count / 1 mL	4	17/02/2009	03/11/2009
Tot. coliforms	Total coliform bacteria	count / 100 mL	4	17/02/2009	03/11/2009
Faecal coliforms	Faecal coliform bacteria	count / 100 mL	4	17/02/2009	03/11/2009
E. coli	*Escherichia* coliform	count / 100 mL	4	17/02/2009	03/11/2009

(1) As provided by the Mogale City Local Municipality

ANNEXURE A.19 : EXAMPLE TEST REPORT FOR A BOTTLED MINERAL WATER PRODUCT

SGS

SGS South Africa (Pty) Limited
Environmental Services
259 Kent Avenue
Ferndale, 2194
Tel: 011 326 3902

Angela M Potgieter

Exclusive Mineral Water

P O Box 275
Tarlton
1749

TEST REPORT

Report Status: **Preliminary Report**

Number of Samples: 1 Water Sample

Lab. Ref.: ENV 10-00640
Client Ref.: Exclusive Mineral Water
Quote No.: ENV 2010-0144
Date Received: 24/08/2010
Report Date: **06/09/2010**

Notes: 1.The analytical results reported herein refer to the samples as received.
2.Test marked with an asterisk in this report are included in the SANAS accreditation schedule for this laboratory.
3. Tests marked with a hash has been outsourced to another laboratory.
4. TF Results to follow

Authorised by:

Tasneem Tagari
Technical Signatory

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sanas
T0107

SGS

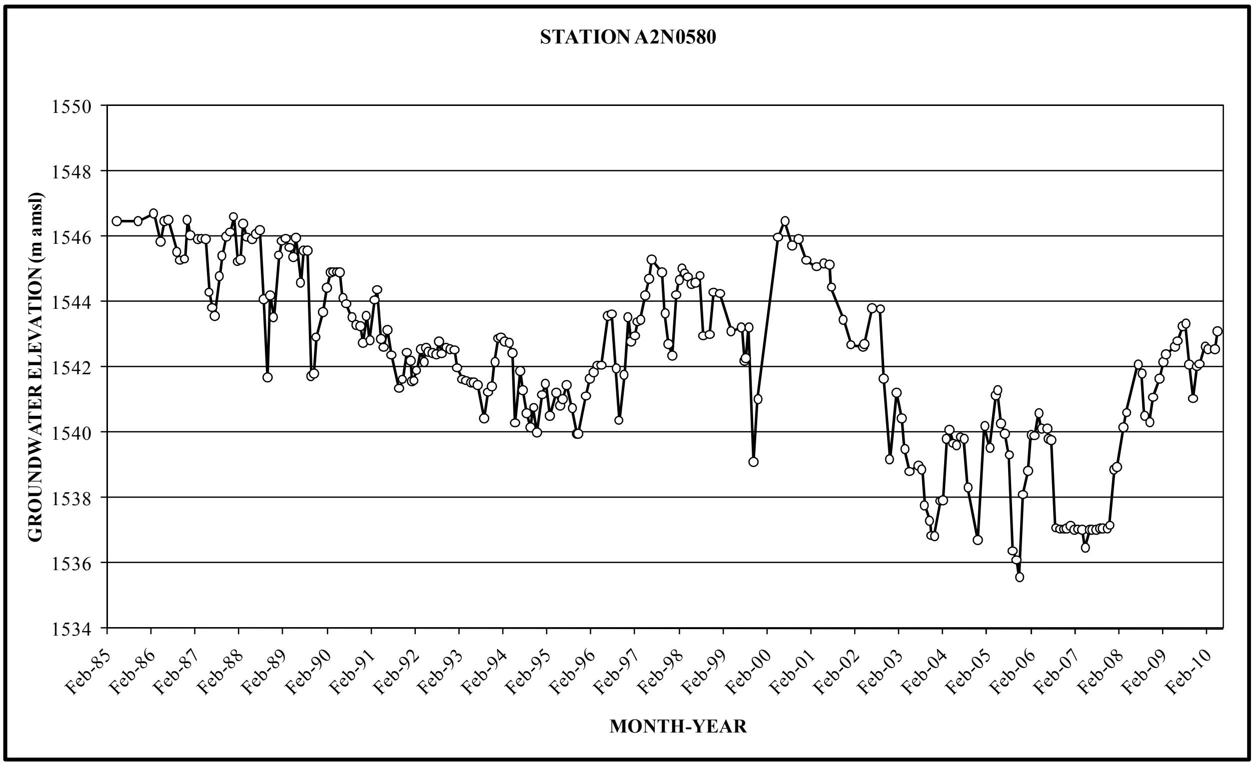
SGS South Africa (Pty) Limited
Environmental Services
259 Kent Avenue
Ferndale, 2194
Tel: 011 326 3902

Lab. Ref.: ENV 10-00640
Client Ref.: Exclusive Mineral Water

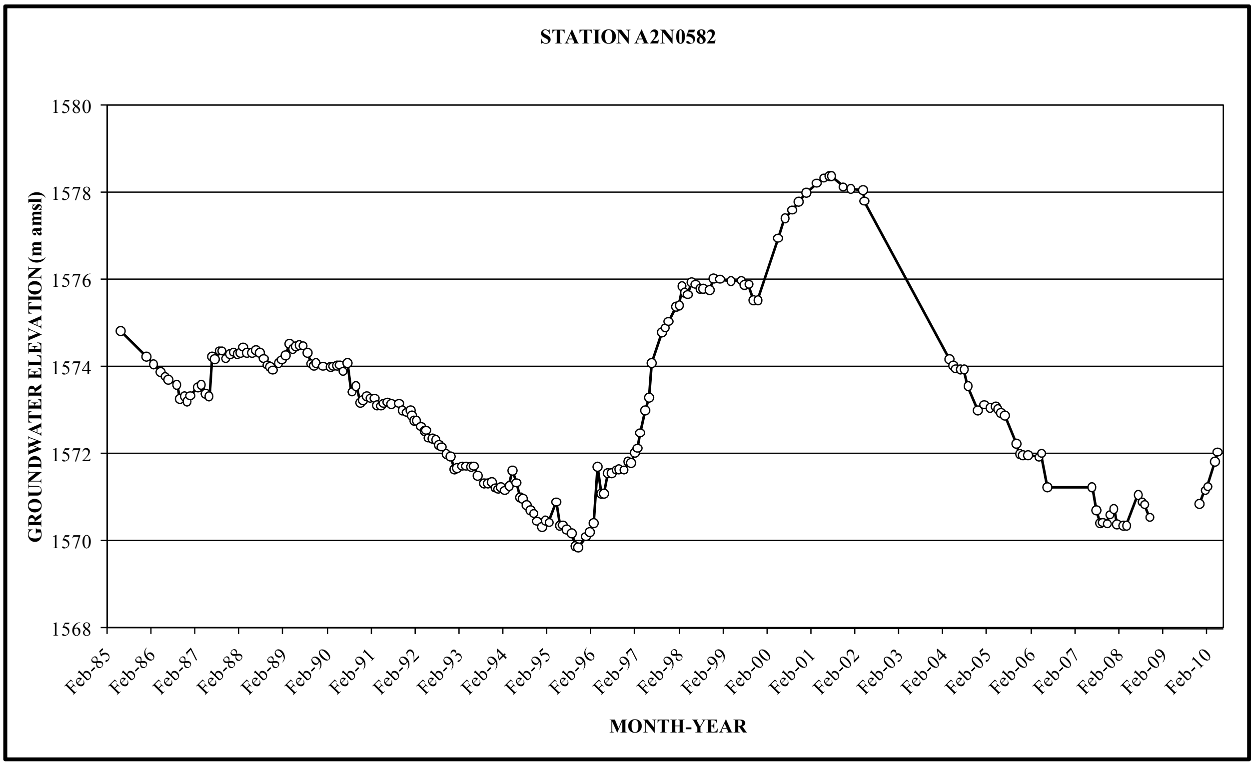
Sample ID			**Exclusive Mineral Water**
Lab ID			640-1
Analysis	**Units**	**MDL**	
Ammonia	mg/l	0.05	< 0.05
Total Dissolved Solids	mg/L	1	247
Total Alkalinity	mg/L as CaCO3	10	139
Chloride	mg/L	1.4	20
Fluoride	mg/L	0.03	< 0.03
Sulphate	mg/L	0.13	39
Nitrate	mg/L	0.30	3.9
Nitrite	mg/L	0.30	< 0.3
pH	units	0.05	8.4
Electrical Conductivity	mS/m		38
Turbidity	NTU	0.13	0.7
Free Chlorine	mg/L	0.10	0.1
Free Cyanide #			TF
Colour #			TF
Phenolics #			TF
Trihalomethanes #			TF
Dissolved Organic Carbon #			TF
ICP-OES			
Calcium	mg/L	0.20	61.7
Magnesium	mg/L	0.09	18.3
Potassium	mg/L	0.09	1.38
Sodium	mg/L	1.00	17.9
ICP-MS	mg/L		
Aluminium	mg/L	0.003	< 0.003
Antimony	mg/L	0.007	< 0.007
Arsenic	mg/L	0.003	< 0.003
Cadmium	mg/L	0.002	< 0.002
Chromium	mg/L	0.003	< 0.003
Cobalt	mg/L	0.002	0.004
Copper	mg/L	0.004	< 0.004
Iron	mg/L	0.008	0.041
Lead	mg/L	0.004	< 0.004
Manganese	mg/L	0.003	< 0.003
Mercury	mg/L	0.0001	< 0.0001
Nickel	mg/L	0.007	< 0.007
Selenium	mg/L	0.004	0.009
Vanadium	mg/L	0.003	< 0.003
Zinc		0.015	< 0.015

ANNEXURE B : LONG-TERM GROUNDWATER LEVEL TRENDS

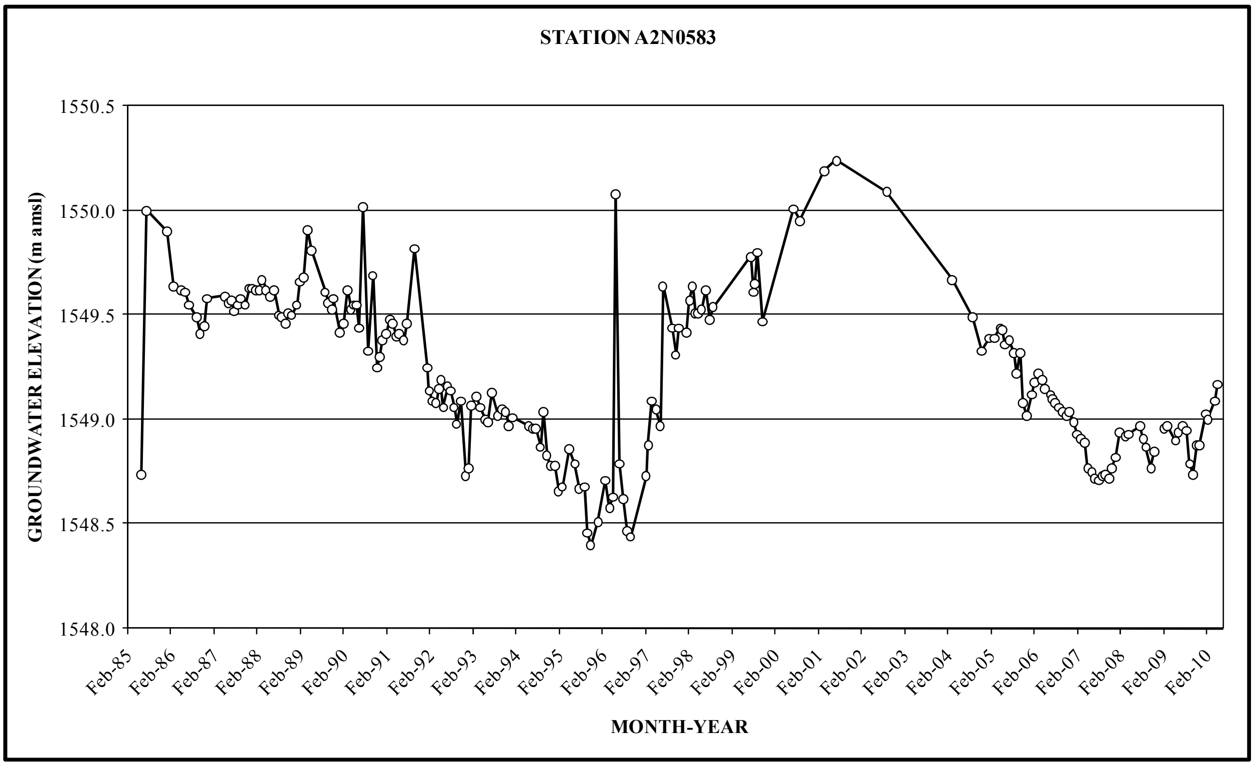
B.1 : STATION A2N0580



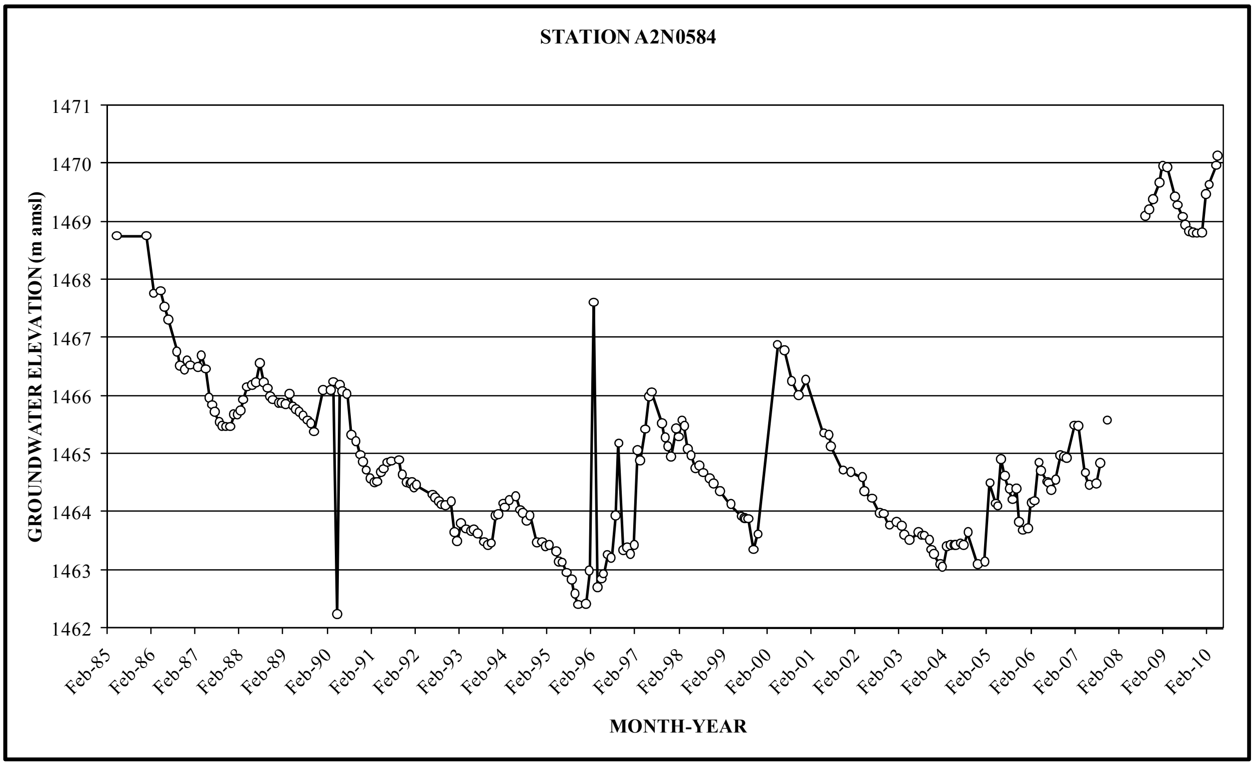
B.2 : STATION A2N0582



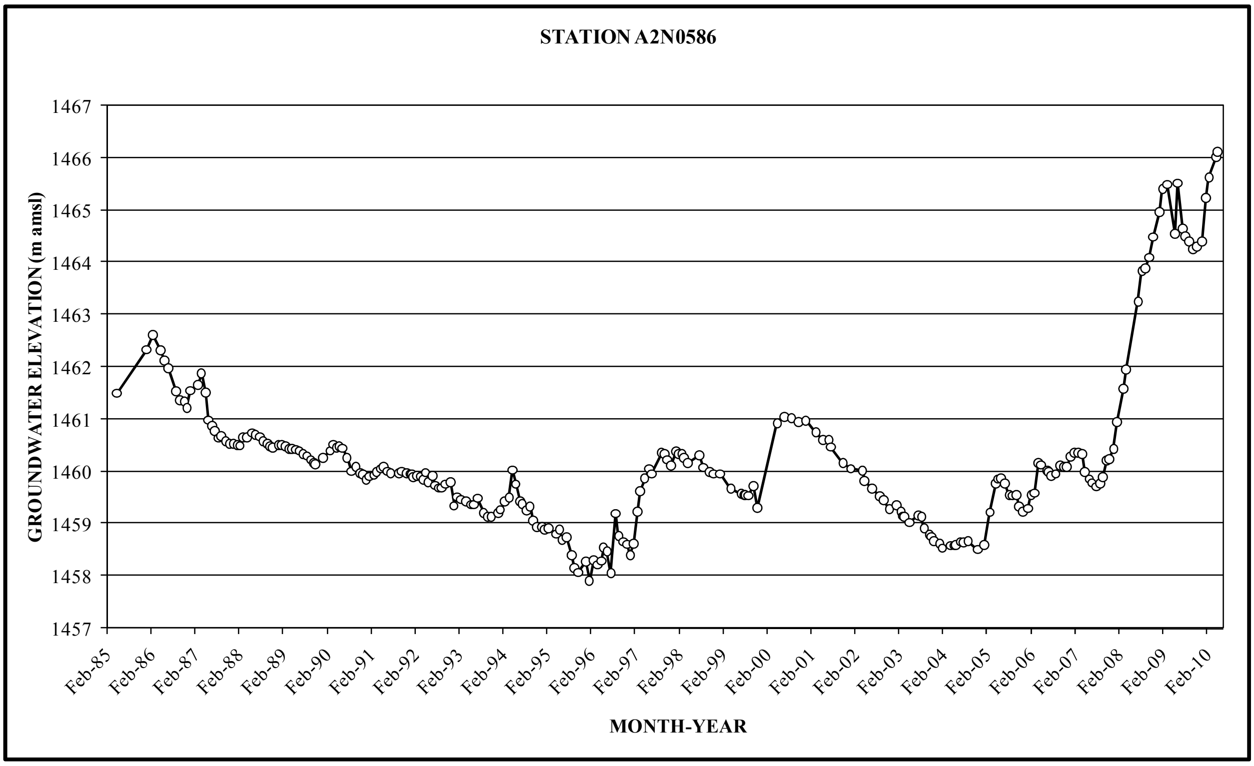
B.3 : STATION A2N0583



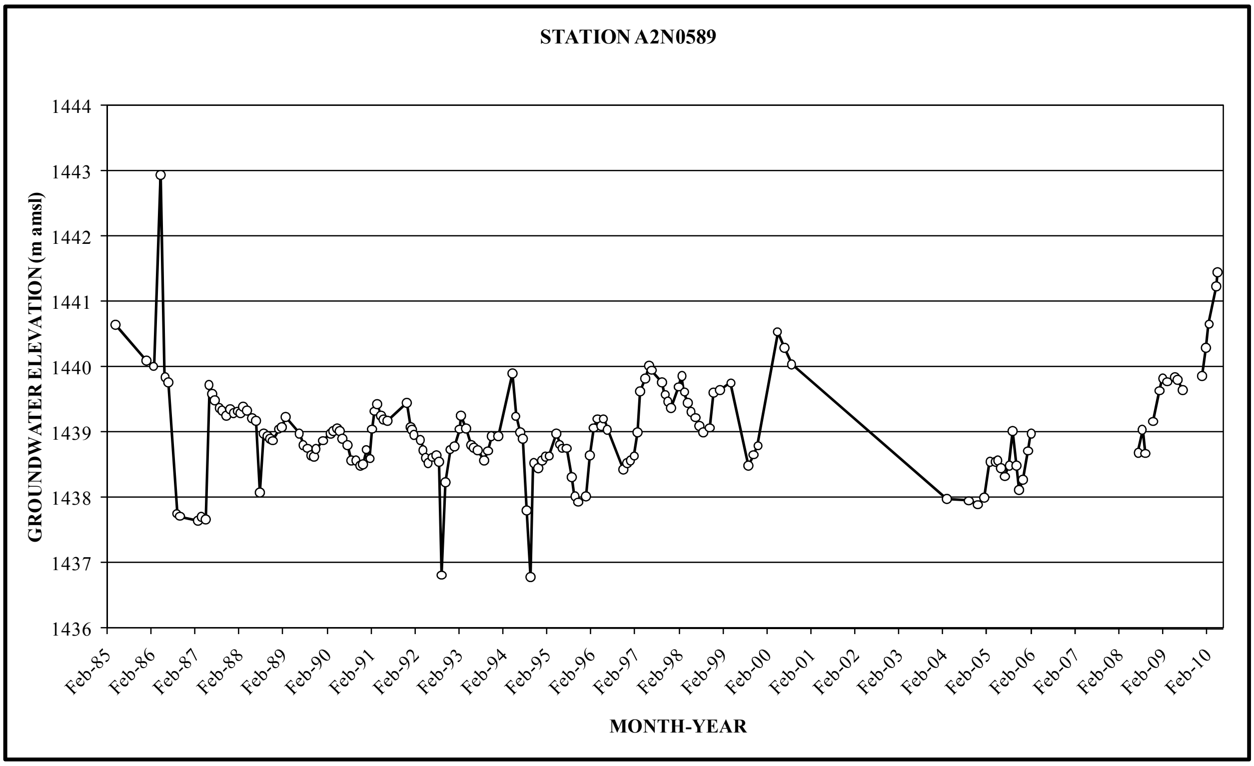
B.4 : STATION A2N0584



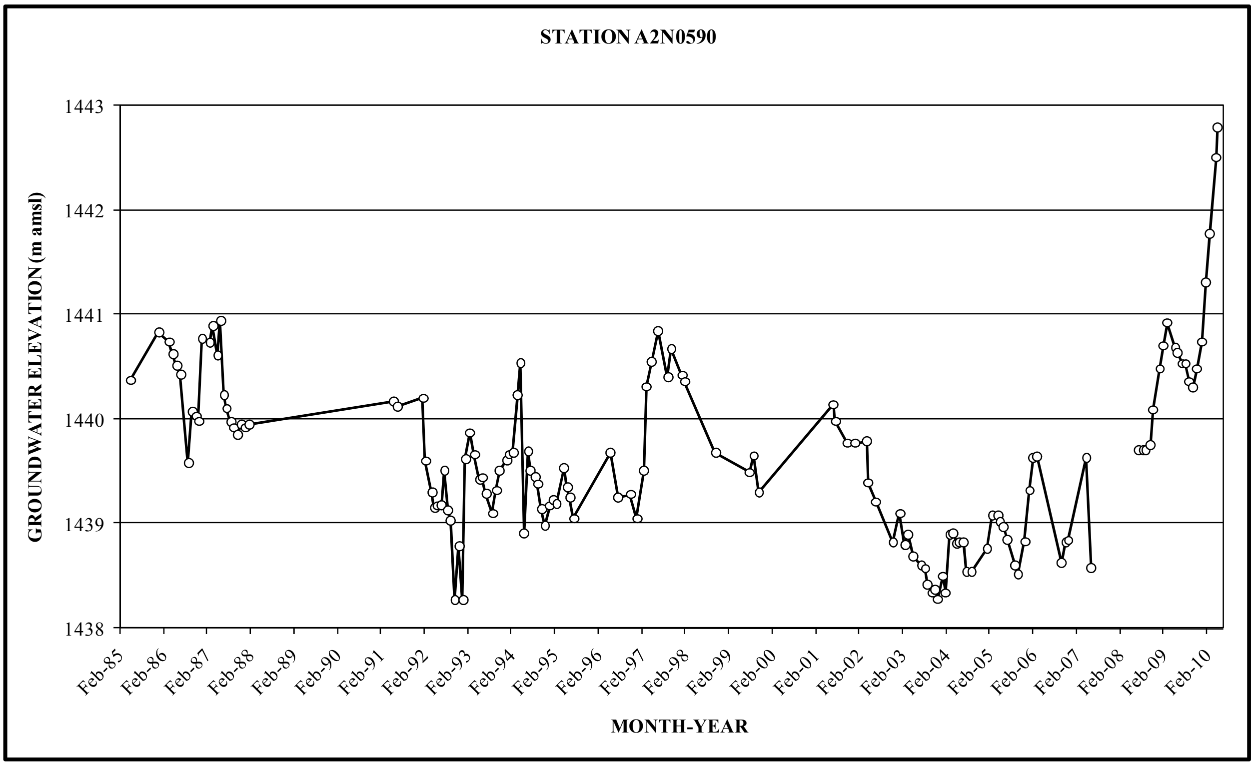
B.5 : STATION A2N0586



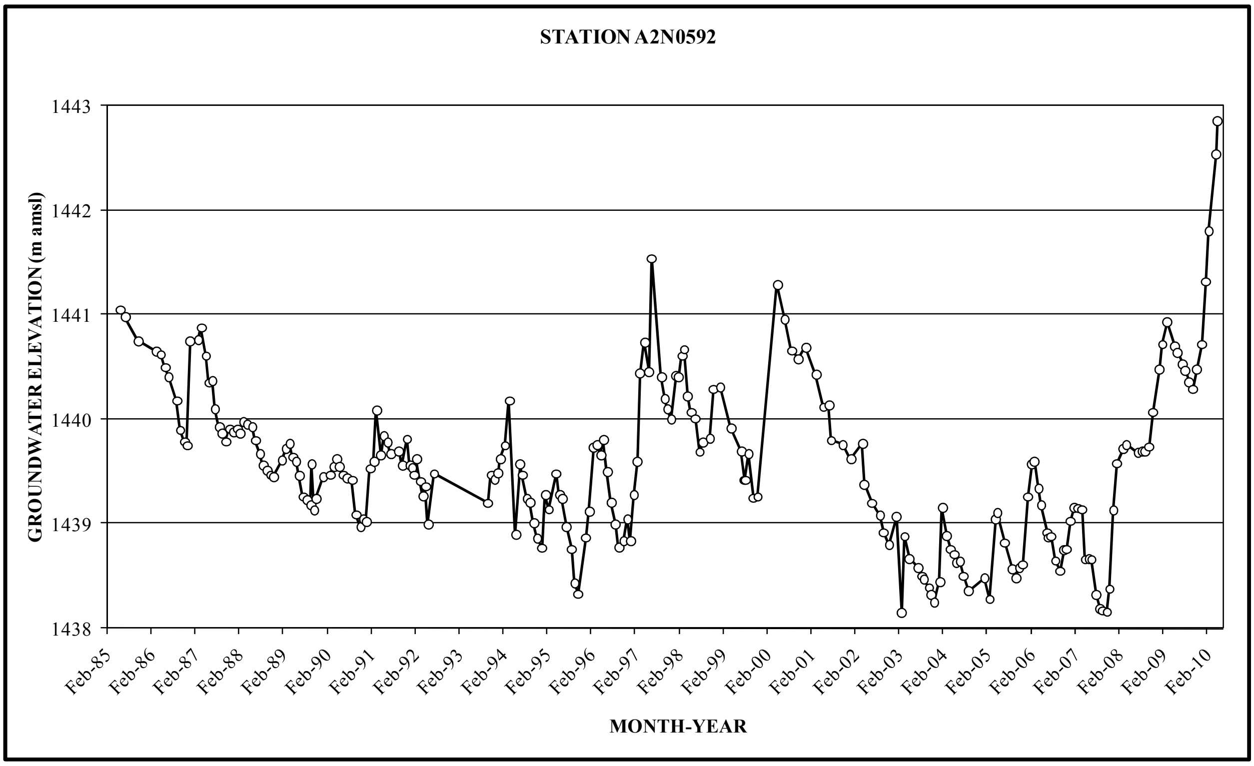
B.6 : STATION A2N0589



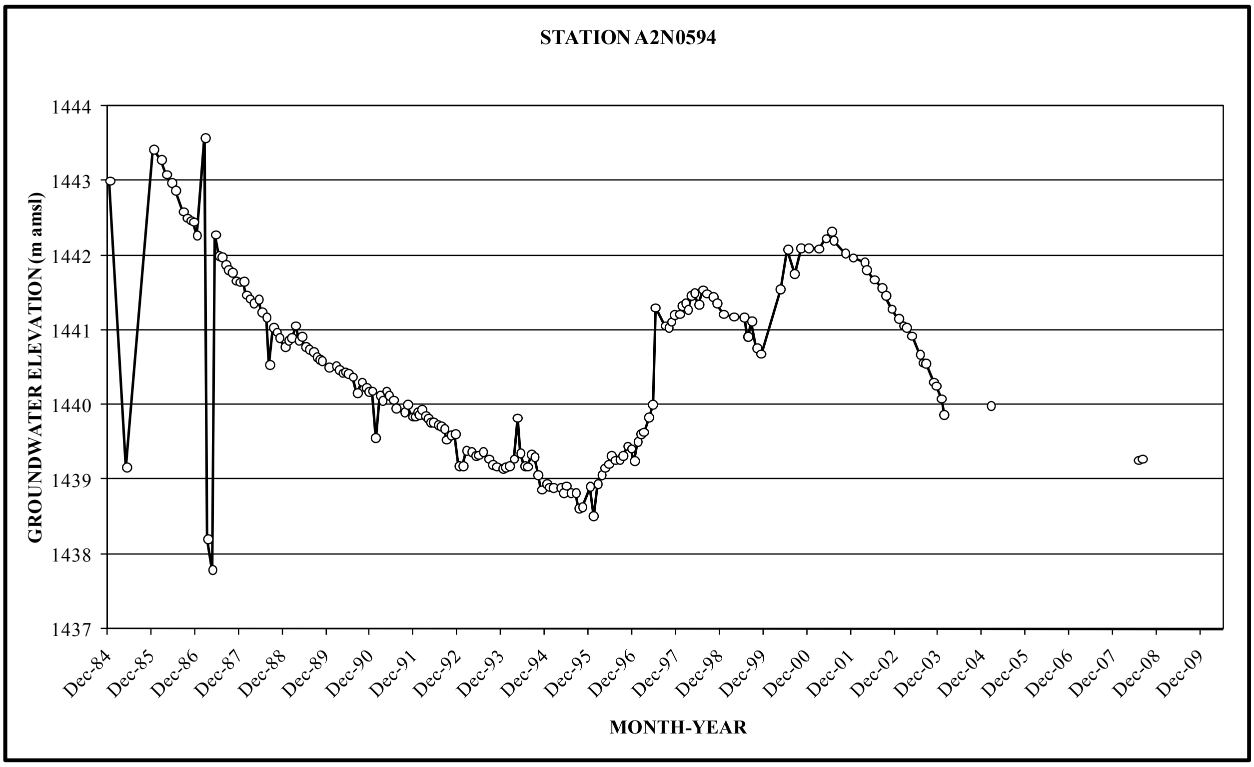
B.7 : STATION A2N0590



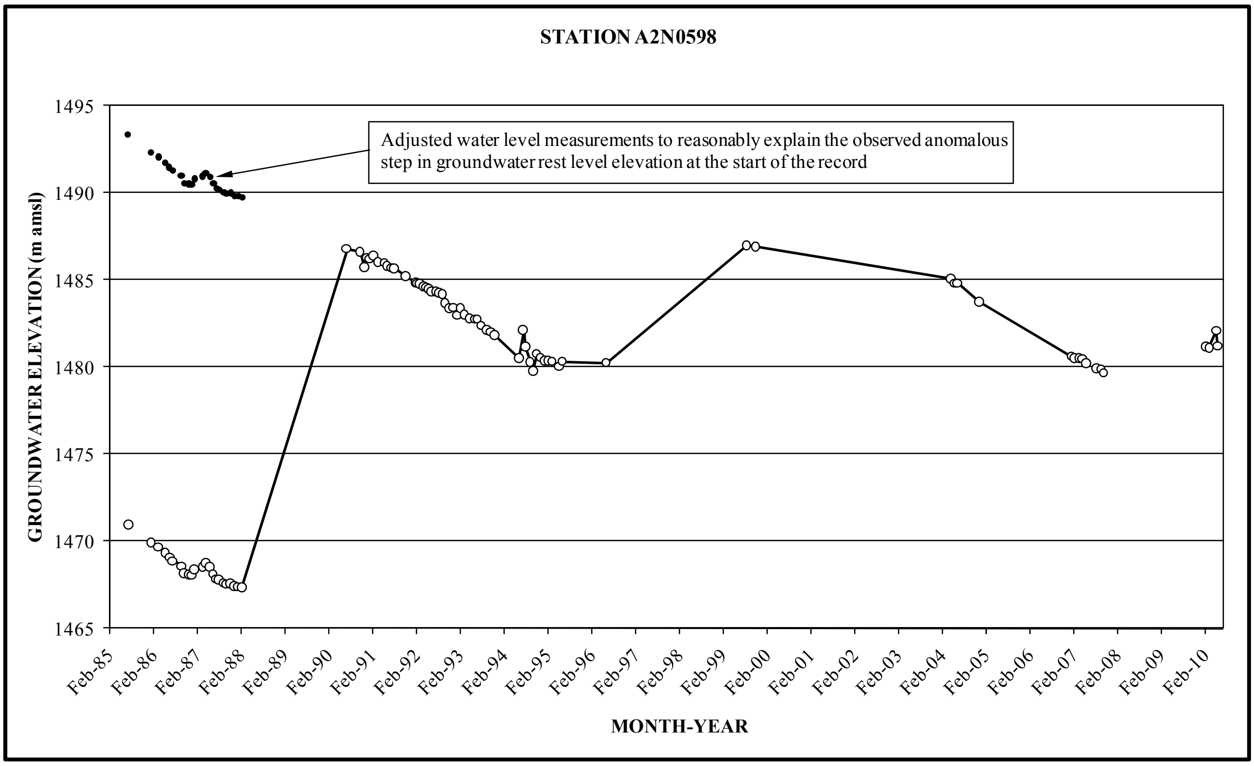
B.8 : STATION A2N0592



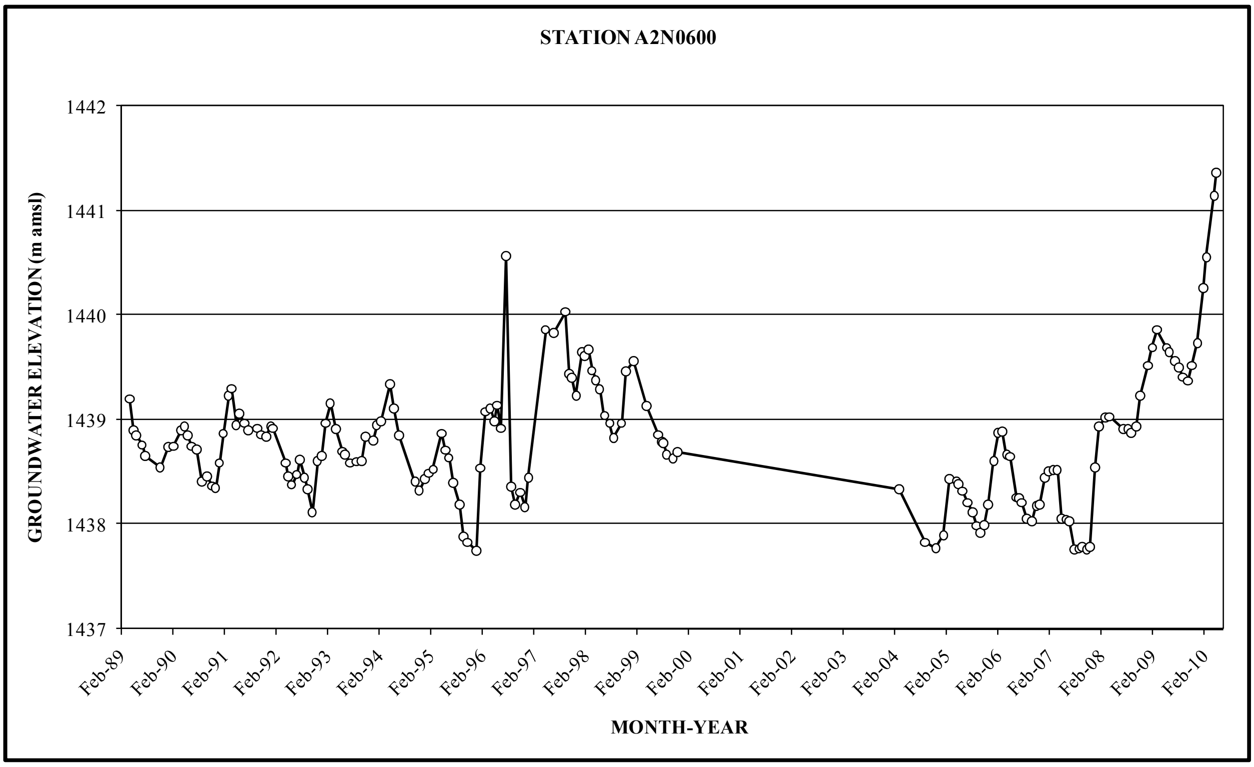
B.9 : STATION A2N0594



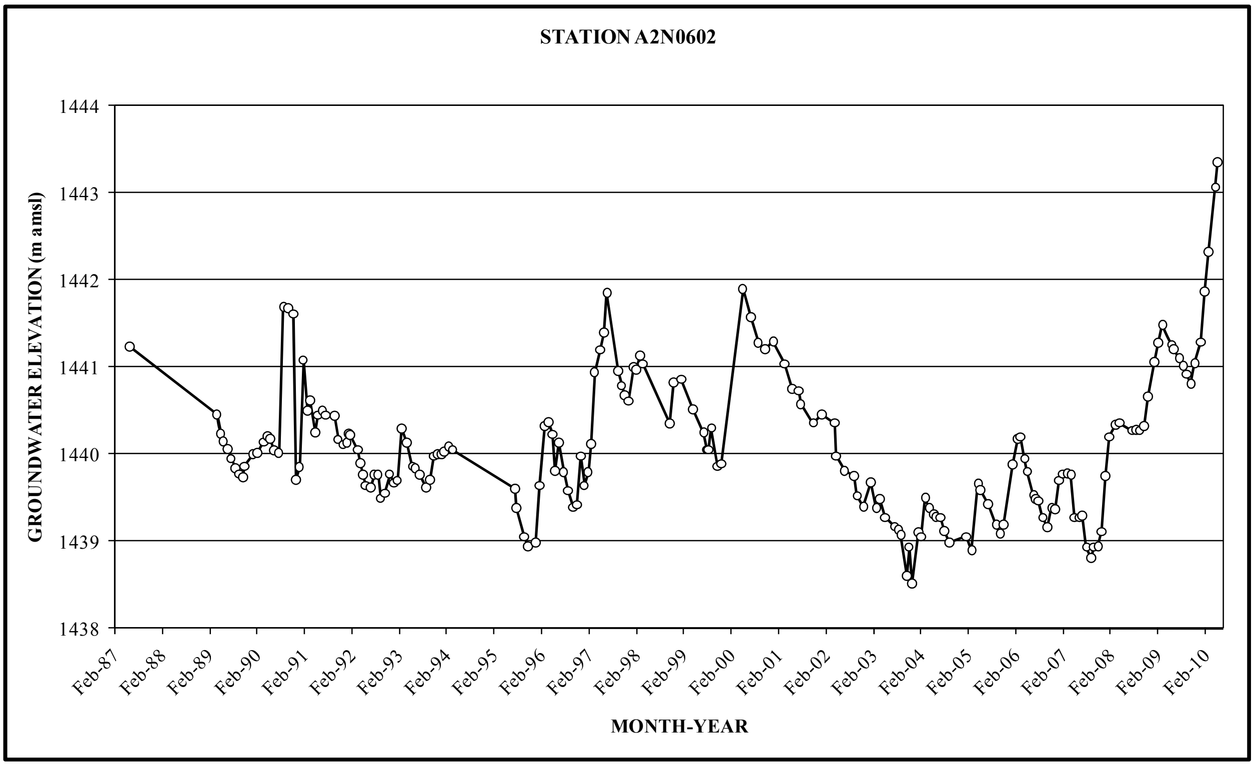
B.10 : STATION A2N0598



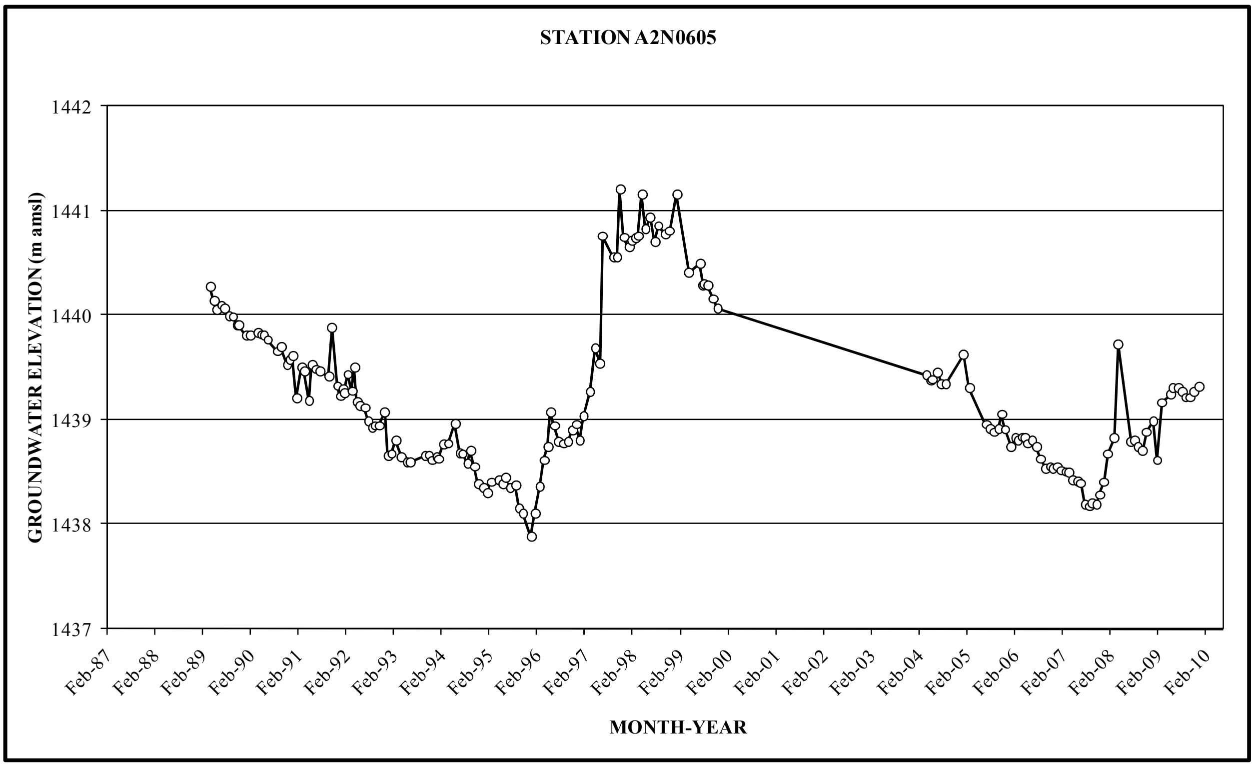
B.11 : STATION A2N0600



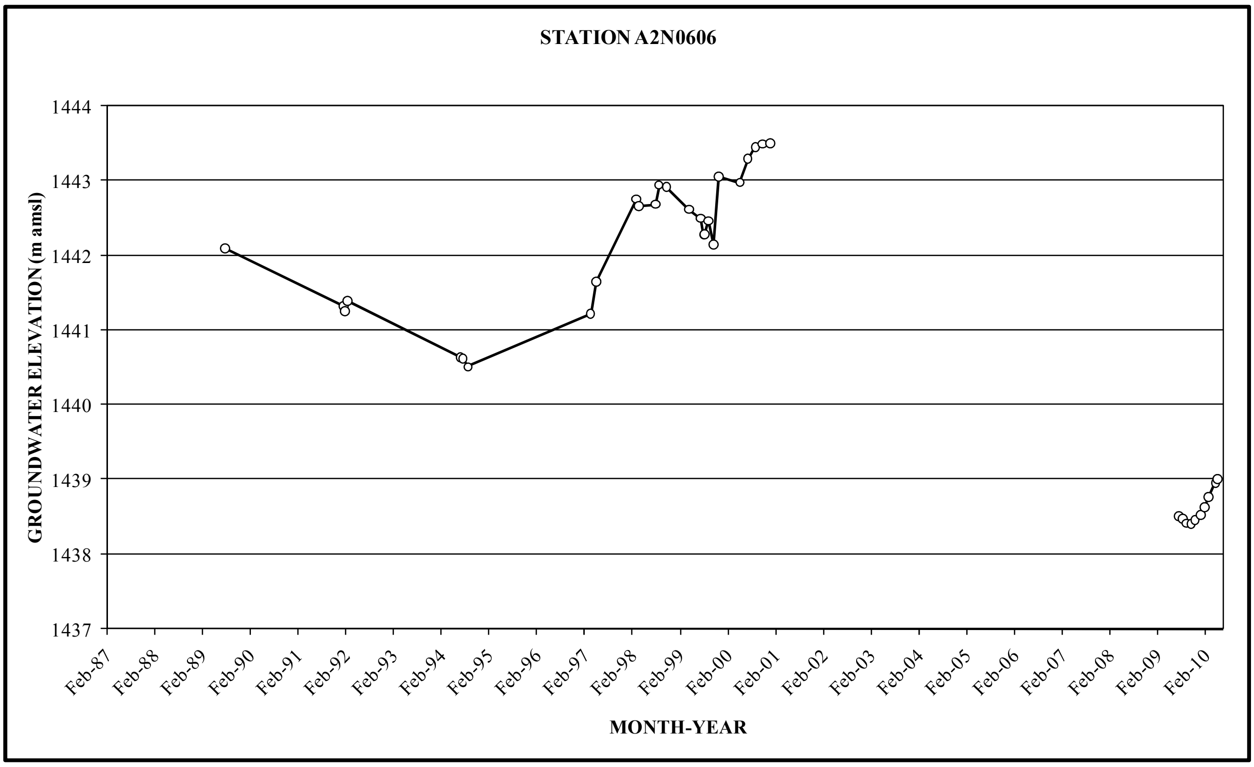
B.12 : STATION A2N0602



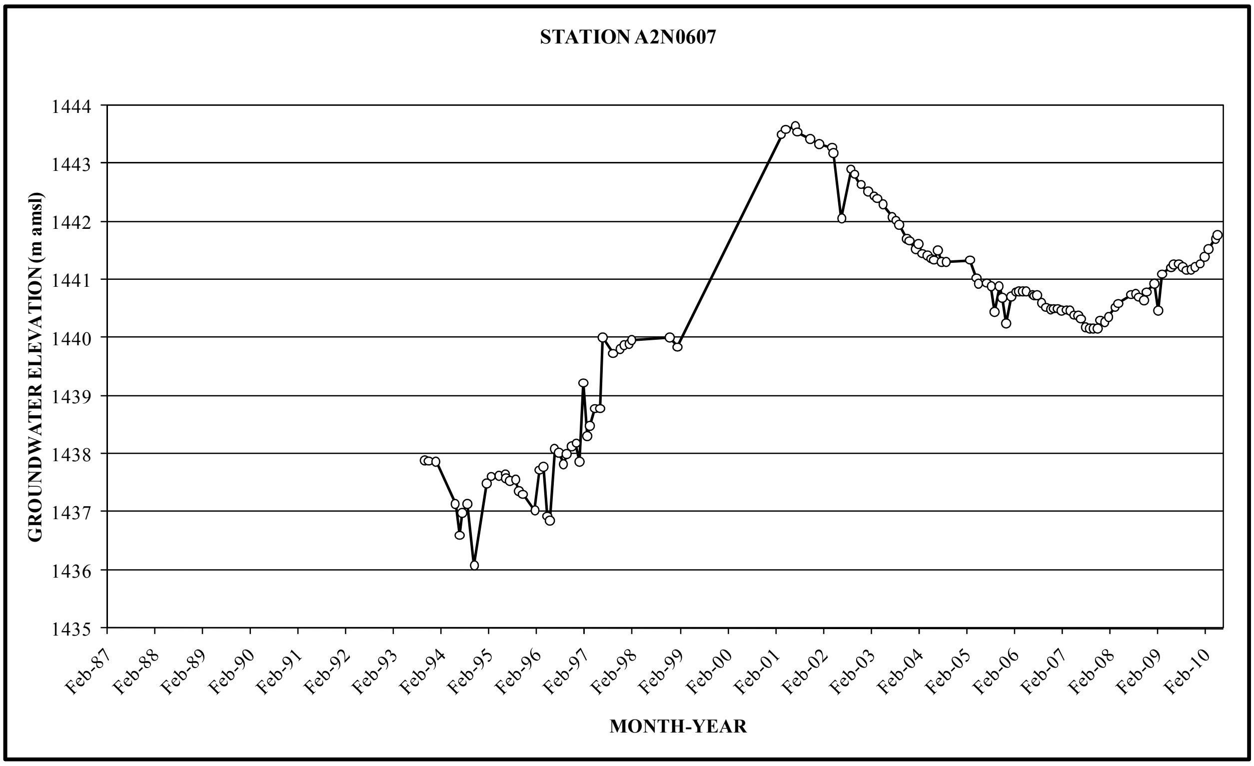
B.13 : STATION A2N0605



B.14 : STATION A2N0606



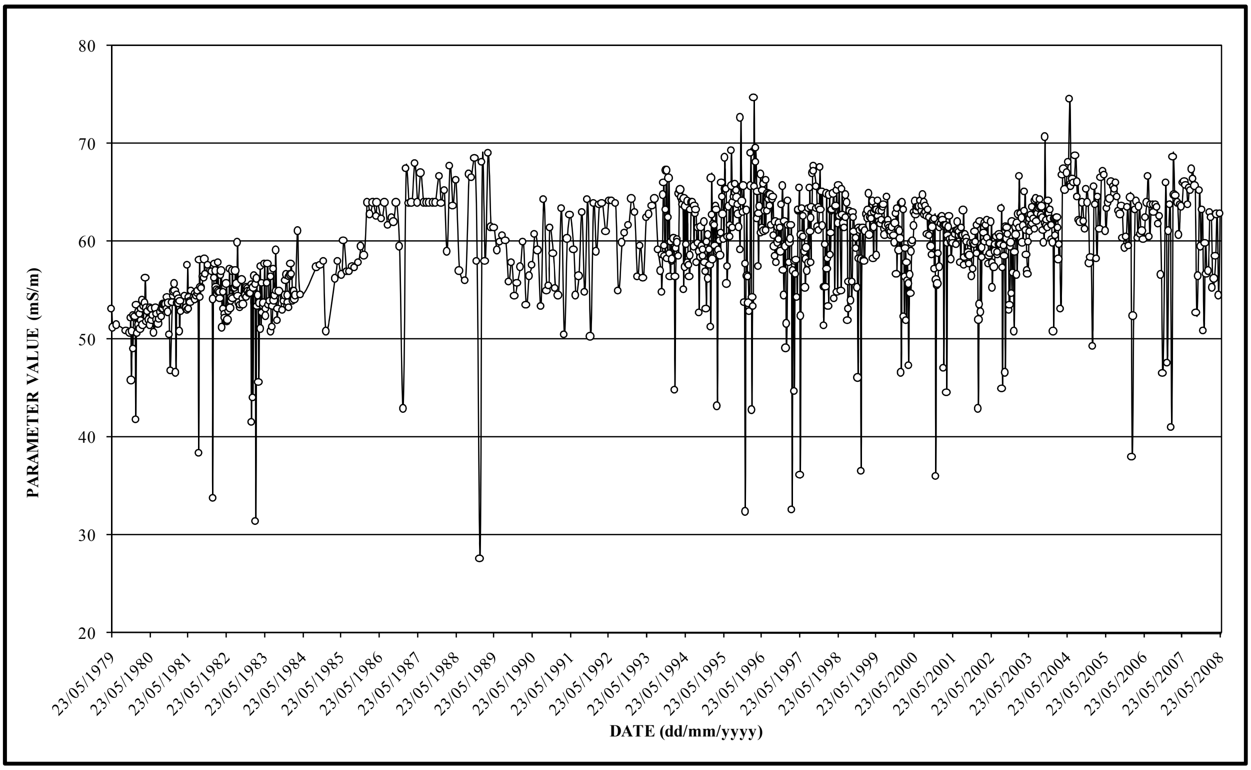
B.15 : STATION A2N0607



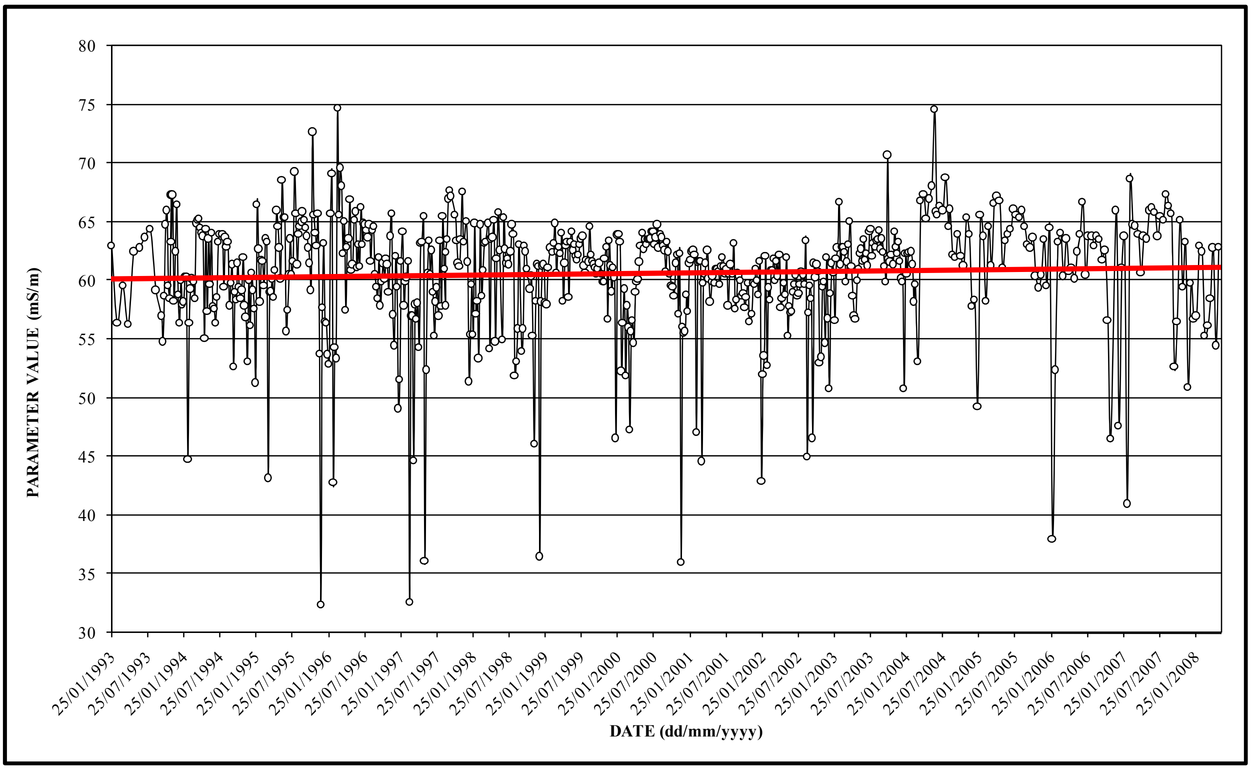
Unnumbered plate.
Aquaduct over the Bloubank Spruit at Plateau Farm on Kromdraai 520JQ fed from former trout dams at centre back.
(Photo: Phil Hobbs).

