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THE HYDROGEOLOGY OF THE KRUGERSDORP GAME RESERVE AREA AND IMPLICATIONS FOR THE MANAGEMENT OF MINE WATER DECANT

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ABSTRACT

Acidic mine water draining from the West Rand Mining Basin first daylighted in late-August 2002. Initial estimates of the decant volume ranged between 7 ML/d in winter and 12.5 ML/d in summer. Recent estimates put the rate of decant between 18 and 36 ML/d with a pH of ~3.0 and electrical conductivity (EC) of ~550 mS/m, compared to the pH of ~8.0 and EC of <30 mS/m of ambient karst groundwater. The acid mine drainage (AMD) that daylights is collected and contained in various holding facilities, from where it is pumped to a treatment plant for neutralization and iron removal. The Krugersdorp Game Reserve lies immediately downslope of the locus of AMD. Other potential receptors of AMD include neighbouring smallholdings and, further afield, the Cradle of Humankind World Heritage Site. It is imperative, therefore, that the hydrogeological environment which hosts mine water decant and is the potential recipient of AMD, is understood in regard to all potential impacts and contaminant migration pathways. This is required to formulate the most appropriate management solution within the framework of technical, socio-economic and governance challenges faced by industry and regulators.

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INTRODUCTION

Acid mine drainage (AMD) emanating from defunct flooded underground gold mine workings of the West Rand Mining Basin in the vicinity of Krugersdorp and Randfontein on the Witwatersrand (Figure 1) first daylighted in late-August 2002 (Coetzee, 2005; JFA, 2006). The AMD reports to surface via defunct mine structures and as diffuse seepage in an area described as the locus of decant (LoD). Initial estimates of the decant volume issuing at an elevation of some 1660 m above mean sea level (amsl) ranged between 7 ML/d in winter and 12.5 ML/d in summer (JFA, 2004). In early-2005, additional decant issued from an abandoned shaft (Coetzee, 2005) occupying an elevation of ~1672 m amsl. The build-up of hydrostatic head in the flooded mine workings resulted in the decant rate increasing to between 18 and 36 ML/d (Coetzee, 2005). Increased hydrostatic head also resulted in the development of a permanent water body in the Hippo Dam further downstream on the Tweelopie Spruit (Figure 2) in the southern part of the Krugersdorp Game Reserve (KGR), as well as the rejuvenation of proximate seeps and contact springs previously effected by mine dewatering. The AMD is collected and contained in various holding facilities, from where it is pumped to a treatment plant for neutralization and iron removal at a rate of 15 ML/d on average. In the order of 5 ML/d (33 %) of the treated AMD cannot be re-used in current mining operations and other consumptive practices, and is released into the Tweelopie Spruit immediately upstream of the KGR on condition that it meets quality directives set by the Department of Water Affairs and Forestry (DWAF).

The ramifications of mine water decant for the subregion are enormous. The greatest focus in this regard is undoubtedly the Cradle of Humankind World Heritage Site (CoHWHS), which includes the home of “Mrs Ples” in the Sterkfontein Cave system (Figure 2). Of no lesser concern, however, are the downstream landowners and agricultural activities that are largely or wholly dependant on groundwater for potable and business use. In order to determine and implement the most appropriate acid mine water drainage management measure(s), it is necessary to first understand the hydrophysical environment that defines and informs the groundwater dynamic in the subregion. This dynamic includes the response of the groundwater regime to both natural and anthropogenic recharge mechanisms. The latter are predominantly mining-related, as might be associated with defunct underground workings, defunct and operational surface (opencast) workings and tailings dams. The

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interaction between surface water and groundwater represents another facet of this dynamic and, apart from AMD, also finds relevance in the discharge from a municipal waste water treatment works (WWTW) on the Blougat Spruit to the east (Figure 2). This paper explores the groundwater dynamic and ancillary issues by consolidating and comparing readily available historical data with additional data sourced in early-2007 (Hobbs and Cobbing, 2007).