ANNEXURE C : LONG-TERM SURFACE WATER CHEMISTRY TREND AT STATION A2H049

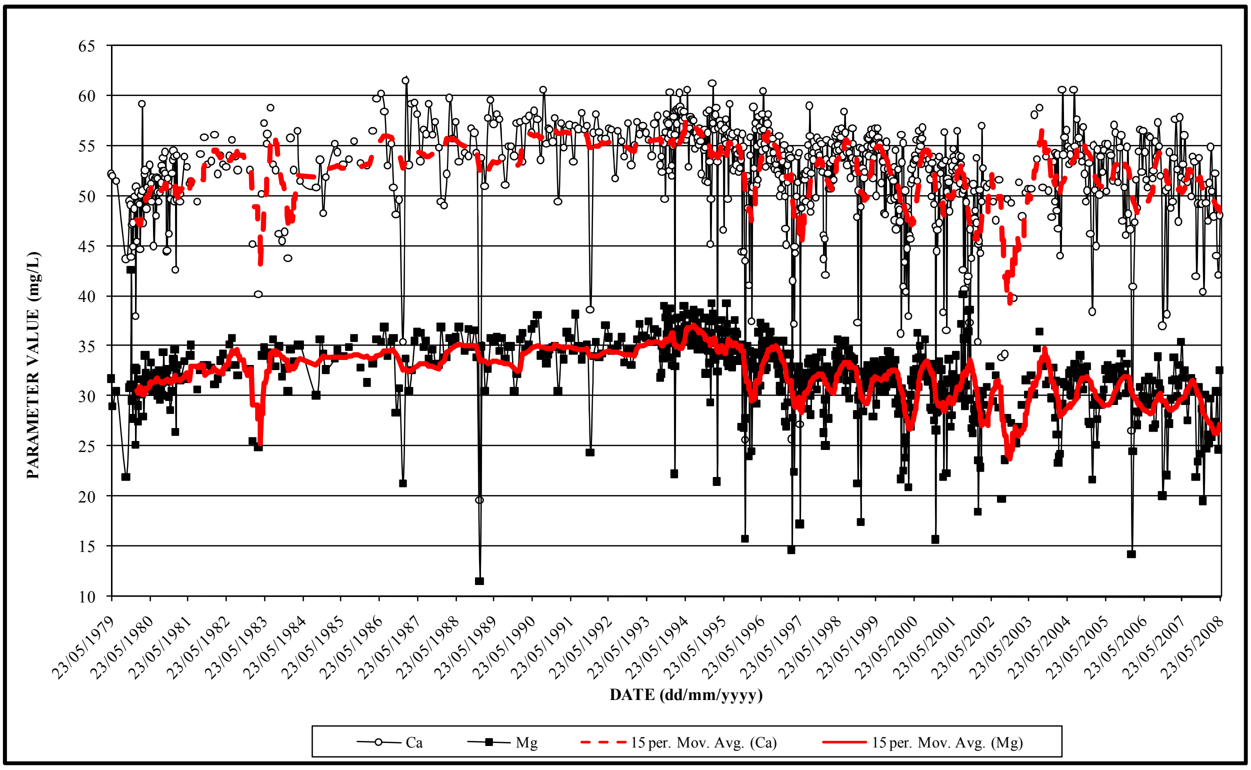
C.1a : LONG-TERM EC TREND AT STATION A2H049



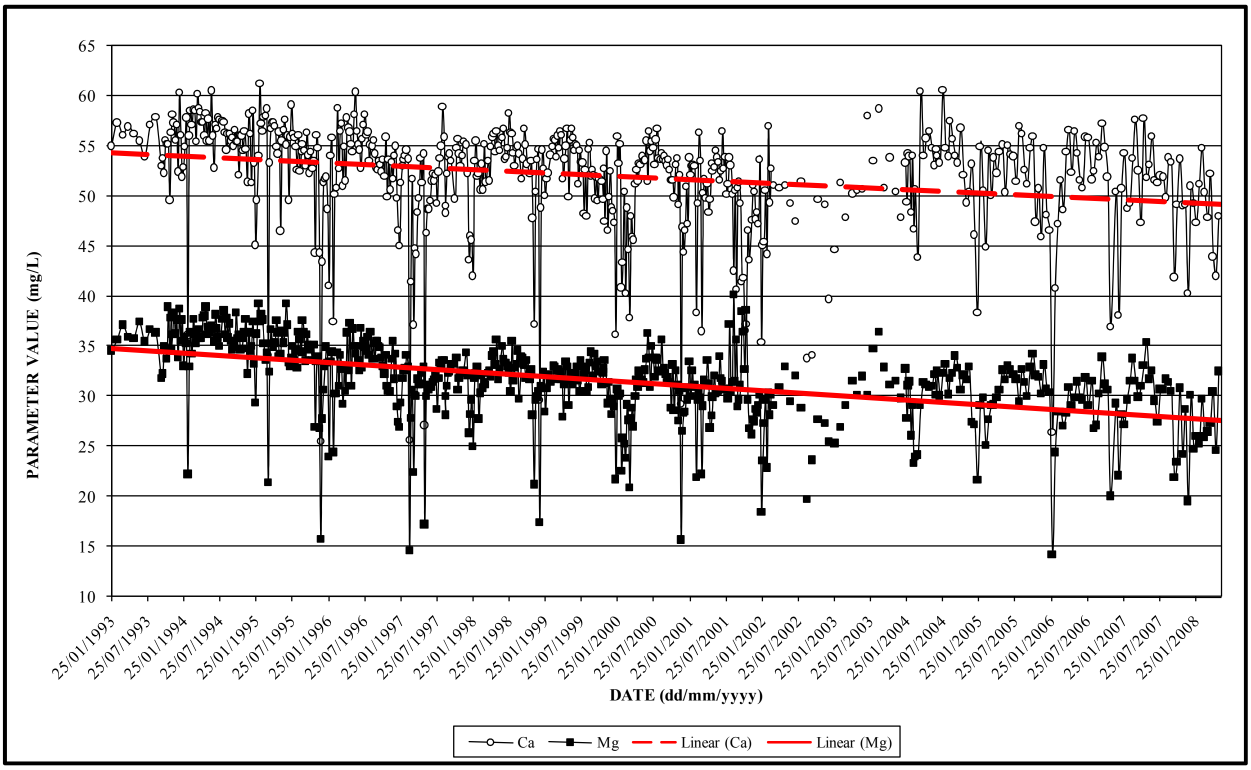
C.1b : EC TREND AT STATION A2H049 SINCE 1993



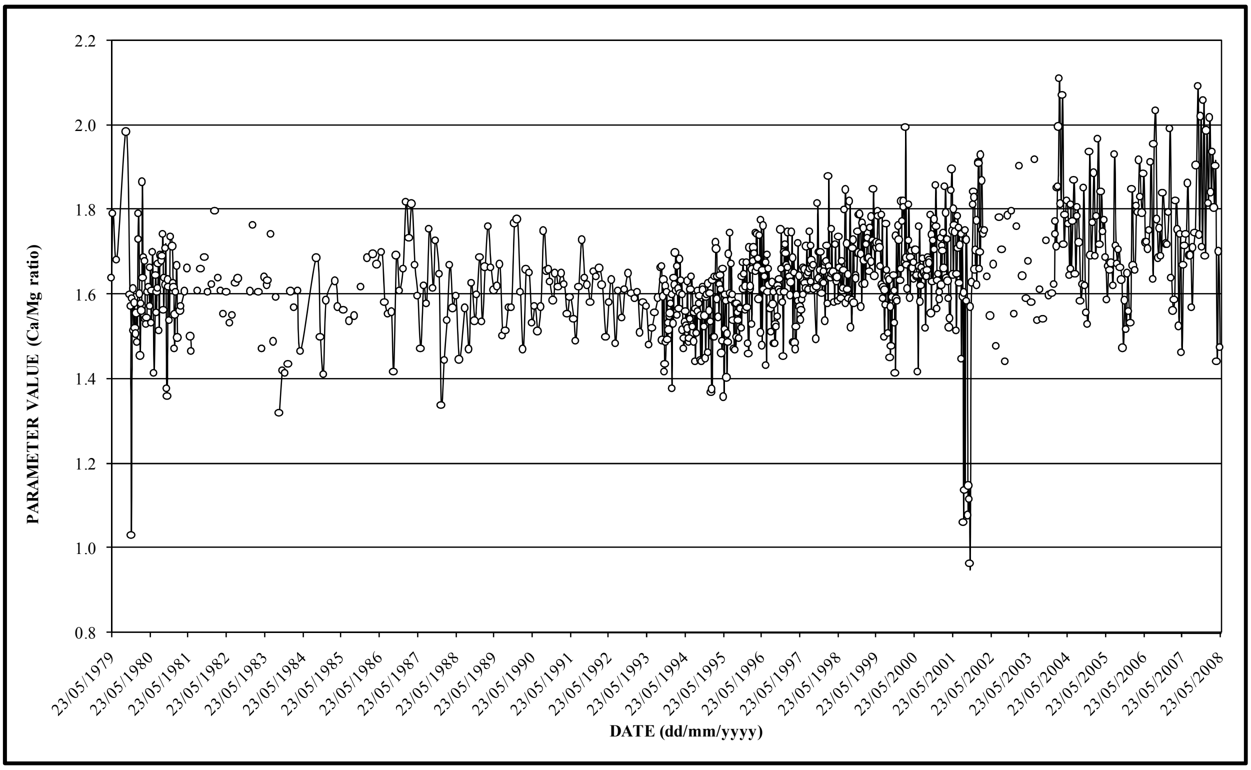
C.2a : LONG-TERM Ca AND Mg TREND AT STATION A2H049



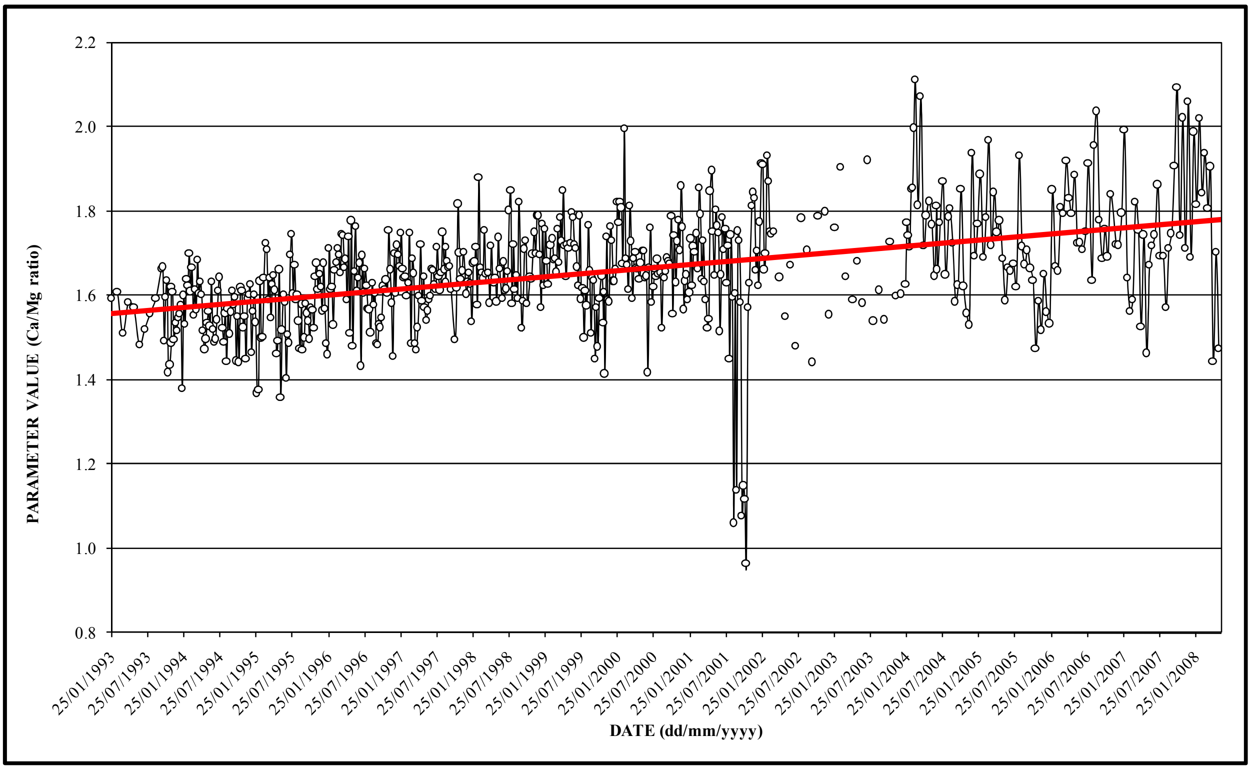
C.2b : Ca AND Mg TREND AT STATION A2H049 SINCE 1993



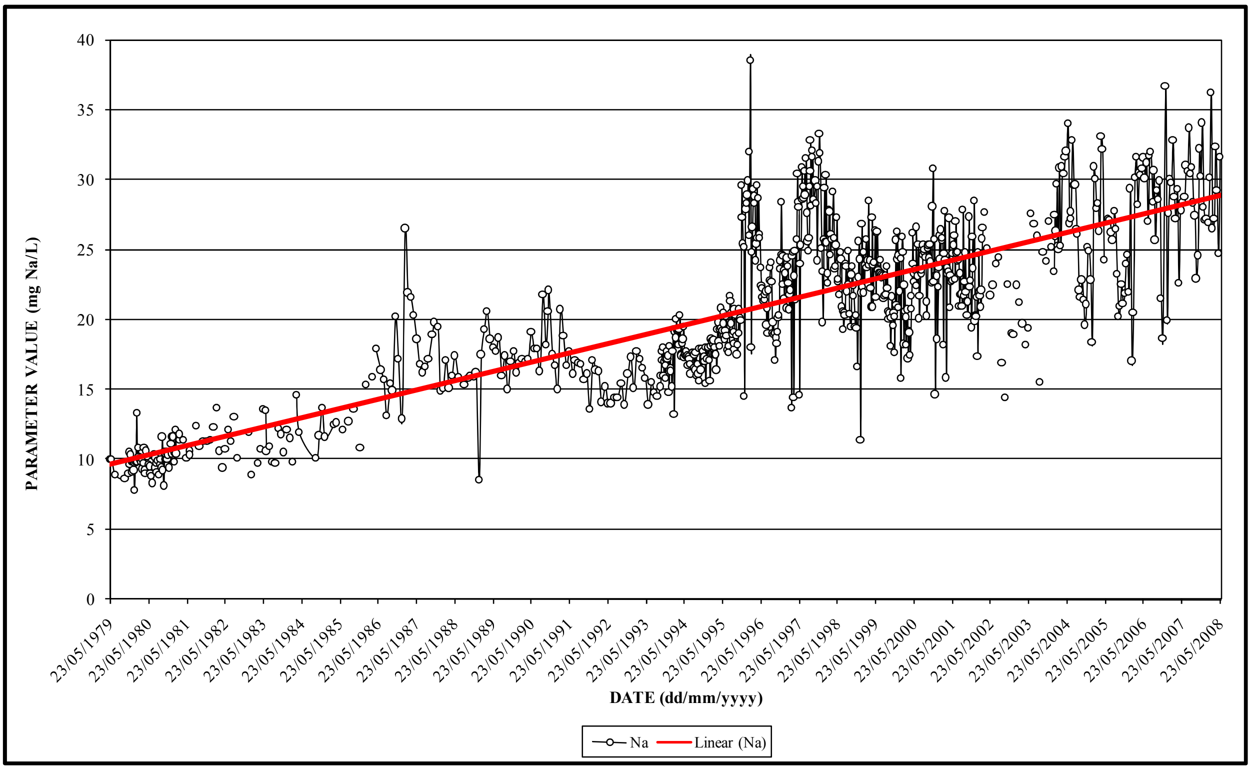
C.3a : LONG-TERM Ca:Mg RATIO TREND AT STATION A2H049



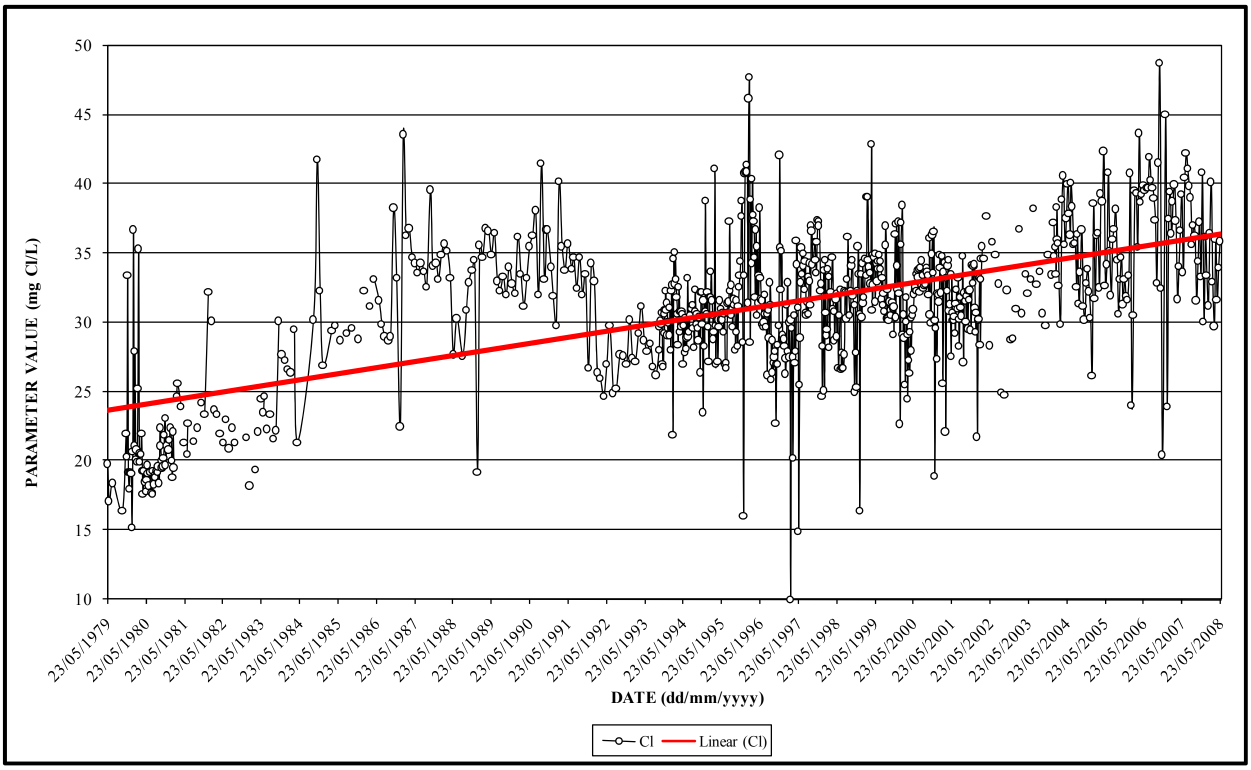
C3b : Ca:Mg RATIO TREND AT STATION A2H049 SINCE 1993



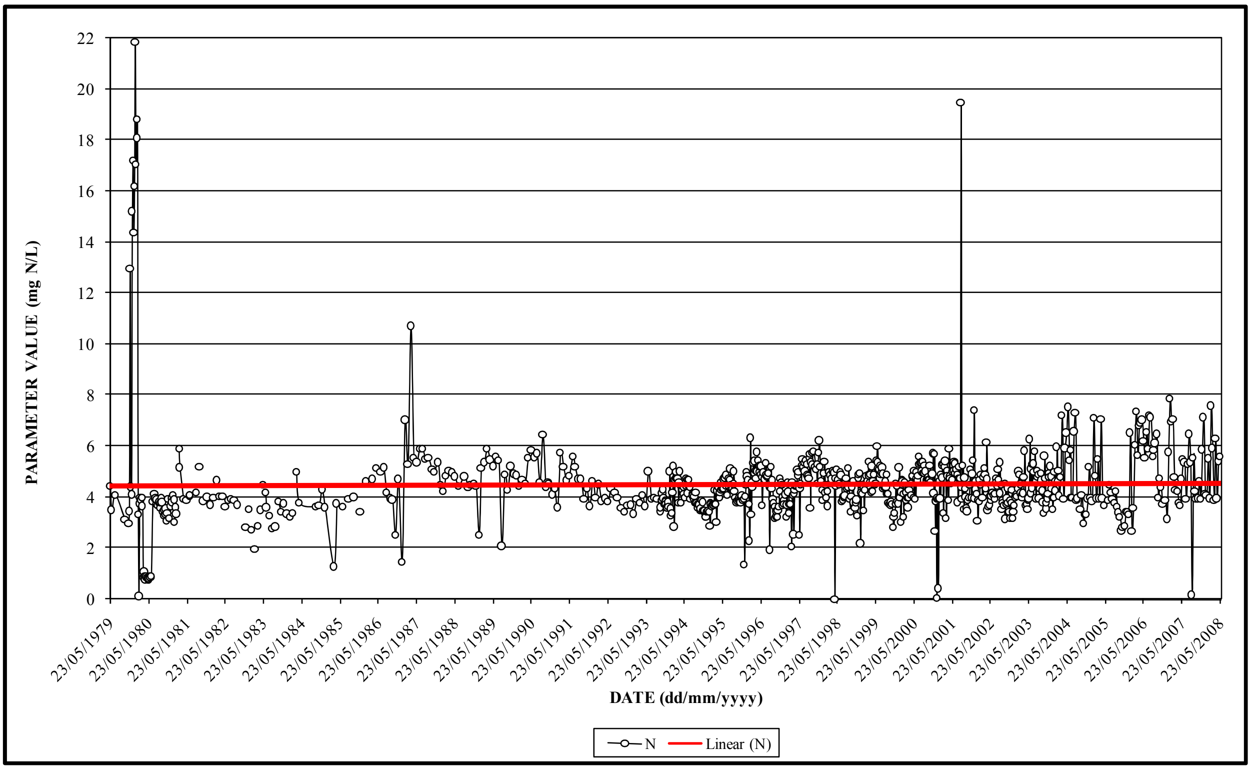
C.4 : LONG-TERM Na TEND AT STATION A2H049



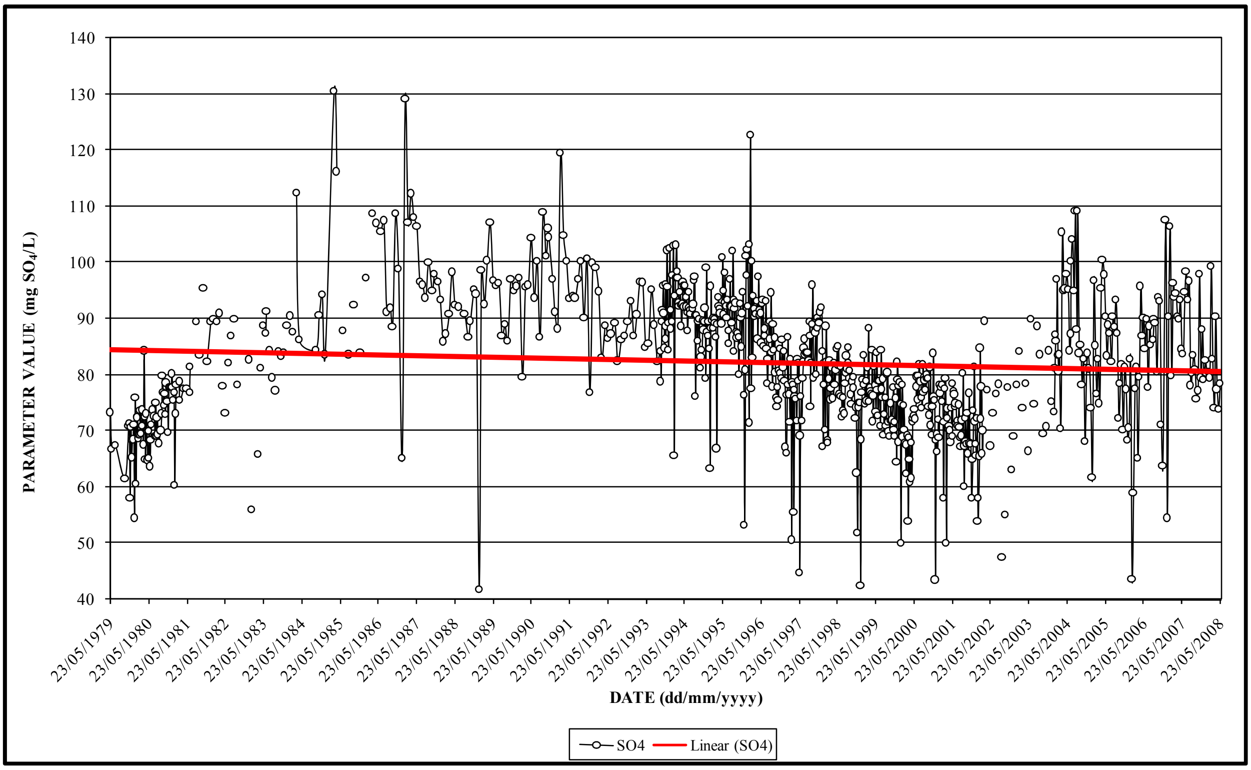
C.5 : LONG-TERM Cl TEND AT STATION A2H049



C.6 : LONG-TERM N TEND AT STATION A2H049



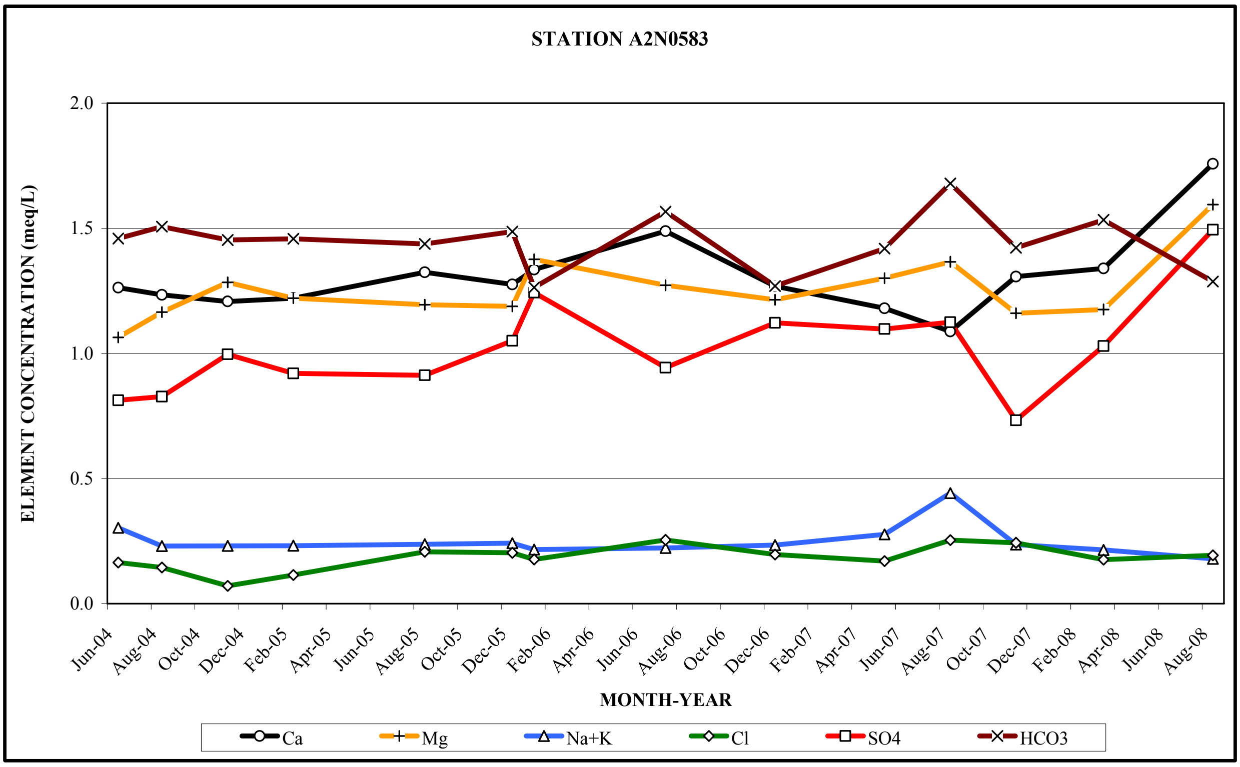
C.7 : LONG-TERM SO_4 TEND AT STATION A2H049



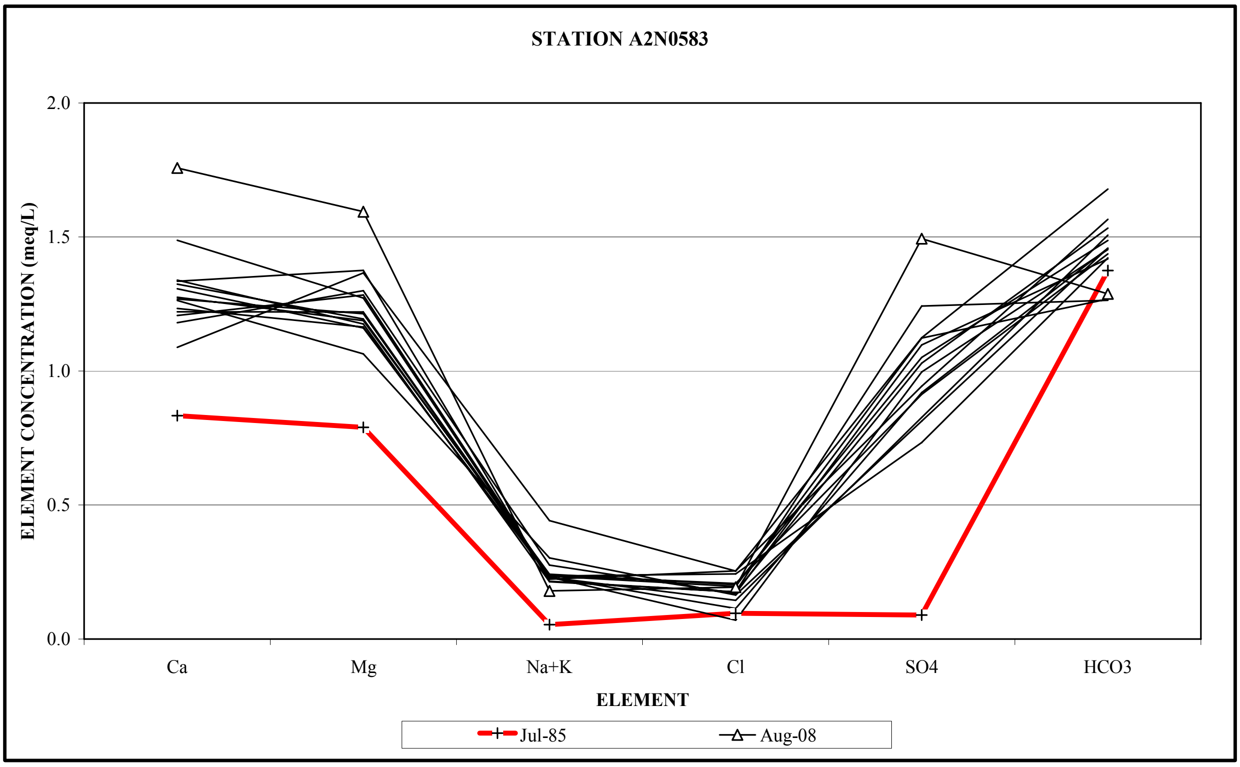
Unnumbered plate.
Syenite boulders marking the position of the Plover's Lake Sill immediately downstream of the ~2 L/s Cradle Spring, discharging at left of picture, in the Motsetse Nature Reserve.
(Photo: Phil Hobbs).

ANNEXURE D : LONG-TERM GROUNDWATER CHEMISTRY TRENDS

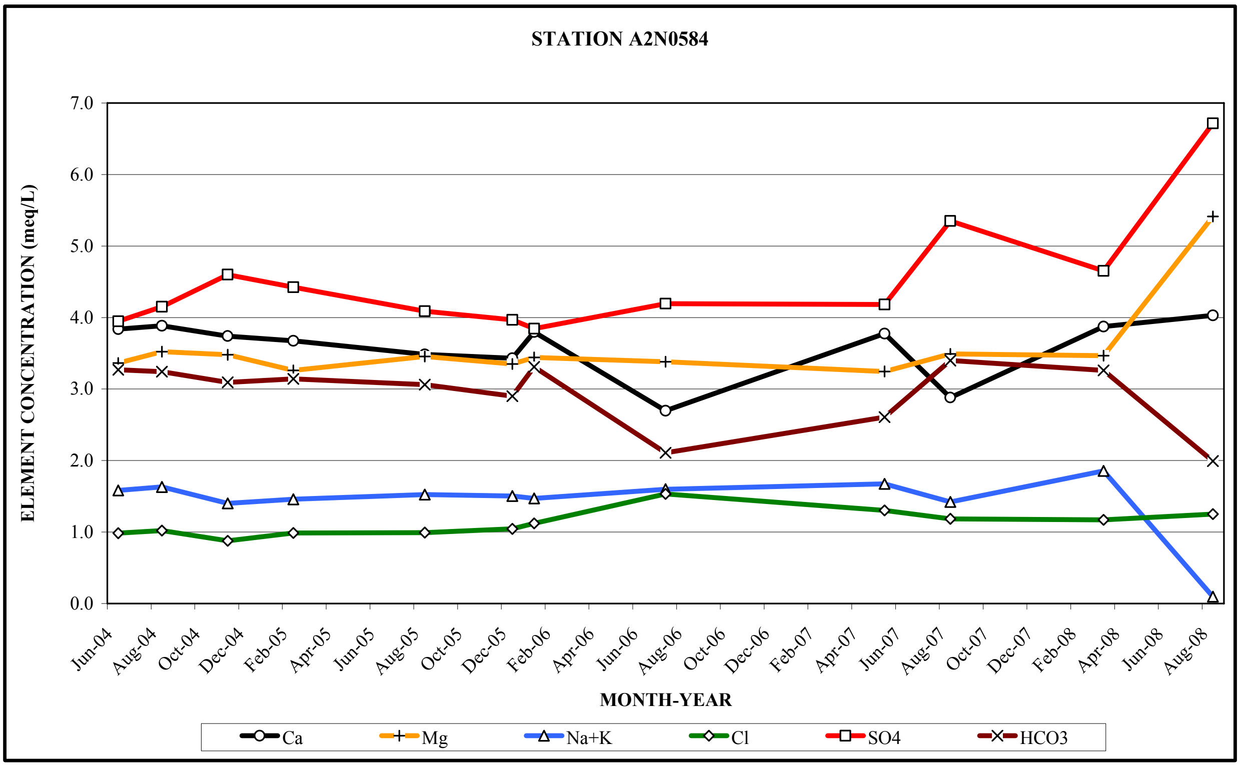
D.1a : MAJOR ION TREND AT STATION A2N0583



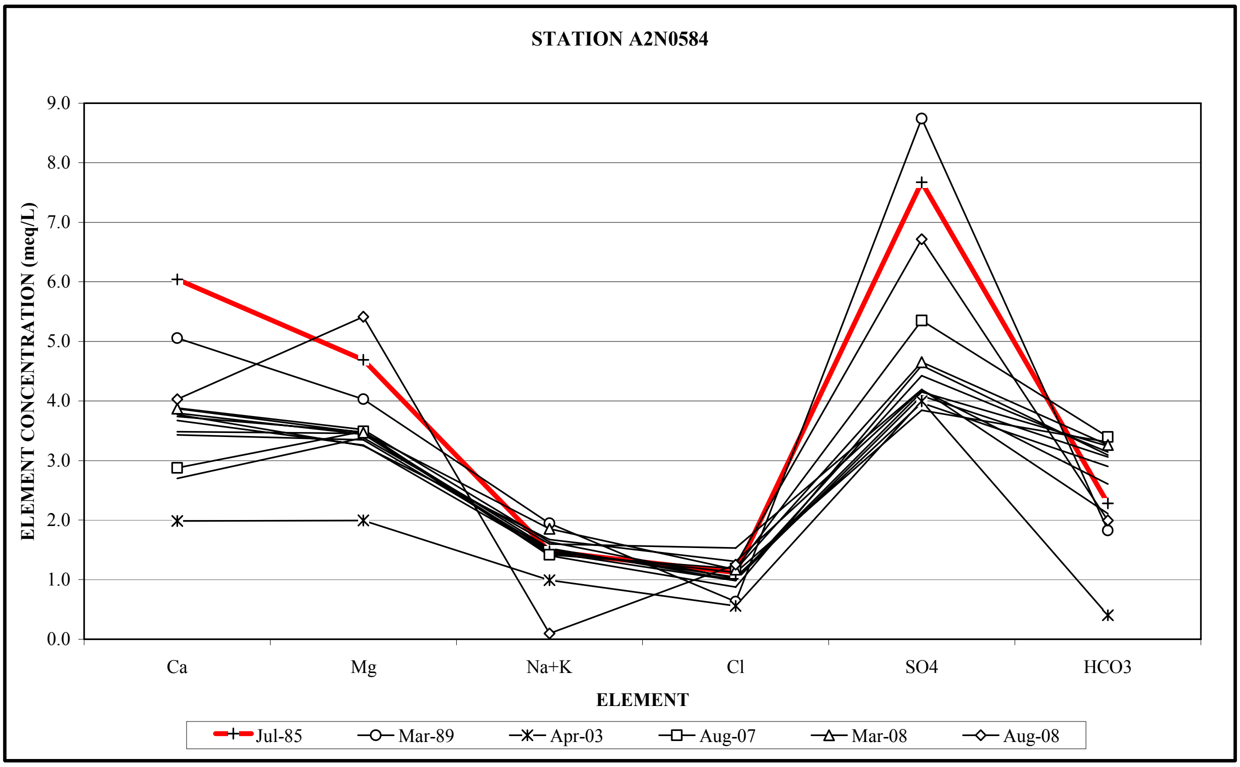
D.1b : VARIATION IN CHEMICAL COMPOSITION AT STATION A2N0583



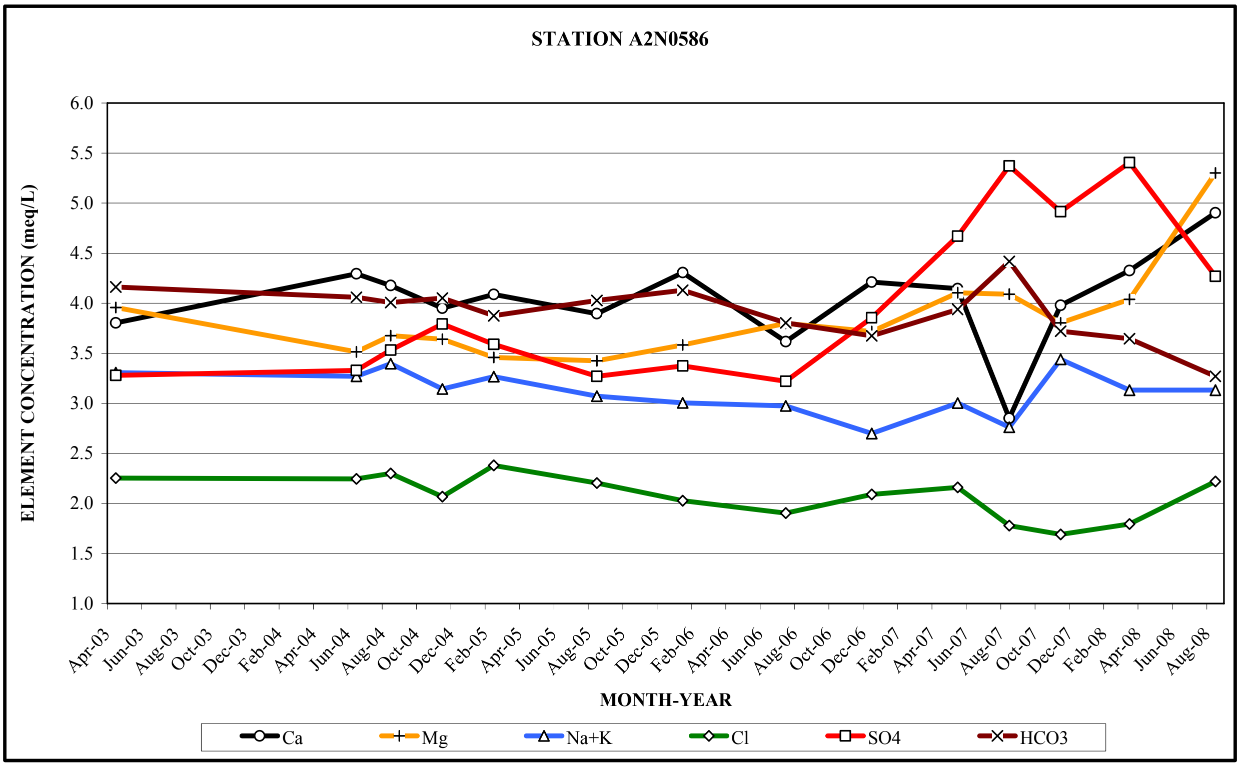
D.2a : MAJOR ION TREND AT STATION A2N0584



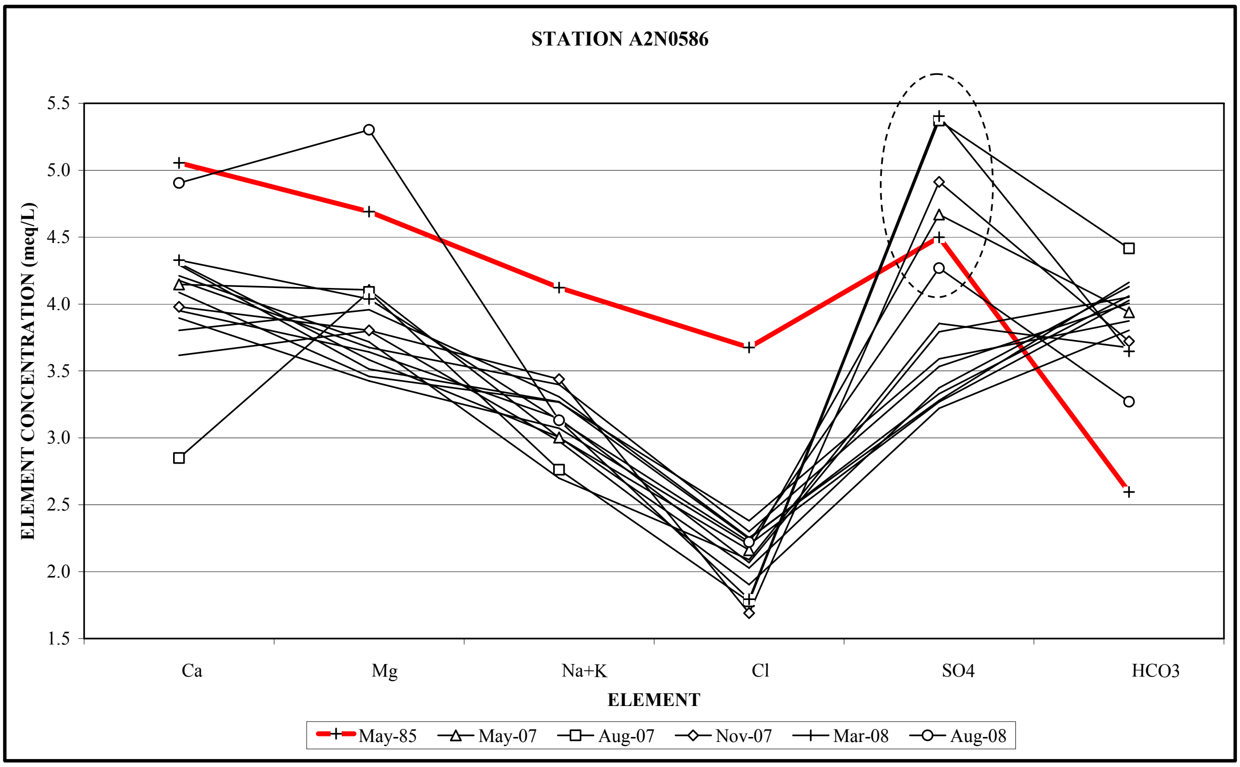
D.2b : VARIATION IN CHEMICAL COMPOSITION AT STATION A2N0584



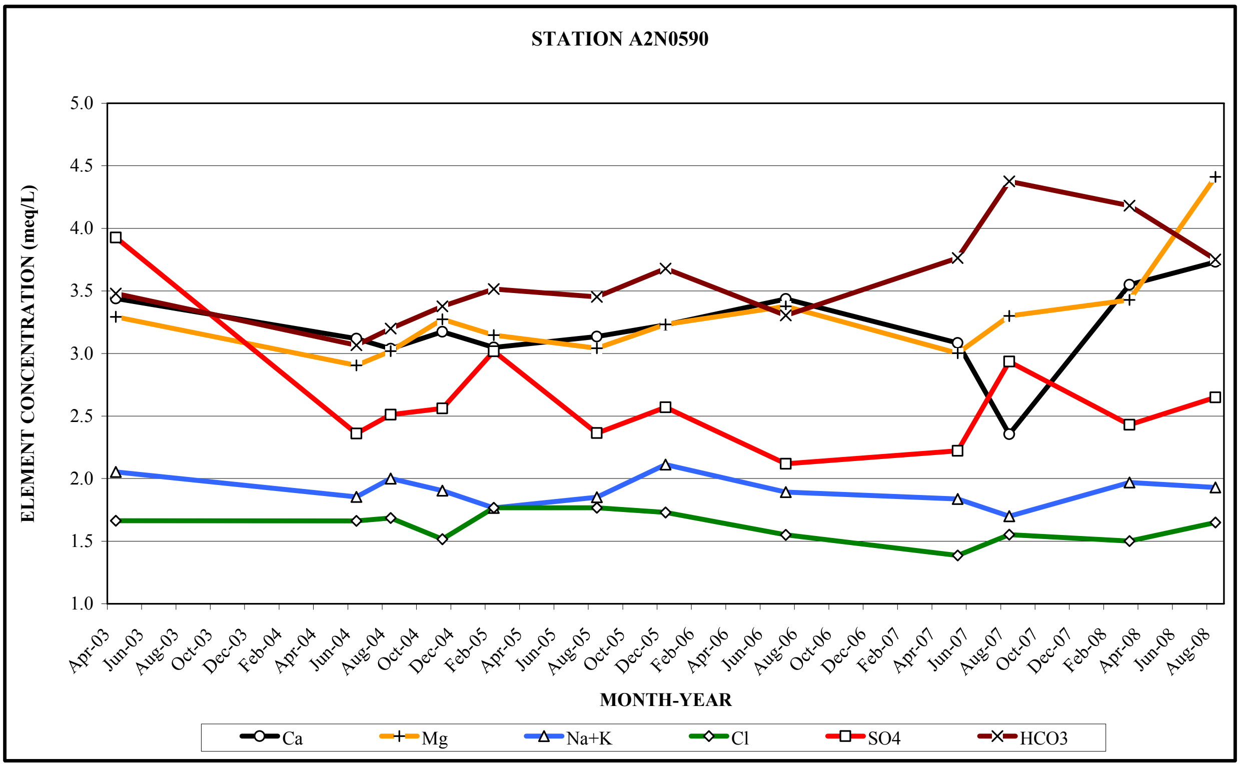
D.3a : MAJOR ION TREND AT STATION A2N0586



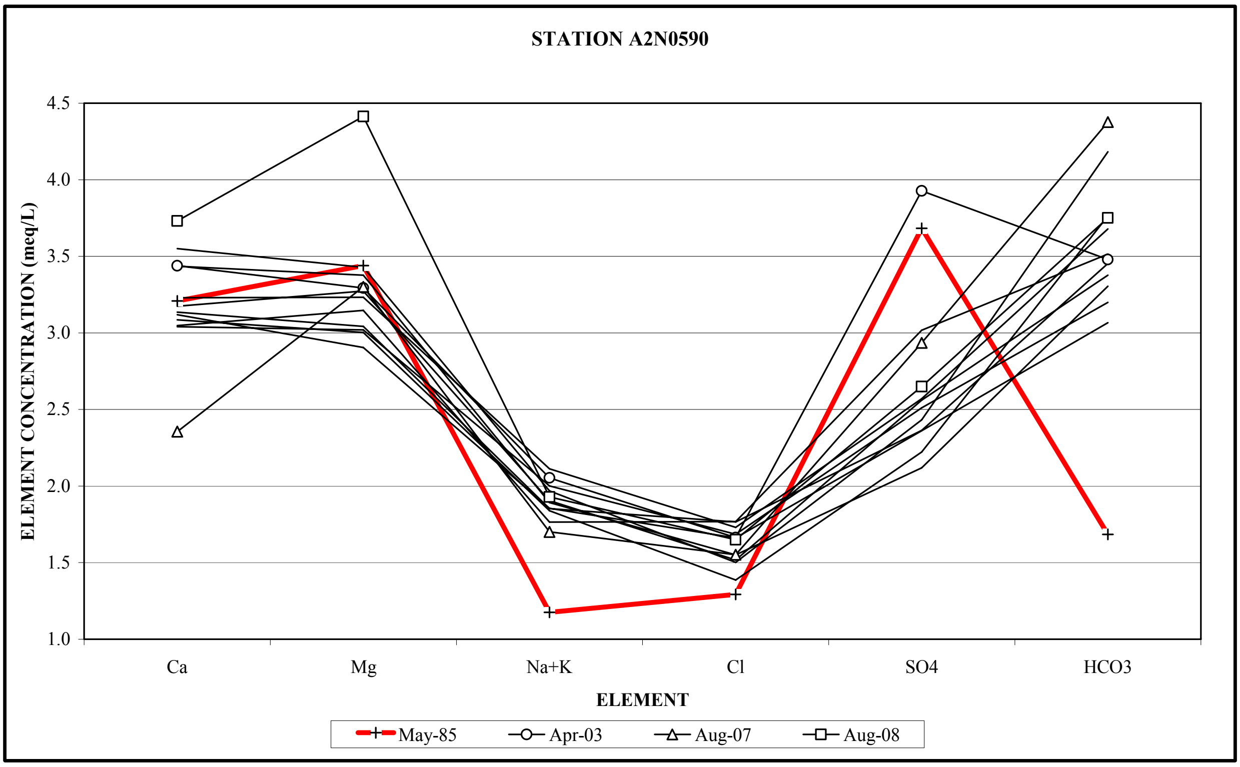
D.3b : VARIATION IN CHEMICAL COMPOSITION AT STATION A2N0586



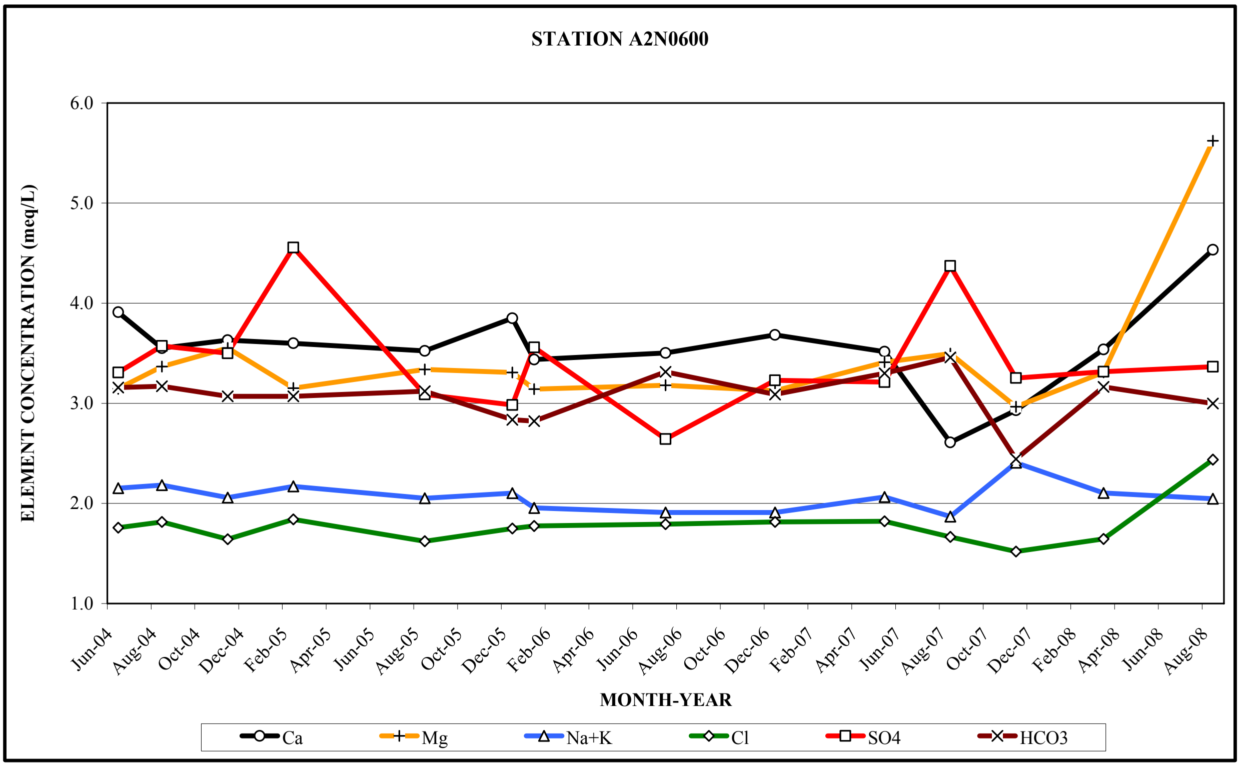
D.4a : MAJOR ION TREND AT STATION A2N0590



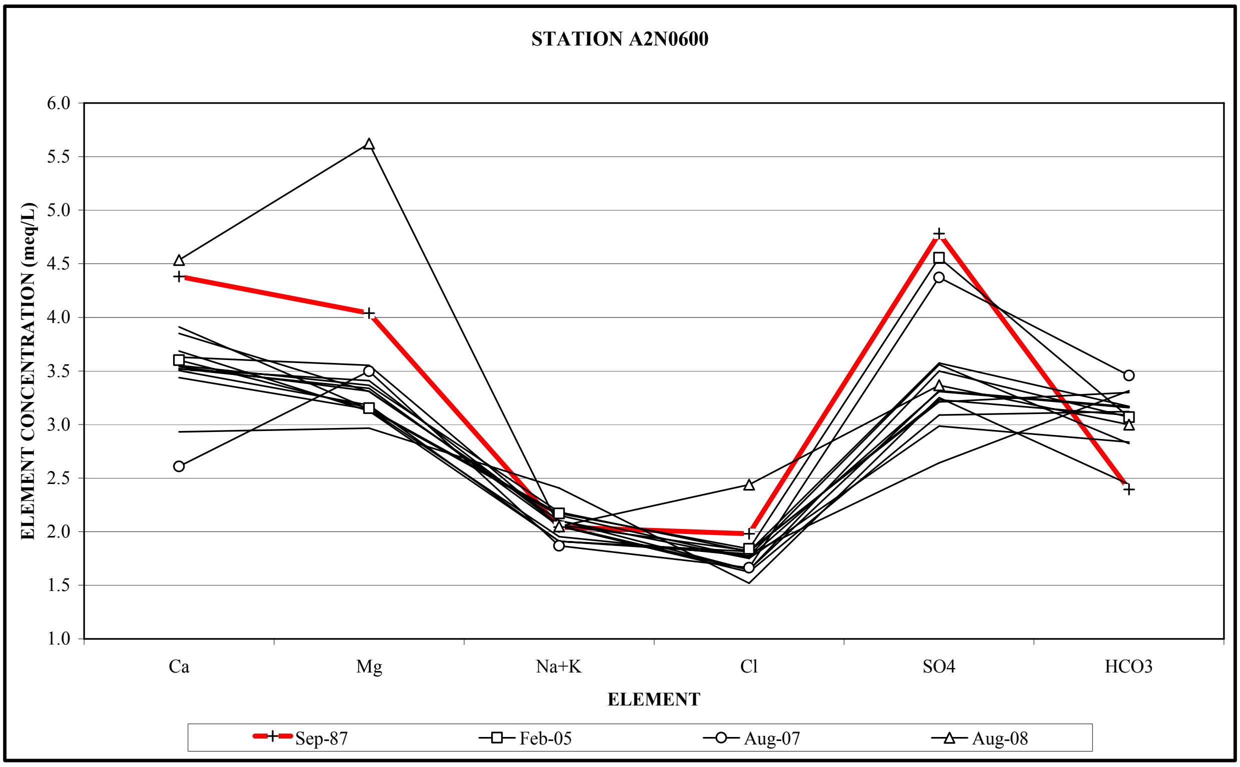
D.4b : VARIATION IN CHEMICAL COMPOSITION AT STATION A2N0590



D.5a : MAJOR ION TREND AT STATION A2N0600



D.5b : VARIATION IN CHEMICAL COMPOSITION AT STATION A2N0600



Unnumbered plate.
Resistant quartzite of the Witwatersrand Supergroup creating a ~15 m high waterfall on the Blougat Spruit downstream of the Percy Stewart Wastewater Treatment Works; the ameliorative effect of the aeration generated in the cascading water on its downstream quality is a fortuitous natural intervention. (Photo: Phil Hobbs).

ANNEXURE E : DEFINITION OF LEVEL 3 HAZARD CATEGORIES AND ASSOCIATED WEIGHTING VALUES (after ZWAHLEN, 2003)

No.	Hazards	Weighting Value
1	**Infrastructural development**	
1.1	Waste Water	
1.1.1	urbanisation (leaking sewer pipes and sewer systems)	35
1.1.2	urbanisation without sewer systems	70
1.1.3	detached houses without sewer systems	45
1.1.4	septic tank, cesspool, latrine	45
1.1.5	sewer farm and waste water irrigation system	55
1.1.6	discharge from an inferior treatment plant	35
1.1.7	surface impoundment for urban waste water	60
1.1.8	runoff from paved surfaces	25
1.1.9	waste water discharge into surface water courses	45
1.1.10	waste water injection well	85
1.2	Municipal Waste	
1.2.1	garbage dump, rubbish bin, litter bin	40
1.2.2	waste loading station and scrap yard	40
1.2.3	sanitary landfill	50
1.2.4	spoils and building rubble depository	35
1.2.5	sludge from treatment plants	35
1.3	Fuels	
1.3.1	storage tank, above ground	50
1.3.2	storage tank, underground	55
1.3.3	drum stock pile	50
1.3.4	tank yard	50
1.3.5	fuel loading station	60
1.3.6	gasoline station	60
1.3.7	fuel storage cavern	65
1.4	Transport and traffic	
1.4.1	road, unsecured	40
1.4.2	road tunnel, unsecured	40
1.4.3	road haulier depot	35
1.4.4	car parking area	35
1.4.5	railway line	30
1.4.6	railway tunnel, unsecured	30
1.4.7	railway station	35
1.4.8	marshalling yard	40
1.4.9	runway	35
1.4.10	pipline of hazardous liquids	60
1.5	Recreational facilities	
1.5.1	tourist urbanisation	30
1.5.2	camp ground	30
1.5.3	open sport stadion	25
1.5.4	golf course	35
1.5.5	skiing course	25
1.6	Diverse hazards	
1.6.1	graveyard	25
1.6.2	animal burial	35
1.6.3	dry cleaning premises	35
1.6.4	transformer station	30
1.6.5	military installations and dereliction	35
2	**Industrial activities**	
2.1	Mining (in operation and abandoned)	
2.1.1	mine, salt	60
2.1.2	mine, other non-metallic	70
2.1.3	mine, ore	70
2.1.4	mine, coal	70
2.1.5	mine, uranium	80
2.1.6	outdoor stock piles of hazardous raw material	85
2.1.7	ore milling and enrichment facilities	70
2.1.8	mine waste heap and dirt refuse	70
2.1.9	ore tailings	70
2.1.10	mine drainage	65
2.1.11	tailing pond	65

No.	Hazards	Weighting Value
2.2	Excavation sites	
2.2.1	Excavation and embankment for development	10
2.2.2	gravel and sand pit	30
2.2.3	quarry	25
2.3	Oil and gas exploitation	
2.3.1	production wells	40
2.3.2	reinjection wells	70
2.3.3	loading station	55
2.3.4	oil pipline	55
2.4	Industrial plants (none mining)	
2.4.1	smelter	40
2.4.2	iron and steel works	40
2.4.3	metal processing and finifhing industry	50
2.4.4	electroplating works	55
2.4.5	oil refinery	85
2.4.6	chemical factory	65
2.4.7	rubber and tyre industry	40
2.4.8	paper and pulp manufacture	40
2.4.9	leather tannery	70
2.4.10	food industry	45
2.5	Power plants	
2.5.1	gasworks	60
2.5.2	caloric power plants	50
2.5.3	nuclear power plant	65
2.6	Industrial storage	
2.6.1	stock piles of raw materials and chemicals	60
2.6.2	containers for hazardous substances	70
2.6.3	cinder tip and slag heaps	70
2.6.4	non hazardous waste site	45
2.6.5	hazardous waste site	90
2.6.6	nuclear waste site	100
2.7	Diverting and treatment of waste water	
2.7.1	waste water piplines	65
2.7.2	surface impoundment for industrial waste water	65
2.7.3	discharge of treatment plants	40
2.7.4	waste water injection well	85
3	**Livestock and Agriculture**	
3.1	Livestock	
3.1.1	animal barn (shed, cote, sty)	30
3.1.2	feedlot	30
3.1.3	factory farm	30
3.1.4	manure heap	45
3.1.5	slurry storage tank or pool	45
3.1.6	area of intensive pasturing	25
3.2	Agriculture	
3.2.1	open silage (field)	25
3.2.2	closed silage	20
3.2.3	stockpiles of fertilisers and pesticides	40
3.2.4	intensive agriculture area (with high demand of fertilisers and pesticides)	30
3.2.5	allotment garden	15
3.2.6	greenhouse	20
3.2.7	waste water irrigation	60

Unnumbered plate.
View from downstream of the sluice gate at the entrance to the A-furrow downstream of the Zwartkrans Spring following the high discharge conditions experienced in the Bloubank Spruit in mid-December 2010.
(Photo: Phil Hobbs).

ANNEXURE F : ENUMERATED GEOSITES

Source Information		Position Information										
		Datum = Hartebeesthoek 94 / Ref. ellipsoid = WGS84								LO (27)		
Station	Source Type	Latitude	Longitude	Latitude			Longitude			Y	X	Z
		dd.ddddd S	dd.ddddd E	d	m	s.s	d	m	s.s	(m)	(m)	(m)
CSIR1	Borehole	26.08814	27.70167	26	5	17.3	27	42	6.0	-70198	2886788	1593
CSIR2	Borehole	26.09064	27.69573	26	5	27.2	27	41	40.6	-69490	2887089	1616
CSIR3	Borehole	26.08978	27.69403	26	5	23.2	27	41	38.5	-69433	2886966	1614
CSIR4	Borehole	26.09717	27.69800	26	5	49.8	27	41	52.8	-69826	2887787	1601
CSIR5	Borehole	26.09650	27.70178	26	5	47.4	27	42	6.4	-70204	2887715	1607
CSIR6	Borehole	26.09150	27.69836	26	5	29.4	27	41	54.1	-69865	2887159	1612
CSIR7	Borehole	26.03467	27.71886	26	2	4.8	27	43	7.9	-71951	2880873	1472
CSIR8	Borehole	26.03256	27.72103	26	1	57.2	27	43	15.7	-72169	2880641	1475
CSIR9	Borehole	26.03514	27.71794	26	2	6.5	27	43	4.6	-71859	2880925	1468
CSIR10	Shaft	26.13544	27.72006	26	8	7.6	27	43	12.2	-72009	2892040	1714
CSIR11	Borehole	26.10383	27.70011	26	6	13.8	27	42	0.4	-70033	2888526	1625
CSIR12	Borehole	26.07808	27.66972	26	4	41.1	27	40	11.0	-67008	2885657	1576
CSIR13	Borehole	26.08092	27.66978	26	4	51.3	27	40	11.2	-67012	2885971	1579
CSIR14	Borehole	26.07842	27.66953	26	4	42.3	27	40	10.3	-66988	2885694	1576
CSIR15	Borehole	26.08914	27.69633	26	5	20.9	27	41	46.8	-69664	2886896	1613
CSIR16	Borehole	26.09350	27.69133	26	5	36.6	27	41	28.8	-69161	2887377	1618
CSIR17	Borehole	26.08664	27.67492	26	5	11.9	27	40	29.7	-67522	2886608	1597
CSIR18	Borehole	26.08592	27.67442	26	5	9.3	27	40	27.9	-67473	2886528	1593
CSIR19	Lake	26.14603	27.71072	26	8	45.7	27	42	38.6	-71069	2893207	1717
CSIR20	Spring	26.09044	27.71625	26	5	25.6	27	42	58.5	-71655	2887052	1600
CSIR21	Stream	26.08947	27.71811	26	5	22.1	27	43	5.2	-71842	2886945	1590
CSIR22	Shaft	26.11522	27.72306	26	6	54.8	27	43	23.0	-72321	2889801	1662
CSIR23	Shaft	26.11514	27.72489	26	6	54.5	27	43	29.6	-72505	2889793	1672
CSIR24	Borehole	26.11539	27.72628	26	6	55.4	27	43	34.6	-72643	2889821	1678
CSIR25	Borehole	26.11217	27.72469	26	6	43.8	27	43	28.9	-72487	2889463	1667
CSIR26	Borehole	26.11225	27.72275	26	6	44.1	27	43	21.9	-72292	2889471	1659
CSIR27	Borehole	26.11117	27.72258	26	6	40.2	27	43	21.3	-72276	2889351	1658
CSIR28	Borehole	26.10992	27.72067	26	6	35.7	27	43	14.4	-72085	2889212	1663
CSIR29	Borehole	26.09989	27.71989	26	5	59.6	27	43	11.6	-72014	2888100	1646
CSIR30	Spring	26.09808	27.71892	26	5	53.1	27	43	8.1	-71918	2887900	1641
CSIR31	Borehole	26.07119	27.67536	26	4	16.3	27	40	31.3	-67576	2884897	1565
CSIR32	Borehole	26.05706	27.70183	26	3	25.4	27	42	6.6	-70233	2883345	1505
CSIR33	Borehole	26.05844	27.69967	26	3	30.4	27	41	58.8	-70015	2883497	1491
CSIR34	Borehole	26.06333	27.69672	26	3	48.0	27	41	48.2	-69718	2884037	1505
CSIR35	Borehole	26.07944	27.69169	26	4	46.0	27	41	30.1	-69205	2885820	1593
CSIR36	Borehole	26.10106	27.68831	26	6	3.8	27	41	17.9	-68854	2888212	1624
CSIR37	Spring	26.09092	27.72011	26	5	27.3	27	43	12.4	-72041	2887106	1626
CSIR38	Stream	26.10750	27.72231	26	6	27.0	27	43	20.3	-72251	2888945	1652
CSIR39	Stream	26.09919	27.72108	26	5	57.1	27	43	15.9	-72134	2888024	1645
CSIR40	Stream	26.07403	27.69853	26	4	26.5	27	41	54.7	-69892	2885223	1518
CSIR41	Stream	26.07692	27.69928	26	4	36.9	27	41	57.4	-96648	2885714	1527
CSIR42	Stream	26.08417	27.70819	26	5	3.0	27	42	29.5	-70853	2886352	1544
CSIR43	Borehole	26.05331	27.72433	26	3	11.9	27	43	27.6	-72487	2882941	1491
CSIR44	Stream	26.05511	27.72322	26	3	18.4	27	43	23.6	-72375	2883141	1485
CSIR45	Borehole	26.05817	27.72256	26	3	29.4	27	43	21.2	-72306	2883479	1503
CSIR46	Borehole	26.05689	27.72322	26	3	24.8	27	43	23.6	-72374	2883338	1491
CSIR47	Borehole	26.11906	27.68703	26	7	8.6	27	41	13.3	-68715	2890206	1663
CSIR48	Borehole	26.12181	27.68750	26	7	18.5	27	41	15.0	-68761	2890511	1658
CSIR49	Borehole	26.12192	27.68750	26	7	18.9	27	41	15.0	-68761	2890523	1658
CSIR50	Spring	26.12408	27.68328	26	7	26.7	27	40	59.8	-68337	2890761	1652
CSIR51	Spring	26.10925	27.68908	26	6	33.3	27	41	20.7	-68927	2889121	1623
CSIR52	Borehole	26.10119	27.69742	26	6	4.3	27	41	50.7	-69765	2888233	1611
CSIR53	Borehole	26.10928	27.72675	26	6	33.4	27	43	36.3	-72694	2889144	1669
CSIR54	Borehole	26.03453	27.72497	26	2	4.3	27	43	29.9	-72563	2880861	1486
CSIR55	Spring	26.07753	27.70092	26	4	39.1	27	42	3.3	-70129	2885612	1530

CSIR56	Borehole	26.10956	27.72903	26	6	34.4	27	43	44.5	-72922	2889176	1673
CSIR57	Borehole	26.04756	27.71233	26	2	51.2	27	42	44.4	-71290	2882298	1473
CSIR58	Borehole	26.04761	27.70903	26	2	51.4	27	42	32.5	-70959	2882302	1487
CSIR59	Shaft	26.12150	27.72136	26	7	17.4	27	43	16.9	-72148	2890495	1669
CSIR60	Shaft	26.12633	27.72428	26	7	34.8	27	43	27.4	-72436	2891033	1705
CSIR61	Borehole	26.07922	27.68628	26	4	45.2	27	41	10.6	-68664	2885792	1594
CSIR62	Borehole	26.11419	27.72258	26	6	51.1	27	43	21.3	-72274	2889687	1661
CSIR63	Spring	26.09814	27.71958	26	5	53.3	27	43	10.5	-71984	2887906	1638
CSIR64	Stream	26.12083	27.72008	26	7	15.0	27	43	12.3	-72020	2890421	1670
CSIR65	Borehole	26.09714	27.70147	26	5	49.7	27	42	5.3	-70173	2887785	1606
PLSp1	Spring	25.97786	27.77858	25	58	40.3	27	46	42.9	-77966	2874614	1419
PLSp2	Spring	25.97847	27.77844	25	58	42.5	27	46	42.4	-77952	2874682	1419
ZWSp1	Spring	26.00822	27.74500	26	0	29.6	27	44	42.0	-74584	2877958	1432
ZWSp2	Spring	26.00644	27.74398	26	0	23.2	27	44	38.3	-74482	2877761	1433
MNR1	Borehole	25.91168	27.83923	25	54	42.0	27	50	21.2	-84086	2867317	1444
MNRSp	Spring	25.91412	27.84978	25	54	50.8	27	50	59.2	-85142	2867595	1405
DRSp	Spring	25.97875	27.74322	25	58	43.5	27	44	35.6	-74424	2874692	1486
WBD1	Borehole	26.07208	27.71308	26	4	19.5	27	42	47.1	-71350	2885016	1576
KDSp	Spring	25.98978	27.77551	25	59	23.2	27	46	31.8	-77649	2875932	
BSp	Spring	25.81613	27.87049	25	48	58.1	27	52	13.8	-87290	2856754	1281
HW1	Borehole	25.99380	27.77689	25	59	37.7	27	46	36.8	-77786	2876380	1418
RB1	Borehole	25.98801	27.78070	25	59	16.8	27	46	50.5	-78171	2875738	1415
DRP15	Borehole	25.99809	27.74526	25	59	53.2	27	44	43.1	-74621	2876838	1475
SWBH1	Borehole	26.00532	27.75706	26	0	19.2	27	45	25.4	-75793	2877645	1445
SBH1	Borehole	25.99973	27.76391	25	59	59.0	27	45	50.1	-76483	2877027	1437
MB1	Borehole	26.01045	27.73609	26	0	37.6	27	44	9.9	-73690	2878200	1450
SF1	Borehole	26.01342	27.73567	26	0	48.3	27	44	8.4	-73646	2878528	1454
G36325	Borehole	26.03504	27.68205	26	2	6.1	27	40	55.4	-68267	2880894	1513
G37794	Borehole	26.01794	27.71106	26	1	4.6	27	42	39.8	-71180	2879016	1463
SW1	Borehole	26.02619	27.71864	26	1	34.3	27	43	7.1	-71934	2879935	1459
ZW1	Borehole	26.01686	27.70794	26	1	0.7	27	42	28.6	-70869	2878895	1468
G37786	Borehole	26.02772	27.70513	26	1	39.8	27	42	18.5	-70581	2880096	1495
B1	Borehole	25.95514	27.79928	25	57	18.5	27	47	57.4	-80054	2872109	1473
BolandB1	Borehole	26.00261	27.73458	26	0	9.3	27	44	4.6	-73547	2877327	1459
GB1	Borehole	26.03273	27.71722	26	1	57.9	27	43	1.9	-71785	2880660	1463
G36326	Borehole	26.03761	27.70904	26	2	15.4	27	42	32.5	-70965	2881194	1492
VW1	Borehole	25.95636	27.80137	25	57	22.9	27	48	4.9	-80262	2872244	1458
SF2	Borehole	26.03757	27.70808	26	2	15.3	27	42	29.1	-70869	2881191	1495
G36327	Borehole	26.03668	27.71534	26	2	12.0	27	42	52.2	-71513	2881093	1467
DRGF2	Borehole	25.96622	27.74442	25	57	58.4	27	44	39.9	-74552	2873304	1513
DRGF1	Borehole	25.97580	27.74239	25	58	32.9	27	44	32.6	-74343	2874365	1497
G36357	Borehole	26.07922	27.68628	26	4	45.2	27	41	10.6	-68664	2885792	1594
SAV4	Borehole	25.99722	27.70119	25	59	50.0	27	42	4.3	-70205	2876715	1539
SAV5	Borehole	25.97458	27.72456	25	58	28.5	27	43	28.4	-72558	2874220	1543
SAV6	Borehole	25.98500	27.73914	25	59	6.0	27	44	20.9	-74012	2875382	1480
SAV7	Borehole	25.98514	27.73914	25	59	6.5	27	44	20.9	-74011	2875397	1480
PB1	Borehole	25.99814	27.73114	25	59	53.3	27	43	52.1	-73202	2876833	1476
RLGR1	Borehole	25.97511	27.79303	25	58	30.4	27	47	34.9	-79414	2874318	1410
RLGR2	Borehole	25.97256	27.79339	25	58	21.2	27	47	36.2	-79452	2874035	1412
RLGR3	Borehole	25.96253	27.78719	25	57	45.1	27	47	13.9	-78839	2872920	1448
RLGR4	Borehole	25.95669	27.77272	25	57	24.1	27	46	21.8	-77393	2872265	1474
RLGR5	Borehole	25.94569	27.77906	25	56	44.5	27	46	44.6	-78035	2871050	1485
GSSp	Spring	25.94681	27.81467	25	56	48.5	27	48	52.8	-81601	2871195	1436
GS2	Borehole	25.94758	27.81344	25	56	51.3	27	48	48.4	-81478	2871281	1453
GS3	Borehole	25.94822	27.81353	25	56	53.6	27	48	48.7	-81486	2871351	1447
BolandC	Borehole	26.00633	27.73928	26	0	22.8	27	44	21.4	-74012	2877746	1442
BolandB	Borehole	26.00444	27.74144	26	0	16.0	27	44	29.2	-74230	2877538	1443
BolandA	Borehole	26.00506	27.74358	26	0	18.2	27	44	36.9	-74444	2877606	1435
DROost	Borehole	25.99014	27.74161	25	59	24.5	27	44	29.8	-74256	2875953	1473
DRAnglo	Borehole	25.95425	27.73600	25	57	15.3	27	44	9.6	-73716	2871973	1548
RT1	Borehole	26.01203	27.69508	26	0	43.3	27	41	42.3	-69584	2878352	1490
KE1	Borehole	25.93597	27.69900	25	56	9.5	27	41	56.4	-70021	2869928	1500

KE2	Borehole	25.93781	27.69997	25	56	16.1	27	41	59.9	-70118	2870132	1487
KE3	Borehole	25.93797	27.70039	25	56	16.7	27	42	1.4	-70159	2870150	1486
WEL2	Borehole	25.93539	27.72167	25	56	7.4	27	43	18.0	-72292	2869876	1497
KH01	Borehole	25.96361	27.68247	25	57	49.0	27	40	56.9	-68350	2872981	1549
CFM1	Borehole	26.02373	27.72242	26	1	25.4	27	43	20.7	-72313	2879663	1466
PM1	Borehole	26.02548	27.72879	26	1	31.7	27	43	43.6	-72949	2879860	1481
ME1	Borehole	26.04442	27.71931	26	2	39.9	27	43	9.5	-71989	2881954	1485
PR1	Borehole	26.03689	27.72919	26	2	12.8	27	43	45.1	-72292	2869876	1499
GB2	Borehole	26.03196	27.71616	26	1	55.1	27	42	58.2	-71683	2880573	1477
PS2	Borehole	26.07638	27.72417	26	4	35.0	27	43	27.0	-72456	2885499	1597
PS3	Borehole	26.06288	27.72480	26	3	46.4	27	43	29.3	-72528	2884003	1546
PS6	Borehole	26.06243	27.71823	26	3	44.7	27	43	5.6	-71870	2883948	1511
AM1	Borehole	26.04301	27.71368	26	2	34.8	27	42	49.2	-71426	2881794	1497
SCH1	Borehole	26.03657	27.70727	26	2	11.7	27	42	26.2	-70790	2881079	1502
SCH2	Borehole	26.03879	27.70763	26	2	19.6	27	42	27.5	-70825	2881323	1503
NR1	Borehole	26.01850	27.71836	26	1	6.6	27	43	6.1	-71911	2879082	1457
DC1	Borehole	26.00782	27.67982	26	0	28.2	27	40	47.4	-68060	2877879	1535
MVR1	Borehole	25.92777	27.77121	25	55	40.0	27	46	16.4	-77262	2869061	1513
PvW1	Borehole	25.95523	27.79958	25	57	18.8	27	47	58.5	-80084	2872118	1470
AS1	Borehole	26.09693	27.69550	26	5	48.9	27	41	43.8	-69576	2887758	1613
SWBH2	Borehole	26.00323	27.75616	26	0	11.6	27	45	22.2	-75705	2877411	1435
OB1	Borehole	25.99622	27.78117	25	59	46.4	27	46	52.2	-78213	2876650	1439
JNNR1	Spring	25.90806	27.79755	25	54	29.1	27	47	51.2	-79913	2866892	1450
JNNR2	Spring	25.87531	27.78589	25	52	31.1	27	47	9.2	-78766	2863256	1330
JNNR3	Spring	25.89417	27.76500	25	53	39.0	27	45	54.0	-76660	2865333	1365
JNNR4	Spring	25.90949	27.73770	25	54	34.2	27	44	15.7	-73915	2867015	1410
KGM1	Borehole	26.00361	27.77591	26	0	13.0	27	46	33.3	-77682	2877465	1432
G36332	Borehole	26.06581	27.66622	26	3	56.9	27	39	58.4	-66664	2884295	1543
PD1	Borehole	26.03639	27.71484	26	2	11.0	27	42	53.4	-71547	2881062	1469
PN1	Borehole	25.98941	27.77536	25	59	21.9	27	46	31.3	-77636	2875892	1412
IJ1	Borehole	26.03984	27.71942	26	2	23.4	27	43	9.9	-72003	2881446	1475
IJ2	Borehole	26.03980	27.72023	26	2	23.3	27	43	12.8	-72084	2881443	1474
NOE1	Borehole	25.97764	27.79995	25	58	39.5	27	47	59.8	-80106	2874602	1395
NOE2	Borehole	25.97647	27.79996	25	58	35.3	27	47	59.9	-80108	2874473	1404
NOE3	Borehole	25.97300	27.80492	25	58	22.8	27	48	17.7	-80607	2874091	1416
MV1	Borehole	26.05066	27.68176	26	3	2.4	27	40	54.3	-68227	2882626	1563
GP00300	Borehole	26.04771	27.70914	26	2	51.8	27	42	32.9	-70970	2882315	1487
GP00301	Borehole	26.04699	27.70170	26	2	49.2	27	42	6.1	-70225	2882230	1524
GP00302	Borehole	26.05854	27.69975	26	3	30.7	27	41	59.1	-70024	2883507	1491
GP00304	Borehole	26.07927	27.68637	26	4	45.4	27	41	10.9	-68672	2885798	1594
GP00305	Borehole	26.09338	27.71940	26	5	36.2	27	43	9.8	-71969	2887379	1633
GP00306	Borehole	26.09238	27.72124	26	5	32.6	27	43	16.5	-72154	2887269	1629
GP00307	Borehole	26.08102	27.70507	26	4	51.7	27	42	18.3	-70543	2886001	1538
GP00308	Borehole	26.07342	27.69938	26	4	24.3	27	41	57.8	-69978	2885156	1525
GP00309	Borehole	26.03602	27.71517	26	2	9.7	27	42	54.6	-71580	2881021	1466
GP00311	Borehole	26.04455	27.68438	26	2	40.4	27	41	3.8	-68495	2881950	1548
GP00312	Borehole	26.04516	27.71504	26	2	42.6	27	42	54.1	-71561	2882035	1474
GP00313	Borehole	26.01226	27.72678	26	0	44.1	27	43	36.4	-72757	2878394	1460
GP00314	Borehole	26.00750	27.73830	26	0	27.0	27	44	17.9	-73914	2877874	1440

Unnumbered plate.
Discharge in the Riet Spruit at its intersection with the Malmani Road on 12/01/2011; note the red colouration of the water indicative of a strong acid mine water impact as revealed by the following field values: pH = 2.3, EC = 410 mS/m, Eh = 254 mV.
(Photo: Phil Hobbs).

ANNEXURE G : GROUNDWATER LEVEL MEASUREMENT DATA

Station	Source Type	Surface Elevation (m amsl)	Collar Stickup (m agl)	Water Rest Level Depth (m bc)	Date (dd/mm/yyyy)	Groundwater Elevation (m amsl)	Water Rest Level Depth (m bc)	Date (dd/mm/yyyy)	Groundwater Elevation (m amsl)	Water Rest Level Depth (m bc)	Date (dd/mm/yyyy)	Groundwater Elevation (m amsl)	Water Rest Level Depth (m bc)	Date (dd/mm/yyyy)	Groundwater Elevation (m amsl)	Water Rest Level Depth (m bc)	Date (dd/mm/yyyy)	Groundwater Elevation (m amsl)
CSIR1	Borehole	1593	0.27	30.96	31/01/2007	1562												
CSIR2	Borehole	1616	0.20	46.22	31/01/2007	1570				46.20	09/03/2010	1570						
CSIR3	Borehole	1614	0.18	44.20	31/01/2007	1570	44.33	28/02/2008	1570	44.10	09/03/2010	1570						
CSIR4	Borehole	1601	0.18	60.00	31/01/2007	1541												
CSIR5	Borehole	1607	0.16	26.85	08/02/2007	1580	24.88	28/02/2008	1582									
CSIR7	Borehole	1472	0.55	24.72	01/02/2007	1448												
CSIR8	Borehole	1475	0.22	28.42	13/02/2007	1447				24.28	14/04/2010	1451						
CSIR9	Borehole	1468	0.11	21.00	*circa* 2002	1447				17.35	14/04/2010	1451						
CSIR10	Shaft	1714	0.24	41.46	01/02/2007	1673	41.23	27/02/2008	1673									
CSIR11	Borehole	1625	0.00	53.09	01/02/2007	1572	53.83	28/02/2008	1571									
CSIR12	Borehole	1576	0.37	73.03	01/02/2007	1503												
CSIR13	Borehole	1579	0.23	76.26	01/02/2007	1503												
CSIR15	Borehole	1613	0.28	42.00	01/02/2007	1571												
CSIR17	Borehole	1597	0.10	76.65	06/02/2007	1520												
CSIR20	Spring	1600	0.00	0.00		1600												
CSIR22	Shaft	1662	0.00	0.00	07/02/2007	1662												
CSIR23	Shaft	1672	1.35	0.00	07/02/2007	1673												
CSIR24	Borehole	1678	0.70	9.61	07/02/2007	1669	9.12	28/02/2008	1670									
CSIR25	Borehole	1667	0.70	6.02	07/02/2007	1662	4.45	28/02/2008	1663									
CSIR26	Borehole	1659	0.00	0.00	07/02/2007	1659												
CSIR27	Borehole	1658	0.15	0.00	07/02/2007	1658												
CSIR28	Borehole	1663	0.57	7.19	07/02/2007	1656	6.43	28/02/2008	1657									
CSIR30	Spring	1641	0.00	0.00		1641												
CSIR31	Borehole	1565	0.10	61.61	08/02/2007	1503												
CSIR32	Borehole	1505	0.00	36.40	10/12/2006	1469												
CSIR33	Borehole	1491	0.23	25.71	08/02/2007	1466	23.96	28/02/2008	1467	21.78	16/02/2010	1469	21.1	09/06/2010	1470			
CSIR34	Borehole	1505	0.36	35.10	13/02/2007	1470				33.99	14/04/2010	1471						
CSIR35	Borehole	1593	0.30	43.95	08/02/2007	1549												
CSIR37	Spring	1626	0.00	0.00		1626												
CSIR47	Borehole	1663	0.05	13.75	21/02/2007	1649												
CSIR48	Borehole	1658	0.33	2.32	21/02/2007	1656												
CSIR49	Borehole	1658	0.00	1.94	21/02/2007	1656												
CSIR50	Spring	1652	0.00	0.00		1652												
CSIR51	Spring	1623	0.00	0.00		1623												
CSIR52	Borehole	1611	0.32	39.54	21/02/2007	1572				38.38	11/05/2010	1573						
CSIR53	Borehole	1669	0.00	15.23	21/02/2007	1654												
CSIR55	Spring	1530	0.00	0.00		1530												
CSIR56	Borehole	1673	0.21	18.50	08/03/2007	1655												
CSIR57	Borehole	1473	0.18	12.32	08/03/2007	1461	7.92	22/09/2009	1465	7.06	16/02/2010	1466	6.46	27/07/2010	1467			
CSIR58	Borehole	1487	0.26	26.96	08/03/2007	1460	25.91	28/02/2008	1461	21.98	16/02/2010	1465						
CSIR59	Shaft	1669	0.00	0.00	14/03/2007	1669												
CSIR60	Shaft	1705		0.00	14/03/2007	1705												
CSIR62	Borehole	1661		0.00	25/07/2007	1661												
CSIR63	Spring	1638	0.00	0.00		1638	0.00	26/02/2008	1638									
PLSp1	Spring	1419	0.00	0.00		1419												
PLSp2	Spring	1419	0.00	0.00		1419												
ZWSp1	Spring	1432	0.00	0.00		1432												
MNR1	Borehole	1444	0.22													12.08	21/12/2010	1432
MNRSp	Spring	1405	0.00	0.00		1405										0.00	21/12/2010	1405
DRSp	Spring	1486	0.00	0.00		1486												

WBD1	Borehole	1576	0.25				78.29	09/09/2009	1498									
KDSp	Spring	1408	0.00			1408												
BSp	Spring	1281	0.00													0.00	21/12/2010	1281
KBH1	Borehole	1405		8.30	30/07/2006	1397												
RBTB1	Borehole	1413		12.26	30/07/2006	1401												
RBWB1	Borehole	1417		15.83	30/07/2006	1401												
HW1	Borehole	1418	0.00	8.00	30/07/2006	1410				6.09	13/05/2010	1412						
RB1	Borehole	1415	0.00	11.65	30/07/2006	1403				10.49	22/07/2010	1405						
DRP15	Borehole	1475	0.16	59.00	30/07/2006	1416	58.63	02/12/2009	1417									
DPL1	Borehole	1433		15.00	25/01/2006	1418												
GBH	Borehole	1442		23.00	09/12/2005	1419												
SWBH1	Borehole	1445	0.26	28.00	30/07/2006	1417				27.30	13/05/2010	1418						
SBH1	Borehole	1437	0.30	22.26	30/07/2006	1415				21.18	13/05/2010	1416						
MB1	Borehole	1450	-0.30	15.07	30/07/2006	1435	14.21	18/02/2010	1435	13.79	13/05/2010	1436						
SF1	Borehole	1454		17.00	30/07/2006	1437	17.43	01/10/2007	1437	16.13	17/02/2010	1438	15.54	09/06/2010	1438	14.88	14/01/2011	1439
OA1	Borehole	1463		26.00	09/12/2005	1437												
G36325	Borehole	1513	0.30	74.00	25/01/2006	1439	73.43	08/02/2010	1440									
G37791	Borehole	1508		70.00	09/12/2005	1438												
MB2	Borehole	1446		7.53	30/07/2006	1438												
G36324	Borehole	1517		78.00	09/12/2005	1439												
G37789	Borehole	1502		63.00	09/12/2005	1439												
G37794	Borehole	1463	0.29	25.06	30/07/2006	1438	23.79	02/12/2009	1440	23.03	17/02/2010	1440						
G36323	Borehole	1475		36.13	30/07/2006	1439												
G36320	Borehole	1468		29.00	25/01/2006	1439												
SW1	Borehole	1459	0.15	18.00	09/12/2005	1441	16.29	02/12/2009	1443	11.36	11/02/2010	1448						
NRB1	Borehole	1509		70.00	11/08/2006	1439												
ZW1	Borehole	1468	0.13	29.64	30/07/2006	1438	28.37	02/12/2009	1440	27.64	17/02/2010	1440						
G33786	Borehole	1495		56.00	30/07/2006	1439												
HV1	Borehole	1456		15.00	09/12/2005	1441												
G37792	Borehole	1508		67.00	09/12/2005	1441												
B1	Borehole	1473	0.58	34.16	30/07/2006	1439	13.56	04/11/2009	1460									
BolandB1	Borehole	1459	0.90	22.15	30/07/2006	1438	22.29	03/11/2009	1438	21.77	17/02/2010	1438						
GB1	Borehole	1463	1.63	20.36	30/07/2006	1444	18.91	02/12/2009	1446	17.64	11/02/2010	1447						
G36326	Borehole	1492	0.16	51.00	25/01/2006	1441				dry	23/02/2010							
VW1	Borehole	1458	0.30	13.14	30/07/2006	1445				9.71	06/05/2010	1449						
SF2	Borehole	1495	0.25	54.50	30/07/2006	1441												
G36327	Borehole	1467	0.60	21.00	25/01/2006	1447												
G36328	Borehole	1544		67.00	25/01/2006	1477												
G36335	Borehole	1544		61.00	25/01/2006	1483												
DRGF2	Borehole	1513	0.20	26.93	30/07/2006	1486	26.37	01/12/2009	1487	26.30	11/02/2010	1487						
DRGF1	Borehole	1497	0.46	11.00	30/07/2006	1486	10.76	01/12/2009	1487	10.45	11/02/2010	1487						
G36356	Borehole	1597		58.00	30/07/2006	1539												
G36337	Borehole	1594	0.24	45.00	25/01/2006	1549				45.20	01/04/2010	1549						
SAV4	Borehole	1539	0.66	103.53	03/11/2009	1436												
SAV5	Borehole	1543	0.00	111.70	03/11/2009	1431												
SAV7	Borehole	1480	0.43	62.73	03/11/2009	1418	62.64	17/02/2010	1418									
PB1	Borehole	1476	0.27	60.27	03/11/2009	1416	60.13	10/02/2010	1416									
RLGR1	Borehole	1410	0.12	3.00	04/11/2009	1407	0.30	11/02/2010	1410									
RLGR2	Borehole	1412	0.12	5.67	04/11/2009	1406												
RLGR3	Borehole	1448	0.00	23.08	04/11/2009	1425												
RLGR4	Borehole	1474	0.55	52.18	04/11/2009	1422	51.38	11/02/2010	1423									
RLGR5	Borehole	1485	0.00	63.71	04/11/2009	1421	63.96	11/02/2010	1421									
GSSp	Spring	1436	0.00	0.00	04/11/2009	1436												
GS2	Borehole	1453	0.00	18.80	04/11/2009	1434	17.50	10/02/2010	1436									
GS3	Borehole	1447	0.10	13.43	04/11/2009	1434												
BolandC	Borehole	1442	0.19	7.90	01/12/2009	1434	7.50	10/02/2010	1435									