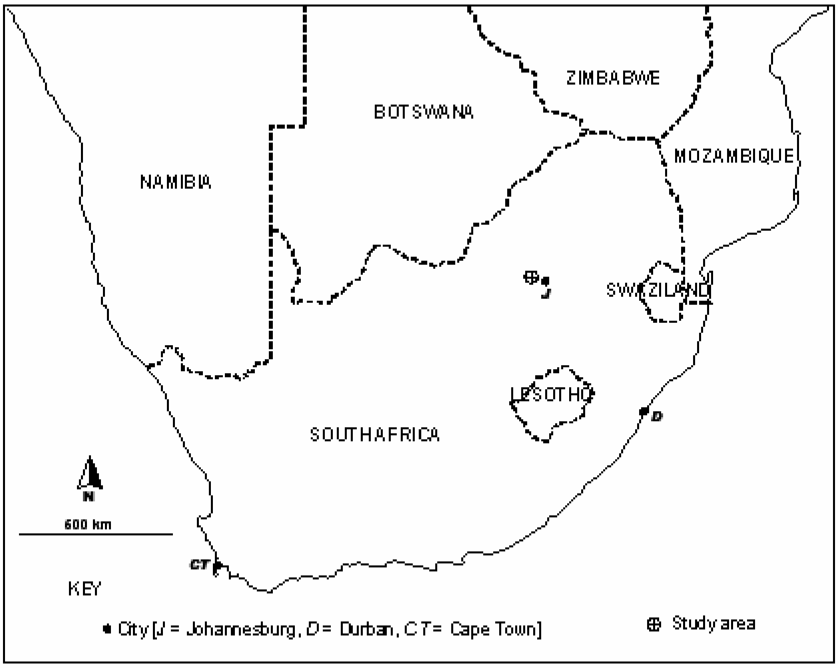

Figure 1: Regional map showing location of study area west of Johannesburg.

GEOLOGY

The locus of AMD is characterised at surface by dolomitic strata that represent an outlier associated with the Vaalian (2.65 to 2.43 Ga) Chuniespoort Group, and in particular the Malmani Subgroup within this lithostratigraphic unit. These strata are encapsulated within Black Reef Formation quartzite which is surrounded and underlain by older Randian (3 to 2.75 Ga) basement rocks associated with the Witwatersrand Supergroup. This relationship is shown in Figures 2 and 3. The defunct underground mine workings intersect the Johannesburg Subgroup strata that host the auriferous Main, Leader and South reefs, and the uraniferous Bird reefs. Older and much shallower mine workings exploited the near-surface gold occurrences in the Black Reef Formation and the Kimberley reefs of the Turffontein Subgroup (Whiteside et al., 1976). Testimony to the latter are large (1500 m x 500 m) and ~100 m deep surface excavations, such as the West Wits Pit (Figure 2).

The geology is rendered more complex by numerous WNW−ESE trending faults, such as the regional Rietfontein Fault (Figure 2), that intersect both Witwatersrand and Chuniespoort Group strata. This strike direction characterises most faults and fracture systems in the region (Jamison, pers. comm., 2007). Plate 1 indicates that the Government Subgroup strata in the KGR have also been subjected to deformation. Under these circumstances, the structural geology of the KGR and its possible relevance to groundwater movement, is a matter of substantial interest and concern. Dolerite intrusions mainly in the form of sub-vertical dyke structures, and occasionally in the form of sub-horizontal sills, represent equally significant structural geological features in the subregion. The role of the dyke structures in building compartments and subcompartments in the dolomitic formations has been described by Bredenkamp et al. (1986) and Rison (2006). Their concomitant role in controlling groundwater levels, discharge and flow is less well described or understood, and requires further study.