BolandB	Borehole	1443	0.40	6.59	01/12/2009	1437												
BolandA	Borehole	1435	0.37	15.77	01/12/2009	1420	15.63	10/02/2010	1420									
DROost	Borehole	1473	0.10	55.91	01/12/2009	1417												
DRAnglo	Borehole	1548	0.40	>116	01/12/2009	>1432												
RT1	Borehole	1490	0.43	51.47	02/12/2009	1439	51.08	17/02/2010	1439									
KE1	Borehole	1500	0.33	11.65	03/12/2009	1489												
KE2	Borehole	1487	0.31	55.08	03/12/2009	1432	54.86	11/02/2010	1432									
WEL2	Borehole	1497	0.25	66.88	03/12/2009	1430	66.91	11/02/2010	1430									
KH01	Borehole	1549	0.18	48.50	03/12/2009	1501												
CFM1	Borehole	1466	0.00	22.47	08/02/2010	1444												
PM1	Borehole	1481	-0.27	37.29	08/02/2010	1443												
ME1	Borehole	1485	0.18	18.29	09/02/2010	1467												
PR1	Borehole	1499	0.52	55.28	10/02/2010	1444												
GB2	Borehole	1477	0.21	n.m.	11/02/2010													
PS2	Borehole	1597	0.00	n.m.	16/02/2010													
PS3	Borehole	1546	0.17	41.22	16/02/2010	1505												
PS6	Borehole	1511	0.51	21.68	16/02/2010	1490												
AM1	Borehole	1497	0.27				30.29	23/02/2010	1467									
SCH1	Borehole	1502	0.46				57.80	09/03/2010	1445									
SCH2	Borehole	1503	0.37				59.13	09/03/2010	1444									
NR1	Borehole	1457	0.47				15.59	14/04/2010	1442									
DC1	Borehole	1535	0.13				>97.00	14/04/2010	<1438									
MVR1	Borehole	1513	0.00				>145	06/05/2010	<1368									
PvW1	Borehole	1470	0.17				13.25	06/05/2010	1457									
AS1	Borehole	1613	0.00				40.88	11/05/2010	1572									
SWBH2	Borehole	1435	-0.15							19.05	13/05/2010	1416						
OB1	Borehole	1439	0.00							18.75	13/05/2010	1420						
JNNR1	Spring	1450	0.00							0.00	19/05/2010	1450						
JNNR2	Spring	1330	0.00							0.00	19/05/2010	1330						
JNNR3	Spring	1365	0.00							0.00	19/05/2010	1365						
JNNR4	Spring	1410	0.00							0.00	19/05/2010	1410						
KGM1	Borehole	1432	0.37							12.07	26/05/2010	1420						
G36332	Borehole	1543	0.45							61.14	09/06/2010	1482						
PD1	Borehole	1469	0.60							19.15	07/06/2010	1450						
PN1	Borehole	1412	0.00							6.12	22/07/2010	1406						
IJ1	Borehole	1475	-1.01							17.98	27/07/2010	1456						
IJ2	Borehole	1474	0.00							17.75	27/07/2010	1456						
NOE1	Borehole	1395	0.00										5.67	19/11/2010	1389			
NOE2	Borehole	1404	0.00										11.02	19/11/2010	1393			
NOE3	Borehole	1416	0.20										6.59	19/11/2010	1410			
MV1	Borehole	1563	0.10										86.10	24/11/2010	1477			
GP00300	Borehole	1487	0.30							20.91	27/07/2010	1466						
GP00301	Borehole	1524	0.28										58.85	05/11/2010	1465			
GP00302	Borehole	1491	0.21													21.60	21/12/2010	1470
GP00304	Borehole	1594	0.36													45.34	21/12/2010	1549
GP00305	Borehole	1633	0.21										3.18	19/11/2010	1630			
GP00306	Borehole	1629	0.24										3.23	19/11/2010	1626			
GP00307	Borehole	1538	0.24							2.21	23/08/2010	1536	2.26	19/11/2010	1536			
GP00308	Borehole	1525	0.24							9.63	23/08/2010	1516	6.49	19/11/2010	1519			
GP00309	Borehole	1466	0.26										18.31	05/11/2010	1448	18.55	13/12/2010	1448
GP00311	Borehole	1548	0.20										70.56	24/11/2010	1478	70.4	13/12/2010	1478
GP00312	Borehole	1474	0.43													6.84	13/12/2010	1468
GP00313	Borehole	1460	0.41													20.56	19/12/2010	1440
GP00314	Borehole	1440	0.45													3.55	21/12/2010	1437

ANNEXURE H : SURFACE WATER AND GROUNDWATER CHEMISTRY DATA

Laboratory No.	Station	Sample Date (dd/mm/yyyy)	Field Temp. (°C)	Field pH	Lab. pH	Field EC (mS/m)	Lab. EC (mS/m)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO_4 (mg/L)	T. Alk. (mg/L)	NO_3 (mg/L)	Fe (mg/L)	Mn (mg/L)	Ni (mg/L)	U (mg/L)	Si (mg/L)	Total Coliform (c/100 mL)	*E. Coli.* (c/100 mL)	SAR	CTR	Electrical Balance (%)	Source Type
WLab/1100	DRP15	10/02/2010	20.6	7.2	8.1	45	42.8	45	27	6	<1.0	14	25	168	3.5	<0.025	<0.025	<0.025	—	5.0	—	—	0.17	0.27	4.5	G/water
WLab/1101	DRGF2	10/02/2010	18.9	6.8	7.6	22	21.5	23	14	3	<1.0	6	<5	100	0.9	<0.025	<0.025	<0.025	—	18.0	—	—	0.12	0.11	4.5	G/water
WLab/1102	DRSp	10/02/2010	20.4	6.9	8.0	26	25.1	33	18	<1	<1.0	<5	<5	128	0.7	<0.025	<0.025	<0.025	<0.001	5.9	21	13	0.03	0.05	8.4	G/water
WLab/1103	GS1	10/02/2010	19.2	6.8	7.5	63	59.2	87	48	4	<1.0	10	7	320	<0.2	2.570	0.380	<0.025	<0.001	7.5	—	—	0.09	0.07	10.8	G/water
WLab/1104	GS2	10/02/2010	19.2	6.6	7.4	53	48.3	58	40	5	4.0	8	12	240	0.6	<0.025	<0.025	<0.025	0.003	11.1	—	—	0.12	0.10	10.4	G/water
WLab/1105	BolandA	10/02/2010	20.8	7.0	7.9	81	72.1	80	44	32	1.1	48	126	164	9.6	0.053	<0.025	<0.025	<0.001	6.6	4	0	0.71	1.21	9.9	G/water
WLab/1386	BolandC	17/02/2010	19.6	7.1	7.8	88	79.0	75	44	45	1.6	52	151	156	12.0	0.076	<0.025	<0.025	<0.001	6.1	15	13	1.02	1.48	8.3	G/water
WLab/1106	PR1	10/02/2010	20.8	7.2	8.0	66	59.4	58	35	31	1.0	43	108	108	7.8	<0.025	<0.025	<0.025	<0.001	6.5	0	0	0.79	1.60	10.9	G/water
WLab/1107	PB1	10/02/2010	21.4	7.1	7.9	46	42.5	55	30	4	<1.0	7	22	192	1.7	<0.025	<0.025	<0.025	<0.001	6.2	—	—	0.11	0.17	8.9	G/water
WLab/1162	RLGR1	11/02/2010	23.2	7.2	7.8	67	62.2	85	47	7	3.2	11	32	288	2.3	<0.025	<0.025	<0.025	0.001	6.2	5	1	0.15	0.17	11.3	G/water
WLab/1165	RLGR5	11/02/2010	22.6	7.0	7.8	59	55.4	54	33	8	<1.0	16	4.5	224	12.0	<0.025	<0.025	<0.025	—	13.8	5	4	0.21	0.12	5.1	G/water
WLab/1163	WEL2	11/02/2010	22.2	7.4	8.2	22	22.0	23	14	<1	<1.0	<5	4.5	116	0.3	0.054	<0.025	<0.025	—	5.3	—	—	0.04	0.07	-2.7	G/water
WLab/1164	KE3	11/02/2010	20.0	6.3	7.1	8	11.1	8	7	3	<1.0	<5	4.5	36	1.1	0.192	<0.025	<0.025	—	5.0	—	—	0.19	0.23	10.8	G/water
WLab/1166	GB2	11/02/2010	18.8	6.9	8.0	145	137.0	127	63	110	3.2	165	151	252	15.0	<0.025	<0.025	<0.025	<0.001	7.9	2	0	1.99	1.55	11.2	G/water
WLab/1167	WL1	11/02/2010	22.4	7.0	7.8	10	17.6	16	9	5	<1.0	5	5	80	0.2	<0.025	0.213	<0.025	—	10.5	—	—	0.25	0.15	-2.1	G/water
WLab/1383	SAV4	17/02/2010	20.5	7.2	8.0	14	40.1	42	25	9	<1.0	<5	38	144	2.8	<0.025	<0.025	<0.025	—	—	—	—	0.27	0.30	9.3	G/water
WLab/1385	SAV6	17/02/2010	20.7	7.2	7.9	41	37.9	42	25	7	<1.0	12	33	144	2.6	<0.025	<0.025	<0.025	<0.001	5.4	—	—	0.21	0.36	6.2	G/water
WLab/1384	ZW1	17/02/2010	20.0	7.2	7.9	85	77.5	74	43	43	<1.0	46	155	168	9.1	<0.025	<0.025	<0.025	<0.001	6.1	—	—	0.98	1.35	6.3	G/water
WLab/1387	RT1	17/02/2010	20.1	7.2	7.9	90	79.4	71	38	40	1.6	50	169	56	10.0	<0.025	<0.025	<0.025	<0.001	6.3	0	0	0.95	4.40	15.3	G/water
WLab/1388	ME1	16/02/2010	19.8	6.4	7.2	58	53.1	37	26	36	1.1	57	77	60	12.0	<0.025	<0.025	<0.025	<0.001	5.0	0	0	1.11	2.68	9.6	G/water
WLab/1389	CSIR57	16/02/2010	17.4	6.3	6.7	286	268.0	614	90	105	8.8	39	1899	28	1.2	0.237	0.044	<0.025	<0.001	9.8	—	—	1.05	72.63	1.9	G/water
WLab/1390	F11S12	16/02/2010	20.6	4.2	3.1	338	319.0	546	113	68	11.3	38	2130	<5	0.3	8.940	47	1.640	0.026	5	—	—	0.69	909.15	-6.7	S/water
WLab/1391	CFM1	16/02/2010	19.7	7.2	7.8	89	80.4	82	47	30	2.2	60	140	168	11.0	0.057	<0.025	<0.025	<0.001	7.1	2	2	0.65	1.37	6.8	G/water
WLab/1392	LK1	16/02/2010	19.8	6.8	7.9	36	33.5	35	23	4	<1.0	10	13	196	0.4	<0.025	<0.025	<0.025	—	5.3	—	—	0.13	0.14	-7.8	G/water
WLab/1393	BC1	16/02/2010	25.6	7.4	7.8	45	57.9	69	12	23	<1.0	44	77	148	4.7	0.492	0.486	0.068	<0.001	6.8	91000	52000	0.67	0.96	-3.8	S/water
WLab/1394	PM1	16/02/2010	19.7	7.1	8.1	89	80.4	77	47	18	<1.0	60	146	168	11.0	0.042	0.030	<0.025	<0.001	7.400	—	—	0.40	1.41	1.4	G/water
WLab/1395	PS3	16/02/2010	23.1	6.0	6.6	4	5.0	2	3	2	0.41	6	<5	8	1.2	<0.025	<0.025	<0.025	—	4.6	—	—	0.21	1.38	5.2	G/water
WLab/1396	MRd1	16/02/2010	24.6	4.2	3.3	335	315.0	644	138	11	<1.0	37	2221	<5	0.4	2.490	64	2.340	0.026	7	—	—	0.10	946.51	-3.7	S/water
WLab/2336	SCH1	09/03/2010	20.2	6.8	7.6	147	138.0	148	82	63	2.1	53	568	160	8.3	0.436	<0.025	<0.025	<0.001	7.1	—	—	1.03	4.17	0.8	G/water
WLab/2337	CSIR2	09/03/2010	19.5	7.1	7.3	19	20.0	20	13	3	<1.0	<5	17	80	2.2	<0.025	<0.025	<0.025	<0.001	5.0	—	—	0.13	0.27	3.6	G/water
WLab/2338	CSIR3	09/03/2010	20.1	7.4	8.0	33	31.0	30	17	18	<1.0	5	27	144	0.2	<0.025	0.035	<0.025	<0.001	5.3	—	—	0.65	0.24	1.5	G/water
WLab/3712	CSIR34	14/04/2010	18.5	6.1	7.0	194	182.0	271	74	70	1.4	31	902	56	1.1	0.1450	<0.025	<0.025	<0.001	4.8	—	—	0.97	17.56	4.4	G/water
WLab/3710	CSIR8	14/04/2010	19.2	6.9	8.0	124	107.0	107	60	71	2.9	70	276	140	14.0	0.0360	<0.025	<0.025	<0.001	5.2	56	0	1.36	2.76	11.1	G/water
WLab/3711	CSIR9	14/04/2010	18.9	6.7	7.7	159	158.0	187	82	81	3.0	61	621	128	8.5	0.0450	<0.025	<0.025	<0.001	4.8	5	2	1.24	5.73	6.3	G/water
WLab/3713	NR1	14/04/2010	19.5	7.1	7.9	96	89.2	64	38	52	2.1	60	112	224	14.0	1.6200	0.061	<0.025	<0.001	4.7	500	0	1.27	0.90	-0.5	G/water
WLab/3714	DC1	14/04/2010	20.2	7.5	8.3	27	27.6	27	18	2	<1.0	<5	<5	148	0.5	0.0370	<0.025	<0.025	<0.001	3.7	—	—	0.07	0.04	-2.7	G/water
WLab/4978	CSIR52	11/05/2010	19.8	6.6	6.6	15	15.0	12	9	5	<1.0	5	41	20	3.0	0.1500	<0.025	<0.025	—	4.7	—	—	0.27	2.49	4.2	G/water
WLab/4979	MVR1	11/05/2010	20.9	7.4	7.4	31	31.0	33	20	<1	<1.0	<5	<5	160	0.5	<0.025	<0.025	<0.025	—	4.6	—	—	0.03	0.04	0.3	G/water
WLab/5049	OB1	13/05/2010	20.0	7.6	7.3	27	27.0	22	18	3	1.3	12	6	84	8.0	<0.025	<0.025	<0.025	<0.001	5.8	310	110	0.11	0.28	9.4	G/water
WLab/5050	MB1	13/05/2010	17.3	7.5	7.6	92	86.0	71	39	38	1.4	61	149	152	12.0	0.039	<0.025	<0.025	<0.001	6.1	7	0	0.90	1.59	2.3	G/water
WLab/5051	ZWSp	13/05/2010	18.8	7.5	7.6	84	79.0	66	37	36	1.5	57	154	160	12.0	<0.025	<0.025	<0.025	<0.001	6.0	230	120	0.88	1.51	-1.6	G/water
WLab/5052	SC1	13/05/2010	15.8	7.1	7.9	62	59.0	47	26	20	1.1	27	58	152	8.2	<0.025	<0.025	<0.025	<0.001	5.5	—	—	0.58	0.65	2.3	G/water
WLab/5053	KDSp	13/05/2010	19.8	7.7	7.7	38	36.0	51	29	2	<1.0	<5	5	192	0.9	<0.025	<0.025	<0.025	<0.001	5.9	—	—	0.06	0.05	11.1	G/water
WLab/5054	SBH1	13/05/2010	19.2	7.5	7.5	81	76.0	86	46	39	1.6	53	121	180	10.0	0.035	<0.025	<0.025	—	5.1	—	—	0.84	1.12	11.6	G/water
WLab/5055	SWB2	13/05/2010	15.3	7.7	7.7	80	75.0	90	47	43	2.0	54	130	172	10.0	0.029	<0.025	<0.025	—	5.5	—	—	0.91	1.23	13.5	G/water
WLab/5342	BB@PL	18/05/2010	17.0	7.0	7.6	60	56.2	54	29	34	3.0	40	78	140	6.0	0.358	0.293	<0.025	<0.001	5.3	720	470	0.93	0.98	8.1	S/water
WLab/5343	BB@M	18/05/2010	17.0	6.9	7.6	64	59.5	45	15	52	8.1	50	74	128	3.2	0.906	0.665	0.029	<0.001	5.4	3500	3000	1.71	1.15	3.4	S/water
WLab/5344	HS1	18/05/2010	16.0	6.9	7.8	22	23.0	15	18	5	1.1	12	15	80	1.9	0.073	0.087	<0.025	<0.001	5.3	0	0	0.21	0.41	4.1	S/water
WLab/5345	BC1	18/05/2010	17.6	7.1	7.5	59	55.6	41	10	55	8.6	52	56	132	0.2	0.528	0.279	0.049	<0.001	5.2	140000	65000	2.00	1.00	1.9	S/water
WLab/5346	BG@N14	18/05/2010	16.3	6.9	7.5	51	50.8	38	11	48	8.0	45	42	120	0.5	0.682	0.470	0.035	<0.001	4.9	34000	26000	1.76	0.89	5.6	S/water
WLab/5347	F11S12	18/05/2010	14.2	5.5	5.3	335	311.0	662	70	115	10.4	43	1794	<5	0.6	0.431	10	0.145	<0.001	0.8	—	—	1.14	771.94	6.6	S/water

WLab/5348	MRd1	18/05/2010	14.1	4.4	3.8	356	329.0	689	81	103	9.4	44	1819	<5	0.6	0.934	18	0.117	<0.001	1.7	—	—	0.99	782.92	7.8	S/water
WLab/5405	JNNR1	19/05/2010	20.6	6.5	6.5	39	37.9	47	27	<1	<1.0	<5	8	196	0.8	<0.025	<0.025	<0.025	—	5.0	—	—	0.03	0.06	5.2	G/water
WLab/5406	JNNR3	19/05/2010	21.4	7.0	7.0	25	25.2	30	18	<1	<1.0	<5	<5	132	0.5	<0.025	<0.025	<0.025	—	5.5	—	—	0.04	0.05	4.6	G/water
WLab/5407	JNNR4	19/05/2010	14.9	7.0	7.0	1	3.7	<2	3	1	<1.0	<5	<5	16	0.4	0.315	0.466	<0.025	—	4.1	—	—	0.11	0.38	-11.9	G/water
WLab/5408	JNNRSP	19/05/2010	22.6	6.9	6.9	39	36.8	47	27	<1	<1.0	<5	<5	196	0.6	<0.025	<0.025	<0.025	—	5.2	—	—	0.03	0.03	6.6	G/water
WLab/6403	KGM1	09/06/2010	19.1	5.9	7.5	18	16.9	12	12	4	2.4	12	<5	60	4.6	0.044	<0.025	<0.025	<0.001	3.7	—	—	0.20	0.33	4.5	G/water
WLab/6404	KGMMW	09/06/2010	15.7	6.2	7.5	13	12.6	3	12	3	3.2	11	<5	48	3.0		<0.025	<0.025	<0.001	3.9	—	—	0.17	0.38	-0.7	G/water
WLab/6405	A2N0598	09/06/2010	19.8	6.6	8.1	30	27.4	26	17	10	<1.0	24	30	92	1.0	<0.025	<0.025	<0.025	<0.001	4.6	36	5	0.37	0.71	-0.2	G/water
CSIR/78949	WBD1	07/07/2010	—	—	7.4	—	103.0	86	46	82	4.0	103	110	211	51.0	—	—	—	—		—	—	1.78	1.23	6.9	G/water
CSIR/82198	BSp	07/01/2011	22.8	7.3	7.3	49	35.9	54	34	<1	0.9	<5	11	272	0.4	<0.020	<0.005	—	—	6.5	—	—	0.03	0.06	-1.6	G/water
CSIR/82235	BB@M	12/01/2011	23.9	2.9	3.2	155	122.0	149	49	50	9.0	40	758	<5	4.8	44	16	—	—	—	—	—	0.91	338.49	-10.2	S/water
CSIR/82256	SC1	14/01/2011	16.7	7.8	7.6	56	45.5	48	27	22	1.0	37	71	154	9.3	<0.020	<0.005	—	—	—	—	—	0.63	0.82	-1.3	G/water

ANNEXURE I : ENVIRONMENTAL ISOTOPE DATA
(from iThembaLABS)

Laboratory No.	**Station**	**Source Description**	**Sampling Date (dd/mm/yyyy)**	**^{2}H (deuterium) (‰)**	**^{18}O (‰)**	**^{3}H (tritium) (T.U.)** ± 1σ error
CSIR 529	DRGF2	Borehole	10/02/2010	-28.5	-4.63	0.9 ± 0.2
CSIR 530	DRSp	Karst spring	10/02/2010	-28.8	-4.81	1.3 ± 0.2
CSIR 531	PB1	Borehole	10/02/2010	-27.8	-4.59	0.6 ± 0.2
CSIR 532	BolandA	Borehole	10/02/2010	-21.1	-3.57	1.2 ± 0.2
CSIR 533	PR1	Borehole	10/02/2010	-19.4	-3.37	1.2 ± 0.2
CSIR 534	GS1	Spring	10/02/2010	-28.0	-4.64	3.4 ± 0.3
CSIR 535	G-B2	Borehole	11/02/2010	-11.1	-2.17	3.1 ± 0.3
CSIR 536	RLGR5	Borehole	11/02/2010	-24.5	-4.23	5.1 ± 0.4
CSIR 537	CSIR57	Borehole	16/02/2010	-11.4	-2.31	2.8 ± 0.3
CSIR 538	ME1	Borehole	16/02/2010	-14.0	-2.80	1.7 ± 0.3
CSIR 539	PM1	Borehole	16/02/2010	-14.3	-2.78	1.6 ± 0.3
CSIR 540	CFM1	Borehole	16/02/2010	-14.3	-2.83	1.3 ± 0.2
CSIR 541	BolandC	Borehole	17/02/2010	-17.1	-3.26	1.6 ± 0.3
CSIR 542	SAV6	Borehole	17/02/2010	-26.3	-4.62	0.3 ± 0.2
CSIR 543	ZW1	Borehole	17/02/2010	-19.4	-3.58	1.7 ± 0.3
CSIR 544	RT1	Borehole	17/02/2010	-18.9	-3.47	1.6 ± 0.3
CSIR 545	SCH1	Borehole	09/03/2010	-19.5	-3.12	—
CSIR 546	CSIR2	Borehole	09/03/2010	-27.0	-4.59	—
CSIR 547	CSIR3	Borehole	09/03/2010	-28.5	-4.82	—
CSIR 548	CSIR34	Borehole	14/04/2010	-18.7	-3.06	—
CSIR 549	CSIR8	Borehole	14/04/2010	-16.0	-2.60	—
CSIR 550	CSIR9	Borehole	14/04/2010	-15.6	-2.63	—
CSIR 551	NR1	Borehole	14/04/2010	-14.7	-2.63	—
CSIR 552	DC1	Borehole	14/04/2010	-28.9	-4.91	—
CSIR 553	MVR1	Borehole	06/05/2010	-29.8	-5.03	—
CSIR 554	CSIR52	Borehole	11/05/2010	-25.8	-4.43	—
CSIR 555	SC1	Borehole	13/05/2010	-20.3	-3.55	—
CSIR 556	MB1	Borehole	13/05/2010	-17.9	-3.14	—
CSIR 557	ZWSp	Karst spring	13/05/2010	-17.6	-3.11	2.1 ± 0.3
CSIR 558	OB1	Borehole	13/05/2010	-23.8	-4.40	—
CSIR 559	KDSp	Karst spring	13/05/2010	-28.5	-5.00	1.4 ± 0.3
CSIR 560	JNNR1	Karst spring	19/05/2010	-27.7	-4.90	3.1 ± 0.3
CSIR 561	JNNR3	Karst spring	19/05/2010	-30.6	-5.22	0.1 ± 0.2

LIST OF SUPPLEMENTARY REPORTS

A **CGS REPORT ON GEOPHYSICAL SURVEYS, STERKFONTEIN CAVES**

B **CGS REPORT ON SEDIMENT CHEMISTRY SAMPLING AND ANALYSIS**

C **SABS PESTICIDE RESIDUES TEST REPORT**

D **CGS REPORT ON PETROGRAPHIC ANALYSIS OF DOLOMITE EXPOSED TO AMD**

E **CGS REPORT ON EXPERIMENTAL STUDY OF THE EFFECTS OF ACID MINE DRAINAGE ON DOLOMITE**

F **CSIR REPORT ON THE KOELENHOF FARM FISH MORTALITY EVENT OF MID-JANUARY 2011**

SUPPLEMENTARY REPORT A

CGS Report on Geophysical Surveys, Sterkfontein Caves

Cradle of Humankind
World Heritage Site

DEPARTMENT OF ECONOMIC DEVELOPMENT
GAUTENG PROVINCIAL GOVERNMENT, SOUTH AFRICA

PROJECT TITLE

ESTABLISHMENT OF A MONITORING SYSTEM FOR SURFACE WATER AND GROUNDWATER IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

GEOPHYSICAL SURVEYS, STERKFONTEIN CAVES

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Report prepared for

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Department of Economic Development

Gauteng Provincial Government

Report prepared by

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TABLE OF CONTENTS

Page

LIST OF FIGURES

1 INTRODUCTION

The geology of the Cradle of Humankind World Heritage Site (COH WHS) study area (Figure 1) is dominated by the dolomitic strata that form the karst landscape with its associated caves and fossil sites. These strata cover ~28 750 ha (or roughly 44%) of the total extent of the study area. The geophysical surveys described in this report sought to provide complementary information needed to understand the geology and structures that might exercise control over groundwater occurrence and movement in the vicinity of the Sterkfontein Caves fossil site in the COH WHS (Figure 1). A situation assessment of the surface water and groundwater resource environments of the COH WHS (Hobbs, 2011) has subdivided the karst strata into 10 compartments that also serve as groundwater resource units (GRUs). The Sterkfontein Caves are located in the Zwartkrans Compartment.

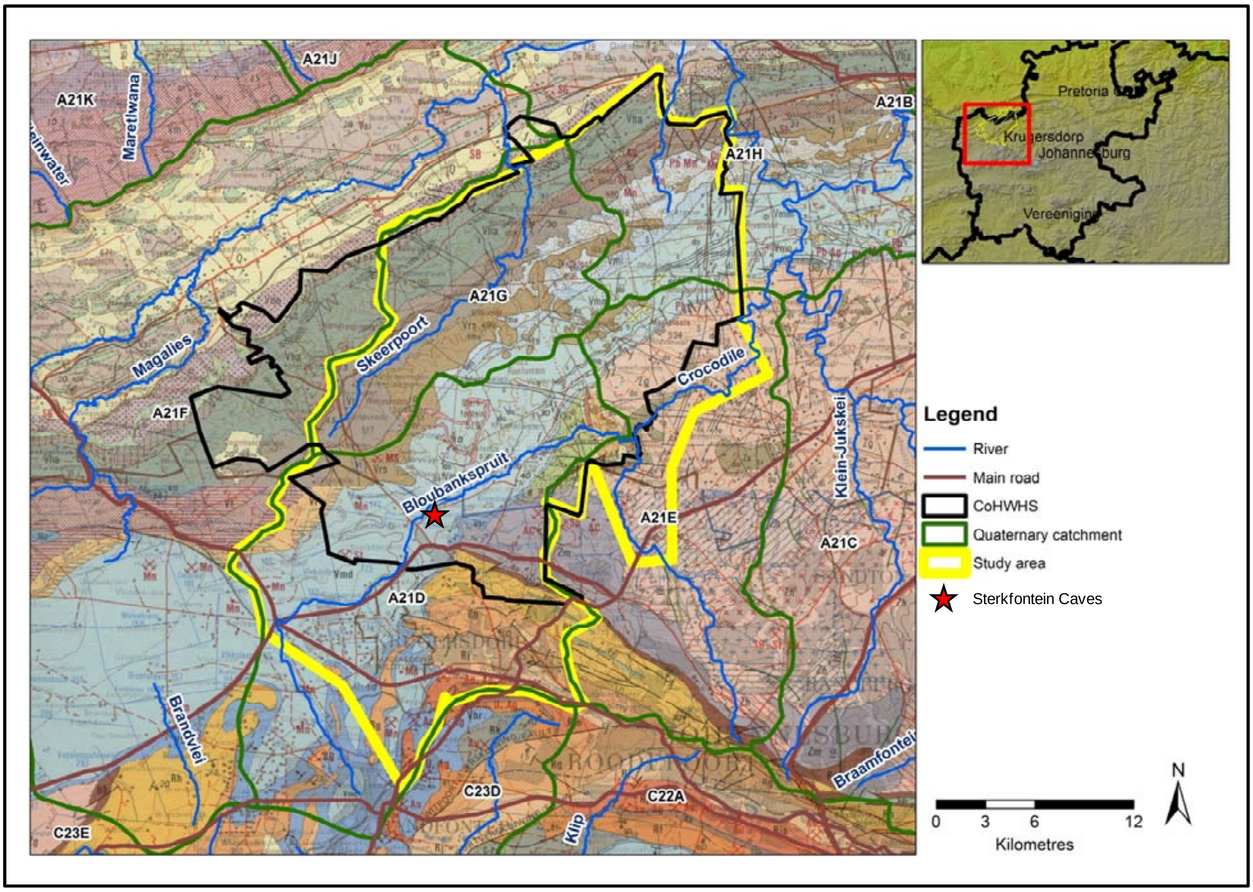

Figure 1. Definition of the study area in regard to the geology, surface water drainages and quaternary catchments in the COH WHS area and environs.

2 METHODOLOGY AND APPROACH

Of the numerous geophysical methods available for mapping the subsurface, those which measure the contrast in the conductivity (or resistivity) of subsurface strata are most suited to investigating the hydrogeologic nature of the subsurface. Such methods include the multi-electrode direct current (DC) resistivity technique also known as electrical resistivity tomography (ERT), and the frequency domain and time domain electromagnetic (FEM and TEM, respectively) techniques. These methods are typically complemented by the magnetic method for structural mapping, not least because of the comparatively rapid and cost-effective nature of magnetic surveys.

2.1 Magnetic Method

Magnetic data were acquired with two Geometrics G856 magnetometers. These instruments measure variations in the magnetic field of the earth which are attributable to changes of structure or the magnetic susceptibility of near-surface strata. The basic assumption of the method is that the measured parameter, the magnetic field strength, includes a component of the total magnetic intensity (TMI) due to geological structures. The earth's geomagnetic field at any fixed location is not constant at any one point in time, but changes due to magnetic storms and diurnal variations. In order to determine the variance associated with spontaneous ionosphere magnetic values, a second magnetometer is positioned within the survey area to serve as a stationary (fixed) base station measuring and recording these values. The base station values, recorded at 1-minute intervals, are used to adjust (correct) the field traverse- or grid-based TMI values in order to reflect the variation associated with far-field signal inputs during the survey.

Data were collected in a N-S orientation, i.e. roughly perpendicular to the principal regional geologic strike direction. After acquisition, the field data were transferred to a computer and corrected for diurnal variations using the Magmap 2000 software by Geometrics. The corrected data were exported to Geosoft format for gridding, and presented as a contour map of the residual total magnetic field.

2.2 Electromagnetic Method

Electromagnetic (EM) data were acquired with a Geonics EM34 instrument. This instrument generates an electromagnetic field in the frequency domain which induces current in the earth and, in turn, causes the subsurface to create a magnetic field. The instrument also measures the magnitude and phase of induced electromagnetic currents, from which information about subsurface features and their properties can be deduced. The EM currents are related to the electrical conductivity of strata in the subsurface, which again are a function of the soil and rock matrix, percentage of saturation and the conductivity of the pore fluids. The results are similarly used to deduce the presence of water-bearing structures at shallow depths (typically <60 m), depending on the receiver-to-transmitter coil separation distance and orientation.

An EM survey can cover a large area quickly and therefore economically. However, despite rapid data collection and high lateral resolution, the method suffers from limited vertical resolution and is susceptible to interference from induced noise from power lines and cultural features such as buried metal pipes, fences, vehicles and electricity utilities. The commonly used coil configuration is the horizontal dipole mode. In this configuration the measurement is relatively insensitive to coil misalignment because the secondary magnetic field is in maximum coupling with the receiver coil (McNeill, 1985). The theoretical depth of investigation depends on the transmitting (Tx) to receiving (Rx) coil separation distance, with a separation of 20 m expected to investigate ~15 m deep in horizontal mode.

Processing of the acquired data entailed transfer to a computer using the DUMP34W software, followed by its conversion to an XYZ format and filtering to remove 'noisy' values before plotting in Oasis Montaj to produce terrain conductivity maps.

2.3 Resistivity Method

The DC multi-electrode resistivity method is used to deduce the subsurface resistivity distribution by carrying out measurements on surface. The resistivity measurements are normally made by introducing current into the ground through two current electrodes, and measuring the resulting voltage difference at two potential electrodes. The ground resistivity is related to various geological parameters such as the mineral and fluid content, porosity and degree of water saturation in the rock. The ERT results can be used to infer the thickness and depth of geological strata on the basis of their differing resistive (or conductive) properties, as well as to define geological structures such as dykes, sills, faults and contact zones. All of these features may have relevance to the occurrence and movement of groundwater.

Data were acquired with a Syscal Pro Switch 72 multi-electrode instrument using the dipole-dipole array at 10 m spacing to ensure fast and maximum depth coverage at high lateral resolution. Input voltages varied between 500 and 800 V to ensure maximum current penetration in the strata of the study area. After the field survey, the resistance measurements were reduced to apparent resistivity values using the Prosys 11 software. A 2-D model for the subsurface consisting of a large number of rectangular blocks was used for interpretation. The computer program RES2DINV (developed by Geotomo Software of Malaysia) was used to generate the model blocks and to determine the resistivity of the blocks so that the calculated apparent resistivity values agree with the measured values from the field survey. The RES2DINV software automatically subdivides the subsurface into a number of blocks, and then uses a least-squares inversion scheme to determine the appropriate resistivity value for each block (Loke, 1996). The program has a set of default parameters which guide the inversion process. In most cases the default parameters give reasonable results. The problem of non-uniqueness is well known in the inversion of resistivity sounding and other geophysical data. For the same measured data set, there is a wide range of models giving rise to the same calculated apparent resistivity values. To restrict the range of possible models, normally some assumptions are made concerning the nature of the subsurface that can be incorporated into the inversion subroutine. The constraints are based on known geological information, proximity to streams and wetlands and occurrence of known mine shafts in areas of known shallow undermining.

The resulting resistivity models were then exported to Surfer (Golden Software) for gridding and adding interpretation annotations. Anomalies of interest were projected to the land surface in Google Earth.

3 RESULTS

3.1 Magnetic Survey

The residual total magnetic field contour map generated for the survey area is presented in Figure 2. The positions of anomalies inferred from the electromagnetic (section 3.2) and electrical resistivity (section 3.3) surveys are superimposed on this map in Figure 3. The composite data reveal the presence of E-W trending magnetic (‘hot’ colours) and non-magnetic (‘cool’ colours) bodies. Cutting across the centre of the survey area is a consistent E-W striking and linear non-magnetic (compared to the background field strength) anomaly that is interpreted as a shear zone. The significance of this inferred structure for groundwater occurrence and flow is indeterminable with the available information.

The location of the caves at the northern end of resistivity traverse R1 (Figure 3) appears to coincide with a non-magnetic anomaly which probably reflects the non-magnetic character of dolomitic strata. However, an E-W trending magnetic anomaly is prominent immediately to the south of the caves. It would appear that east of the caves, this anomaly is displaced toward the north along a N-S fault. The rather narrow and linear geometry of this anomaly suggests that it might be associated with a positively magnetized dyke structure. An extensive magnetic body to the south of the inferred shear zone might represent the presence of a subhorizontal intrusive sill structure. Such features in the area are known from previous mapping efforts (Wilkinson, 1973).

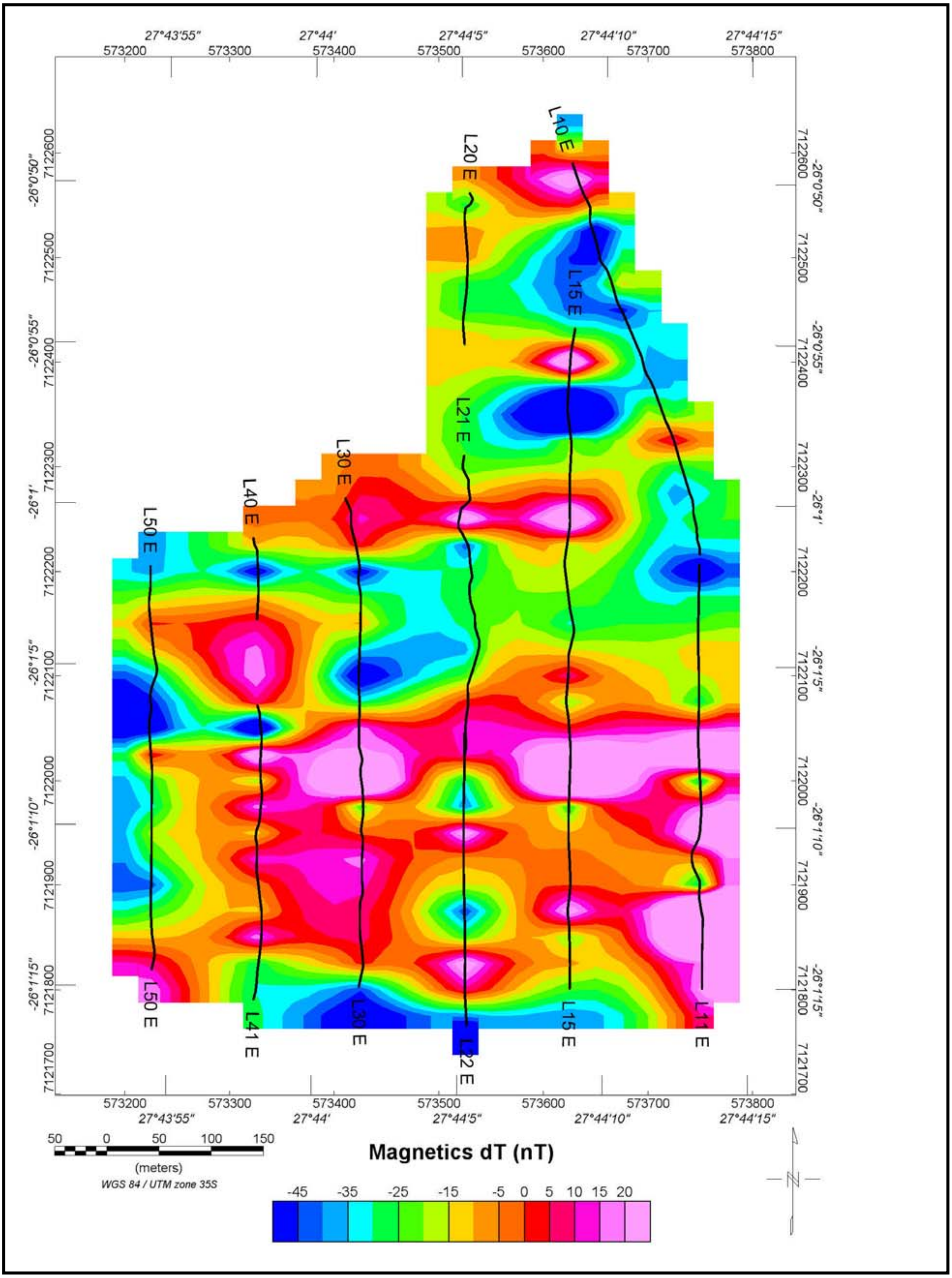

Figure 2. Residual total magnetic field contour map; black N-S oriented lines indicate traverse positions.

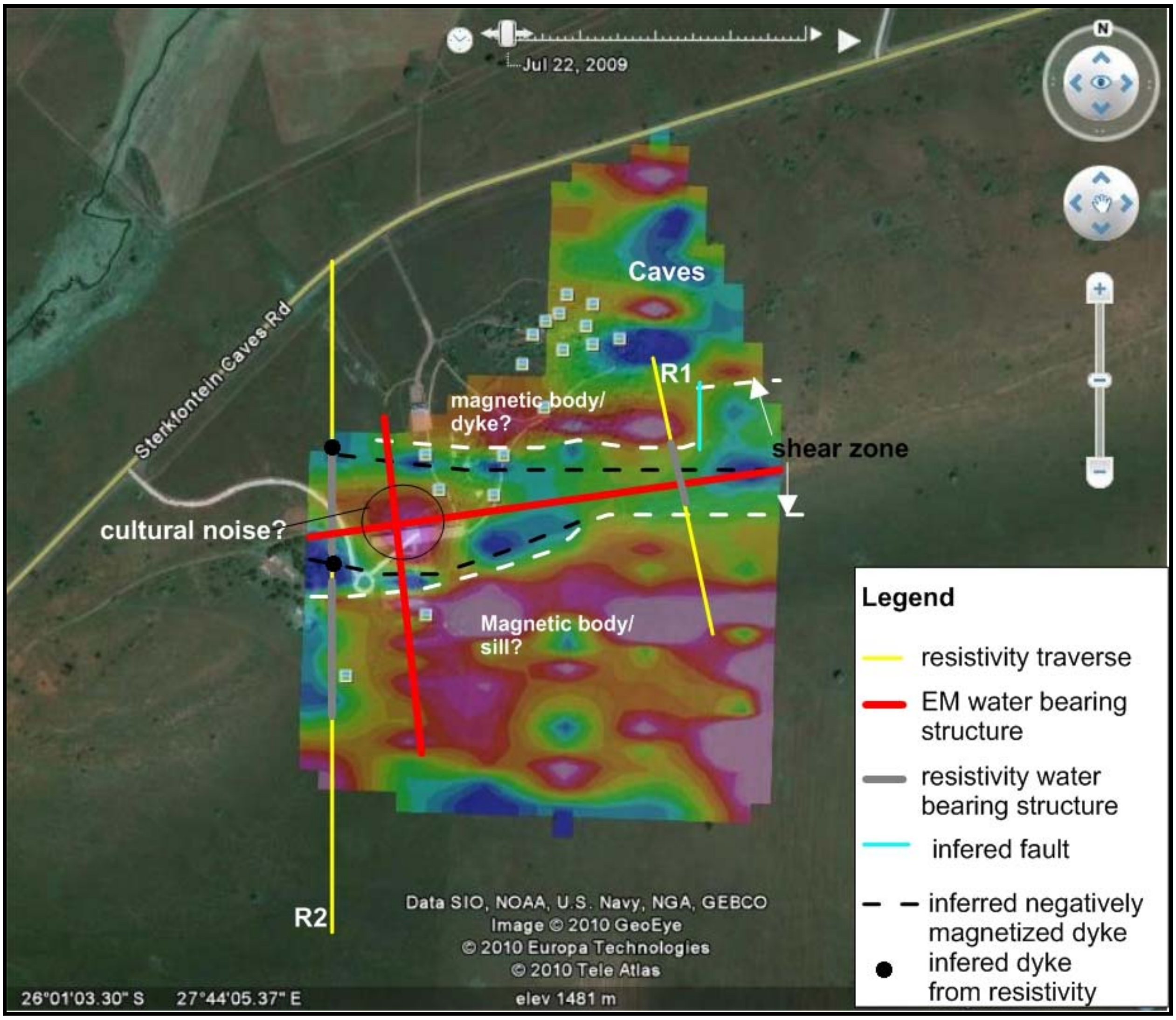

Figure 3. Interpreted residual total magnetic field contour map; yellow lines R1 and R2 with grey interpretation markings, indicate the direct current resistivity traverse locality.

3.2 Electromagnetic Survey

The orientation and position of the electromagnetic survey traverses is shown in Figure 4, which also shows the terrain conductivity contour map generated from the EM survey data. As shown in Figure 5, the contour map reveals the presence of two linear zones of higher conductivity that bisect the survey area in roughly equal quadrants. The more prominent of these is the WSW-ENE striking zone, which intersects a SSE-NNW striking zone at the eastern end of the tourist complex on the property. The anomalies gain (increase) in conductivity westwards and northwards respectively. The congruence of the more prominent WSW-ENE anomaly with the similarly oriented magnetic anomaly (Figure 3) is self-evident.

The southern portion of the SSE-NNW trending EM anomaly approximates the western boundary of the extensive magnetic body that underlies the south-eastern portion of the survey area (Figure 3). The southern margin of the extensive magnetic body similarly coincides with an E-W striking EM anomaly (Figure 5).

On the basis of available information, the significance of the inferred EM anomalies for groundwater occurrence and flow is inscrutable.

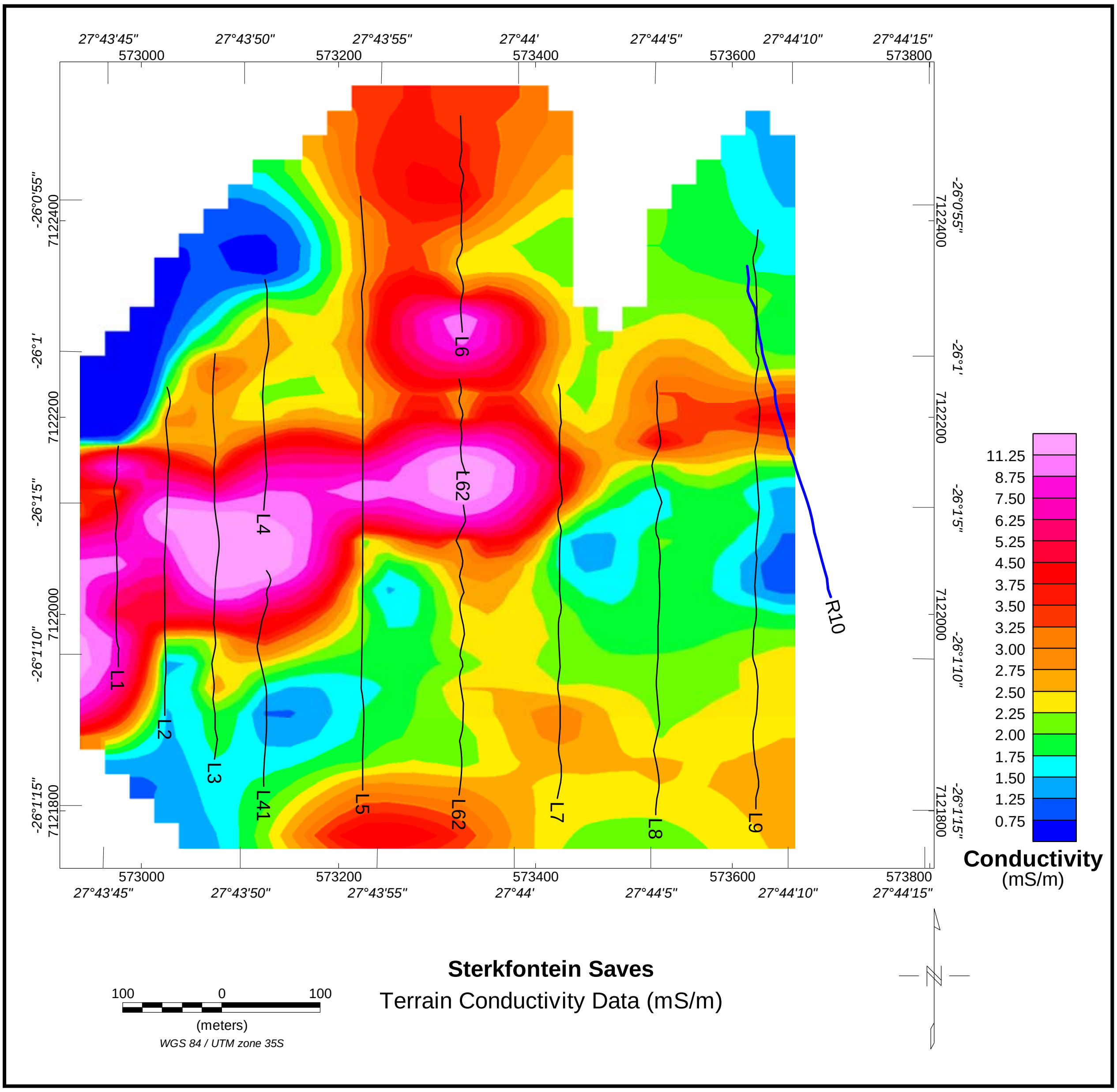

Figure 4. Terrain conductivity contour map; black N-S oriented lines indicate the electromagnetic traverse locality. Blue line R10 is the position of resistivity traverse R1.

3.3 Resistivity Survey

The results of the electrical resistivity survey are portrayed as cross-sections (profiles) for traverses R1 (Figure 6) and R2 (Figure 7) located as shown in Figure 5.

The results of traverse R1 (Figure 6) confirm the strike extension of the interpreted shear zone inferred from the magnetic survey (Figure 3), the EM survey (Figure 5) and resistivity traverse R2 (Figure 7). By extrapolation the highly conductive zone most likely corresponds to compartment 3 in Figure 7. The resistive body to the south is interpreted to represent the sill structure indicated in Figure 3 and Figure 7.

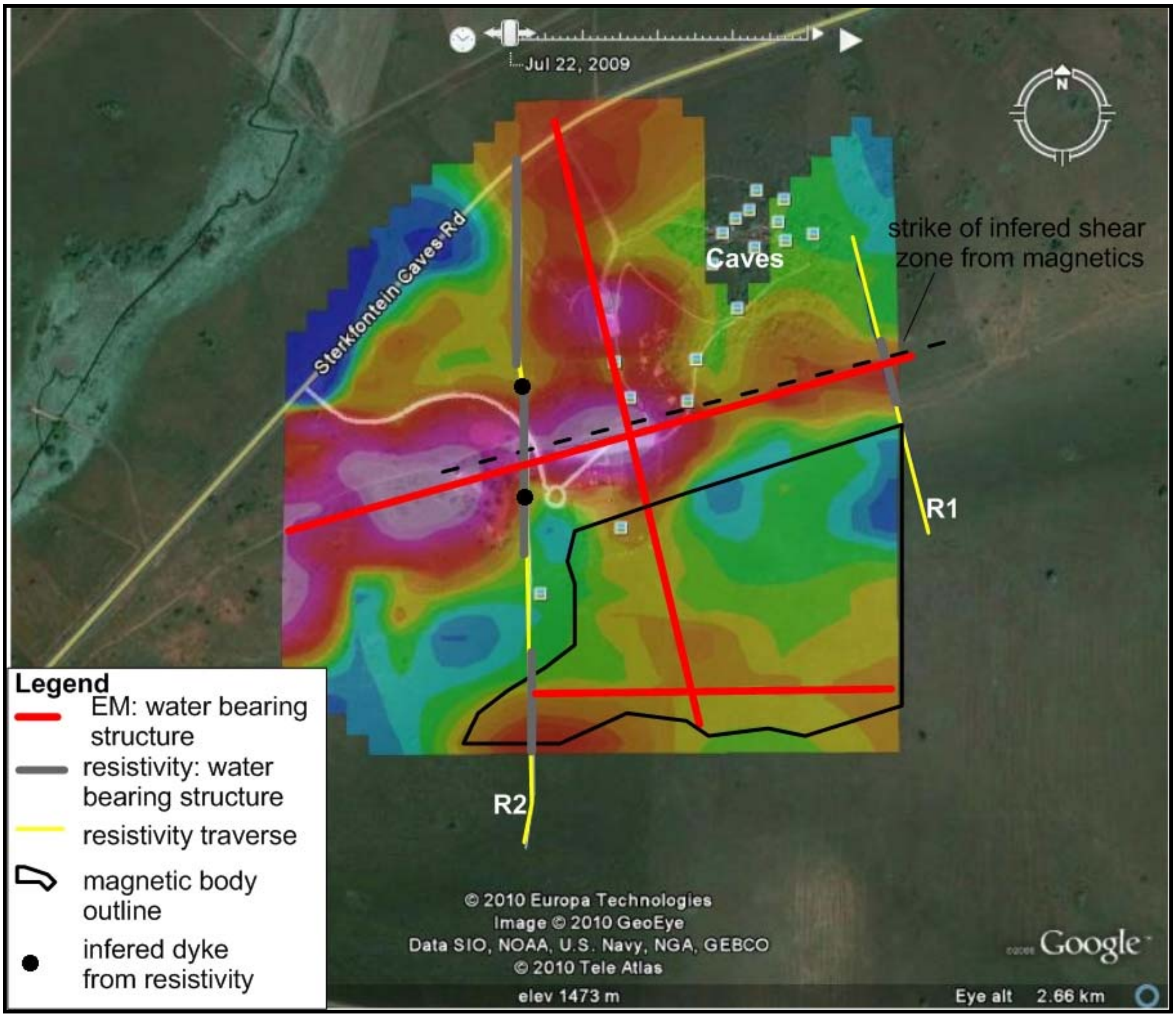

Figure 5. Interpreted terrain conductivity results; yellow lines, R1 and R2 with grey interpretation markings, indicate the direct current resistivity traverse locality.