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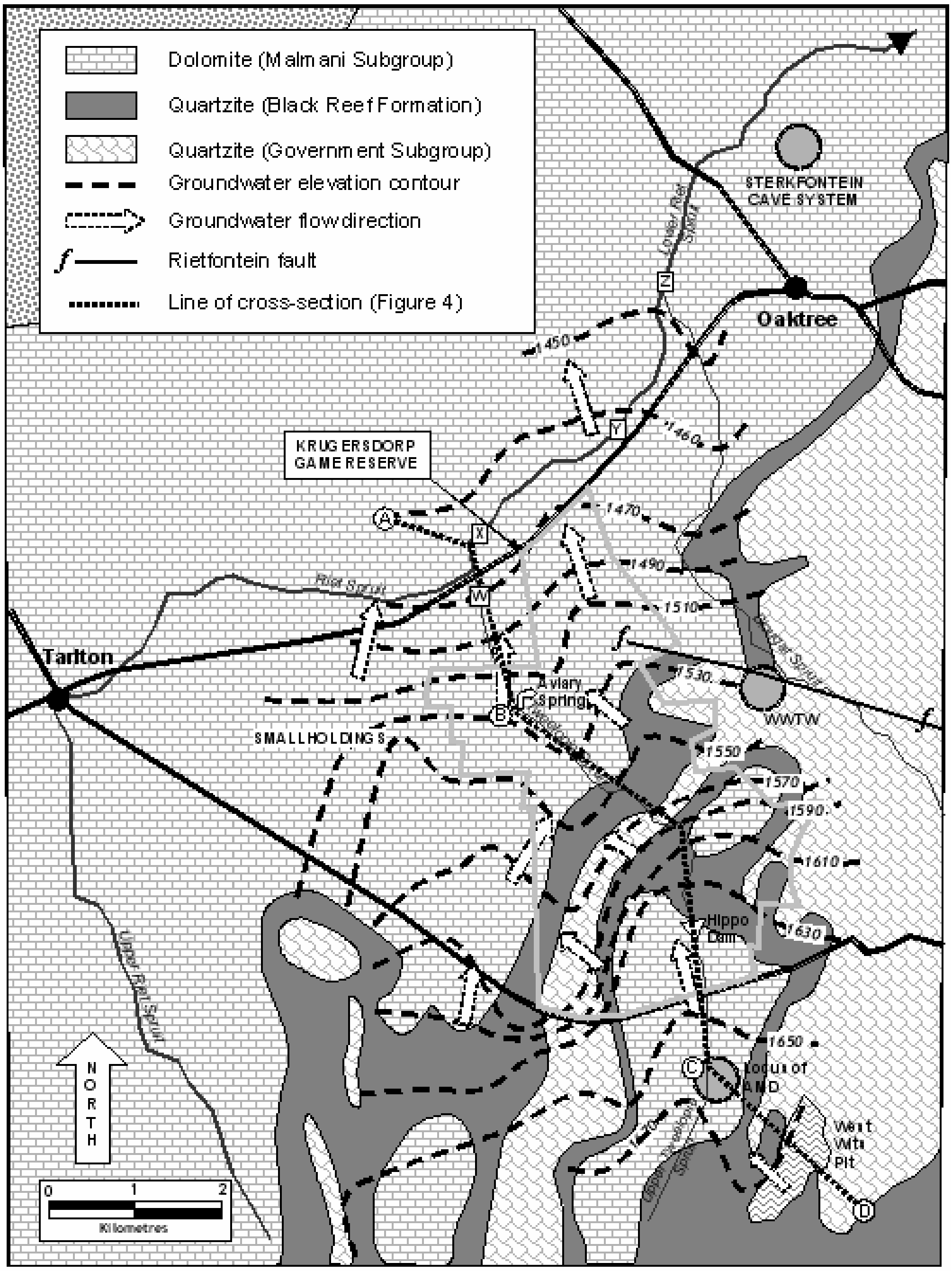

Figure 2: Geologic and hydrogeologic map of the study area.

HYDROGEOLOGY

Physical Hydrogeology

Groundwater occurrence in the study area is associated with three formations, viz. the Malmani Subgroup dolomite, the older Black Reef Formation quartzite and the still older West Rand Group strata. Of these, the dolomitic strata typically represent a karst aquifer characterised by modest (<100 m^2/d) to extremely high (>1000 m^2/d) transmissivity values (Bredenkamp et al., 1986; Leskiewicz, 1986; Hobbs, 1988; Kuhn, 1989) and, despite karstification, modest (in the order of a few per cent) storativity values (Bredenkamp et al., 1995). The Black Reef Formation and West Rand Group strata are conceptually associated with fractured aquifers characterised by similar modest to low (<10 m^2/d) transmissivity and low (<1 %) storativity values. In all instances, however, heterogeneity prevails over homogeneity. In the case of the Malmani Subgroup strata, this is defined by zones of preferential dissolution (possibly informed by regional fault structures) and, in the case of the older arenaceous strata, by fault structures, fracture/joint patterns and bedding plane geometries (Figure 3).

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Plate 1: Steeply dipping and folded Government Subgroup quartzite in the KGR.

The groundwater contours shown in Figure 2 derive from 48 depth to groundwater rest level measurements reduced to absolute groundwater elevations, together with six spring elevations. The flow directions that des

cribe groundwater movement in the study area are replicated in the conceptual hydrogeologic profile presented in Figure 3. Upstream of its confluence with the Riet Spruit, the Tweelopie Spruit is an effluent stream fed mainly by treated mine water effluent, but also receiving impacted dolomitic groundwater from the Malmani Subgroup outliers to the south, and pristine dolomitic groundwater from the Smallholdings area in the Zwartkrans Compartment. The potentiometric surface shown in Figure 2 indicates a separation of some 30 m between this surface and the streambed elevation in the vicinity of the confluence. The Tweelopie Spruit therefore becomes an influent stream in its lower reaches, losing water to the karst aquifer of the Zwartkrans Compartment. As shown in Table 1, these circumstances prevail along the course of the Riet Spruit for almost 4 km down to the Blougat Spruit confluence.

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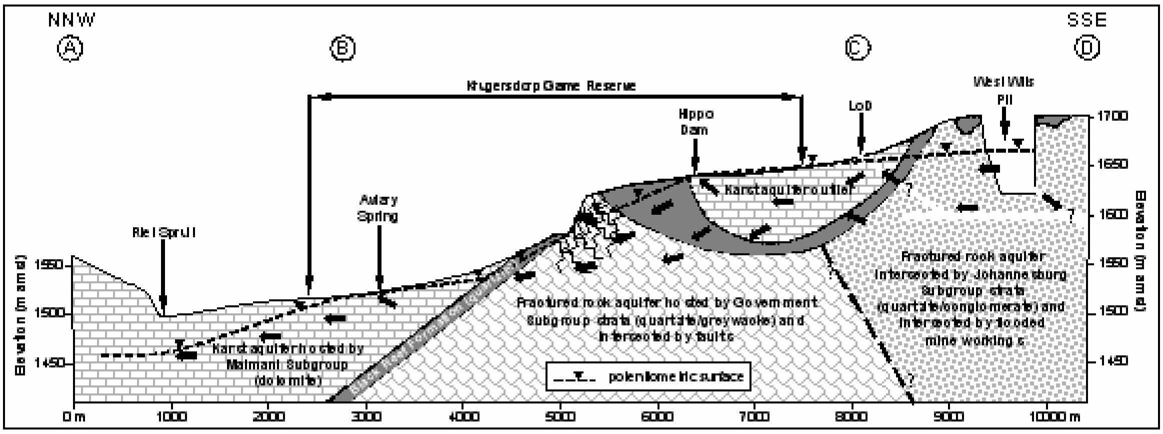

Figure 3: Conceptual hydrogeologic cross-section along the Tweelopie Spruit showing the potentiometric surface from the West Wits Pit in the south to the Riet Spruit in the north.

Table 1: Groundwater rest level information along the influent Lower Riet Spruit.

Measurement Position (refer Figure 2)	W	X	Y	Z
Distance along Drainage (m from locus of ingress)	0	800	2300	3800
Groundwater Rest Level Depth (m below riverbed)	30	21	12	18
Groundwater Rest Level Elevation (m amsl)	1470	1469	1463	1447

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Upstream (west) of its confluence with the Tweelopie Spruit, the Riet Spruit is dry as far as Tarlton (Figure 2), where the Tarlton dyke forms the boundary between the Zwartkrans Compartment and the Steenkoppies Compartment to the west. The influent nature of the Riet Spruit downstream of its confluence with the Blougat Spruit and past the Sterkfontein Cave system (Figure 2) is recorded in stream flow gaugings reported by Bredenkamp et al. (1986).

The magnitude of hydrostatic head from south to north revealed by the potentiometric contours is significant. Between the West Wits Pit and the Hippo Dam, this amounts to ~40 m, i.e. ~400 kPa (Figure 2). Across the ridge formed by Government Subgroup quartzite flanked by Black Reef Formation quartzite (Figure 3), this increases to ~100 m between the Hippo Dam and the Aviary Spring, and to ~150 m between the Hippo Dam and the valley of the Riet Spruit. The steeper hydraulic gradient across the quartzite ridge indicates a lower transmissivity associated with these formations compared to the dolomite. Nevertheless, the probability that hydraulic continuity exists between the dolomite outliers that host the locus of decant to the south, and the Zwartkrans Compartment to the north, must be considered in any geohydrodynamic assessment of the circumstances that inform management implications for mine water decant in the study area.