Resistivity survey R2 (Figure 7) reveals a broad zone of moderate to very low resistivity between stations 280 m and 500 m. This zone is interpreted as coinciding with the shear zone (probably weathered) identified in Figure 3. Figure 7 also shows the subdivision of the cross-section into 4 ‘compartments’ based on zones of contrasting resistivity. The shear zone encompasses two of these ‘compartments’.

The inferred dyke structures located at stations 400 m and 530 m coincide with the linear non-magnetic anomalies interpreted as negatively magnetized dykes (Figure 3). The significant difference in resistivity values associated with the dyke structures suggests a difference in the degree of weathering associated with each. The dyke at station 530 m is considered to be more competent (less weathered), and may therefore constitute a hydraulic barrier. Between the dyke structures, at station 480 m, is a highly conductive ~50 m wide structure located at the centre of ‘compartment’ 3.

A very resistive zone (Figure 7) with a ‘root’ between stations 230 m and 280 m and extending southwards, corresponds to the outline of the extensive magnetic body (Figure 3) that has been interpreted as a sill intruding the dolomite. The ‘root’ of the interpreted sill may similarly act as a hydraulic barrier in the hydrogeologic environment.

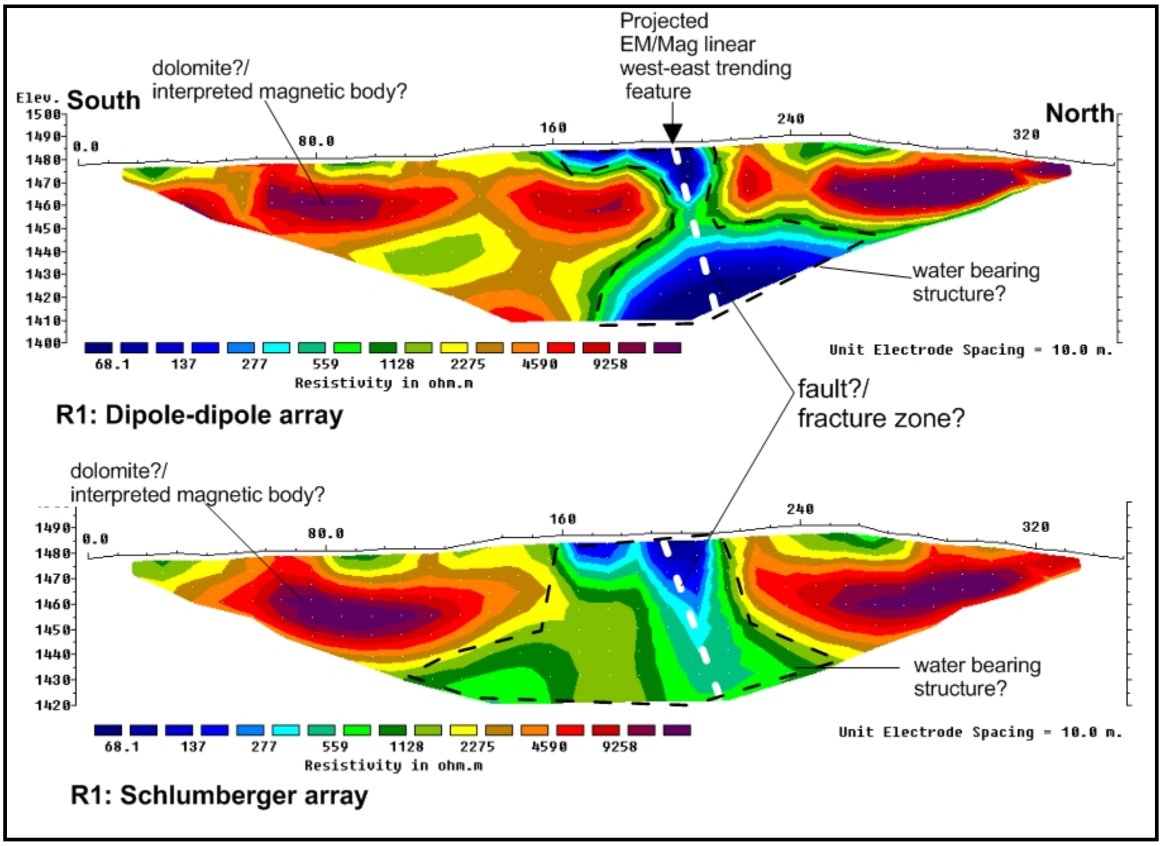

Figure 6. Interpreted resistivity-depth sections for traverse R1; refer to Figure 3 and Figure 5 for traverse locality R1.

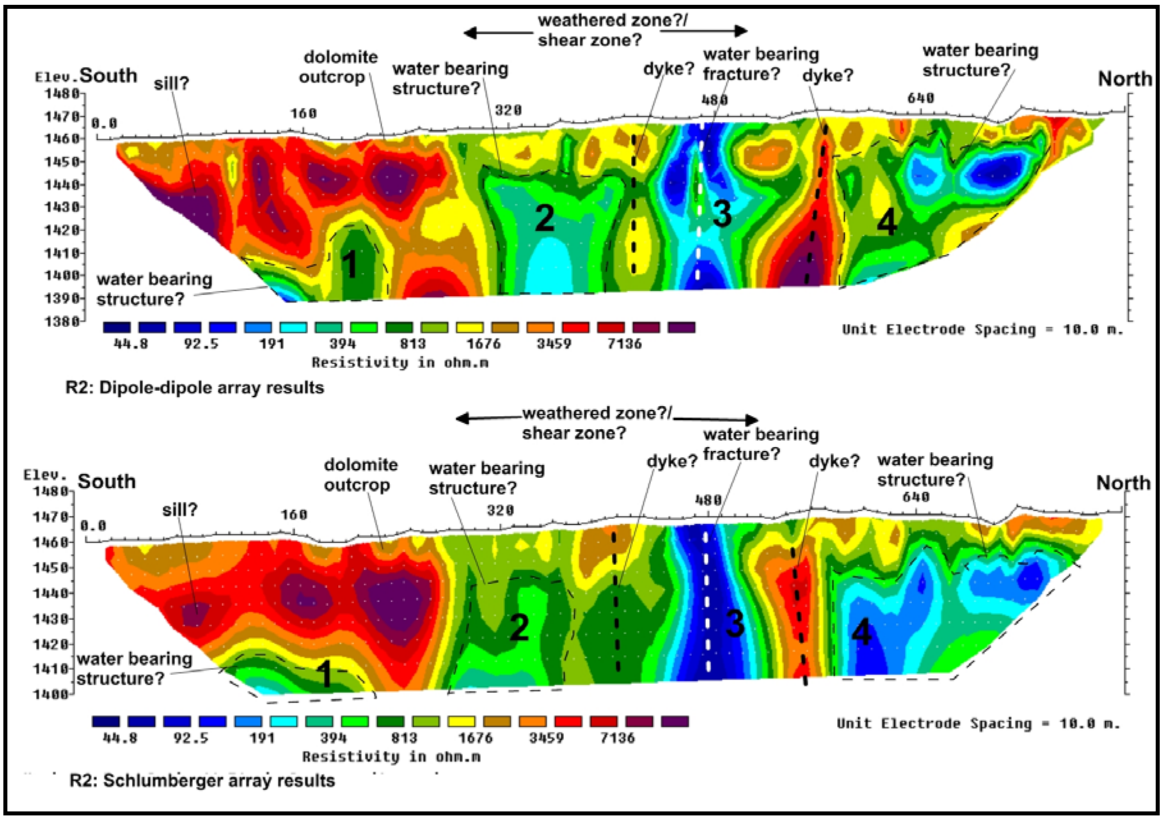

Figure 7. Interpreted resistivity-depth sections for traverse R2; refer to Figure 3 and Figure 5 for R2 traverse locality. Numbers 1 to 4 indicate interpreted 'compartments' discussed in the text.

4 CONCLUSIONS

Geophysical surveys entailing the magnetic, frequency domain electromagnetic and multi-electrode resistivity methods were carried out on the Sterkfontein Caves site in the COH WHS. The outcome precipitates the following main conclusions.

The geophysical surveys provided a quick means of mapping subsurface geological (and possibly hydrogeological) structures with a fair to good correlation in results. These structures, variously interpreted as representing intrusive sills and dykes and a shear zone, were successfully imaged.

The intrusive structures were delineated on the basis of being more magnetic and resistive than the surrounding materials, while the shear zone was delineated as a linear magnetic discontinuity and conductive structure. The resistivity technique mapped the extent and dimensions of the shear zone and the dykes and the probable root of the sill to the south of the study area.

5 RECOMMENDATIONS

It is important to carry out more multi-electrode resistivity traverses in order to fully define the outline and characteristics of the interpreted shear zone and the vertical structures. It is therefore recommended that at least one long resistivity traverse be carried out ~300 m east of and parallel to resistivity traverse R2.

There is a need to integrate the geophysical interpretation with hydrogeological and structural geology mapping results of the study area in order to minimize uncertainty associated with geophysical interpretation.

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SUPPLEMENTARY REPORT B

CGS Report on Sediment Chemistry Sampling and Analysis

Cradle of Humankind ©
World Heritage Site

DEPARTMENT OF ECONOMIC DEVELOPMENT
GAUTENG PROVINCIAL GOVERNMENT, SOUTH AFRICA

PROJECT TITLE

ESTABLISHMENT OF A MONITORING SYSTEM FOR SURFACE WATER AND GROUNDWATER IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

SEDIMENT SAMPLING AND ANALYSIS RESULTS

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Department of Economic Development

Gauteng Provincial Government

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF APPENDIXES

1 INTRODUCTION

As part of the project to develop a monitoring system for the surface water and groundwater resources in the Cradle of Humankind World Heritage Site (COH WHS), the Council for Geoscience (CGS) was tasked to collect and analyse sediment samples. This was done to determine the chemical composition of the sediment, as well as the propensity of elements to be mobilised under selected conditions. Therefore the suite of analyses included X-ray fluorescence (XRF) to determine major and trace elements, as well as leaching tests (Batch Leach, TCLP and Acid Rain). The leach tests simulate certain environmental conditions. X-ray diffraction (XRD) analysis was conducted on a selected sample (JV10/004) to determine the minerals present.

2 SAMPLING LOCATIONS

The sampling locations were selected either as the inflow to impoundments, or in areas of the stream which will be conducive to sediment deposition (as well as access to the stream). Table 1 gives a description of the selected sample sites (Hobbs, 2010).

Table 1. Description of sampling site locations.

Site No.	Sample No.	Coordinates		Site Description
		Latitude	Longitude	
1	JV10/001 JV10/002 JV10/003 JV10/004	26.06452°S	27.69613°E	Hippo Dam inlet on the Tweelopie Spruit in the Krugersdorp Game Reserve. First impoundment downstream of the mine area receiving AMD.
2	JV10/005 JV10/006	26.10235°S	27.72122°E	Lion Camp entrance dam inlet on the Tweelopie Spruit in the Krugersdorp Game Reserve. Third impoundment downstream of the mine area receiving a mixture of AMD and better quality karst groundwater.
3	JV10/007	26.10345°S	27.72145°E	Krugersdorp Brickworks Dam inlet on the Tweelopie Spruit. Fifth impoundment downstream of the mine area receiving an improved (better quality) mixture of AMD and karst groundwater.
4	JV10/008 JV10/009	26.08570°S	27.70988°E	Piet Schutte Dam inlet on the Riet Spruit. Seventh impoundment downstream of the mine area receiving a mixture of AMD and karst groundwater.
5	JV10/010 JV10/011	26.04800°S	27.71213°E	Lower end of the Blougat Spruit receiving treated municipal wastewater effluent from the Percy Stewart WWTW.
6	JV10/012 JV10/013	26.02203°S	27.72005°E	Bridge where the R563 crosses the Bloubank Spruit. Receives primarily the discharge from site #5.
7	JV10/014 JV10/015	26.04003°S	27.72110°E	Causeway over the Bloubank Spruit downstream of Makiti. Receives primarily the discharge from site #6.
8	JV10/016 JV10/016	25.97883°S	27.74323°E	Danielsrust Spring. Off-channel natural spring to serve as "pristine" background sample.

The sampling locations are shown in Figure 1. Sampling was conducted in various streams in the area, namely the Tweelopie Spruit, the Riet Spruit, the Blougat Spruit and the Bloubank Spruit. Pictorials of the sampling sites are presented at the end of the text (Plates 1 to Plate 10).

3 MATERIALS & METHODS

Where high percentages of organic material was expected to be present, such as the wetland upstream of Hippo Dam, the sampling method as described in McCarthy and Venter (2000) was followed (sample JV10/001). Sediment samples collected in areas with low expected percentages of organic material was collected using a spade or hand auger. All samples were collected in the top 0.3 to 0.5 m of the profile, mostly below a water column of up to 1 m. Descriptions of the samples collected and submitted for analyses are given in Table 2.

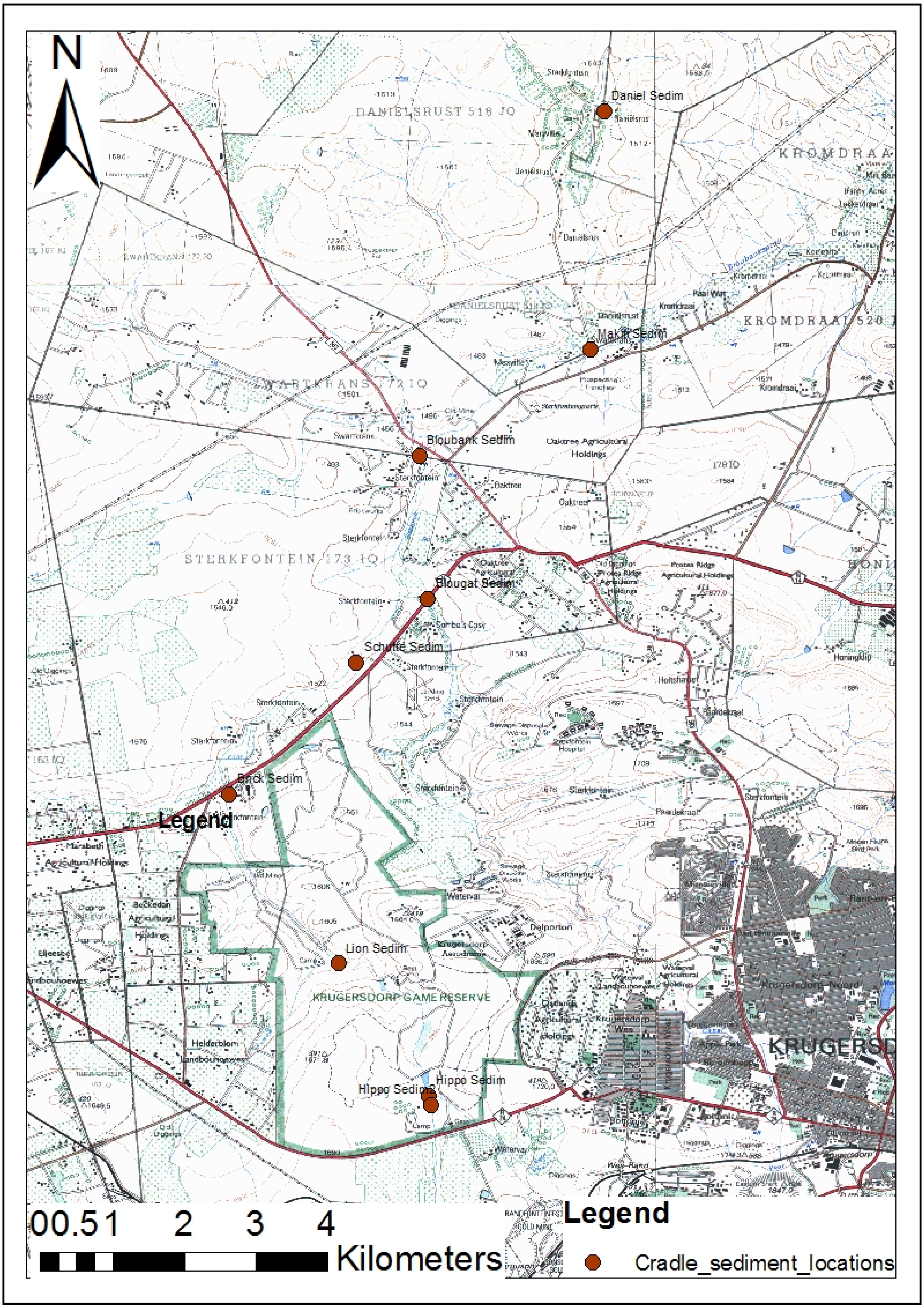

Figure 1. Sediment sampling locations.

Table 2. Description of samples collected and analyses carried out.

Sample	Description of the site and sample	Analysis requested
1. Hippo (JV10/001)	Wetland sediment at the inflow to the Hippo Dam sampled ~20 m from the edge of the wetland. Water column of ~0.5 m.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
2. Hippo 2 River (JV10/002)	Tweelopie Spruit before entering wetland upstream of Hippo Dam. Stream sediment below water level.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
3. Hippo 2 Stream bank (JV10/003)	Sediment collected on stream bank.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
4. Hippo 2 Jaro (JV10/004)	Gypsum crystals collected where water has receded (dry floodplain).	XRD, ICPMS metals
5. Lion Camp 1 (JV10/005)	Stream sediment of top 0.5 m of profile; below water level.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
6. Lion Camp 2 (JV10/006)	Same as JV10/005 ~20 m from first location.	Combine with Lion Camp 1
7. Brick (JV10/007)	Orange colouring of sediments still visible. Sample collected from top 0.5 m of profile, ~0.5 m below water surface.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
8. Schutte 1 (JV10/008)	Sediment collected by hand from the northern embankment of the dam.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
9. Schutte 2 (JV10/009)	Sediment collected by hand from the inflow of the dam.	Combine with Schutte 1
10. Blougat (JV10/010)	Stream sediment collected from below water level with a spade. Collected from embankment where deposition took place.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
11. Blougat 2 (JV10/011)	Stream sediment collected below road bridge.	Combine with Blougat
12. Bloubank (JV10/012)	Sample collected below fast flowing water with hand auger at a depth of ~0.2 m.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
13. Boubank 2 (JV10/013)	Same as above, ~5 m from first location.	Combine with Bloubank
14. Makiti 1 (JV10/014)	Sandy stream sediment collected downstream of small road bridge.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
15. Makiti 2 (JV10/015)	Sandy stream sediment collected downstream of small road bridge.	Combine with Makiti 1
16. Daniel 1 (JV10/016)	Grey sandy sediment collected from man made pond at Danielsrust as a background sample.	Batch leach, Alkalinity, TCLP, Acid rain, XRF majors and traces
17. Daniel 2 (JV10/017)	Grey sandy sediment collected from man made pond at Danielrust as a background sample.	Combine with Daniel 1

XRF analyses were conducted to determine the total chemical composition of the samples. This was conducted on all the samples submitted. As shown in Table 2, certain duplicate samples were combined to obtain a more representative sample, and to reduce analysis costs at this screening level stage of the investigation.

XRD analysis was performed on a sample (JV10/004) of what appeared to be gypsum collected at the Hippo Dam sampling site 1. This confirmed that the sample is gypsum (99.40%). Three different leach tests were conducted on the samples (except JV10/004) to determine the mobile fraction under different environmental conditions. The batch leach test uses 10 g of sample, and is shaken in 200 ml of water for a standard length of time. Slightly more aggressive leach tests, namely toxicity characteristics leaching procedure (TCLP) and acid rain (AR) were then performed on the same samples (not in a sequential manner).

4 RESULTS & DISCUSSION

The results of the analyses performed are presented in the Appendixes. In order to assess whether downstream contamination is present, the US EPA Tier 1 risk assessment was applied to the dataset. This method was described by Wade et al. (2002).

4.1 Tier 1 Risk Assessment

In this method, the measured concentrations are compared to a regulatory standard. Since South Africa does not yet have legislated limits for most contaminants in soil (Coetzee et al., 2006), values from the European Union (EU) and the National Nuclear Regulator (NNR) were used. Figure 2 and Figure 3 show Tier 1 risks for uranium (U) and nickel (Ni) respectively. A risk quotient of greater than 1 indicates areas where the measured concentration is larger than the regulatory standard, and will require follow-up studies and possible remedial action (Coetzee et al., 2006). The ranking used in Figure 2 and Figure 3 was chosen such that risk quotients below 0.5 (shown in green) pose no risk at all. Values between 0.5 and 2.0 (shown as yellow) allow for any sampling and/or laboratory errors. Risk quotients in this range might pose a risk and may warrant follow-up studies. Risk quotients that are above 2 (shown in red) definitely pose a risk. However, it should be noted that these risk quotients were calculated on the total composition as measured by XRF, and it does not mean that the total concentration will be mobile.

4.2 Extractable Fraction

Leach tests were conducted to determine the extractable (mobile) fraction of the total concentration of elements measured by XRF. The results for uranium and nickel are shown in Figure 4 to Figure 6 for each of the three types of leach test. These two elements were chosen as indicators of gold mining activity. None of the leach tests extracted a U concentration higher than the regulatory limit of 16 mg/kg as proposed by the NNR (Coetzee et al., 2006).

Although the highest total concentration of Ni was measured at the Hippo Dam on the stream bank (sample JV10/003), the highest extractable concentration was obtained for the Brickworks Dam site (sample JV10/007). Further investigations into site-specific conditions may reveal the reason for this. This is also the only site where the extractable fraction is higher than the regulatory limit of 35 mg/kg as proposed by the EU (ANTEA, 2000 in Coetzee et al., 2006).

5 CONCLUSION

The finding that the measure of extractable U and Ni concentrations is an order of magnitude lower (smaller) than the total observed concentrations provides a measure of mitigation of the risk associated with the mobilization/remobilization of sediment-bound trace/heavy metals. However, the cumulative mass/volume of sediment contained in the various impoundments and river/stream courses cautions against minimization or downplaying of the associated risk.

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ACKNOWLEDGEMENTS

The landowners Messrs. P. Schutte (Ptn. 8/2 of Sterkfontein 173IQ) and P. van der Merwe (Danielsrust Game Farm) are thanked for permission to access the sampling sites 4 (sample nos. JV10/008-009) and 8 (sample nos. JV10/016-017), respectively.

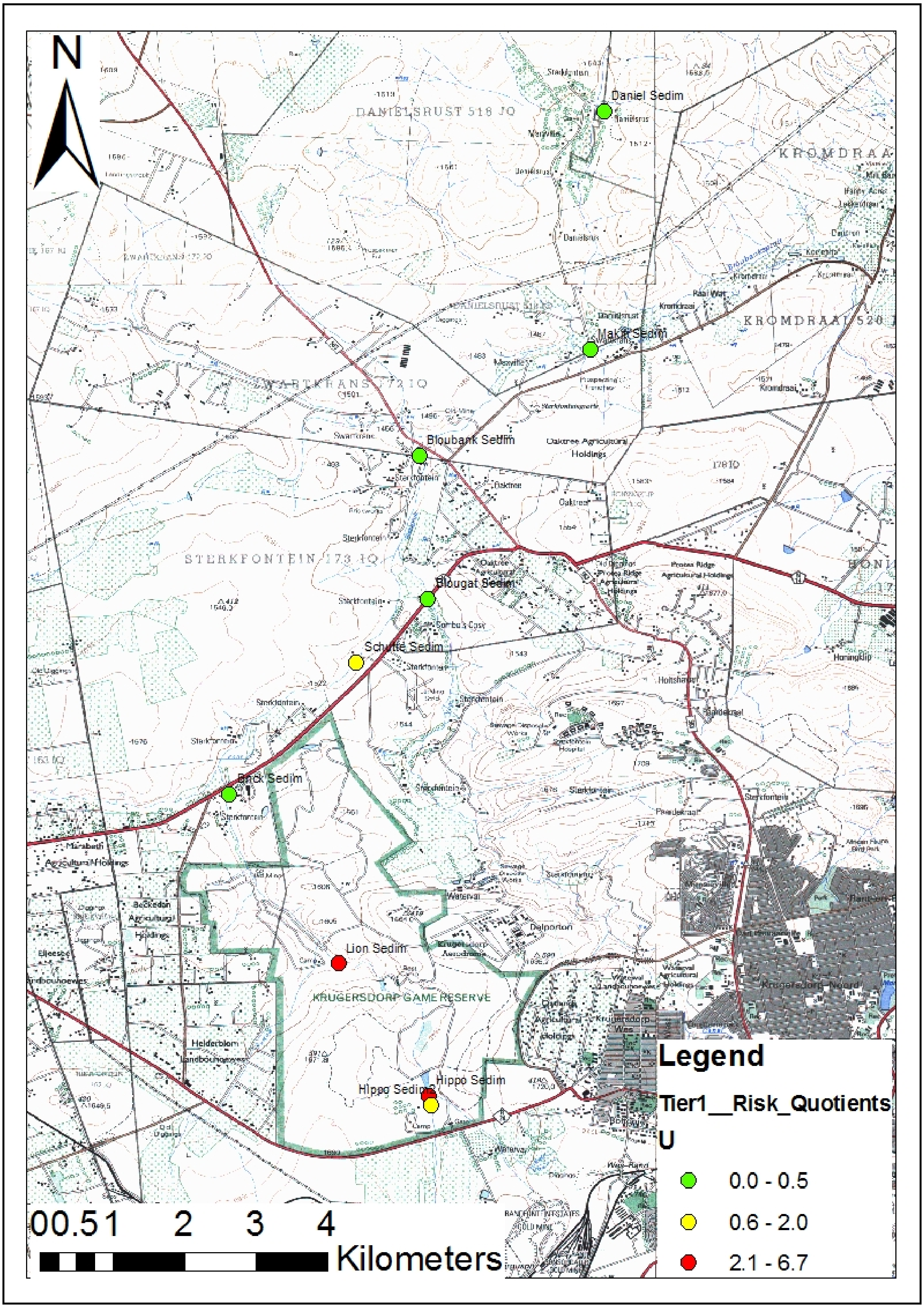

Figure 2. Tier 1 risk quotient for uranium.

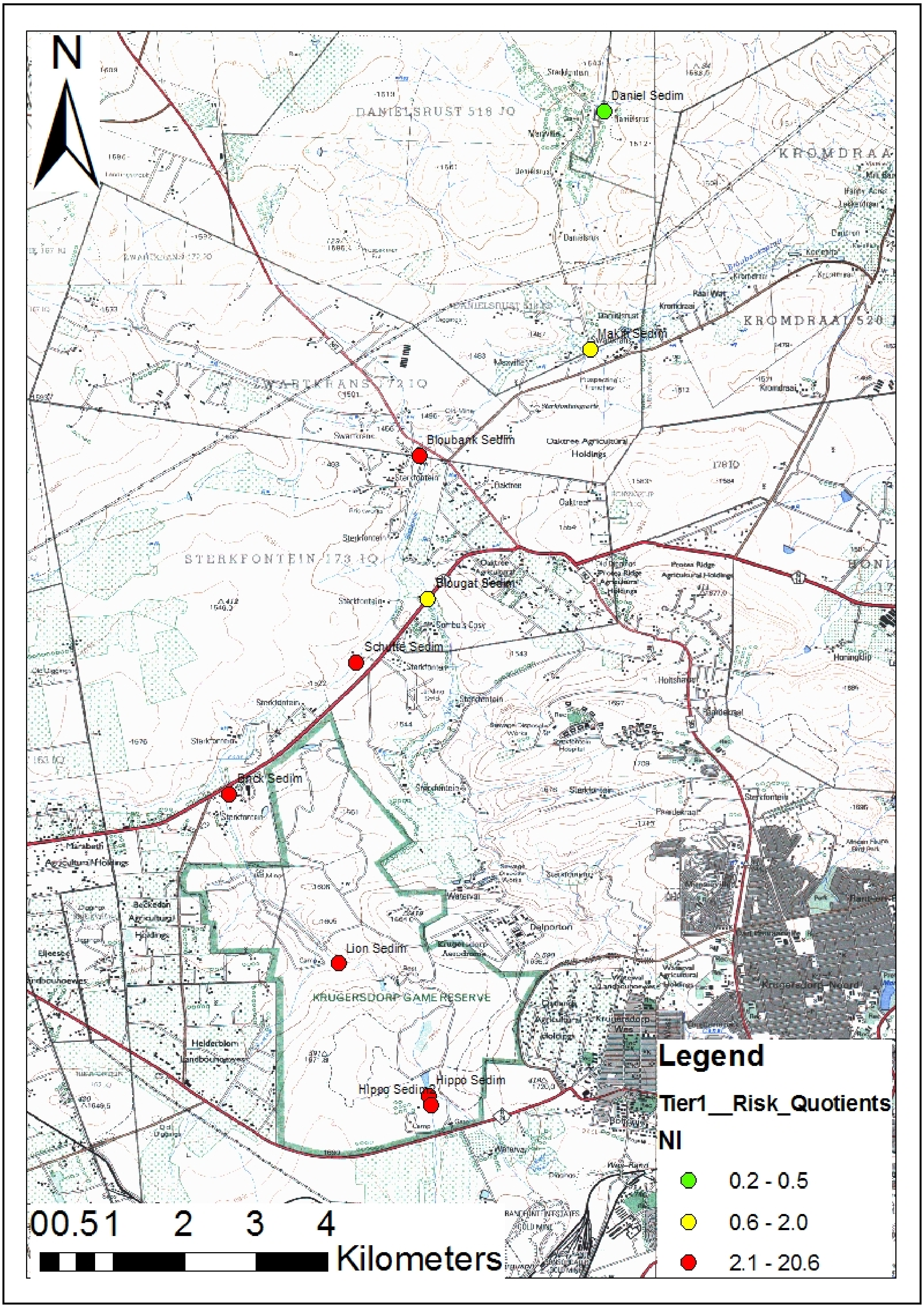

Figure 3. Tier 1 risk quotient for nickel.

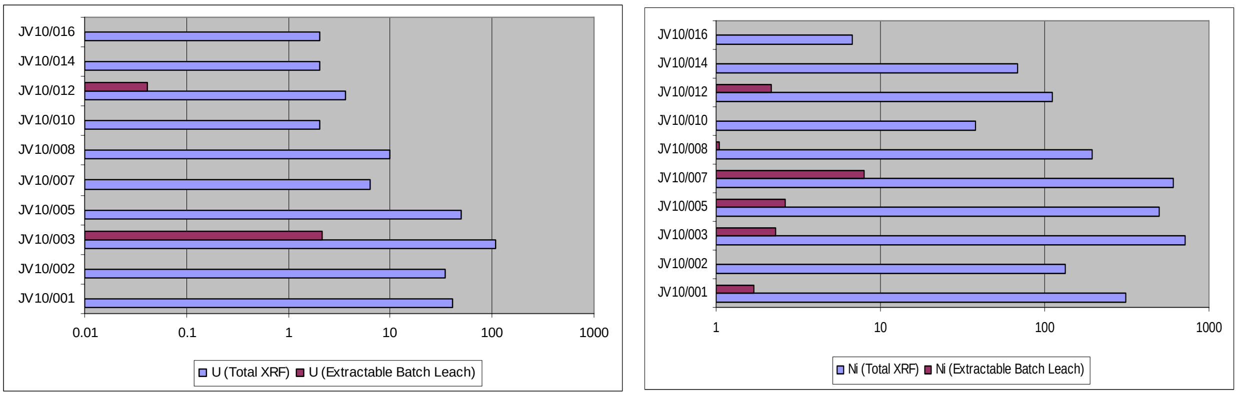

Figure 4. Batch leach extractable fraction versus XRF total concentration for U (left) and Ni (right).

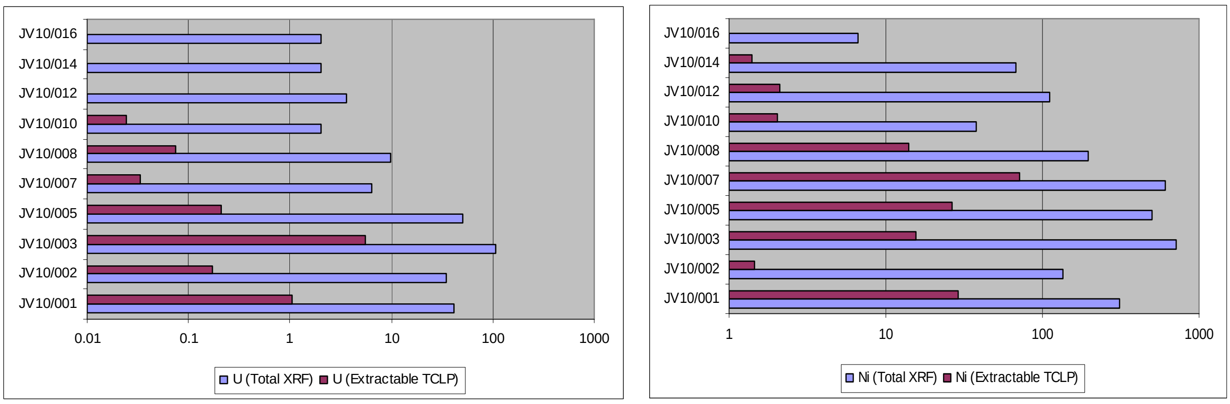

Figure 5. TCLP extractable fraction versus XRF total concentration for U (left) and Ni (right).

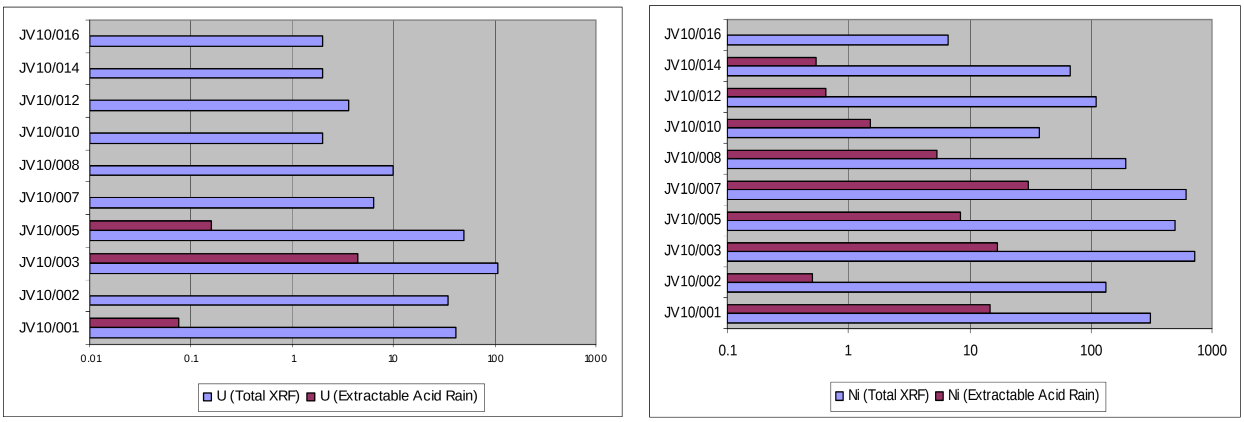

Figure 6. Acid rain extractable fraction versus XRF total concentration for U (left) and Ni (right). Note the logarithmic horizontal axis scale.


Plate 1. JV10/001 (Hippo).


Plate 2. JV10/002 (Hippo 2 river).


Plate 3. JV10/004 (Hippo 2 Jaro).


Plate 4. JV10/005 (Lion Camp 1).

Plate 5. JV10/007 (Brick).

Plate 6. JV10/008 (Schutte 1).

Plate 7. JV10/010 (Blougat).

Plate 8. JV10/012 (Bloubank).

Plate 9. JV10/014 (Makiti 1).

Plate 10. JV10/016 (Daniel 1).

APPENDIX A : XRF MAJOR ELEMENT RESULTS (weight%)

Major Element	Sample No.										
	JV10/001	**JV10/002**	**JV10/003***	**JV10/004***	**JV10/005**	**JV10/007**	**JV10/008**	**JV10/010**	**JV10/012**	**JV10/014**	**JV10/016**
SiO_2	73.29	74.66	28.5	2.8	54.88	92.43	75.76	92.30	72.98	87.02	92.43
TiO_2	0.51	0.72	0.43	0.04	0.75	0.07	0.48	0.13	0.52	0.12	0.07
Al_2O_3	9.12	12.46	7.2	0.96	10.62	1.11	7.77	2.46	9.49	3.23	1.11
Fe_2O_3(t)	7.23	1.38	7.7	2.8	8.70	0.61	5.28	2.68	8.99	4.97	0.61
MnO	0.589	0.028	0.01	0.08	1.014	0.02	0.562	0.136	1.129	1.097	0.02
MgO	0.25	0.24	0.46	0.28	0.46	0.10	0.25	0.12	0.22	0.32	0.10
CaO	0.23	0.60	13.4	27.5	1.44	0.09	0.46	0.03	0.10	0.20	0.09
Na_2O	0.05	0.04	0.16	0.22	0.13	<0.01	0.07	0.00	0.00	0.09	-0.03
K_2O	0.52	0.43	0.27	0.05	0.76	0.19	0.55	0.23	0.64	0.33	0.19
P_2O_5	0.088	0.035	0.10	-	0.269	0.05	0.107	0.112	0.217	0.094	0.05
Cr_2O_3	0.054	0.039	-	-	0.041	0.01	0.033	0.020	0.041	0.019	0.01
SO_3	-	-	14.5	38.4	-	-	-	-	-	-	-
L.O.I.	7.18	9.49	22.2	23.7	20.50	4.91	8.96	1.61	5.66	2.18	4.91
Total	99.09	100.12	-	-	99.56	99.56	100.27	99.83	100.00	99.70	99.56
H_2O^-	1.57	2.21	3.9	1.0	3.81	0.71	3.04	0.35	1.28	0.52	0.71

* Samples were measured using IQ+ scans due to the high abundance of sulphur in the sample.

APPENDIX B : XRF TRACE ELEMENT RESULTS (mg/kg)

Trace Element	Sample No.										
	JV10/001	**JV10/002**	**JV10/003***	**JV10/004***	**JV10/005**	**JV10/007**	**JV10/008**	**JV10/010**	**JV10/012**	**JV10/014**	**JV10/016**
As	83	9.3	65	9.3	83	18	14	6.4	15	7.8	<4
Ba	531	120	122	13	173	549	307	101	751	446	21
Bi	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Br	<2	3.4	8.4	<2	11	4.3	3.7	<2	4.8	<2	<2
Ce	100	126	130	29	83	100	48	<10	48	31	<10
Co	119	17	202	227	154	149	72	11	28	25	1.7
Cr	603	425	290	37	401	367	339	223	413	214	95
Cs	6.3	<5	8.2	5.9	<5	<5	5.5	<5	<5	<5	<5
Cu	105	60	135	34	174	49	57	15	46	35	4.2
Ga	13	16	11	1.8	14	13	11	3.7	12	4.9	2
Ge	<1	1.6	<1	<1	1	1.5	1	<1	1.5	<1	1.3
Hf	5.4	5.4	4	<3	4.1	6.2	4.2	<3	5.6	<3	<3
La	37	57	62	16	66	64	37	<10	33	18	<10
Mo	2	<2	<2	<2	<2	<2	<2	<2	2.3	<2	<2
Nb	10	13	8.9	2.7	10	9.4	9	3.6	9.6	4	2.5
Nd	30	61	73	20	61	46	29	10	27	10	<10
Ni	313	134	720	623	497	607	196	38	111	68	6.7
Pb	52	25	31	3.9	32	29	37	9.4	13	17	2.9
Rb	28	35	23	4.4	43	37	42	9.4	47	17	7.5
Sc	16	19	17	11	17	16	14	5.1	16	7.4	<3
Se	1.2	1.2	2	<1	1.8	<1	<1	<1	<1	<1	<1
Sm	<10	12	15	<10	<10	<10	<10	<10	<10	<10	<10
Sr	30	11	39	49	27	38	16	14	17	19	2.1
Ta	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Th	10	8.6	8.7	<3	8.4	7	6.3	<3	7.2	3.7	<3
Tl	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
U	41	35	107	13	50	6.3	9.9	<2	3.6	<2	<2
V	126	137	100	15	116	99	84	30	97	51	9.6
W	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Y	18	31	36	7.4	41	26	18	4.8	18	7.6	1.9
Yb	<3	3.8	5	<3	4.3	<3	<3	<3	<3	<3	<3
Zn	216	72	460	263	943	430	261	53	56	81	12
Zr	227	213	143	16	197	154	164	61	177	50	21

APPENDIX C : BATCH LEACH TEST PHYSICAL AND LEACHATE ANION CONCENTRATIONS

Major Element	Sample No.									
	JV10/001	JV10/002	JV10/003	JV10/005	JV10/007	JV10/008	JV10/010	JV10/012	JV10/014	JV10/016
pH	6.59	6.1	6.36	6.21	6.48	6.76	7.15	7.22	7.18	6.84
EC (µS/cm)	1196	860	2490	2190	948	1719	159.2	216	501	258
EC (mS/m)	120	86	249	219	95	172	16	22	50	26
Alkalinity (mg/L $CaCO_3$)	96	113	131	90	123	98	96	88	95	91
Cl (mg/L)	4	2	12	3	3	3	2	2	2	2
SO_4 (mg/L)	105	147	1611	144	101	61	5	5	3	2
F (mg/L)	0	0	0	0	0	0	0	1	0	0
NO_2 (mg/L N)	0	0	0	0	0	0	0	0	0	0
NO_3 (mg/L N)	0	0	0	0	0	0	0	0	0	0
PO_4 (mg/L P)	0	0	0	14	4	0	1	4	1	1
Br (mg/L)	0	0	0	0	0	0	0	0	0	0

APPENDIX D : BATCH LEACH TEST LEACHATE CATION CONCENTRATIONS (µg/L)

Sample No.	Element and Concentration (µg/L)																			
	Li	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Fe**	**Mn**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Se**	**Sr**	**Cd**	**Ba**	**Pb**	**U**
JV10/001	<2	1827	7183	151	1010	33562	1	<5	<100	3114	42	85	28	<300	<20	6	53	<1	69	<30	<2
JV10/002	<2	3264	4136	127	1318	50993	7	<5	<100	541	2	<50	40	<300	<20	3	40	<1	38	<30	<2
JV10/003	5	8958	14524	130	2705	556413	<1	<5	<100	1345	37	114	34	<300	<20	5	174	<1	35	<30	106
JV10/005	<2	6186	5090	249	2009	56462	1	<5	<100	3825	69	132	36	<300	<20	4	57	1	65	<30	<2
JV10/007	24	3800	4604	299	1780	31394	<1	<5	<100	7118	121	401	20	<300	<20	<2	45	1	85	<30	<2
JV10/008	11	3474	3474	839	2458	27417	<1	<5	218	3505	24	53	29	<300	<20	4	35	<1	118	<30	<2
JV10/010	5	2425	1188	1824	1626	4519	6	11	3157	832	4	<50	30	<300	<20	2	18	<1	37	<30	<2
JV10/012	30	2698	1009	51431	5198	2736	65	120	39365	3665	23	108	67	<300	<20	<2	17	<1	338	<30	2
JV10/014	<2	2057	1796	1059	920	5625	2	<5	545	149	<1	<50	< 20	<300	<20	4	6	<1	27	<30	<2
JV10/016	<2	1315	2142	275	4574	4095	9	8	<100	100	<1	<50	26	<300	<20	<2	4	<1	<20	<30	<2

APPENDIX E : BATCH LEACH TEST LEACHATE CATION CONCENTRATIONS (mg/kg)

Sample No.	Element and Concentration (mg/kg)													
	Na	**Mg**	**Al**	**K**	**Ca**	**Fe**	**Mn**	**Co**	**Ni**	**Cu**	**Rb**	**Sr**	**Ba**	**U**
JV10/001	36.53	143.66	3.02	20.21	671.25		62.28	0.83	1.70	0.55	0.19	1.07	1.39	
JV10/002	65.29	82.72	2.53	26.36	1019.87		10.83	0.04		0.80	0.16	0.81	0.76	
JV10/003	179.15	290.49	2.59	54.09	11128.26		26.90	0.74	2.29	0.69	0.45	3.47	0.70	2.12
JV10/005	123.72	101.81	4.97	40.18	1129.23		76.51	1.38	2.63	0.71	0.31	1.14	1.30	
JV10/007	76.00	92.07	5.99	35.59	627.87		142.36	2.41	8.02	0.41	0.27	0.91	1.70	
JV10/008	69.47	69.47	16.78	49.15	548.34	4.37	70.11	0.49	1.05	0.59	0.38	0.70	2.36	
JV10/010	48.49	23.76	36.48	32.51	90.37	63.14	16.65	0.08		0.60	0.13	0.37	0.75	
JV10/012	53.96	20.18	1028.63	103.95	54.73	787.30	73.30	0.47	2.16	1.34	0.92	0.35	6.76	0.04
JV10/014	41.14	35.92	21.19	18.40	112.50	10.90	2.97				0.12	0.12	0.55	
JV10/016	26.30	42.83	5.51	91.47	81.91		2.00			0.52	0.22	0.08		

APPENDIX F : TCLP EXTRACTION CATION CONCENTRATIONS (µg/L)

Sample No.	Element and Concentration (µg/L)																	
	Li	Mg	Al	K	Ca	V	Cr	Fe	Mn	Co	Ni	Cu	Zn	As	Sr	Cd	Ba	Pb	U
JV10/001	4	11840	362	2421	79523	<1	18	<100	56557	1593	2889	86	2209	<20	165	4	444	<30	104
JV10/002	8	7674	373	2617	128264	6	21	383	2878	37	144	35	369	<20	94	<1	103	<30	17
JV10/003	14	28015	99	6307	1147269	<1	20	<100	11932	587	1561	46	409	<20	282	1	46	<30	557
JV10/005	9	14296	253	5818	231943	<1	18	458	123141	1796	2650	59	8750	<20	222	9	257	<30	21
JV10/007	65	9246	305	5252	99683	<1	17	<100	80319	2388	7124	49	5156	<20	135	4	394	<30	3
JV10/008	42	9282	317	7206	119051	<1	16	<100	72712	984	1397	66	2630	<20	129	6	503	<30	7
JV10/010	14	2427	498	2566	19570	<1	26	<100	19928	102	203	55	797	<20	112	1	505	<30	2
JV10/012	6	4221	266	7681	37071	<1	20	<100	116219	140	209	59	<300	<20	156	<1	3642	<30	<2
JV10/014	12	8346	366	2926	39177	<1	21	<100	19899	7	140	47	516	<20	83	2	456	<30	<2
JV10/016	3	8367	281	7618	36531	3	34	3734	2136	14	<50	50	<300	<20	18	3	38	<30	<2

APPENDIX G : TCLP EXTRACTION CATION CONCENTRATIONS (mg/kg)

Sample No.	Element and Concentration (mg/kg)																	
	Li	Mg	Al	K	Ca	V	Cr	Fe	Mn	Co	Ni	Cu	Zn	Se	Sr	Cd	Ba	U
JV10/001	0.04	118.40	3.62	24.21	795.23		0.18		565.57	15.93	28.89	0.86	22.09		1.65	0.04	4.44	1.04
JV10/002	0.08	76.74	3.73	26.17	1282.64	0.06	0.21	3.83	28.78	0.37	1.44	0.35	3.69		0.94		1.03	0.17
JV10/003	0.14	280.15	0.99	63.07	11472.69		0.20		119.32	5.87	15.61	0.46	4.09	0.07	2.82	0.01	0.46	5.57
JV10/005	0.09	142.96	2.53	58.18	2319.43		0.18	4.58	1231.41	17.96	26.50	0.59	87.50	0.06	2.22	0.09	2.57	0.21
JV10/007	0.65	92.46	3.05	52.52	996.83		0.17		803.19	23.88	71.24	0.49	51.56	0.05	1.35	0.04	3.94	0.03
JV10/008	0.42	92.82	3.17	72.06	1190.51		0.16		727.12	9.84	13.97	0.66	26.30	0.03	1.29	0.06	5.03	0.07
JV10/010	0.14	24.27	4.98	25.66	195.70		0.26		199.28	1.02	2.03	0.55	7.97		1.12	0.01	5.05	0.02
JV10/012	0.06	42.21	2.66	76.81	370.71		0.20		1162.19	1.40	2.09	0.59		0.05	1.56		36.42	
JV10/014	0.12	83.46	3.66	29.26	391.77		0.21		198.99	0.07	1.40	0.47	5.16		0.83	0.02	4.56	
JV10/016	0.03	83.67	2.81	76.18	365.31	0.03	0.34	37.34	21.36	0.14		0.50		0.03	0.18	0.03	0.38	

APPENDIX H : ACID RAIN LEACH TEST CATION CONCENTRATIONS (μg/L)

Sample No.	Element and Concentration (μg/L)																		
	Li	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Fe**	**Mn**	**Co**	**Ni**	**Cu**	**Zn**	**As**	**Sr**	**Cd**	**Ba**	**Pb**	**U**
JV10/001	2	2206	10426	181	1555	59727	<1	<5	<100	30188	884	1458	22	705	<20	110	<1	135	<30	8
JV10/002	3	3607	6023	174	1529	88104	5	<5	<100	1773	15	51	<20	381	<20	63	<1	44	<30	<2
JV10/003	11	13967	23424	230	3698	706733	<1	<5	<100	10710	685	1699	22	524	<20	199	<1	37	<30	448
JV10/005	7	7286	10104	175	2695	133291	<1	<5	<100	22051	618	833	22	2010	<20	128	2	106	<30	16
JV10/007	46	3756	6308	173	1928	57060	<1	<5	<100	38140	1086	3037	<20	1528	<20	77	<1	133	<30	<2
JV10/008	27	3979	6560	188	4839	73646	<1	<5	<100	38358	407	532	21	851	<20	77	1	180	<30	<2
JV10/010	12	2415	2102	634	1943	16205	<1	<5	<100	18021	82	150	<20	509	<20	92	<1	234	<30	<2
JV10/012	4	2825	2875	166	5874	19441	<1	<5	<100	36120	44	65	<20	<300	<20	85	<1	1122	<30	<2
JV10/014	8	2459	6403	162	1771	27531	<1	<5	<100	10097	3	54	<20	<300	<20	52	<1	94	<30	<2
JV10/016	3	1430	6145	199	6078	21043	2	6	1753	840	7	<50	<20	<300	<20	10	<1	25	<30	<2

APPENDIX I : ACID RAIN LEACH TEST CATION CONCENTRATIONS (mg/kg)

Sample No.	Element and Concentration (mg/kg)																	
	Li	**Na**	**Mg**	**Al**	**K**	**Ca**	**V**	**Cr**	**Fe**	**Mn**	**Co**	**Ni**	**Cu**	**Zn**	**Sr**	**Cd**	**Ba**	**U**
JV10/001	0.02	22.06	104.26	1.81	15.55	597.27				301.88	8.84	14.58	0.22	7.05	1.10		1.35	0.08
JV10/002	0.03	36.07	60.23	1.74	15.29	881.04	0.05			17.73	0.15	0.51		3.81	0.63		0.44	
JV10/003	0.11	139.67	234.24	2.30	36.98	7067.33				107.10	6.85	16.99	0.22	5.24	1.99		0.37	4.48
JV10/005	0.07	72.86	101.04	1.75	26.95	1332.91				220.51	6.18	8.33	0.22	20.10	1.28	0.02	1.06	0.16
JV10/007	0.46	37.56	63.08	1.73	19.28	570.60				381.40	10.86	30.37		15.28	0.77		1.33	
JV10/008	0.27	39.79	65.60	1.88	48.39	736.46				383.58	4.07	5.32	0.21	8.51	0.77	0.01	1.80	
JV10/010	0.12	24.15	21.02	6.34	19.43	162.05				180.21	0.82	1.50		5.09	0.92		2.34	
JV10/012	0.04	28.25	28.75	1.66	58.74	194.41				361.20	0.44	0.65			0.85		11.22	
JV10/014	0.08	24.59	64.03	1.62	17.71	275.31				100.97	0.03	0.54			0.52		0.94	
JV10/016	0.03	14.30	61.45	1.99	60.78	210.43	0.02	0.06	17.53	8.40	0.07				0.10		0.25	

APPENDIX J : XRD MINERALOGICAL RESULTS FOR JV10/004

The result of the XRD analysis performed on sample **JV10/004** is reported below.