Chemical Hydrogeology

The analytical results of 49 water samples collected in February/March 2007 provides the means to distinguish hydrochemically between different water sources. The latter include natural groundwater produced by the karst (dolomitic) and fractured (quartzitic) aquifers, surface water and groundwater impacted by effluent discharges from mine and waste water treatment plants, and acid mine drainage. This characterization is less evident in the Schoeller graph (Figure 4) based on the data in Table 2, than in the Piper diagram (Figure 5). Figure 4 reveals the contrasting $CaHCO_3$ chemical character of dolomitic groundwater, $CaSO_4$ composition of the AMD-associated and Tweelopie Spruit surface water, and $NaHCO_3$ character of the Blougat Spruit surface water. The ionic imbalance of the AMD-associated water evident in Figure 4 is explained by elevated iron and manganese concentrations of ~1100 and ~100 mg/L, respectively.

Table 2: Summarised water quality data for different sources in the study area.

Parameter	Water Source					
	A	B&D	C	E	F	G
pH	7.3	5.8	7.2	7.1	4.8	7.8
Electrical conductivity (mS/m)	19.9	27.7	88.1	299.2	264.2	91.0
Calcium (mg/L Ca)	20.0	20.9	79.4	551.6	222.1	45.0
Magnesium (mg/L Mg)	10.1	13.3	40.4	121.6	125.0	11.0
Sodium (mg/L Na)	5.7	13.8	50.2	152.7	69.1	77.4
Sulphate (mg/L SO_4)	18.7	70.5	204.7	1997.8	1771.6	110.0
Chloride (mg/L Cl)	4.2	17.9	54.6	40.8	43.5	61.0
Total alkalinity (mg/L $CaCO_3$)	68.0	16.7	134.8	27.2	21.5	236.0

A = Pristine karst aquifer
C = Lower Riet Spruit karst groundwater
B&D = Fractured aquifer (quartzites)
E = Tweelopie Spruit surface water
F = Acid mine drainage & associated
G = Blougat Spruit surface water

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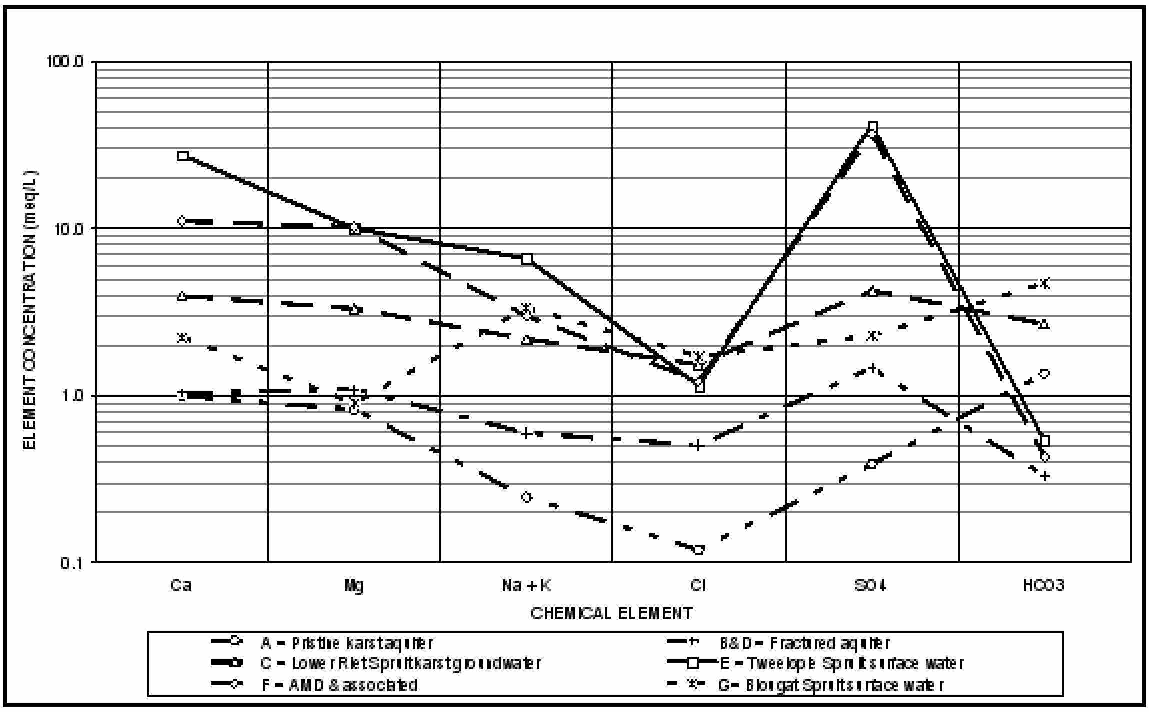

Figure 4: Graphical comparison of water chemistry from different sources.