Phase concentrations were determined by Rietveld quantitative analysis with accuracy in the region of ±1%. Standard deviation σ is given in brackets to the right of each value.

Gypsum	99.40% (0.18%)
Quartz	00.60% (0.18%)

SUPPLEMENTARY REPORT C

SABS Pesticide Residues Test Report

TEST REPORT

SABS

Your ref.:	ON 305727
Enquiries:	P Broere
Tel:	+27124286341
Date:	*17 May 2010*
Report No:	*2418* / **E 377**
Page:	1 of 1

CSIR
PO Box 395
PRETORIA

0001

DESCRIPTION OF SAMPLES

Number of samples	Date received	Date commenced
2	15/04/2010	20/04/2010

All perishable products are prepared on arrival and stored in a freezer

METHOD OF TEST - SABS Inhouse method 039/2008

MULTI-RESIDUE METHOD FOR PESTICIDE RESIDUES IN WATER				
Pesticide group	**Method notes**	**Technique used**	**Limit of quantitation (LOQ)**	**Recovery range measured (%)**
Synthetic Pyrethroids *		GC-ECD	0.5 µg/L	76 - 131
Organochlorine (OC's) and related pesticides *		GC-ECD	0.5 µg/L	75 - 131
Organophosphorus pesticides (OP's) *		GC-FPD / NPD	0.5 µg/L	92 - 129

All pesticides reported are confirmed by GCMS
* See attached list of pesticides included in the analysis

SAMPLE DESCRIPTION AND RESULTS - SABS Inhouse method 039/2008

MULTI-RESIDUE - WATER			
Commodity	**Sample description**	**Pesticide**	**Concentration µg/L**
Water	**CSIR8, Date sampled 14-04-10**		
		No residues detected	
Water	**CFM1 , Date sampled 14-04-10**		
		No residues detected	

HV Garbers
Manager: Chromatographic Services

P Broere
Principal Test Officer
Technical Signatory

Opinions and interpretations expressed herein are outside the scope of SANAS accreditation

The test work relating to this report was performed by SABS Commercial (Pty) Ltd. This report and its test results relate only to the specific sample(s) identified herein. They do not imply SABS approval of the quality and/or performance of the item(s) in question and the test results do not apply to any similar item that has not been tested. (Refer also to the conditions of test printed on the back of this page.) This report may not be reproduced except in full. The authenticity of this report and its contents can be confirmed by contacting the person who signed it.

ilac-MRA sanas Testing Laboratory

T0270

SABS Inhouse method 039/2008

MULTI-RESIDUE METHOD FOR PESTICIDE RESIDUES IN WATER

Sub-method **Organochlorine (OC's) and related pesticides ***

Technique **GC-ECD**

Pesticide	*Recovery (%)*	*Note*
Aldrin	101	
BHC (Lindane) Gamma-	115	
BHC Alpha-	107	
DDD pp'-	100	
DDE pp'-	131	
DDT op'-	87	
DDT pp'-		
Dieldrin	98	
Endosulfan	130	Sum of alpha- and beta-endosulfan and endosulfan sulphate
Endrin		
Heptachlor		
Heptachlor Epoxide	111	
Methoxychlor	75	

Sub-method **Organophosphorus pesticides (OP's) ***

Technique **GC-FPD / NPD**

Pesticide	*Recovery (%)*	*Note*
Bromophos methyl-	92	
Chlorfenvinphos		
Chlorpyrifos	103	
Chlorpyrifos methyl-	127	
Diazinon	114	
Dichlorvos	129	Includes Trichlorfon
Fenitrothion	92	
Fenthion	113	
Malathion	113	
Mevinphos	99	
Parathion	125	
Parathion methyl-	115	
Pirimiphos methyl-	127	
Profenofos		
Prothiophos		
Sulfotep	115	

Sub-method **Synthetic Pyrethroids ***

Technique **GC-ECD**

Pesticide	*Recovery (%)*	*Note*
Cyfluthrin		
Cyhalothrin Lamda-		
Cypermethrin		
Deltamethrin	81	
Fenvalerate	76	
Permethrin	131	

SUPPLEMENTARY REPORT D

CGS Report on Petrographic Analysis of Dolomite Exposed to AMD

Council for Geoscience

Private Bag X112 Pretoria 0001 SOUTH AFRICA 280 Pretoria Street Silverton Pretoria
Reception: +27 (0) 12 841 1911 Internet: http://www.geoscience.org.za

Laboratory Unit

Petrographic Laboratory

Attention: Dr. Henk Coetzee
CGS-EGU

Date: 12 May 2010

Job no.: 09/886(b)
Project no.: CO-2010-5704

Comparative petrography of dolomite samples before and after exposure to acid mine drainage (AMD).

1. Introduction

Portions of two polished thin sections of a sample of dolomite (HC-01-10-01), previously reported upon in report 09/886(a), were photographed under magnification before and after being exposed to acid mine drainage (AMD) with the aim of petrographically studying any changes associated with the exposure to AMD, the results of which are reported herein.

2. Observations

Both rock sections exposed to AMD exhibited an iridescent surface suggestive of the presence of a thin film / coating covering the carbonate rock. Both sections similarly displayed a brownish mottled appearance under both plane polarized (PPL) and cross polarized light (XPL). This is interpreted to be the result of drops which formed on the surfaces of the sections as they were allowed to dry off.

Figures 1-16 show photomicrographs[1] of portions of each of the two thin sections, both before and after being exposed to AMD. Although changes were difficult to assess quantitatively, a number of qualitative observations could be made. In general, carbonates exposed to AMD had a slight brownish coloration in comparison to the near lack of color in the carbonates before being exposed to AMD. Certain areas in both sections, typically with circular outlines, however, remained colorless (cf. Figure 17 & 18). It also appeared as if the carbonates in the AMD

[1] Images as shown in Figures 1-18 are approximately 2.4mm wide.

exposed samples showed a lesser degree of birefringence in comparison to that exhibited before having been exposed to AMD. Although this could be ascribed to a variety of factors, the most reasonable appears to be the possibility that carbonate was partially dissolved as a result of being exposed to AMD, with the result that the carbonate rock exposed on the surface of the thin section was thinner after exposure to AMD, hence the lower apparent birefringence.

In all instances, carbonate grain boundaries in AMD exposed samples appear more pronounced under magnification as a result of the presence of a dark-brown, almost opaque substance occurring along them. In certain instances exposure to AMD appear to have resulted in a decrease in carbonate grain size, as is strikingly apparent in a comparison between Figures 7 and 8. Also, AMD appears to have preferentially exploited cleavage directions within carbonate grains, as can be seen from Figures 13 to 16.

In order to study the effects on the petrography of a thin section from which a possible surface coating resultant from exposure to AMD has been removed, the polished surface of sample HC-01-10-01(b) was wiped softly with a portion of tissue paper before being examined again using a petrographic microscope. The only discernible effects as a result of this treatment were:

- The loss of the iridescent surface as previously exhibited by the sample.
- The carbonates showing a less pronounced brown coloration when examined microscopically.

Localized brownish mottling thought to be the result of the way in which the sample was dried, however, remained following this treatment.

3. Recommendations

Scanning electron microscopy is recommended in order to identify any reaction products or precipitates present within or coating the samples.

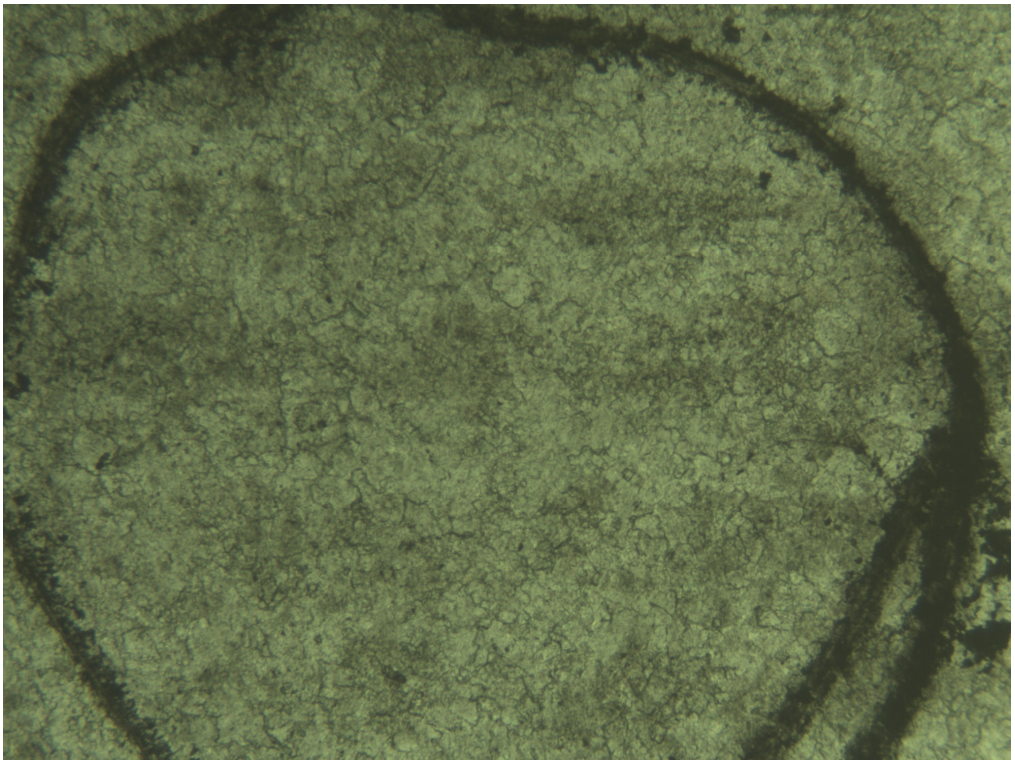

Figure 1: Photomicrograph of area 1, sample HC-01-10-01(a) before exposure to AMD. (PPL)

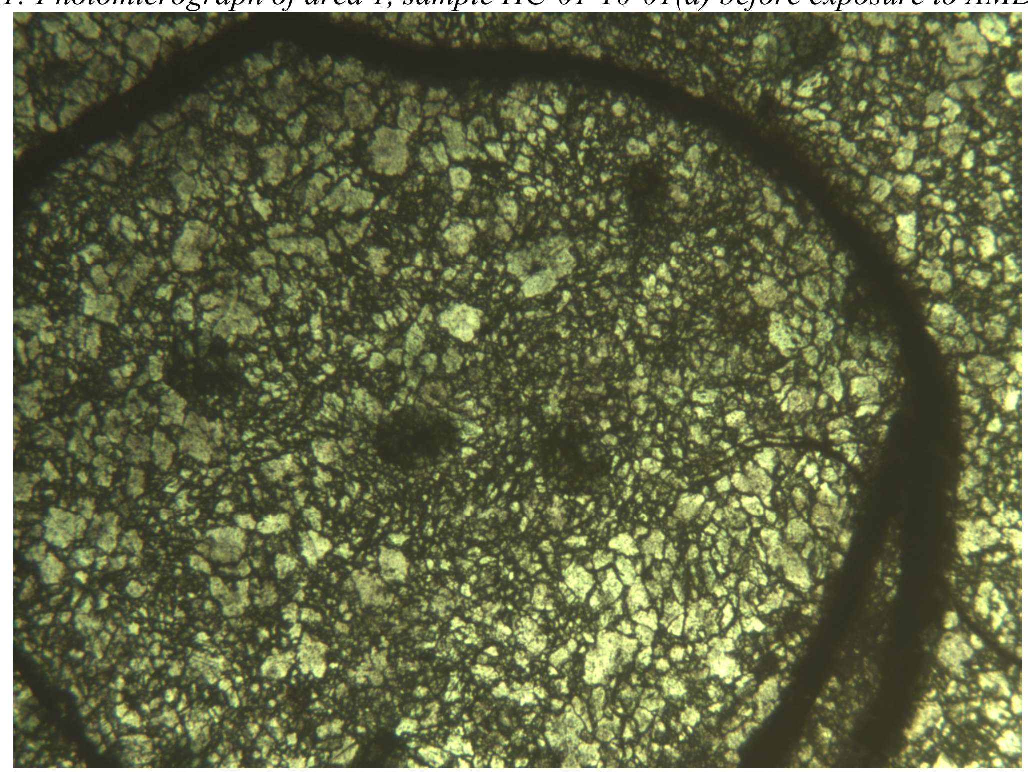

Figure 2: Photomicrograph of area 1, sample HC-01-10-01(a) after exposure to AMD. (PPL)

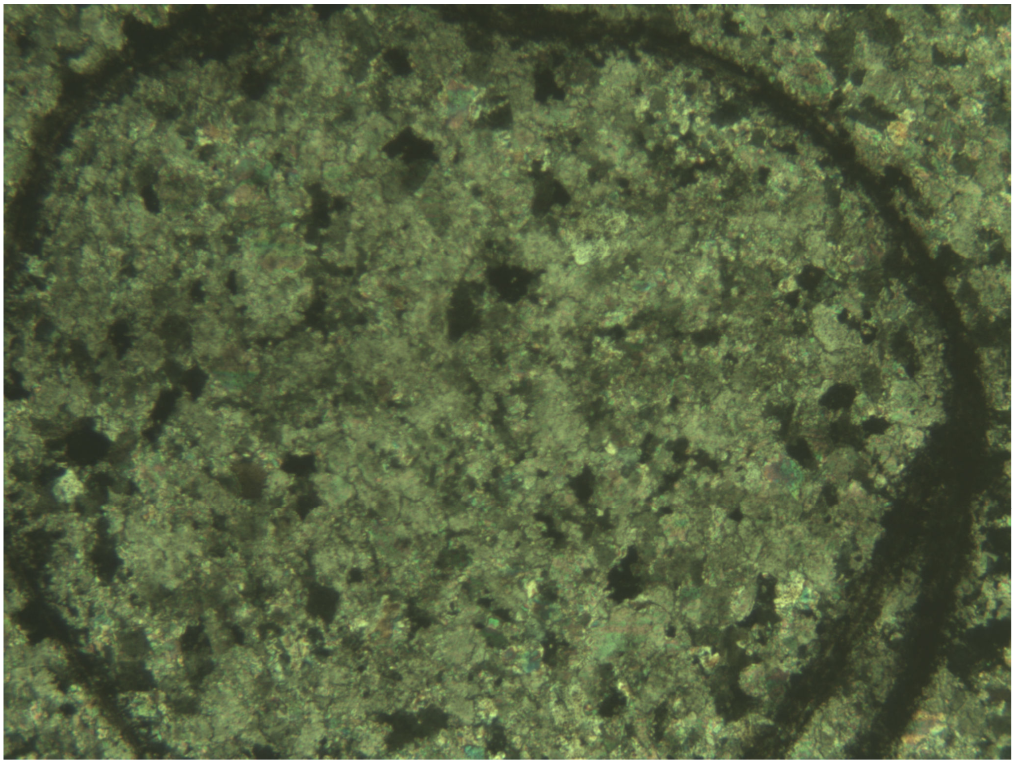
Figure 3: Photomicrograph of area 1, sample HC-01-10-01(a) before exposure to AMD. (XPL)

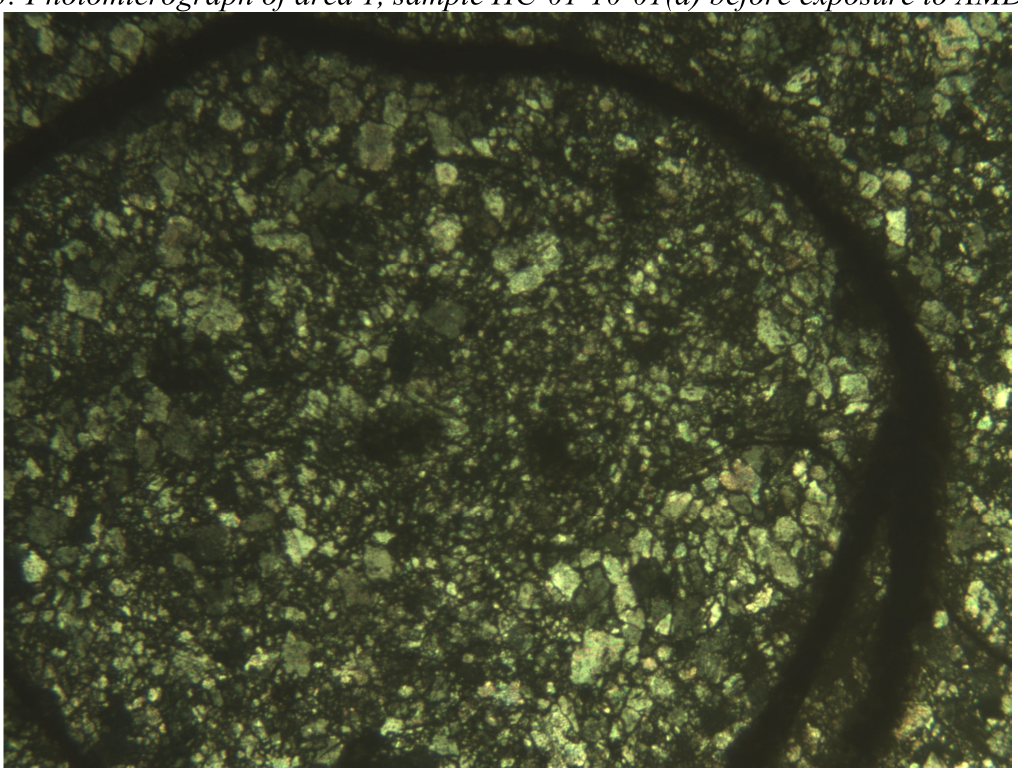
Figure 4: Photomicrograph of area 1, sample HC-01-10-01(a) after exposure to AMD. (XPL)

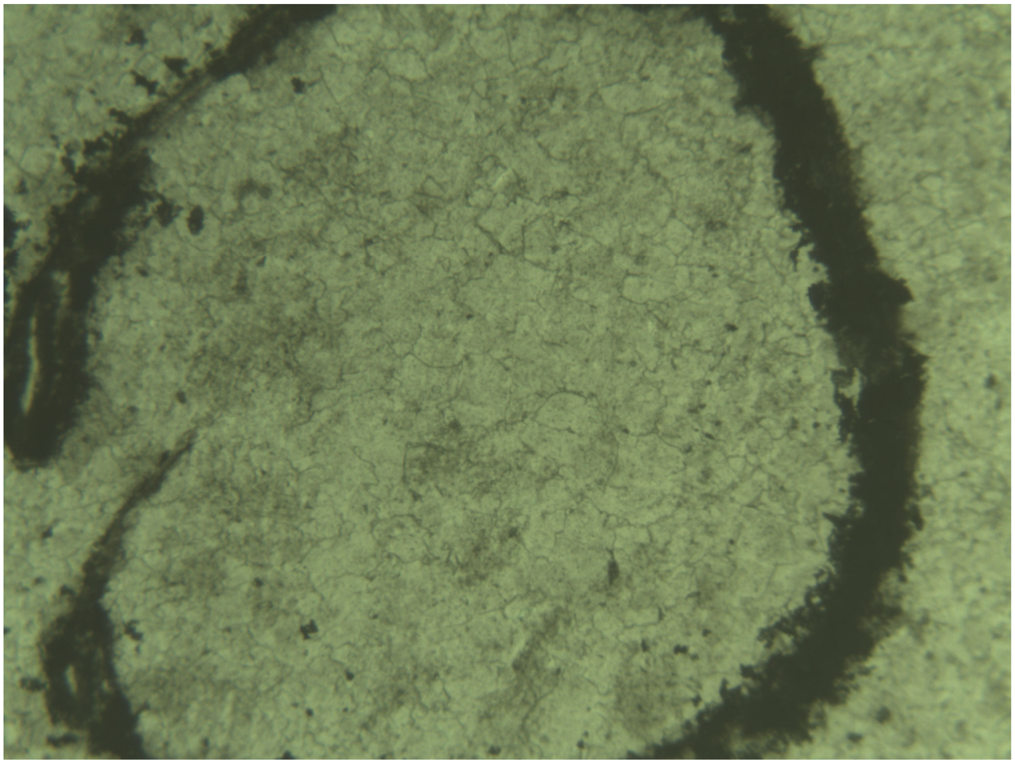

Figure 5: Photomicrograph of area 2, sample HC-01-10-01(a) before exposure to AMD. (PPL)

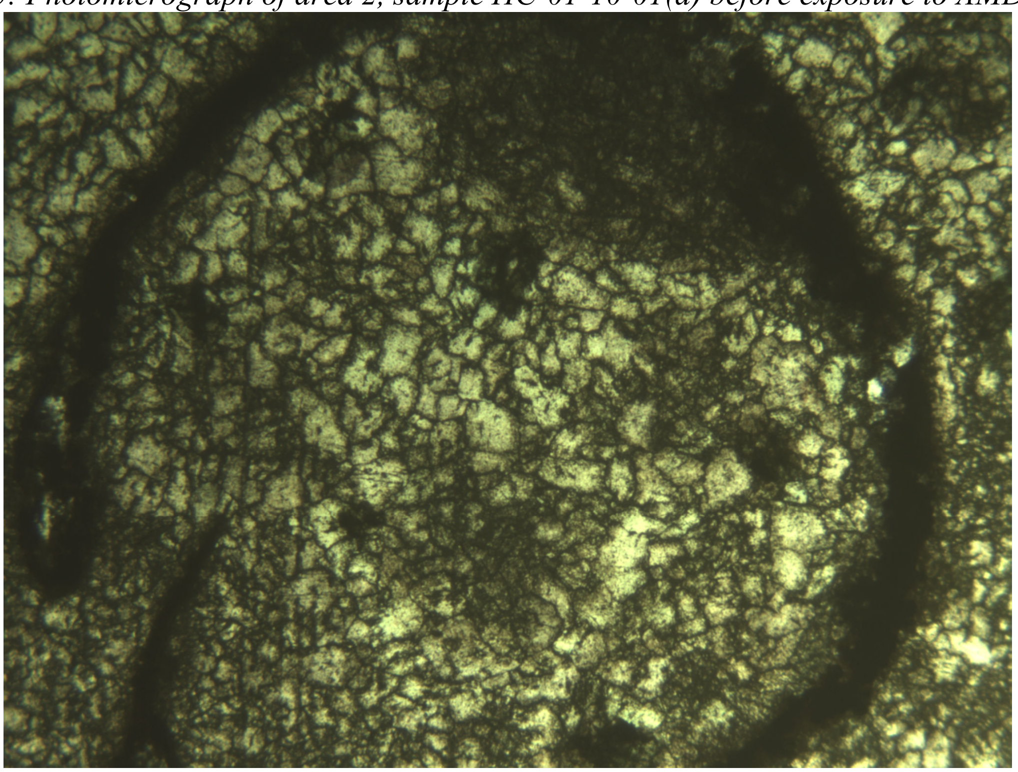

Figure 6: Photomicrograph of area 2, sample HC-01-10-01(a) after exposure to AMD. (PPL)

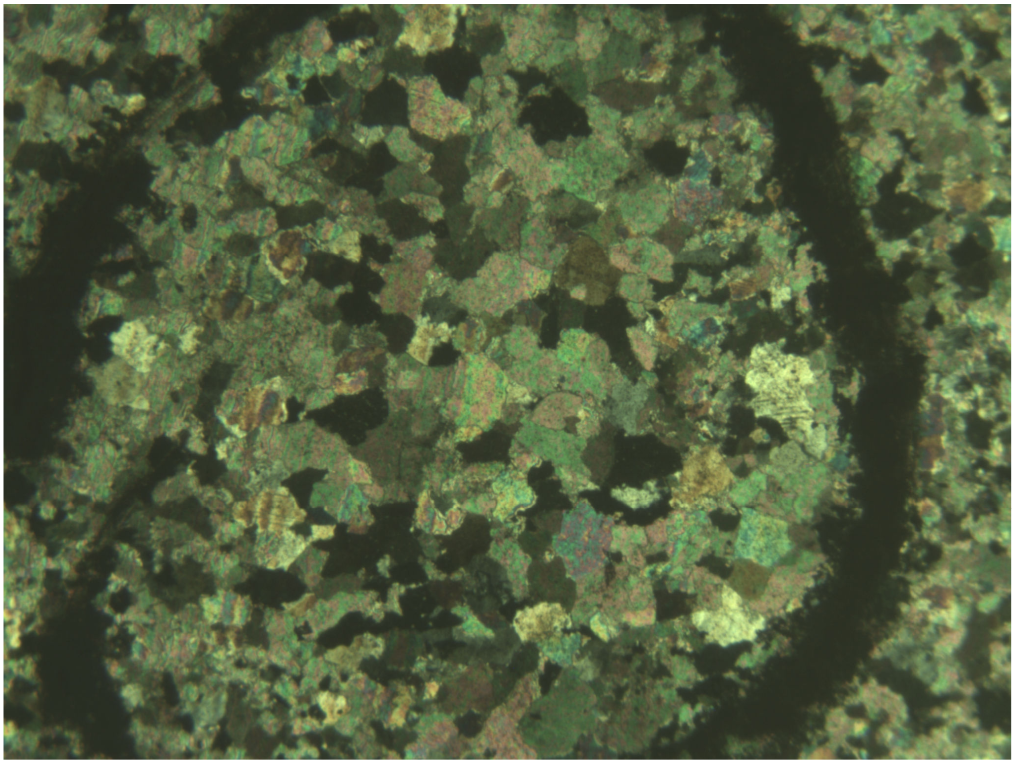
Figure 7: Photomicrograph of area 2, sample HC-01-10-01(a) before exposure to AMD. (XPL)

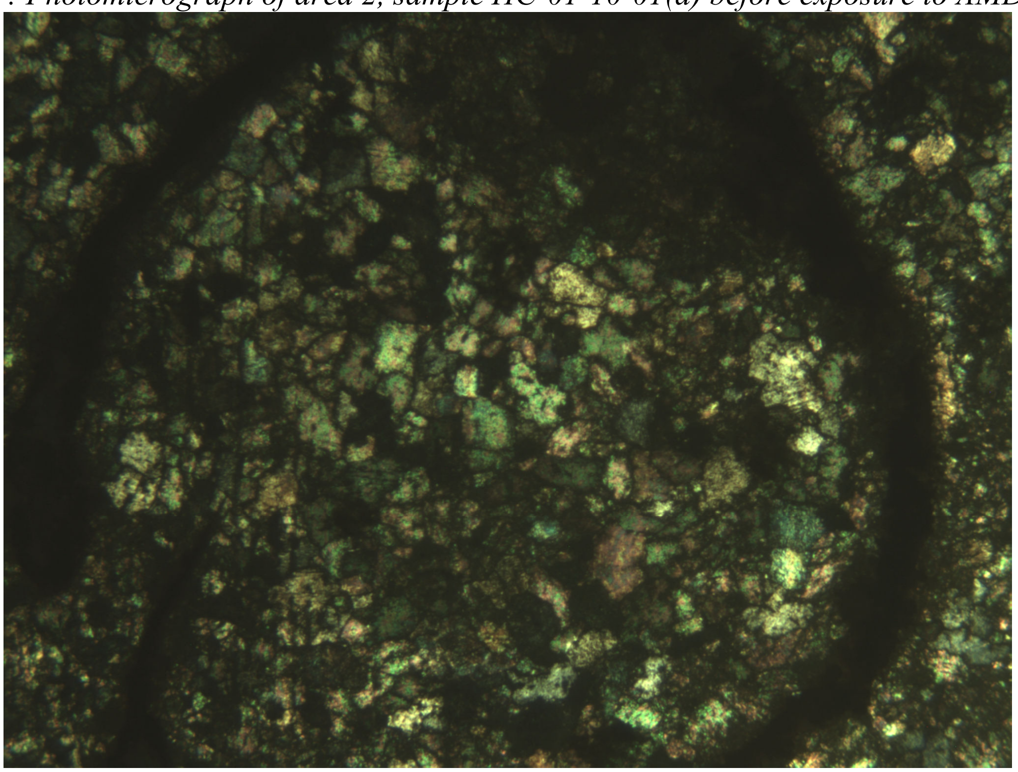
Figure 8: Photomicrograph of area 2, sample HC-01-10-01(a) after exposure to AMD. (XPL)

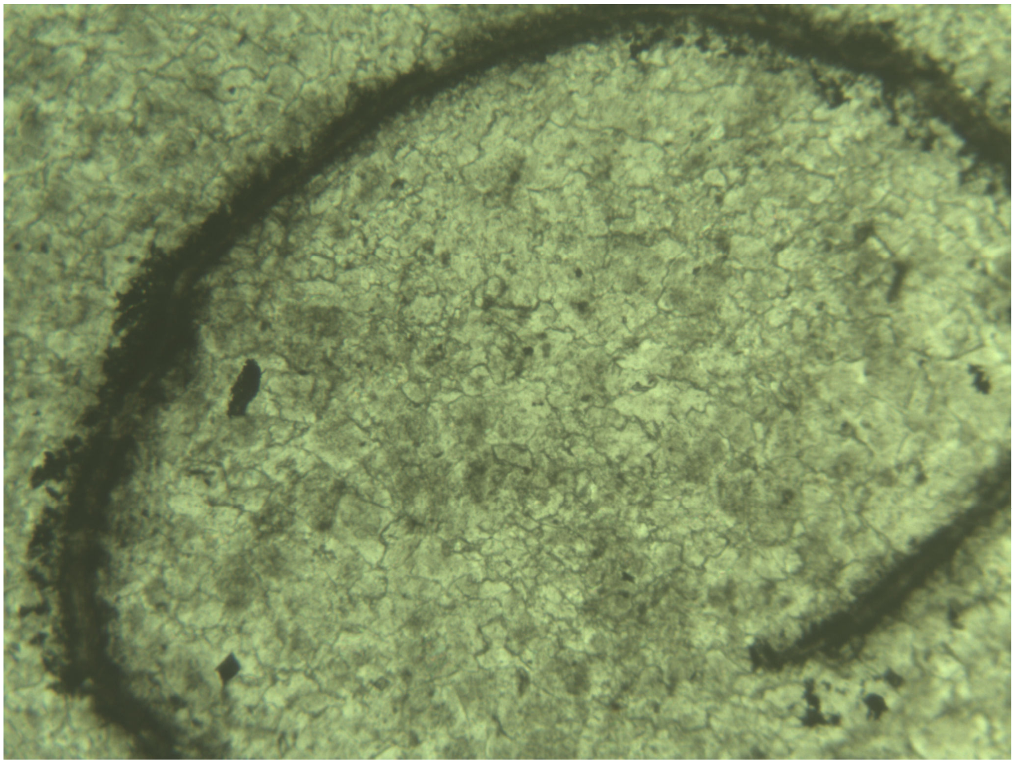

Figure 9: Photomicrograph of area 1, sample HC-01-10-01(b) before exposure to AMD. (PPL)

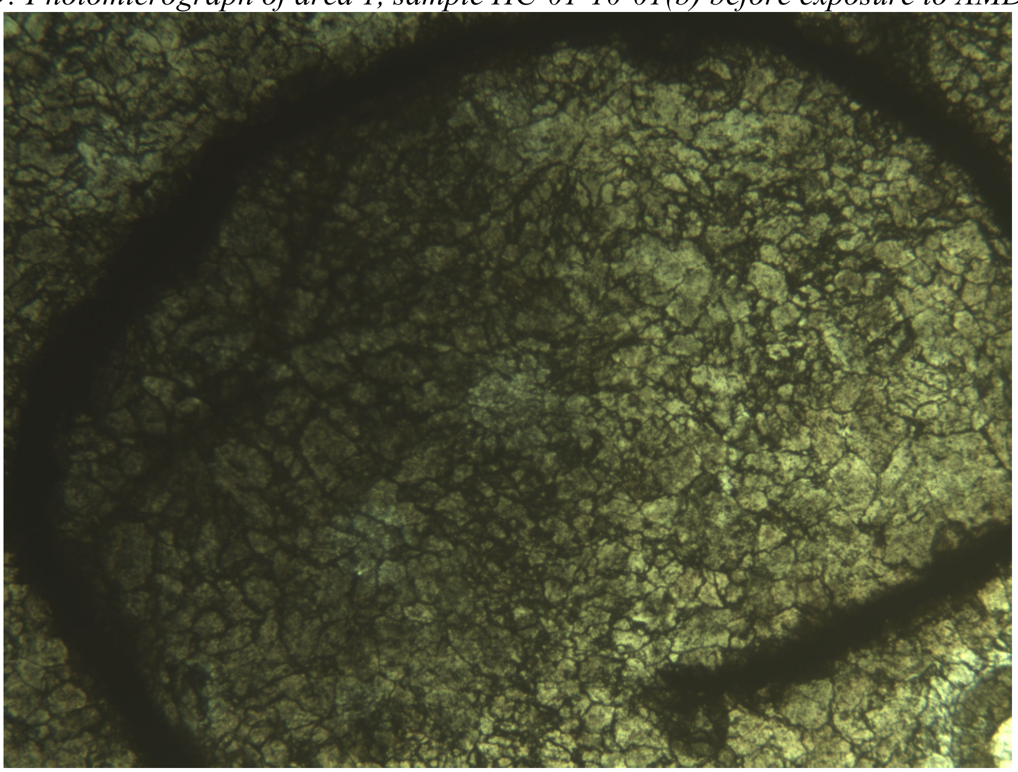

Figure 10: Photomicrograph of area 1, sample HC-01-10-01(b) after exposure to AMD. (PPL)

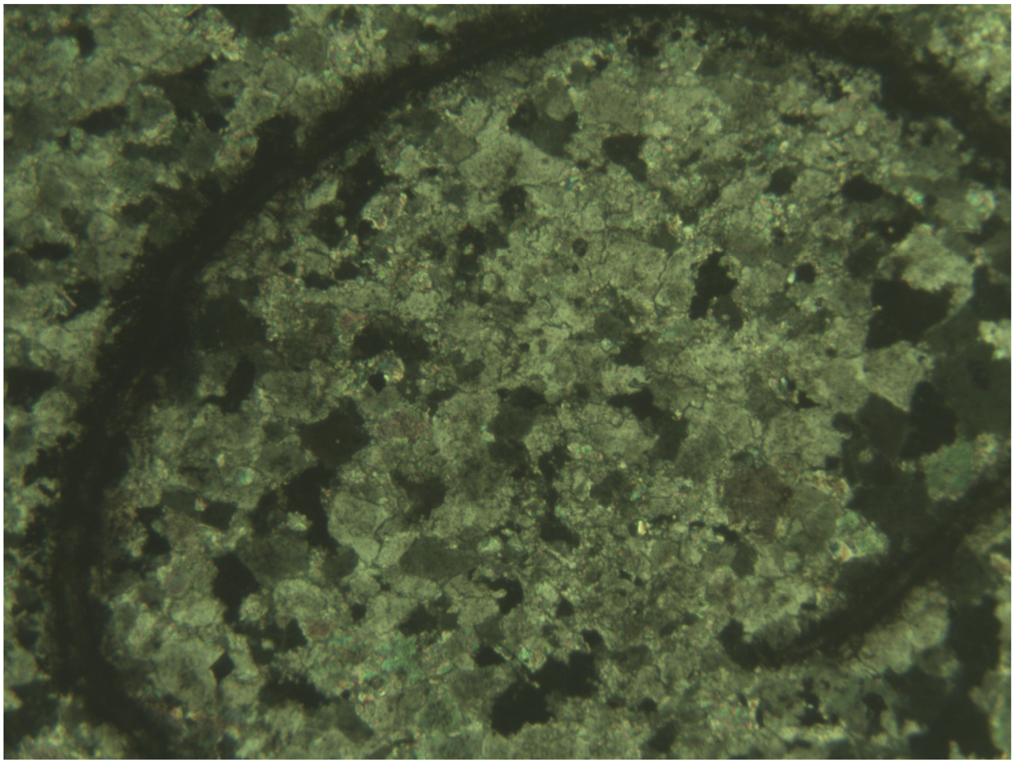

Figure 11: Photomicrograph of area 1, sample HC-01-10-01(b) before exposure to AMD. (XPL)

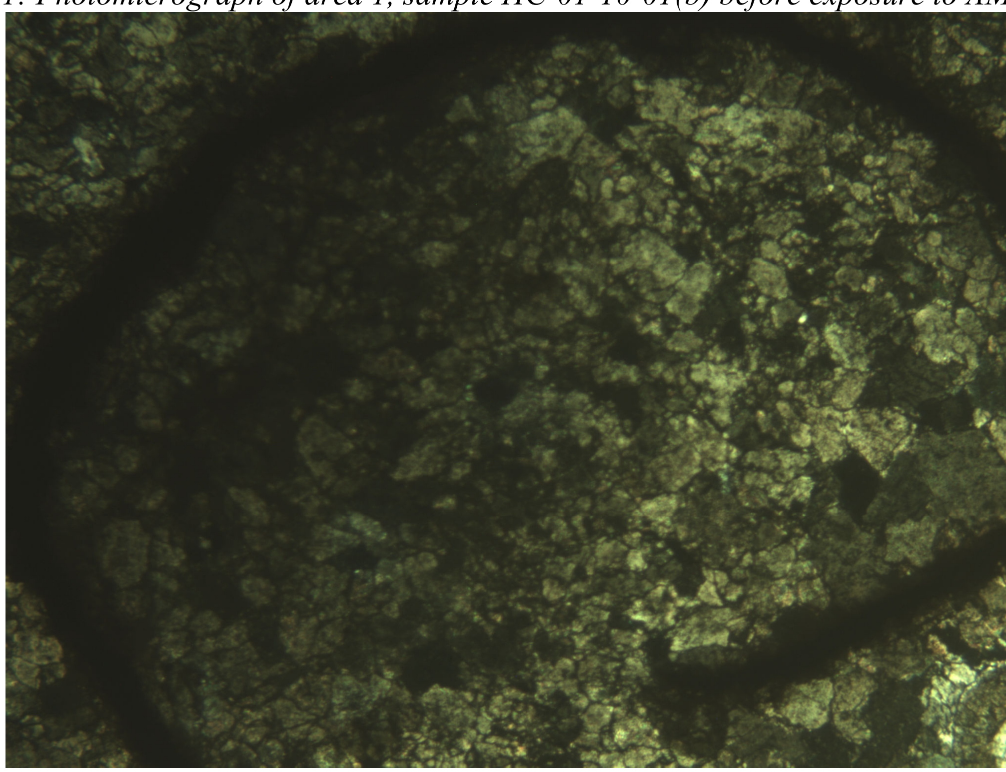

Figure 12: Photomicrograph of area 1, sample HC-01-10-01(b) after exposure to AMD. (XPL)

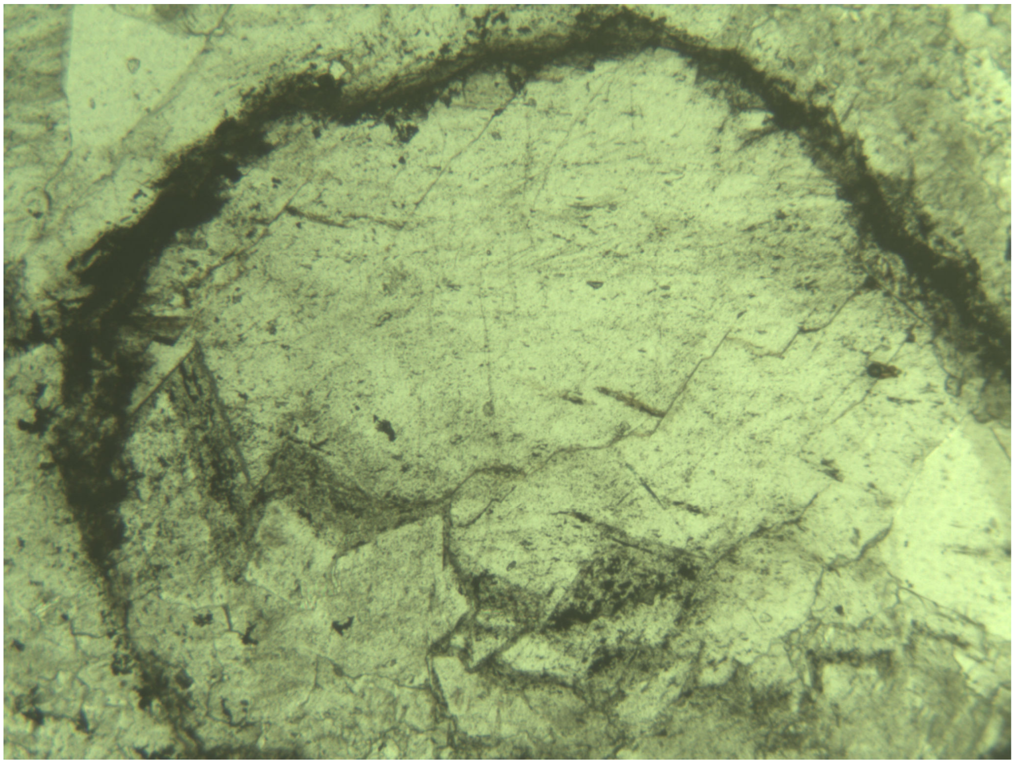

Figure 13: Photomicrograph of area 2, sample HC-01-10-01(b) before exposure to AMD. (PPL)

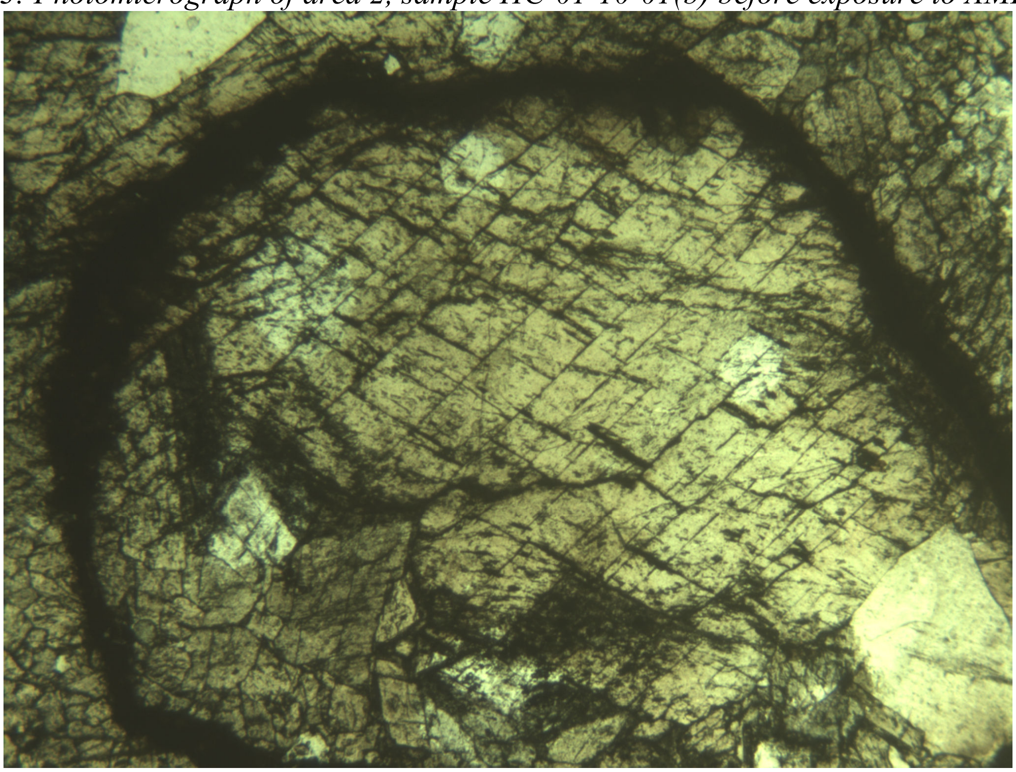

Figure 14: Photomicrograph of area 2, sample HC-01-10-01(b) after exposure to AMD. (PPL)

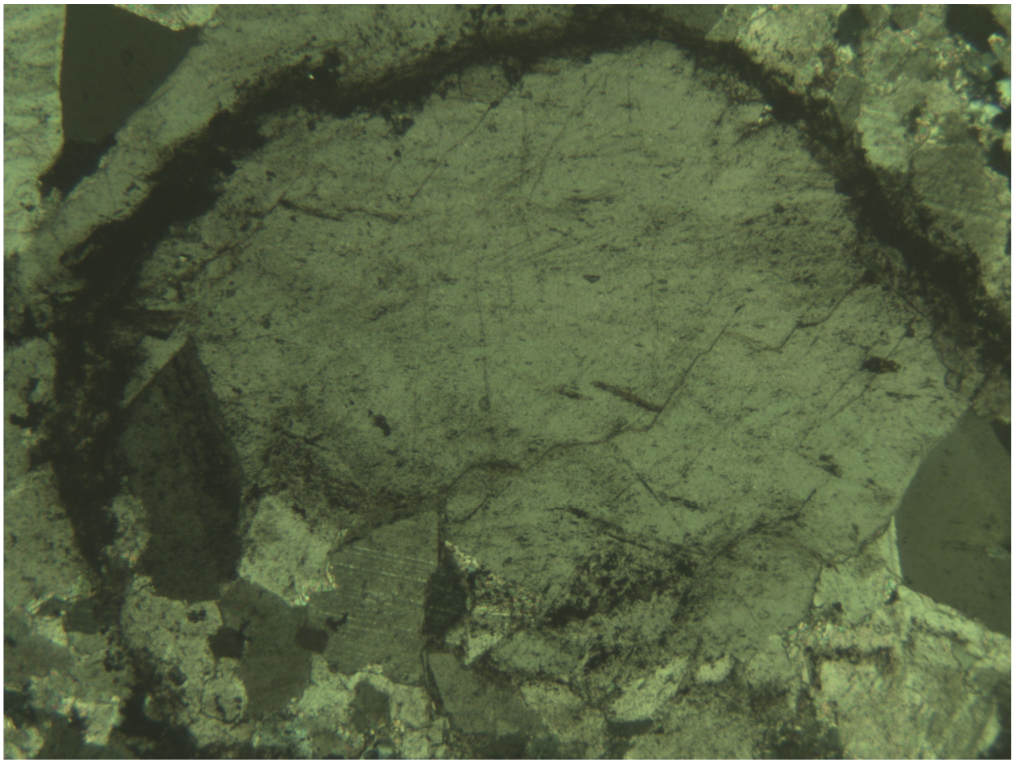

Figure 15: Photomicrograph of area 2, sample HC-01-10-01(b) before exposure to AMD. (XPL)