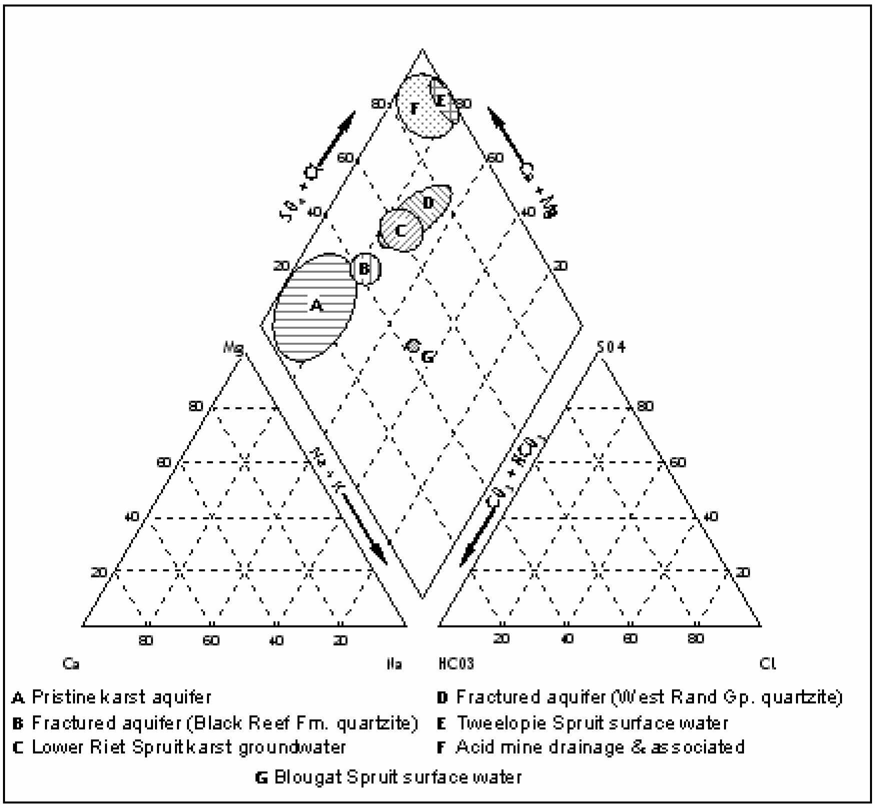

Figure 5: Characterisation of water chemistry from different sources.

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DISCUSSION

The Piper diagram (Figure 6) shows a schematic representation of the mixing that describes the development of Lower Riet Spruit karst groundwater quality (field “E” in Figure 6). The mixing derives from three end-members, viz. pristine dolomitic groundwater (field “A”), the grouping of groundwater influenced by acid mine drainage (field “B”) and Tweelopie Spruit surface water (field “C”), later referred to as field “B+C”, and thirdly Blougat Spruit surface water (field “D”). The slight displacement of the Lower Riet Spruit groundwater chemistry field “E” away from the “A”−“B+C” axis suggests that the contribution of waste water treatment works effluent is subordinate

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to that of treated mine water effluent (and possibly also AMD) in the chemical evolution of Lower Riet Spruit groundwater. Further, this contribution is insufficient to significantly alter the roughly equal contribution of pristine karst groundwater and Tweelopie Spruit/AMD-associated water in this evolvement.

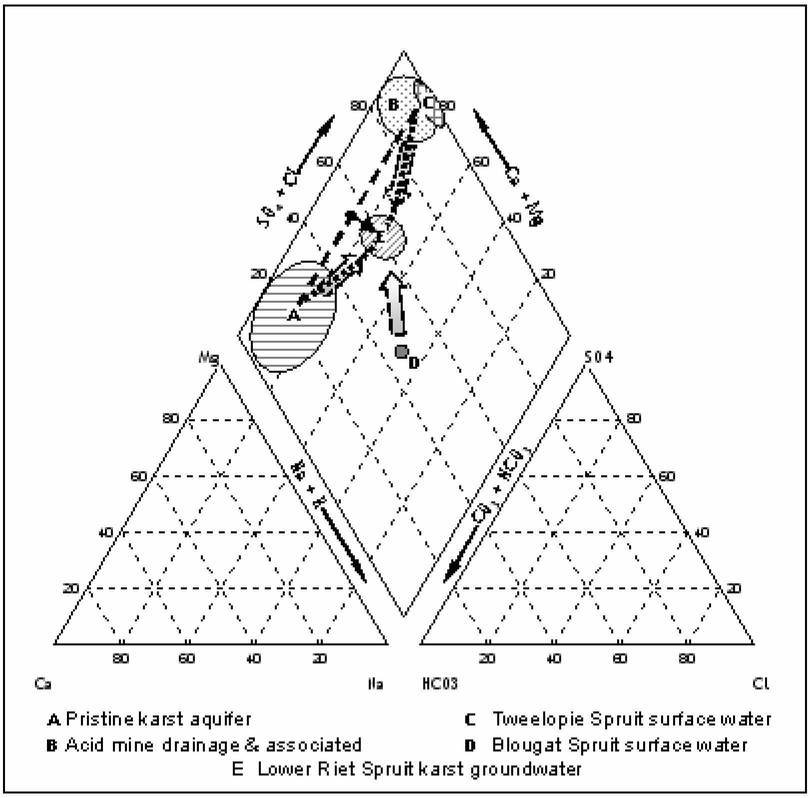

Figure 6: Characterisation of Lower Riet Spruit karst groundwater chemistry development.

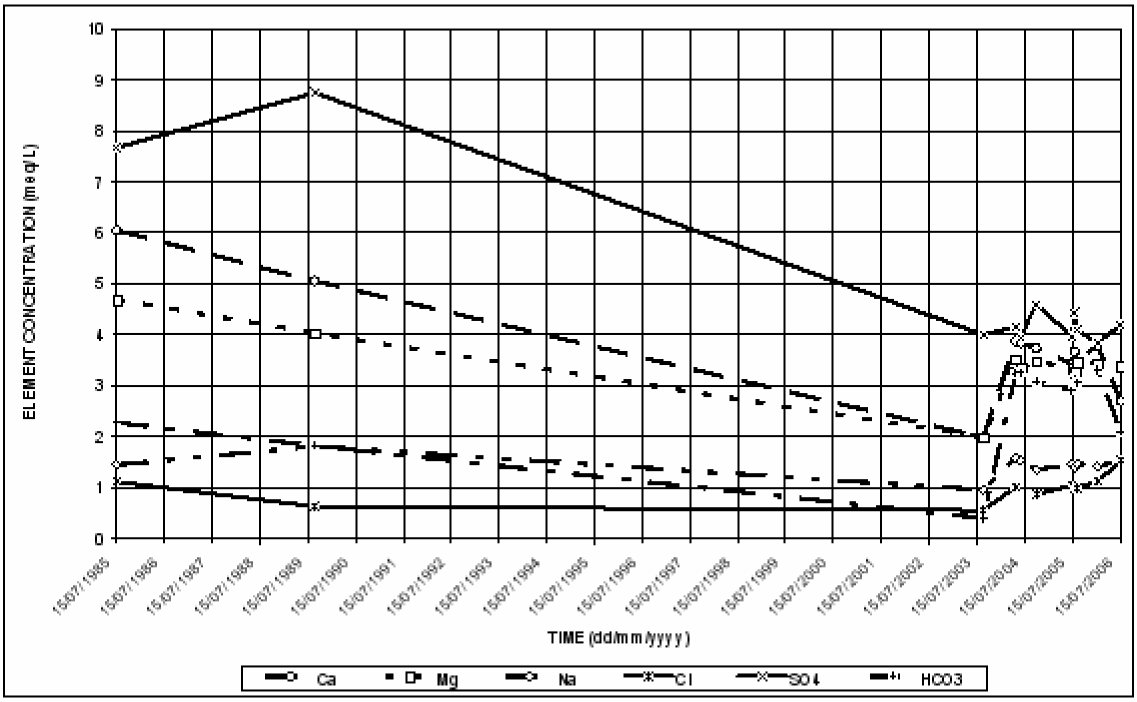

Figure 7: Historic temporal groundwater quality at the Riet/Tweelopie Spruit confluence.

The historic groundwater quality record (Figure 7) for a DWAF monitoring borehole located near the confluence of the Riet and Tweelopie spruits reveals that the poorer quality karst groundwater at this locality is not a recent phenomenon associated with the manifestation of AMD in August 2002. The first chemical analysis (in July 1985) of the groundwater from this source exhibits a sulphate concentration of 368 mg/L, followed by a value of 420 mg/L in September 1989. The recent more continuous record since September 2003 shows a mean SO_4 concentration of ~200 mg/L. These

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circumstances support information in KGR Game Ranger diaries that mine water was historically discharged into the Tweelopie Spruit as a consequence of dewatering in the course of mining operations (Du Toit, pers. comm., 2007).