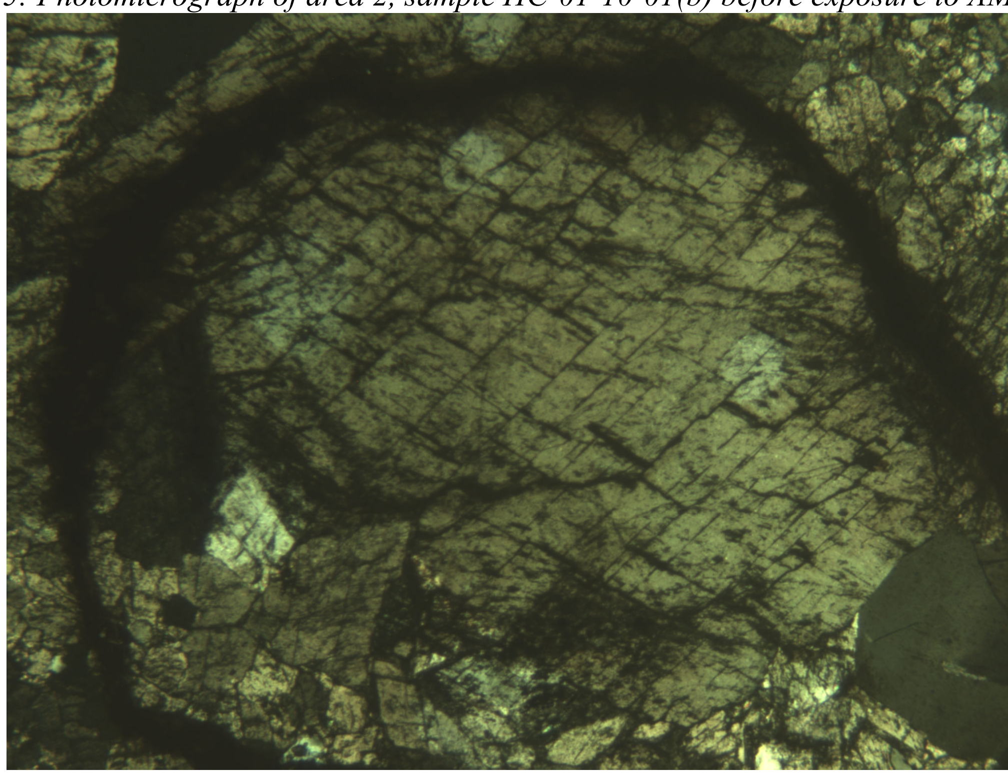

Figure 16: Photomicrograph of area 2, sample HC-01-10-01(b) after exposure to AMD. (XPL)

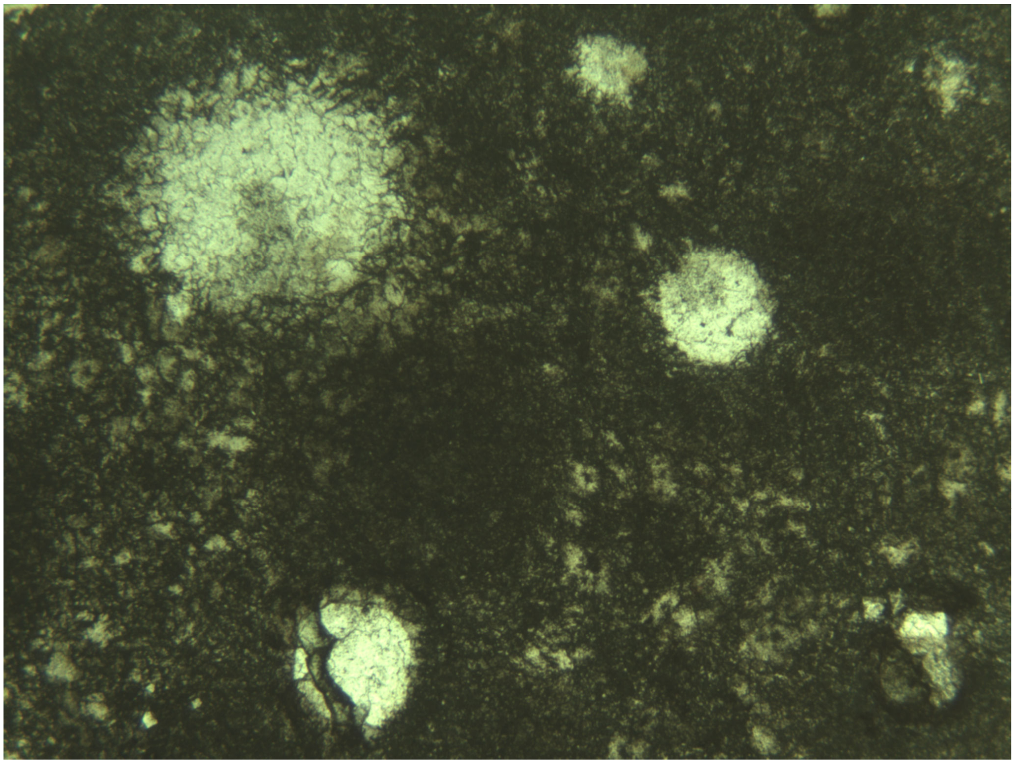

Figure 17: Portion of sample HC-01-10-01(a) showing circular patches of colorless carbonate following exposure to AMD. (PPL)

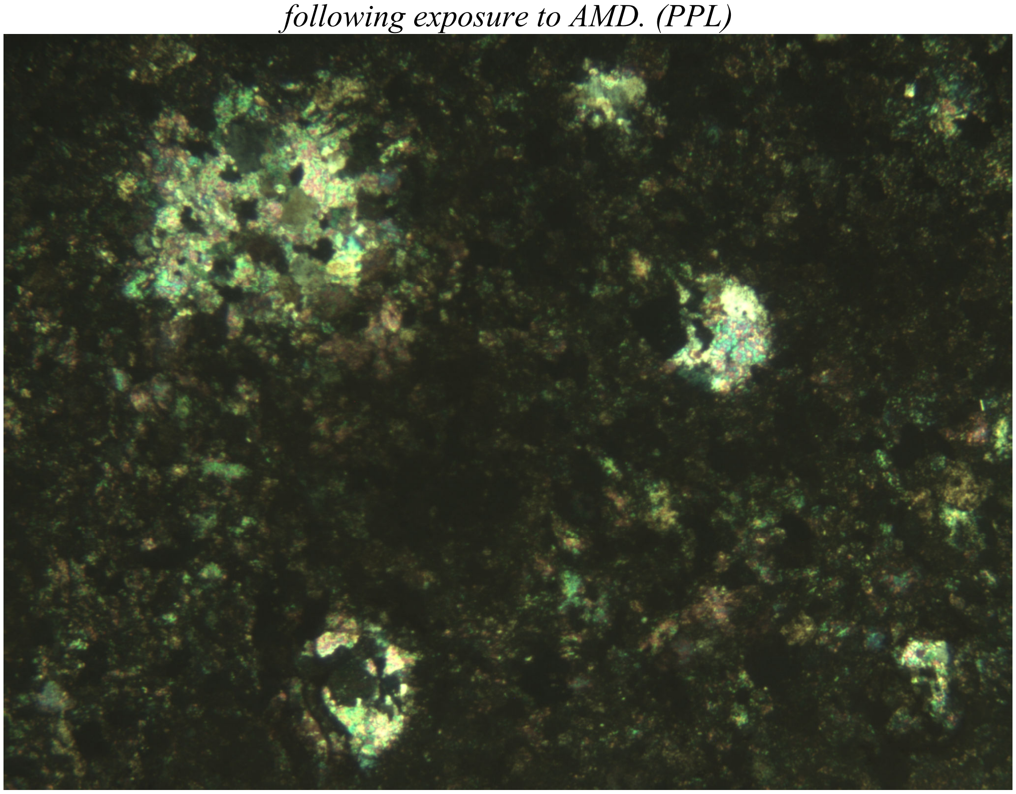

Figure 18: Portion of sample HC-01-10-01(a) showing circular patches of colorless carbonate following exposure to AMD. (XPL)

Report by: F Roelofse (12-5-2010)

SUPPLEMENTARY REPORT E

CGS Report on the Experimental Study of the Effects of Acid Mine Drainage on Dolomite

PROJECT TITLE

ESTABLISHMENT OF A MONITORING SYSTEM FOR SURFACE WATER AND GROUNDWATER IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

EXPERIMENTAL STUDY OF THE EFFECTS OF ACID MINE DRAINAGE ON DOLOMITE

DATE

MARCH 2011

PROJECT

BIQ005/2008

Report prepared for

Management Authority

Cradle of Humankind World Heritage Site & Dinokeng

Department of Economic Development

Gauteng Provincial Government

Report prepared by

Council for Geoscience [CGS]

Report No. 2011-0069

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Editorial review by

P. Hobbs : CSIR-NRE

EXECUTIVE SUMMARY

Batch and kinetic experimental testing of the interactions between acid mine drainage (AMD) and dolomite, such as those typically found in the Western Basin of the Witwatersrand Goldfields, have been undertaken with the specific aim of identifying the effects likely to be experienced in the dolomitic areas to the north, including the Cradle of Humankind World Heritage site. The studies specifically investigated the dissolution of dolomite in AMD, the armouring of the reactive surfaces of the dolomite by precipitated minerals, and the potential which the dolomites offer for the natural attenuation of AMD where it contaminates groundwater.

Chemical data were used to assess the occurrence and effect of various reactions, while petrographic and scanning electron microscopic investigations were used to identify the effects of the dissolution reactions and identify the precipitates formed.

Sufficient experimental evidence was obtained to confirm that the competing processes of dissolution of the dolomite and armouring of the dolomite surfaces were both occurring. It is concluded that AMD plumes would be likely to migrate through dolomitic aquifers, initially being neutralised on reaction with the dolomite, but with the near-simultaneous precipitation of new minerals preventing neutralisation from continuing. As a result, the neutralisation of AMD in the subsurface dolomitic environment is not a sustainable process in the long-term.

Chemical analysis of solutions produced by the reaction of synthetic AMD with dolomite indicate that interactions between dolomite and AMD reduce the concentrations of only a limited number of common contaminants in the dissolved phase. The reaction does not effectively reduce the salinity of the influent mine water. Dolomitic aquifer systems therefore cannot be utilised for the natural attenuation of acid mine drainage.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Since the onset of acid mine water decant from the mine workings of the Western Basin of the Witwatersrand Goldfields in 2002 (Coetzee et al., 2002), considerable concern has been expressed regarding the impacts on the downstream surface water. Concern has also been expressed for groundwater resources (Hobbs and Cobbing, 2007), although this has not always generated as much public outcry. The major concerns which have been raised are:

- Acid water entering dolomitic aquifers will dissolve dolomite, leading to the formation of new cavities and potentially sinkholes.
- Reactions between acid mine drainage (AMD) and the exposed surface of the dolomitic aquifers would result in the precipitation of minerals on the surface of the dolomite, armouring it and leading to the loss of buffer capacity within the aquifer. This would negatively affect the characteristic quality of dolomitic groundwater and reduce the ability of these aquifers to naturally attenuate acid pollution from mines.

Further, the possibility exists that the carbonate content of the dolomite could effectively attenuate groundwater pollution naturally.

2 EXPERIMENTAL METHODOLOGIES

2.1 Assessment of the Dissolution of Dolomite by AMD

The assessment of the dissolution of dolomite by AMD has been undertaken by studying the ability of dolomite to neutralise samples of real and synthetic AMD in batch and kinetic experiments. It is assumed that the neutralisation takes place due to the dissolution of the carbonate rock fraction of the dolomite.

2.2 Assessment of the Ability of AMD to Armour Dolomite

The proposed armouring of the dolomite with minerals precipitated from the AMD in the course of neutralisation or other reactions, has been assessed by studying dolomite samples before and after reactions with real and synthetic AMD. These studies have included petrographic investigation of thin sections using optical microscopy, as well as investigations using a scanning electron microscope (SEM).

2.3 Translation of Analytical Results into Management Recommendations

The focus of the experimental work and the interpretation of the results is the development of recommendations to assist in the management of the impacts of AMD on the dolomitic aquifers which characterise the Cradle of Humankind World Heritage Site (COH WHS).

3 EXPERIMENTAL STUDIES

3.1 Sampling

A sample of fresh dolomite (HC-10-01-01) as might be expected to be encountered in the subsurface environment, was collected at the abandoned Sterkfontein Quarry. The mineralogy of the sample was confirmed by X-Ray Diffraction to comprise 98.35% dolomite and 1.65% quartz.

3.2 Batch Experiment – Reaction of Dolomite with AMD Sampled from 18 Winze

Polished thin sections were cut from the dolomite sample and exposed to AMD collected from 18 Winze, a shaft where water decants on the old Randfontein Estates Gold Mine. The thin sections were placed in beakers which were then filled to the brim with AMD from the shaft and sealed in an attempt to avoid additional oxygen entering the beakers. These were returned to the laboratory and agitated slowly for a period of one week to allow constant flow of AMD over the dolomite surface. Following the week of immersion in AMD, the thin sections were removed and air dried to allow re-investigation to determine the effects of AMD exposure. The pre- and post-leaching chemical variable values of the AMD are given in Table 1. The results indicate a drop in pH during the week of leaching, most likely due to the oxidation of Fe^{2+} to Fe^{3+} with the concomitant lowering of pH, characteristic of acid mine drainage (Coetzee et al., 2007). This was also indicated by the precipitation of Fe^{3+} hydroxide phases observed on the samples. No neutralisation effects are seen in these data. However, this might be expected due to the extremely small volume of dolomite contained in a single thin section.

Table 1. Chemical parameters of AMD pre- and post-leaching of dolomite thin sections.

Sample	Pre-leaching Variable Values			Post-leaching Variable Values		
	pH	EC (mS/m)	ORP (mV)	pH	EC (mS/m)	ORP (mV)
HC 10-01-01 TS (a)	5.44	548	-57	4.405	514	113
HC 10-01-01 TS (b)	5.44	548	-57	4.312	510	110
Blank (a)	5.44	548	-57	4.498	517	85
Blank (b)	5.44	548	-57	3.898	558	119

Petrographic investigation (Roelofse, 2010) shows an exaggeration of grain boundaries within the dolomite, as reduction in dolomite grain size (Figure 1) in some cases and the deposition of a brown coloured opaque precipitate along grain boundaries. These effects suggest etching (Figure 2) of the dolomite surface by partial dissolution of the dolomite as well as the precipitation of new minerals, presumably iron hydroxide minerals, in the etched zones.

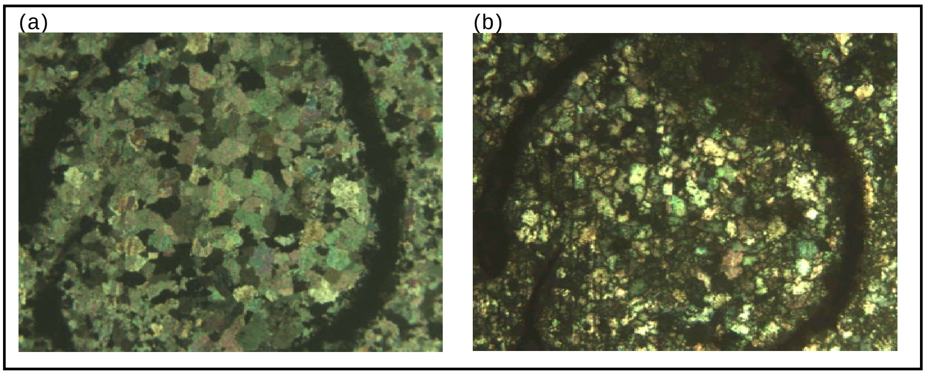

Figure 1. Photomicrographs (XPL) of dolomite before (a) and after (b) leaching with AMD showing the apparent erosion of carbonate mineral grains during the leaching process, suggesting the dissolution of dolomite due to contact with AMD. The dark line in the images is a line scribed on the polished thin section to allow the identification of the same area before and after leaching.

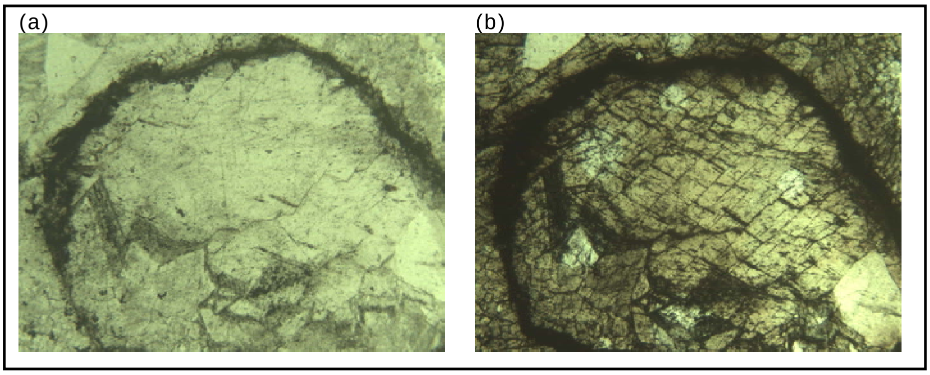

Figure 2. Photomicrographs (PPL) of dolomite before (a) and after (b) leaching with AMD collected from 18 Winze. Note the etching of intragranular fractures in the dolomite, suggesting the dissolution of dolomite due to contact with AMD. (the dark line in the images is a line scribed in the polished thin section to allow the identification of the same area before and after leaching).

The precipitate identified on the samples was further investigated by scanning electron microscopy (SEM) on the same polished thin sections and on crushed dolomite exposed to the same AMD as the polished thin sections, allowing the identification of the mineral precipitates formed. This technique also allows the analysis of spots or areas within samples by electron backscatter and energy dispersive spectroscopy (EDS). Figure 3 shows the growth of gypsum and goethite on the surface of a dolomite sample after exposure to AMD. Figure 4 shows the progressive precipitation of gypsum and goethite, minerals characteristic of the precipitates formed during the neutralisation of AMD on a dolomite surface.

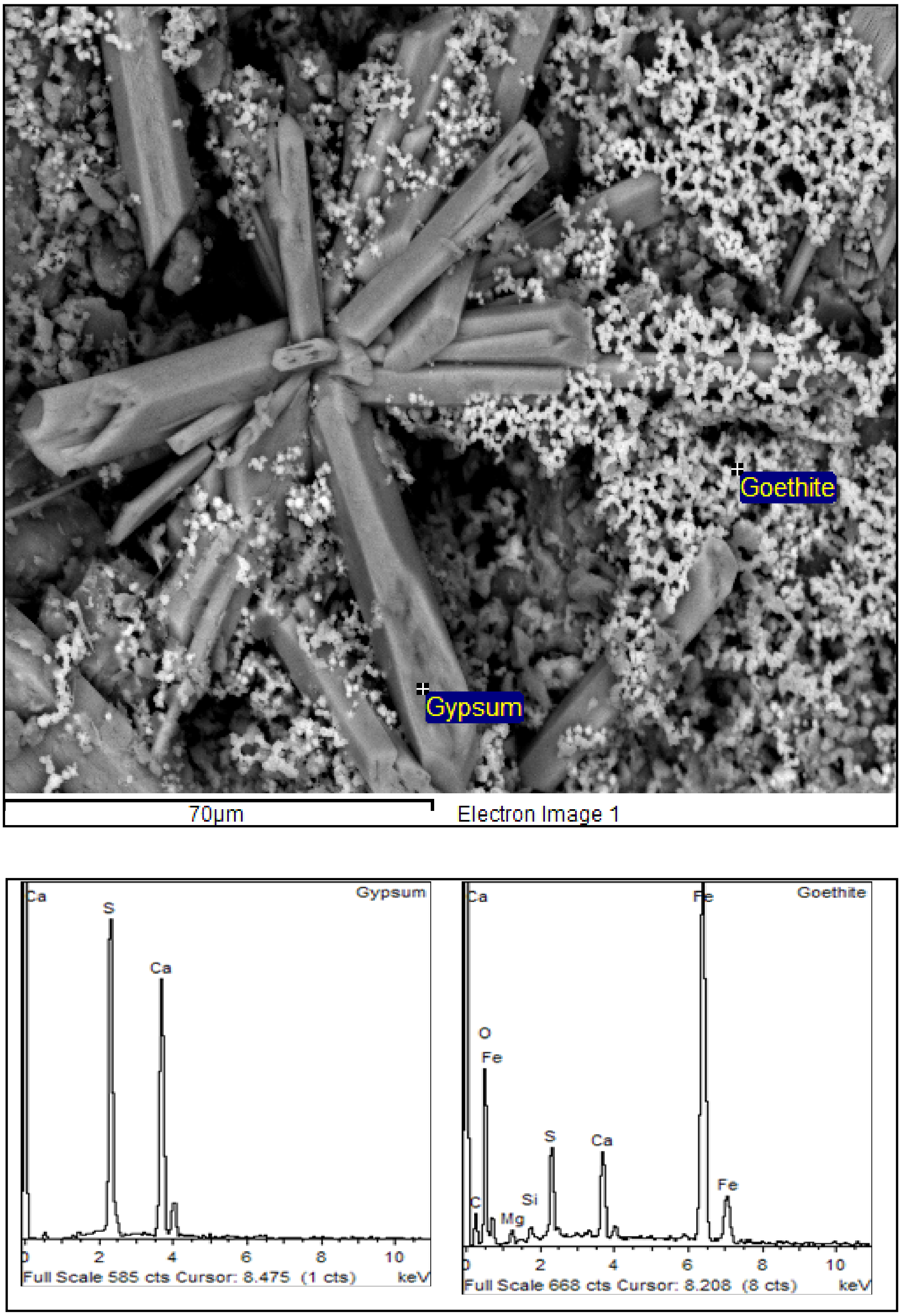

Figure 3. Typical SEM image (top) of the precipitate phases in the leached dolomite samples, showing spot analyses of minerals by EDS (bottom).

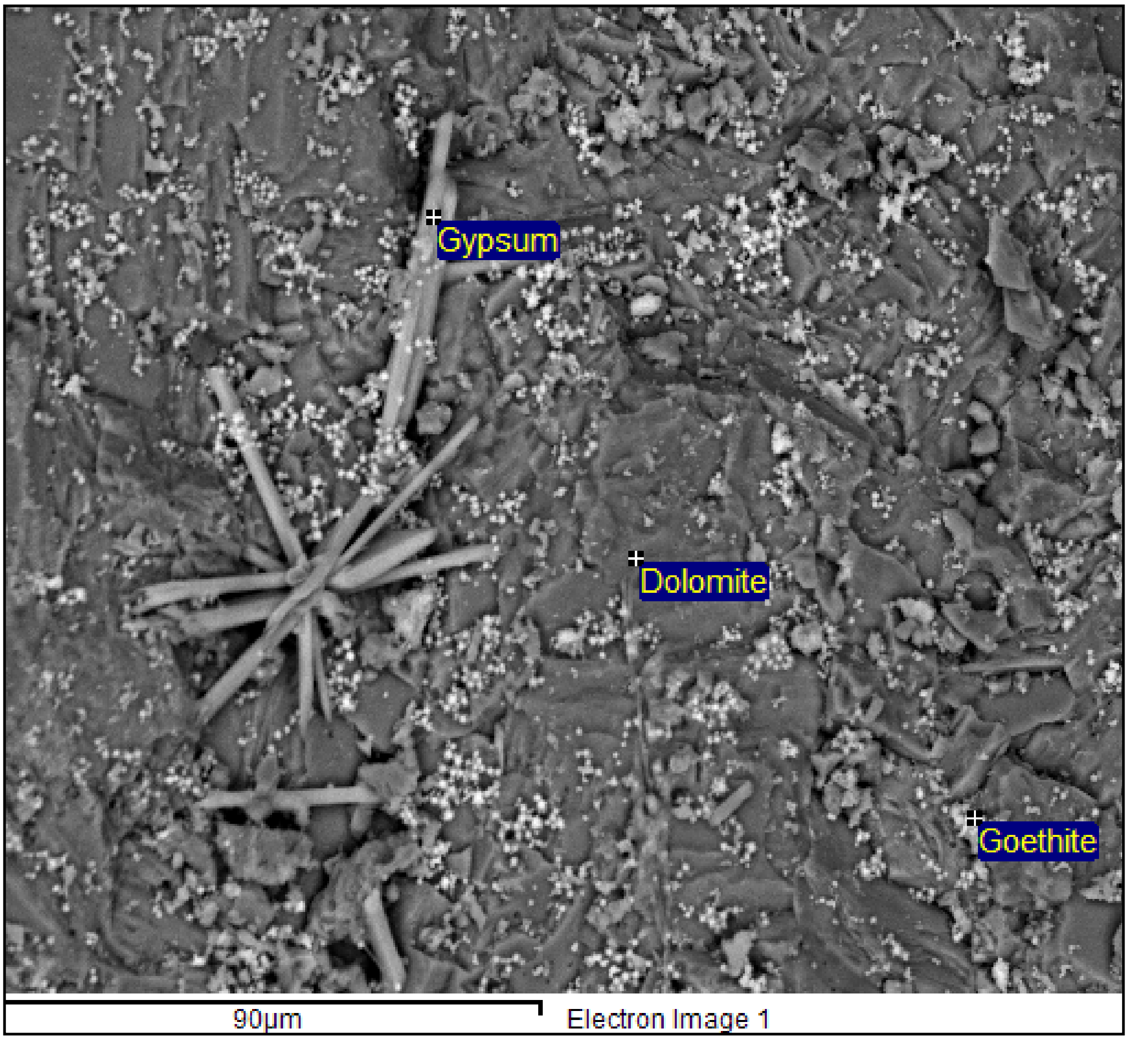

Figure 4. Precipitation of gypsum and goethite on a dolomite surface.

3.3 Kinetic Testing of the Reaction between Dolomite and Synthetic AMD

3.3.1 Preparation of a Synthetic AMD Solution

The handling of original AMD samples is complicated by the precipitation of iron which changes the pH of the solution, adsorbs metals out of solution and precipitates on reactive surfaces, as seen in the example above. A kinetic (column leaching) experiment was devised using synthetic AMD prepared in the laboratory to closely mimic the bulk composition of Western Basin AMD while maintaining the iron in a dissolved state, was prepared as a leachant using the reagents listed in Table 2, and pH adjusted to a value of 3.6 using H_2SO_4. This was passed through columns packed with dolomite of different size fractions at a slow rate to simulate the gradual flow of groundwater through a dolomitic aquifer.

Table 2. Make-up of the synthetic AMD used in the kinetic leaching experiment.

Reagent	Amount (g) for 4 L of Solution
$FeSO_4 \cdot 7H_2O$	20.80
$CaSO_4.2H_2O$	7.61
$MgSO_4 \cdot 7H_2O$	7.48
$MnSO_4 \cdot H_2O$	1.23
$Na_2SO_4 \cdot 10H_2O$	2.80
$Al_2(SO_4)_3 \bullet 18H_2O$	1.95
H_2SO_4	0.27

3.3.2 Column Leach Testing of Dolomite with Synthetic AMD

Five columns of length 700 mm and diameter 50 mm, labelled A to E, were packed with crushed dolomite of different size fractions as presented in Table 3. The sample masses per column are presented in Table 3. The synthetic AMD prepared as described above, was passed slowly up the columns to ensure full wetting and coverage using a 5-channel peristaltic pump at a rate calculated to achieve a liquid/solid/time close to 0.1 L/kg/day. This slow rate of leaching was selected to allow equilibrium to develop during the contact period between the leachate and the dolomite.

Table 3. Sample size fractions and masses for the leaching columns used in the kinetic experiment.

Column	Size Fraction (mm)	Sample Mass (g)
A	<2	1423.0
B	2 – 4	1012.6
C	4 – 8	1027.8
D	8 – 16	1149.4
E	>16	1149.3

3.3.3 Assessment of Dolomite Dissolution

For the assessment of the dissolution of dolomite, the key parameter is the output pH, which will indicate if sufficient dolomite has been dissolved to completely neutralise the AMD. The output pH, as a function of cumulative liquid (L) to solid (S) ratio for the 5 columns, is presented in Figure 5.

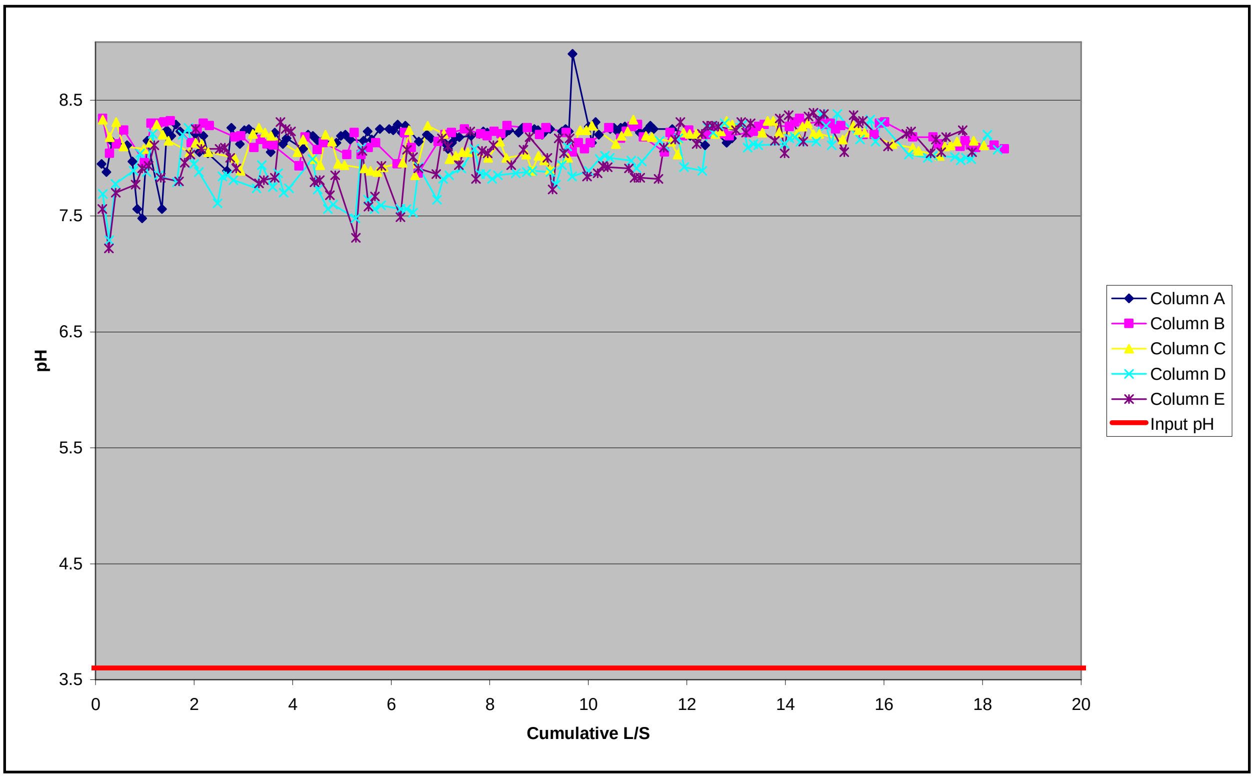

Figure 5. Results of 5 kinetic leach tests looking at the flow of AMD through dolomite under simulated aquifer conditions.

The experimental testing proceeded in all 5 columns until L/S ratios approaching 20 were achieved (a period of 5½ months). During this period the pH leaving the columns maintained a relatively constant value around 8, which is approximately the value that would be expected from an unimpacted dolomitic aquifer.

3.3.4 Assessment of the Attenuation of Pollutants by Reaction with Dolomite

Four samples were collected during the course of the leach test and submitted to the Council for Geoscience Laboratory for analysis of major and trace element chemistry, with the aim of assessing the potential for natural attenuation of AMD within dolomitic systems. The results of these tests for selected elements typical of the AMD encountered in the Western Basin, are presented in Figure 6 to Figure 12 and discussed in Table 4.

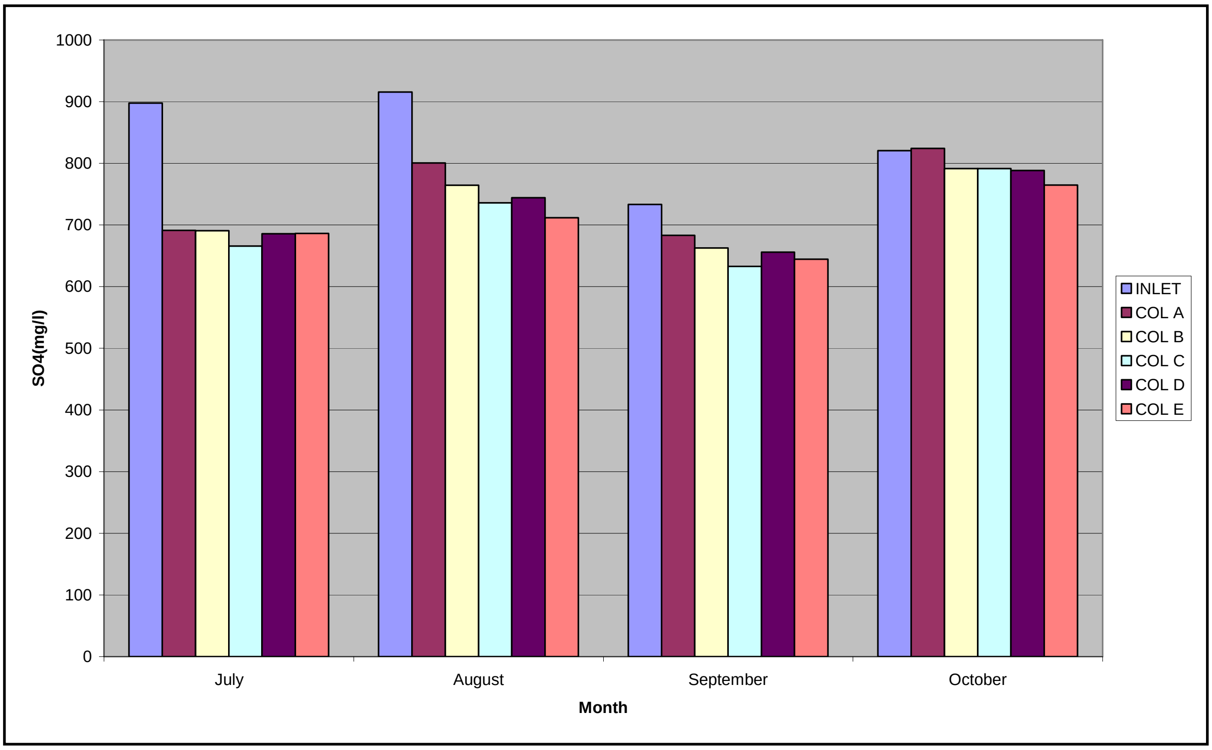

Figure 6. Attenuation test results for sulphate.

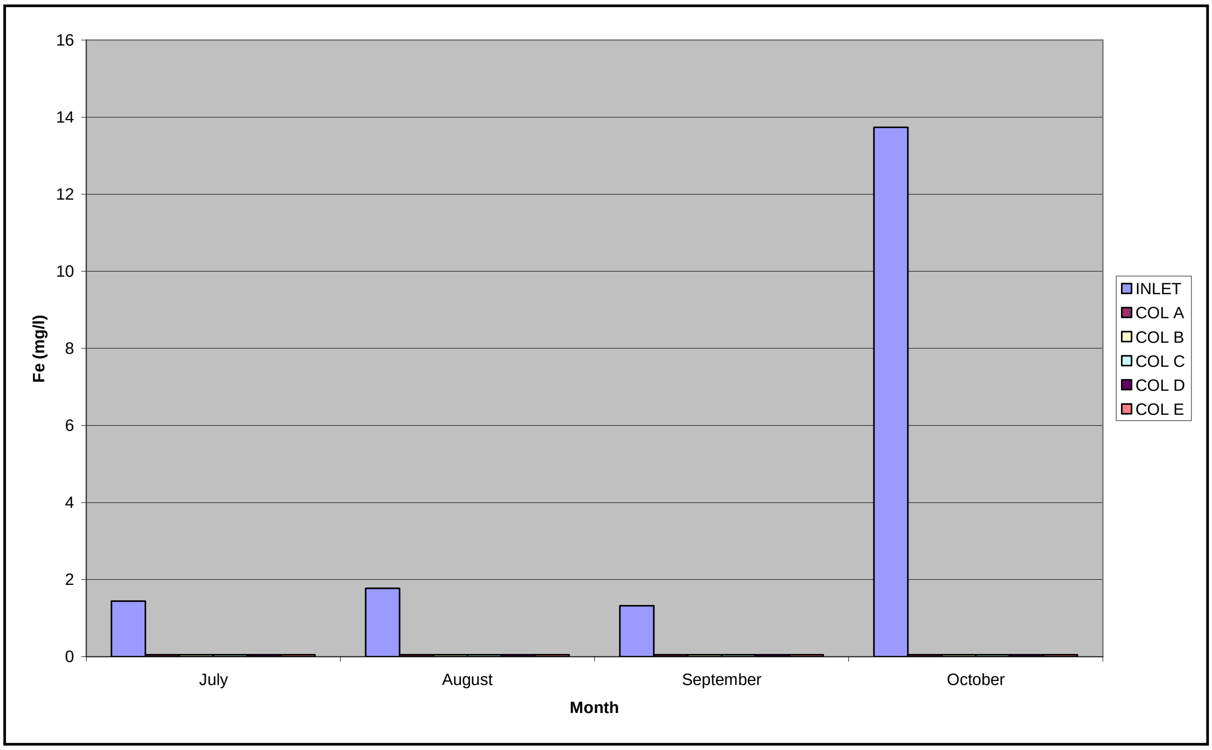

Figure 7. Attenuation test results for iron.

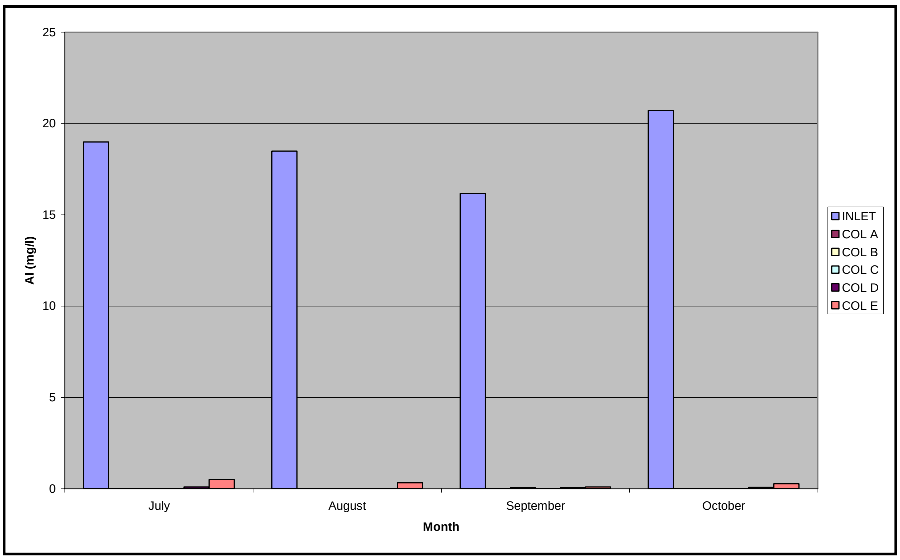

Figure 8. Attenuation test results for aluminium.

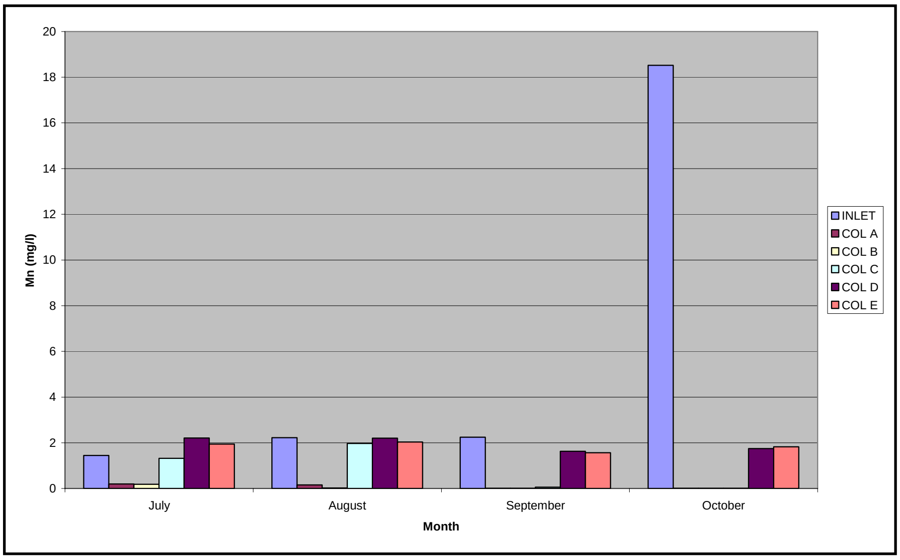

Figure 9. Attenuation test results for manganese.

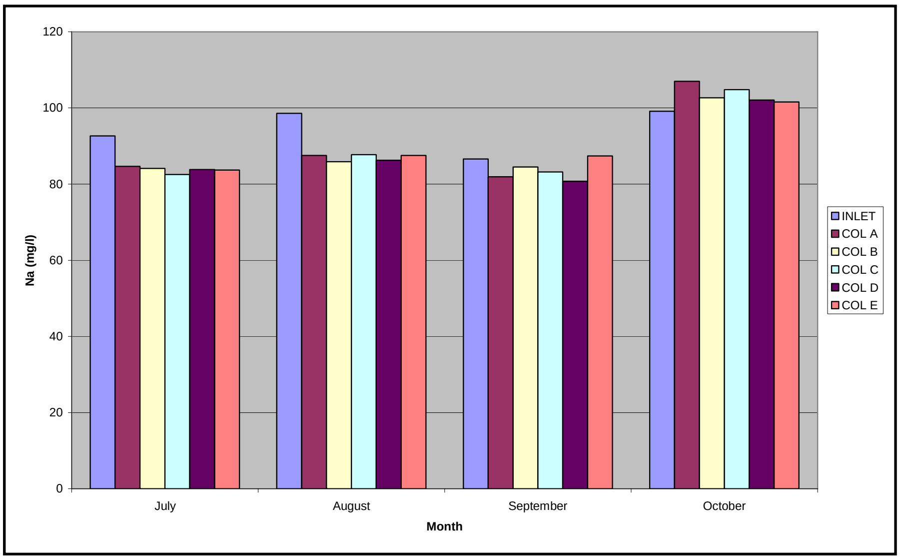

Figure 10. Attenuation test results for sodium.

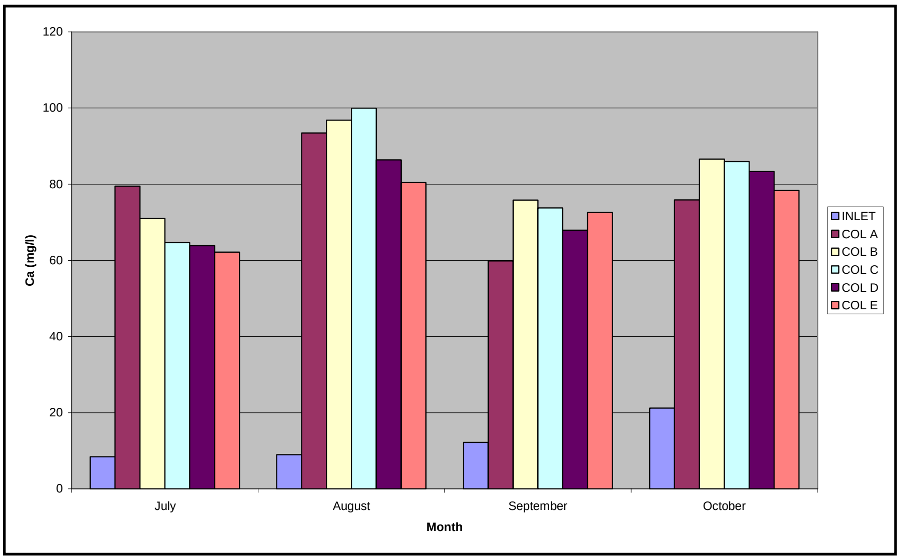

Figure 11. Attenuation test results for calcium.

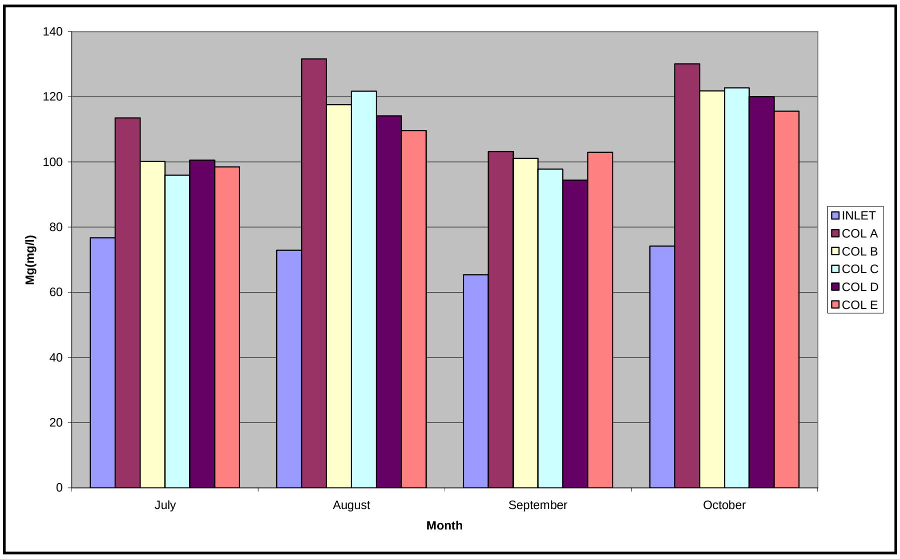

Figure 12. Attenuation test results for magnesium.

Table 4. Summary of the effects of the reactions between dolomite and synthetic AMD.

Contaminant	Observed Effect	Interpretation
SO_4	Little attenuation throughout the experiment	Neutralisation has little effect on the SO_4 concentration, preventing the application of natural attenuation
Fe	Effective attenuation throughout the experiment	Raising the pH of the solution results in the precipitation of Fe from solution
Al	Effective attenuation throughout the experiment	Raising the pH of the solution results in the precipitation of Al from solution
Mn	Mn was removed in the columns containing fine grained material	Mn attenuation would only be feasible in aquifers where large surface areas are exposed. This is not commonly the case in dolomitic aquifers where much of the flow occurs in large solution cavities.
Na	Little attenuation throughout the experiment	Neutralisation has little effect on the Na concentration, preventing the application of natural attenuation
Ca	Ca significantly increased in the column effluents	The preferential dissolution of $CaCO_3$ in dolomite drives the neutralisation of the AMD solution
Mg	Mg increased to a lesser degree than Ca	Some $MgCO_3$ is dissolved in the neutralisation process

3.3.5 Assessment of the Precipitation of Reaction Products in the Neutralisation Process

During the course of the column tests it was noticed that a precipitate was forming at the base of the columns, and that the zone in which the precipitate formed migrated gradually upwards with time. As the flow direction within the columns was upward, this is consistent with the precipitation of reaction products at the point of first contact between the column fill material and the leachant. Figure 13 shows this zone of precipitation in Column E – the column containing the coarsest size fraction of dolomite. The distinctive iron staining in the precipitate, indicating the precipitation of iron in the form of an Fe^{3+} mineral along with a white precipitate, is notable. Figure 14 and Figure 15 show highly magnified scanning electron microscope images of the precipitate phase from Columns C and D. It can be seen in these images that the precipitate forms an overgrowth covering the dolomite surface. In both cases, the mineral phase has been analysed to contain Al, O and S and exists in both a crystalline and an amorphous (botryoidal) form.

Figure 13. Precipitation of reaction products at the base of a column.

4 CONCLUSIONS

4.1 Experimental conclusions

4.1.1 Dissolution of Dolomite

Both the batch and kinetic tests performed demonstrate that dolomite is dissolved during interactions with AMD. This is indicated both by the neutralisation of the AMD at sufficiently high solid to liquid ratios and by petrographic investigations which show the etching of dolomite after interaction with AMD. Whether this will lead to the development of new cavities within the affected dolomitic areas cannot be determined, as this will be influenced by a combination of the flow rate, the surface area exposed and the rate at which mineral precipitation armours the reactive surface of the dolomite within the aquifer.

4.1.2 Precipitation of Minerals during the Interaction between Dolomite and AMD

During both the batch and kinetic tests, new minerals were observed to be precipitated during the interaction between dolomite and original and synthetic AMD solutions. These were identified at a macro-scale (Figure 13) and a micro-scale using both optical and scanning electron microscopy. The exact minerals which precipitate will depend on the chemistry of the input solutions as well as the Eh-pH conditions under which precipitation occurs. In a number of instances armouring of the dolomite surface with reaction products has been observed, and it is reasonable to expect that this process will continue, reducing the quantity of reactive material exposed.

4.1.3 Attenuation of Contaminant Plumes by Interaction with Dolomite

The dissolution of dolomite by AMD causes an increase in the pH of the solution, reducing the solubility of a number of its components. Iron and aluminium are almost completely attenuated, manganese is partially attenuated, with an apparent strong dependence on the available reactive surface area while sodium and sulphate are not attenuated significantly. The final solutions produced in these experiments contained increased concentrations of calcium and magnesium as a result of the dissolution of dolomite, with an apparent preferential dissolution of calcium over magnesium.

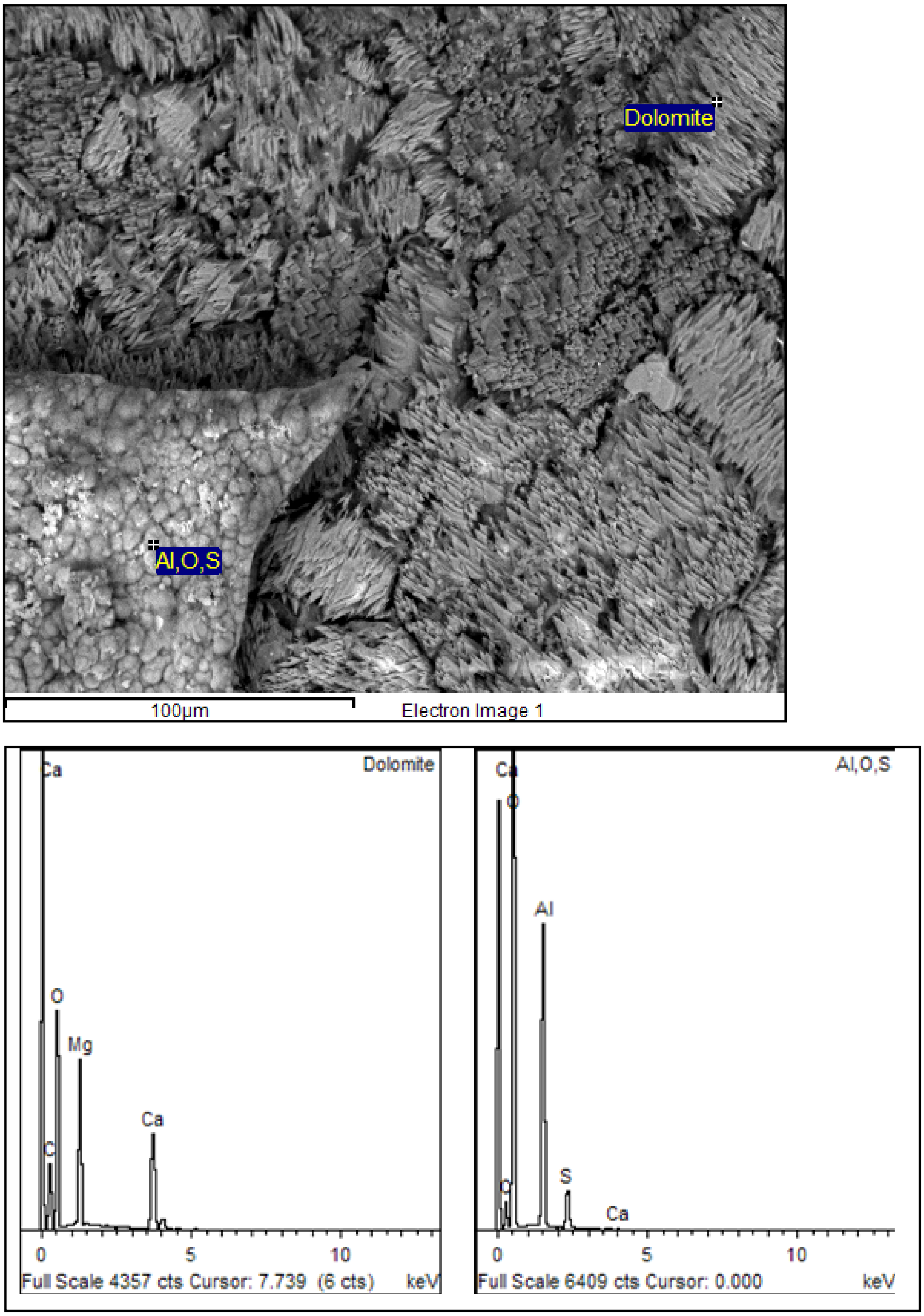

Figure 14. SEM image (top) of the precipitate overgrowth on dolomite in Column C, and (bottom) spot analyses of minerals by EDS.

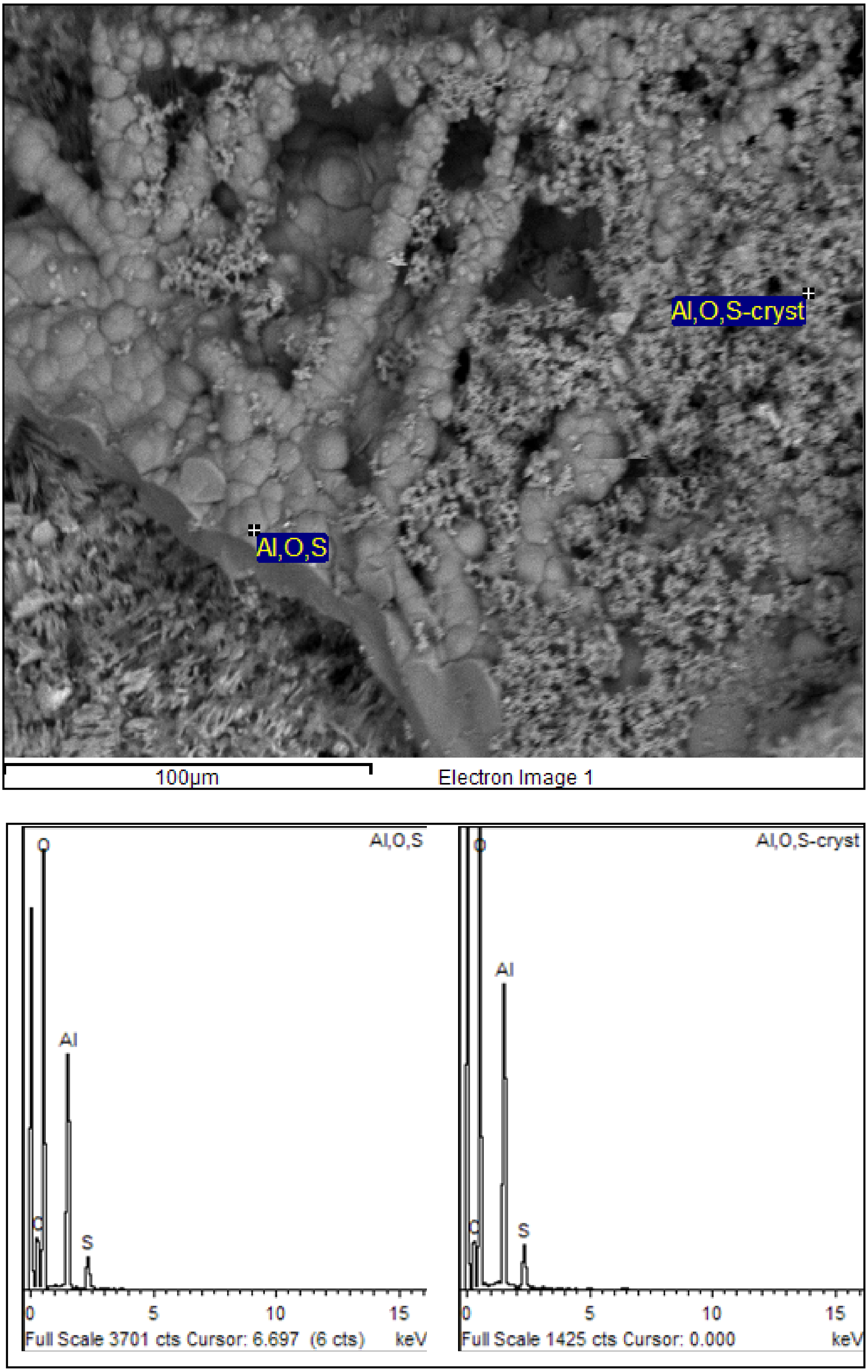

Figure 15. SEM image (top) of the precipitate overgrowth on dolomite in Column D showing both crystalline and botryoidal (amorphous) precipitate, and (bottom) spot analyses of minerals by EDS.

4.2 Explanation of the Experimental Results in the Context of a Dolomitic Aquifer

AMD has been observed to enter dolomitic aquifer systems in the Western Basin, via both underground and surface recharge pathways. The likely effects of this contamination will be a rise in the pH of the AMD to a value comparable to that expected for dolomitic groundwater as a result of the dissolution of dolomite. This could lead to a structural weakening of the subsurface formation if the process continued over a long period of time without the dolomite surfaces becoming armoured. The rise in pH would result in the reduction of the solubility of some of the contaminant species within the AMD, significantly removing iron and aluminium from solution, partially removing manganese and not having a significant effect on the sodium or sulphate concentration.

At the same time new mineral species likely to include gypsum, goethite and crystalline and amorphous (botryoidal) aluminium oxy-hydroxide species, are likely to form on the reactive surfaces of the dolomite, preventing further neutralisation reactions from taking place. An influent AMD plume would therefore tend to react at the point of first contact with the dolomitic aquifer material, resulting in both neutralisation of the AMD and the prevention of further neutralisation from taking place. Over time the AMD plume would therefore migrate further and further into the dolomite and the buffering capacity of the aquifer would be progressively reduced.

4.3 Implications of Natural AMD Attenuation by Interaction with Dolomite

While the reactions between dolomite and AMD are effective at neutralising the low pH of AMD and removing certain contaminants, notably iron and aluminium, they do not remove all of the contaminant species which characterise Witwatersrand AMD. In particular the reactions are not effective in removing sulphate, which is the major contributor to the high salinity of AMD.

Furthermore, the precipitation of a layer of armouring minerals on the reactive surface of the dolomitic aquifer material will, over time, reduce its ability to attenuate even those elements which are attenuated in reactions between dolomite and AMD.

Natural attenuation of AMD by allowing it to enter dolomitic aquifer systems is therefore not regarded as an appropriate or sustainable management strategy.

The experimental tests undertaken did not study the behaviour of hazardous trace elements such as uranium. As the reactions between dolomite and AMD are not regarded as a viable means to naturally attenuate AMD contamination of groundwater, further experimental testing to look at the effect on uranium and other trace elements is not required, unless they aim to investigate the pollution which has already occurred in a number of areas.

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SUPPLEMENTARY REPORT F

CSIR Report on the Koelenhof Farm Fish Mortality Event of mid-January 2011

Cradle of Humankind©
World Heritage Site

DEPARTMENT OF ECONOMIC DEVELOPMENT
GAUTENG PROVINCIAL GOVERNMENT, SOUTH AFRICA

PROJECT TITLE

ESTABLISHMENT OF A MONITORING SYSTEM FOR SURFACE WATER AND GROUNDWATER IN THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

THE KOELENHOF FARM FISH MORTALITY EVENT OF MID-JANUARY 2011

DATE

JANUARY 2011

PROJECT

BIQ005/2008

Report prepared for

Management Authority

Cradle of Humankind World Heritage Site & Dinokeng

Department of Economic Development

Gauteng Provincial Government

Report prepared by

Council for Scientific and Industrial Research [CSIR]

CSIR Natural Resources & the Environment

PO Box 395, Pretoria, 0001, South Africa

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Citation

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EXECUTIVE SUMMARY

The Management Authority (MA) of the Cradle of Humankind World Heritage Site (COH WHS) commissioned project BIQ005/2008 to develop a water resources monitoring programme for the area. A fish mortality event that occurred on Koelenhof Farm *ca.* mid-January 2011 toward the end of this project generated wide coverage in both the print and broadcast media following its 'discovery' on the morning of 13/01/2011. As could be expected, the coverage focused on acid mine drainage (AMD) as the cause of the event. This report aims to piece together the circumstances surrounding the event based on various sources of information and data obtained both before and shortly after the event. The reconstruction hopefully provides a factual narrative that objectively informs the unfortunate situation.

Flood conditions were experienced in the Tweelopie Spruit, the lower Riet Spruit and the Bloubank Spruit following high rainfall experienced in the region in mid-December 2010. The flood event disrupted flow into the A-furrow that serves properties on the right bank of the Bloubank Spruit downstream of the Zwartkrans Spring. This furrow feeds numerous off-channel dams that store primarily irrigation water, but are also stocked with fish. Flow into this furrow from out of the Bloubank Spruit was only restored *ca.* 10/01/2011, when concern was expressed for the yellow appearance of the water and its suitability for various uses including stock watering and irrigation. Both the mid-December 2010 and mid-January 2011 circumstances precipitated a series of field water chemistry variable measurements at 'key' locations along the effected drainages.

The Koelenhof Farm fish mortality event was precipitated by a combination of factors. The first of these, identified as the disruption of flow into the A-furrow feeding the off-channel storage dam that hosted the event, occurred almost a month prior to the event. The second factor is identified as the recent partial restoration of flow from the Bloubank Spruit into the A-furrow, and from there into the Koelenhof Farm dam after almost a month of being cut off. Thereafter, a combination of causative factors including

- the resuspension of anoxic sediments as a result of river floods,
- the presence of oxidizable organic matter represented by a high bacteriological load most likely originating in municipal wastewater (sewage) effluent discharges,
- suspended material in the water,
- high water temperatures in the dam, and
- the presence of a significant (albeit diluted) ferric iron-bearing mine water component in the oxygenated surface discharge,

contributed to reducing dissolved oxygen concentrations to sub-lethal and lethal levels for the resident carp population. Together with the precipitation of iron hydroxides, it is probable that these factors resulted in severe irritation causing the carp to secrete mucus as a protective skin cover and to provide protection against toxins, amongst others ammonia and heavy metals, in the water. Such mucus was especially evident in the gills of a specimen studied at Onderstepoort, indicating that the specimen had suffocated. These circumstances explain the observed fish mortalities in this impoundment.

An assessment of the fitness of the water for irrigation and livestock watering uses is severely constrained by the single sample nature and the limited number of variables that characterize the chemical analysis. Nevertheless, the chemical composition of the surface water sample collected at 13h15 on 12/01/2011 at station BB@M in the Bloubank Spruit is equally unsuited for irrigation use and livestock watering use in the medium- to long-term. Although this might not apply to short-term use provided that other factors remain unchanged, it is advised that caution be exercised and, if necessary, the relevant advisory expertise be sought.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

LIST OF ANNEXURES

DEFINITION OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

~	approximately
>	greater than
%	per cent (parts per hundred)
%ile	percentile
°C	degree(s) Centigrade
Al	aluminium
AMD	acid mine drainage
ca.	*circa* (about)
Ca	calcium
COH WHS	Cradle of Humankind World Heritage Site
Cl	chloride
CN	cyanide
CTR	corrosion tendency ratio
DWA	Department of Water Affairs (formerly DWAF; Department of Water Affairs and Forestry)
EC	electrical conductivity
Fe	iron
HCO_3	bicarbonate
HDS	high density sludge
K	potassium
L/s	litre(s) per second
m	metre(s)
MA	Management Authority
MAV	minimum allowable value
meq/l	milliequivalent(s) per litre
Mg	magnesium
mg/L	milligram(s) per litre
mm	millimetre(s)
Mn	manganese
mS/m	milliSiemens per metre
mV	milliVolt
N	nitrogen
Na	sodium
NH_3	ammonia nitrogen in the un-ionized (free) form
NH_4	ammonia nitrogen in the ionized form as the ammonium ion
Ni	nickel
n.m.	not measured
NO_2	nitrite nitrogen
NO_3	nitrate nitrogen
PO_4	phosphate
pp.	pages
SAR	sodium adsorption ratio
SO_4	sulphate
TWQR	target water quality range
WWTW	wastewater treatment works

1 INTRODUCTION AND BACKGROUND

The Management Authority (MA) of the Cradle of Humankind World Heritage Site (COH WHS) commissioned project BIQ005/2008 to develop a water resources monitoring programme for the area (Figure 1). A fish mortality event occurred on Koelenhof Farm on 11/01/2011 (B. Govender, fax communication) toward the end of this project. The event generated wide coverage in both the print and broadcast media following its 'discovery' on the morning of 13/01/2011. As could be expected, the coverage focussed on acid mine drainage (AMD) as the cause of the event (Tempelhoff, 2011a; 2011b). This report aims to piece together the circumstances surrounding the event based on various sources of information and data obtained both before and shortly after the event. The reconstruction therefore attempts to provide a factual narrative that objectively informs the unfortunate situation.

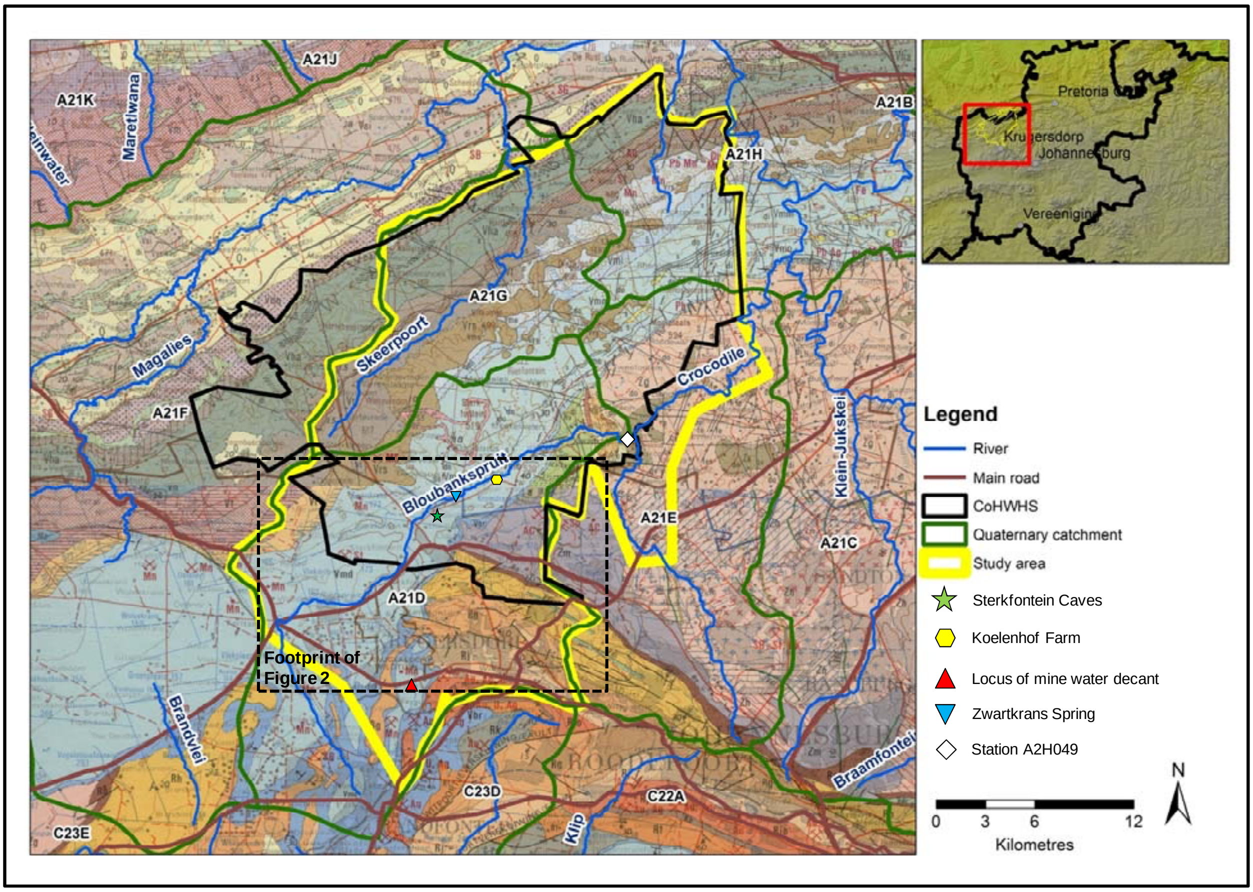

Figure 1. Definition of the study area in regard to the regional geology, surface water drainages and quaternary catchments, and specific locations of relevance to this report.

2 PRE-EVENT CIRCUMSTANCES

Flood conditions were experienced in the Tweelopie Spruit, the lower Riet Spruit and the Bloubank Spruit following the high rainfall experienced in mid-December 2010. Various sources in the area reported precipitation in the order of 130 to 140 mm in a period of ~24 hours *ca.* 16/12/2010. The rainfall gauging station operated by Rand Uranium at the Black Reef Incline in the locus of decant in the upper reaches of the Tweelopie Spruit recorded ~90 mm (B. van der Walt, personal communication) between 07h00 on 16/12/2010 and 07h00 on 17/12/2010. The aftermath of the flood event was still visible on 18/12/2010 (Plate 1), when a series of surface water field chemistry measurements were made at 'key' locations (refer Figure 2) along the effected drainages. The results are presented in Table 1.

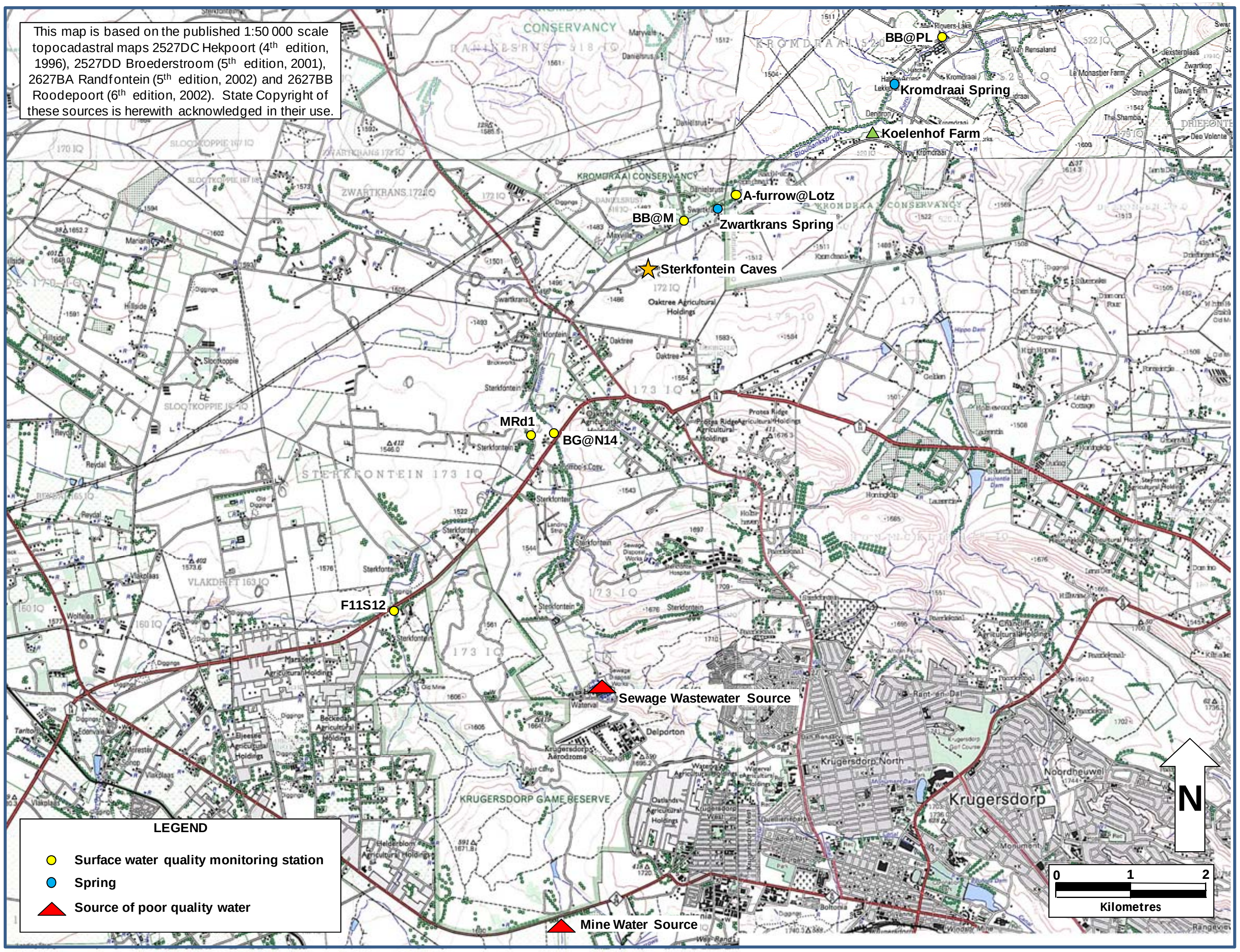

Figure 2. Location of water quality monitoring stations and other relevant sites referred to in this report.

Plate 1. View of station BB@M on 18/12/2010 showing inundation of the causeway following the flood conditions precipitated by high rainfall experienced in the region *ca.* 16/12/2010. Similar flow conditions again prevailed on 14/01/2011. (Photo: Phil Hobbs).

Perhaps the most significant impact was the disruption of flow into the A-furrow (Plate 2) that serves properties on the right bank of the Bloubank Spruit downstream of the Zwartkrans Spring (Figure 2).

Plate 2. View from downstream of the sluice gate at the entrance to the A-furrow downstream of the Zwartkrans Spring following the high discharge conditions experienced in the Bloubank Spruit in mid-December 2010; note the disruption of flow into the furrow and the sediment deposition on the left bank (right foreground). (Photo: Phil Hobbs).

The A-furrow feeds numerous off-channel dams that store primarily irrigation water, but are also stocked with fish. Flow into this furrow from out of the Bloubank Spruit was only restored, albeit partially, on 10/01/2011 (M. Gomes, personal communication), i.e. a day before the fish mortality event. Concern was expressed for the yellow appearance of the furrow water and its suitability for various uses including stock watering and irrigation. Unaware of the fish mortality event, this communication precipitated another round of field water quality monitoring on 12/01/2011, the results of which are also reported in Table 1. Further, a surface water sample was collected at station BB@M for more complete laboratory chemical analysis. The result of this analysis is presented in Annexure A.

Table 1. Surface water field chemistry variables sourced on 18/12/2010 and 12/01/2011.

Station	Field Chemical Variable							
	pH		EC (mS/m)		Eh (mV)		Temp. (°C)	
	18/12/2010	12/01/2011	18/12/2010	12/01/2011	18/12/2010	12/01/2011	18/12/2010	12/01/2011
F11S12	2.7	2.5	416	397	230	243	21.3	21.1
MRd1	3.0	2.3	276	410	217	254	24.1	25.0
BG@N14	n.m.	8.2	n.m.	53	n.m.	–65	n.m.	26.1
BB@M	6.1	2.9	158	155	51	221	24.8	23.9
BB@PL	n.m.	6.8	n.m.	94	n.m.	12	n.m.	21.3
A2H049	n.m.	7.7	n.m.	87	n.m.	–37	n.m.	22.3

The salinity (EC) values of 158 and 155 mS/m recorded at station BB@M are the highest recorded at this station in the year-long course of the main study, and the pH values of 6.1 and 2.9 similarly the lowest observed. These circumstances reflect the dominant contribution of raw mine water discharge to the chemistry of surface water at this locality on this occasion. Of specific relevance to the fish mortality event is the very low pH value of 2.9 observed on 12/01/2011. A further inspection of the 12/01/2011 data (Table 1) reveals the following hydrochemical characteristics:

- The very low pH values and elevated salinity values of ~400 mS/m at the uppermost two stations F11S12 and MRd1 indicating a strong mine water signature at these localities (Plate 3).

- The generally good inorganic quality associated with the Percy Stewart WWTW discharge via the Blougat Spruit (station BG@N14) into the Bloubank Spruit system as shown by the high pH value and low salinity (EC) value; note that this does not imply an acceptable bacteriological quality.

- The very low pH and elevated salinity of the surface water at station BB@M, again indicative of a mine water impact on the quality of the surface water at this locality. Whereas the pH value represents the most extreme value observed at this station in the project period, the EC value is only exceeded by that observed on 18/12/2010 (Table 1). Significantly, the Eh value of 221 mV (indicative of an oxidizing environment) approximates those observed at the upstream stations F11S12 and MRd1.

- The improvement in quality at the downstream station BB@PL, as reflected in a higher pH and lower EC compared to that at station BB@M, is attributed to the mitigatory influence contributed by the ~307 L/s Kromdraai Spring.

- The still quite 'acceptable' pH and EC values at station A2H049 at the bottom end of the Bloubank Spruit system (Figure 1) at Glenburn Lodge near Zwartkop, although the pH value approaches the long-term 5%ile value of 7.4, and the EC value exceeds the long-term 95%ile value of 66 mS/m recorded at this DWA flow gauging and water quality monitoring station. In fact, the observed EC value of 87 mS/m exceeds the maximum value of ~75 mS/m recorded in the 29-year period May 1979 to May 2008 that represents the historical record of water chemistry data available for this station from the DWA.

Plate 3. Discharge in the Riet Spruit at its intersection with the Malmani Road (station MRd1) on 12/01/2011; note the red colouration of the water indicative of a strong acid mine water character (refer Table 1 for supportive field chemistry variable values). Downstream of this position, this water merges with sewage wastewater delivered by the Blougat Spruit. (Photo: Phil Hobbs).

In regard to the surface water sample collected for laboratory analysis, it was observed that the oxidation of dissolved iron in the water sample resulted in the precipitation of an iron oxide in the sample bottle during transport and laboratory storage. This was not observed in the acidified sample bottle. This observation finds support in the iron concentration of 44 mg/L reported in Annexure A. Further inspection of the laboratory report results (Annexure A) reveals the following characteristics:

- The indicator variables pH, EC, Ca, SO_4, Fe and Mn that reflect the presence of mine water in the surface water.

- The indicator variables Cl, NO_3 and NH_4 that reflect the presence of sewage wastewater in the surface water.

- The metals Al and Ni are considered to reflect the presence of both mine water and sewage wastewater sources, although the respective contribution of these sources to the observed concentrations is not readily established.

3 POST-EVENT CIRCUMSTANCES

The first author was notified on 13/01/2011 that fish mortalities had been ‘discovered’ on Koelenhof Farm upstream of the Kromdraai Store T-junction (M. Liefferink, personal communication). The mortalities occurred in an off-channel irrigation water storage dam fed by the A-furrow, and not in the natural stream course of the Bloubank Spruit (G. Krige, personal communication). It is therefore probable that the partially restored flow of Bloubank Spruit water into the A-furrow (refer section 2), and shortly thereafter also into the Koelenhof Farm off-channel storage dam, resulted in the observed fish mortalities for the following reasons.

Firstly, consider that the Koelenhof Dam had experienced a lack of inflow since disruption of the A-furrow flow *ca.* 16/12/2010. When inflow from this source resumed on 10/01/2011, the field water chemistry variable values reported in Table 1 at station BB@M on 12/01/2011 indicate the significant presence of mine water in the surface water discharge at this location. This finds support in the more complete chemical analysis reported in Annexure A. It is therefore reasonable to presume that subsequent replenishment of the Koelenhof Farm dam with turbid Bloubank Spruit water via the A-furrow resulted in the depletion of oxygen associated with the precipitation of iron hydroxides in this low energy impounding environment. It is probable that these factors resulted in severe irritation causing the carp to secrete mucus as a protective skin cover and to provide protection against toxins (note the presence of ammonia[1] in the water as reflected in Annexure A). Such mucus was especially evident in the gills of a specimen studied at Onderstepoort (Dr. J. Myburgh, email communication), indicating that the specimen had suffocated. These circumstances explain the observed fish mortalities in this impoundment, and are also likely to have similar consequences for crustaceans, invertebrates and other aquatic organisms resident in the dam.

Enquiries by the first author on 13/01/2011 also established that abnormally high fish mortalities had recently been experienced at the Brookwood Trout Farm located downstream of station BB@PL (Table 1) (H. Carpenter, personal communication). It is probable that similar activities such as at Kloofzicht Lodge might also have experienced this impact. However, the better quality of the surface water in the lower reaches of the Bloubank Spruit (section 2) is certain to have lessened the magnitude of any negative impact on aquatic life in off-channel storage dams in this part of the study area.

The Koelenhof Farm fish mortality event precipitated further field studies on 14/01/2011 by the authors. The nature of the event that prompted these studies necessitated the measurement of dissolved oxygen (DO) as an additional field water chemistry variable. The results are presented in Table 2 and discussed in greater detail hereunder.

Table 2. Surface and groundwater field chemistry variables sourced on 14/01/2011.

Station	Field Chemical Variable				
	pH	EC (mS/m)	Eh (mV)	DO (%)	Temp. (°C)
Bloubank Spruit at Makiti (BB@M)	6.0	21.9	48	106	21.1
Zwartkrans Spring (ZWSp)	7.3	73.6	–19	66	19.1
A-furrow @ Lotz (upstream of KFD)	6.2	24.0	44	101	21.1
Koelenhof Farm dam (KFD)	3.6	128.7	178	60	24.0
Koelenhof Farm furrow downstream of KFD	5.6	126.8	72.2	103	21.5
Sterkfontein Caves lake	7.8	55.8	–49	66	16.7

[1] At the field pH values of 2.9 on 12/01/2011 at the station BB@M (Table 1) and 3.6 on 14/01/2011 at the station Koelenhof Farm dam (Table 2), this is almost certainly ammonium (NH_4) rather than free ammonia (NH_3).

An inspection of the data presented in Table 2 reveals the following hydrochemical characteristics:

- In regard to the station BB@M;
  - the low pH value that is indicative of, amongst other sources, a combination of very low pH mine water and low pH rain water runoff in the discharge at this position in the Bloubank Spruit,
  - the very low EC value of ~22 mS/m compared to the value of 155 mS/m measured two days earlier on 12/01/2011 (Table 1), which similarly reflects the significant contribution of fresh water in the river on 14/01/2011,
  - the high level of oxygen saturation reflected by the DO value of 106%, which is readily explained by the degree of turbulence in the strong-flowing river and natural diffusion of gaseous oxygen (O_2) from the atmosphere into the water (DWAF, 1996a); the super-saturated oxygen state is possibly indicative of eutrophication (Annexure C) associated with a high nutrient load attributable to the presence of sewage wastewater effluent.

- The similar variable values observed at the station A-furrow @ Lotz as were observed at station BB@M, which establishes the direct hydraulic link between the Bloubank Spruit surface water and that flowing in the A-furrow.

- The very low pH and DO[2] values, and the elevated EC and temperature[3] values of the Koelenhof Farm dam water, which likely represent an artefact of the water quality conditions that gave rise to the fish mortality event.

- The saturated oxygen content of the furrow water downstream of the Koelenhof Farm dam compared to the 60% DO concentration of the dam water.

- The similar variable values (except for temperature) associated with the Zwartkrans Spring and Sterkfontein Caves lake water, which establishes the hydraulic connection between these two groundwater sources. [Note: The cave water level has risen by 0.66 m between 09/06/2010 and 14/01/2011, an average rate of rise of ~0.09 m per month.] Whereas the Zwartkrans Spring salinity of ~74 mS/m is similar to its more recent 'historical' value, the cave water salinity of ~56 mS/m is slightly lower than the typical 59 to 62 mS/m range that characterizes this cave water quality variable. The fresher nature of the cave water is attributed to the influence of considerably fresher rain water directly infiltrating the cave environment from above. For comparison, the DWA reports a salinity value of 74 mS/m in April 2001.

4 FITNESS OF WATER FOR USE

The concern for the suitability of the A-furrow water quality for uses such as irrigation and stock watering is mentioned in section 2. The more complete chemical analysis reported in Annexure A provides some information to address this concern, although the veracity of the assessment must be qualified as follows.

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[2] The Target Water Quality Range (TWQR) for the DO level in aquatic ecosystems brackets the range 80 to 120% of saturation, and a DO level below the Minimum Allowable Value (MAV) defined by a 7-day mean minimum value of >60% (sub-lethal) in combination with a 1-day minimum value of >40% (lethal), is likely to cause acute toxic effects on aquatic biota (DWAF, 1996).

[3] High water temperatures combined with low DO levels can compound stress effects on aquatic organisms (DWAF, 1996).

The analysis represents the quality at the time of sampling, namely at 13h15 on 12/01/2011. The field variable values associated with the 12/01/2011 (Table 1) and 14/01/2011 (Table 2) measurements at the sampling locality BB@M indicate how much the water quality/chemistry may vary over a short space of time. Further, the bacteriological quality of the water was not determined, although the presence of ammonia (NH_4) suggests that elevated bacteria levels (total coliform, faecal coliform and *E. coli*) were most likely also present in the water on 12/01/2011. The assessment is therefore valid only for the sample analysis and the variables reported in Annexure A. Nevertheless, the following discussion attempts to describe the fitness of the water for irrigation and stock watering uses within the framework of these limitations.

4.1 Irrigation

The fitness of water for irrigational use is assessed on the basis of the sodium adsorption ratio (SAR) and salinity (expressed as electrical conductivity) of the water. The SAR is calculated as the ratio between the Na concentration and the combined Ca and Mg concentrations using the formula

$$SAR = Na / [(Ca + Mg)/2]^{½} \qquad \text{(variable concentrations as meq/L)}$$

to derive the sodium hazard (designated S) associated with the water. This value is graphed against the electrical conductivity value, which represents the salinity hazard (designated C), to derive an alpha-numeric classification (e.g. C#-S#) defined by the Wilcox diagram (Figure 3), and where the numeric component ranks from 1 = **low** through 2 = **medium** and 3 = **high** to 4 = **very high**. The C3-S1 classification (Figure 3 and Annexure B) is in keeping with that typically observed in the Blougat Spruit and the Riet Spruit (Hobbs, 2011), and clearly identifies salinity (EC) as the limiting variable.

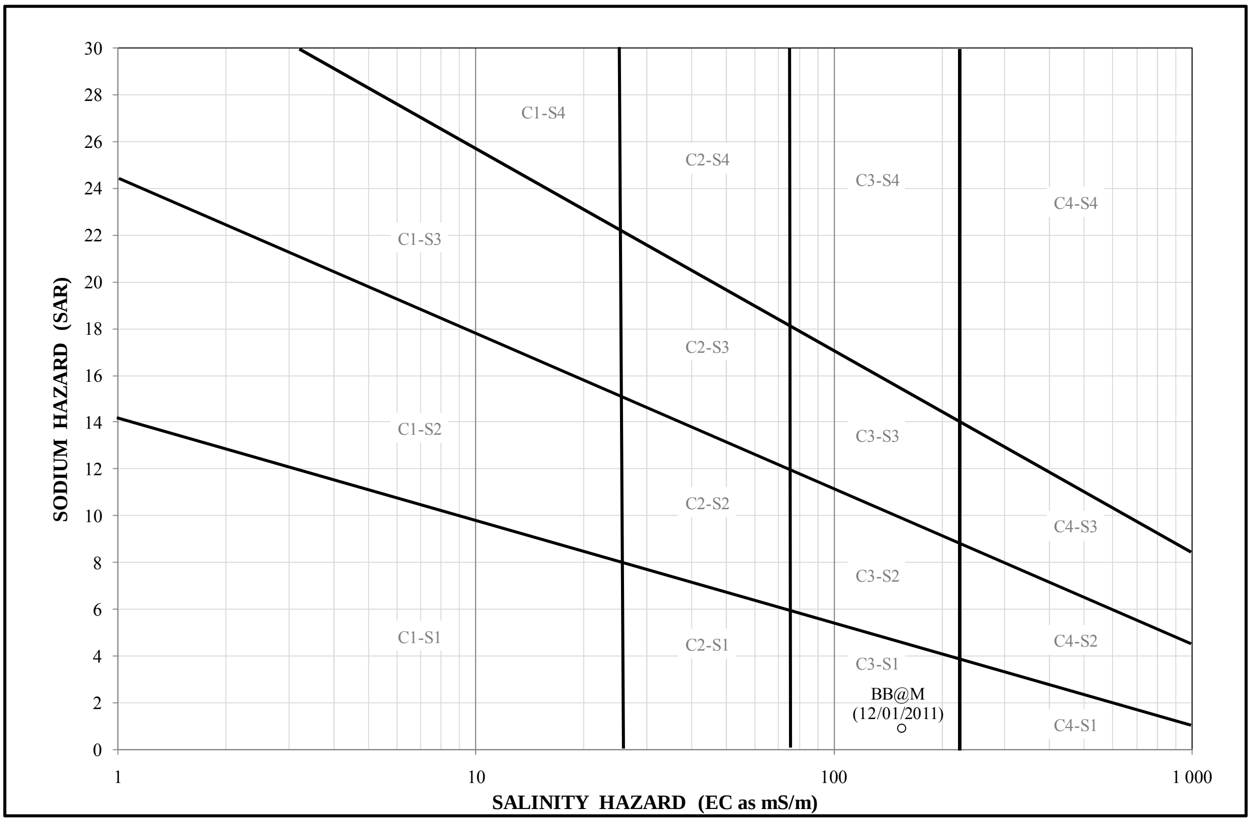

Figure 3. Wilcox diagram illustrating the classification of the Bloubank Spruit surface water chemistry on 12/01/2011 for irrigation purposes

Other aspects of the water chemistry that have relevance to the irrigational use of the water are the N/P ratio and the corrosion tendency ratio (CTR) values. The N/P ratio value of 34:1 (Annexure B) is only slightly smaller than the 41:1 ratio that characterizes the long-term median value at station A2H049 (Hobbs, 2011). It still falls within the >25 to 40:1 range that typically characterizes unimpacted systems[4]. The CTR value of 338, together with the low pH value of ~3, indicates the water is extremely corrosive. However, corrosion of pipelines and fittings is only likely to manifest as a problem through continued and medium- to long-term use of water with this chemical composition. This is unlikely to be the case.

Annexure B shows that 8 out of the 13 reported variables for which TWQR values for irrigation use are specified, exceed this limit. Although this might appear harsh, it should be considered that the listed TWQR values represent the strictest (most conservative) limit, and that higher limits define successively relaxed ranges with associated increasingly negative impacts.

4.2 Livestock Watering

Annexure B shows the metals iron and manganese to be the only variables that exceed the listed TWQR values for the 10 reported variables for which limits are set. It should again be considered that the listed TWQR values represent the strictest (most conservative) limit, and that higher limits define successively relaxed ranges with associated increasingly negative impacts. It is probable that the combination of high Fe and Mn concentrations and low pH value might impart a bitterness to the water that would make it less palatable to livestock. However, adverse chronic effects such as liver and pancreas damage may occur, but are unlikely if feed concentrations are normal and exposure is short-term (DWAF, 1996c).

5 CONCLUSIONS

The Koelenhof Farm fish mortality event was precipitated by a combination of factors. The first of these, identified as the disruption of flow into the A-furrow feeding the off-channel storage dam that hosted the event, occurred almost a month prior to the event. The second factor is identified as the recent partial restoration of flow from the Bloubank Spruit into the A-furrow, and from there into the Koelenhof Farm dam after almost a month of being cut off. Thereafter, a combination of causative factors including (a) the resuspension of anoxic sediments as a result of river floods, (b) the presence of oxidizable organic matter represented by a high bacteriological load most likely originating in municipal wastewater (sewage) effluent discharges, (c) suspended material in the water, (d) high water temperatures in the dam, and (e) the presence of a significant (albeit diluted) iron-bearing mine water component in the oxygenated surface discharge, contributed to reducing dissolved oxygen concentrations in the Koelenhof Farm dam water to sub-lethal and lethal levels for the resident carp population.

An assessment of the fitness of the water for irrigation and livestock watering uses is severely constrained by the single sample nature and the limited number of variables that characterize the chemical analysis. Nevertheless, the chemical composition of the surface water sample collected at 13h15 on 12/01/2011 at station BB@M in the Bloubank Spruit is equally unsuited for irrigation use and livestock watering use in the medium- to long-term. Although this might not apply to short-term use provided that other factors remain unchanged, it is advised that caution be exercised and, if necessary, the relevant advisory expertise be sought.

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[4] Most impacted (eutrophic or hypertrophic) systems are characterized by an N/P ratio of less than 10:1 (DWAF, 1996a).

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ANNEXURE A
Chemical analysis laboratory report for surface water sample collected at station BB@M on 12/01/2011.

Variable	Value	Source Indicator Variable		Drinking Water TWQR (SANS 241: 2006)
		Mine water	Sewage wastewater	
Laboratory	CSIR (Pretoria)	—	—	—
Laboratory report no.	9156	—	—	—
Laboratory sample no.	82235	—	—	—
Report date (dd/mm/yyyy)	19/01/2011	—	—	—
Sample date (dd/mm/yyyy)	12/01/2011	—	—	—
pH (field value)	**2.9**			5.0 – 9.5
pH (lab value)	**3.2**			5.0 – 9.5
EC (mS/m) (field value)	**155**			<150
EC (mS/m) (lab value @ 25°C)	122			<150
Ca (mg/L)	149			<150
Mg (mg/L)	49			<70
Na (mg/L)	50			<200
K (mg/L)	9			<50
Cl (mg/L)	40			<200
SO_4 (mg/L)	**758**			<400
HCO_3 (mg/L)	<6			not specified
$NO_2 + NO_3$ (mg N/L)	4.8			<10
$NH_3 + NH_4$ (mg N/L)	2			
PO_4 (mg P/L)	<0.2			not specified
Fe (mg/L)	**44**			<0.2
Mn (mg/L)	**16**			<0.1
Al (mg/L)	**0.78**			<0.3
Ni (mg/L)	**0.35**			<0.15
CN (mg/L)	<0.01			
Electrical balance (%)	–3.0[(1)]			±5
Chemical character	$CaSO_4$			

(1) Includes Fe and Mn in the calculation. Value reduces to –10% without inclusion of these cations.

Notes: Bold and larger font values denote exceedance of SANS 241 (2006) guideline value for a Class 1 drinking water.
Shaded cells denote dominant source water indicator variable.

ANNEXURE B

Assessment of fitness for selected agricultural use of surface water sample collected at station BB@M on 12/01/2011.

Variable	Value		Fitness for Use: Irrigation TWQR (DWAF, 1996b)	Fitness for Use: Livestock Watering TWQR (DWAF, 1996c)
Sample date (dd/mm/yyyy)	12/01/2011		—	—
pH (field value)	2.9		6.5 – 8.4	not specified
pH (lab value)	3.2			
EC (mS/m) (field value)	155		≤40	<155
EC (mS/m) (lab value @ 25°C)	122			
Ca (mg/L)	149		not specified	<1000
Mg (mg/L)	49		not specified	not specified
Na (mg/L)	50		≤70	<2000
K (mg/L)	9		not specified	not specified
Cl (mg/L)	40		≤100	<1500
SO_4 (mg/L)	758		not specified	<1000
HCO_3 (mg/L)	<6		not specified	not specified
$NO_2 + NO_3$ (mg N/L)	4.8	6.8	≤5	22
$NH_3 + NH_4$ (mg N/L)	2			
PO_4 (mg P/L)	<0.2		not specified	not specified
Fe (mg/L)	44		≤5 ≤0.2(1)	<10
Mn (mg/L)	16		≤0.02 ≤0.1(1)	<10
Al (mg/L)	0.78		≤5	<5
Ni (mg/L)	0.35		≤0.2	<1
CN (mg/L)	<0.01		not specified	not specified
SO_4/Cl ratio	14.0		1.9(2)	not applicable
N/P ratio	34:1		41:1(2)	not applicable
Corrosion Tendency Ratio (CTR)	338		not specified	not applicable
Sodium Adsorption Ratio (SAR)	0.91		≤2	not applicable
Wilcox Classification for Irrigation	C3-S1		C1-S1 (ideal)	not applicable

(1) For clogging of irrigation equipment.

(2) Defined by Hobbs (2011) as the long-term median value for the Bloubank Spruit at station A2H049.

Note: Shaded cells denote TWQR of variable exceeded in water sample.

ANNEXURE C

Notes on dissolved oxygen and iron occurrence in regard to aquatic ecosystems

The South African Water Quality Guidelines – Aquatic Ecosystems (DWAF, 1996a) identifies several causative factors for the reduction in the dissolved oxygen (DO) levels in water. These are replicated hereunder:

- *Resuspension of anoxic sediments, as a result of river floods or dredging activities.*
- *Turnover or release of anoxic bottom water from a deep lake or reservoir.*
- *The presence of oxidizable organic matter, either of natural origin (detritus) or originating in waste discharges, can lead to reduction in the concentration of dissolved oxygen in surface waters.*
- *The amount of suspended material in the water affects the saturation concentration of dissolved oxygen, either chemically, through the oxygen-scavenging attributes of the suspended particles, or physically through reduction of the volume of water available for solution.*

Under anoxic conditions (in the absence of free and bound oxygen) in the water column or in sediments, heavy metals such as iron and manganese can appear in solution, as ferrous (Fe^{2+}) and manganous (Mn^{2+}) species, and toxic sulphides (S) may also be released.

High water temperatures combined with low dissolved oxygen levels can compound stress effects on aquatic organisms. The depletion of dissolved oxygen in conjunction with the presence of toxic substances can also lead to a compounded stress response in aquatic organisms. Under such conditions increased toxicity of zinc, lead, copper, cyanide, sulphide and ammonia have been observed.

Concentrations <100% saturation indicate that dissolved oxygen has been depleted from the theoretical equilibrium concentration. Results in excess of saturation (super-saturation of oxygen) usually indicate eutrophication in a water body.

In regard to iron, a common metal in mine water, the DWAF (1996a) reports the prediction that "……..*at a low pH, ferrous* [Fe^{2+}] *iron will predominate in the absence of oxygen, whilst ferric* [Fe^{3+}] *iron will predominate in oxygenated water*."

Recognition of the pre-event circumstances described in section 2 of this report indicate that at least three (1st, 3rd and 4th) of the four causative factors listed above could have played a role in the Koelenhof Farm fish mortality event. The resuspension of anoxic sediments is self-evident under the circumstances. The more than likely presence of a high bacteriological load in the Percy Stewart WWTW effluent is equally self-evident. Similarly, the amount of suspended material carried in the furrow following its 're-opening' must be acknowledged. The presence of iron associated with the mine water component in the oxygenated surface water is also recognized and acknowledged.

It is evident from the preceding discussion that the unfortunate fish mortality event experienced in the Koelenhof Farm off-channel storage dam cannot be attributed to acid mine water alone. An objective view must recognize other contributory factors as also playing a role. It remains arguable which of the various factors (or grouping of factors), if any, played the dominant role.

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