The significance of the Blougat Spruit surface water contribution to the karst aquifer of the Zwartkrans Compartment lies in the bacteriological quality thereof. A sample of this water collected in March 2007 returned the results presented in Figure 8. The results for a groundwater sample obtained from a private water supply borehole located ~100 m from the stream at a position ~150 m downstream from the surface water sampling site are also shown in this figure. The comparative analytical results, and the consequences thereof for the potability of the groundwater to the landowner, are obvious.

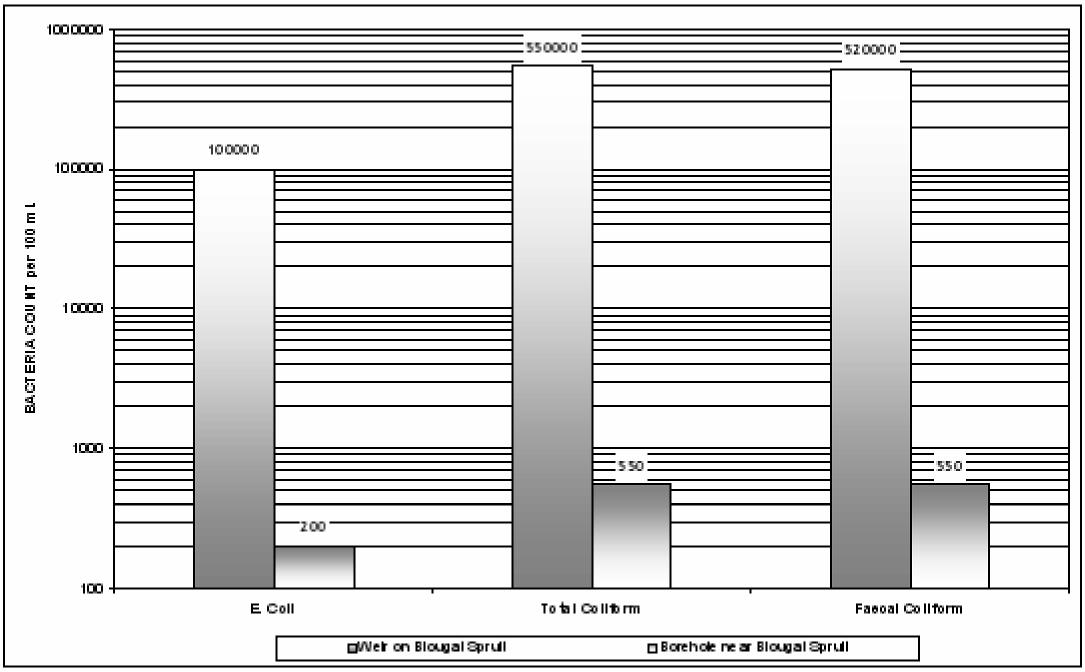

Figure 8: Results of a bacteriological analysis of Blougat Spruit surface water and adjacent groundwater.

CONCLUSIONS

Groundwater quality in especially the karst aquifer of the Zwartkrans Compartment is threatened by treated mine water effluent, acid mine drainage and effluent discharge originating at a municipal waste water treatment works. Whereas the former contribute elevated calcium, sulphate and heavy metal concentrations, the latter primarily contributes exceedingly high bacteriological concentrations to the karst environment.

An assessment of the hydrogeological environment that hosts mine water decant and is the potential recipient of acid mine drainage, reveals that the current understanding of the groundwater regime is obscured by a poor comprehension of the complex structural geology. This is manifested in the "popular" perception that the Government Subgroup strata form a comparatively low permeability "barrier" between the dolomitic outlier (with its associated locus of mine water decant) to the south, and the main dolomitic Zwartkrans Compartment to the north. That this perception may be flawed raises serious concerns for the efficacy of current acid mine drainage management measures as an absolute decant management solution. These circumstances highlight the need to establish as rigorous and credible a conceptual model of the groundwater environment as possible in order to formulate the most appropriate management solution.

RECOMMENDATIONS

There is sufficient cause to undertake a detailed investigation into the structural geology in the subregion insofar as it informs the physical hydrogeology. The Krugersdorp Game Reserve provides the ideal terrain in which to execute such investigation, which should comprise a combination of complementary methods including structural geological mapping, an analysis of available remotely sensed geophysical information, and ground-based geophysical surveys.

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

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