Managing the Threats to the Karst Water Resources of the Cradle of Humankind World Heritage Site, South Africa

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Abstract

The Cradle of Humankind World Heritage Site (COH WHS) in South Africa is the only UNESCO-protected karst landscape in the world that is under threat from acid mine drainage (AMD). A recent water resources study has shed new light on the previously poorly understood hydro-environment and its vulnerability to various threats, including AMD. Apart from the surface water drainages that are *de facto* recipients of AMD, it has been established that less than 30% of the groundwater resources of the WHS are at risk of AMD and other wastewater contamination. Further, that only two of the 14 recognised fossil sites attract a high or very high hydrovulnerability risk, with three attracting a moderate risk and the remainder either a low or very low risk. The study also informs an integrated water resource monitoring programme directed at supporting management efforts to protect the outstanding universal value (OUV) of the site.

1 Background and Introduction

The Cradle of Humankind World Heritage Site (COH WHS) in Gauteng Province, South Africa (**Figure 1**), is among some 50 karst sites worldwide that have been inscribed with UNESCO (Hamilton-Smith, 2006), many of these for other values (e.g. cultural) than purely their karst landforms. The karst environment of the COH WHS is the *raison d'étre* for the palaeontological/archaeological significance of the area. A poor understanding of the water resources within the ~52 000 ha extent of the COH WHS has precipitated often alarmist reporting in the media regarding the negative impacts associated with various sources of poor quality water (e.g. Béga, 2008a; 2008b; 2010; 2012a; 2012b; Seccombe, 2008; Masondo, 2010; Groenewald, 2010). The greatest prominence has been afforded the acid mine drainage (AMD) threat from actively decanting (since late-August 2002) defunct and flooded underground gold mine workings in the West Rand Goldfield (a.k.a the Western Basin). A contributory source of poor quality water is the treated wastewater effluent discharged from the Percy Stewart Wastewater Treatment Works (WWTW), a municipal facility that has received a poor rating (DWA, 2011a) in terms of the Department of Water Affairs (DWA) "Green Drop" scoring system for the operational efficiency of such facilities.

Globally, the COH WHS is the only UNESCO-protected karst landscape that is under threat from AMD. This perceived threat has generated wide and considerable concern for the preservation of the numerous UNESCO-inscribed fossil sites and karst ecosystems in the COH WHS. Apart from the broadcast and print media, well-meaning but nevertheless similarly alarmist reporting has appeared in scientific publications by respected scientists in reputable journals (e.g. Wells *et al.*, 2009; Durand, 2012). A situation assessment of the water resources environment, commissioned by the Management Authority (MA) of the COH WHS to facilitate management based on understanding, has shed new light and provides a different perspective on the matter that warrants communication. It also informs an integrated water resource monitoring programme directed at supporting management efforts by the MA to protect the outstanding universal value (OUV) of the site in the interest and on behalf of all nations and humankind.

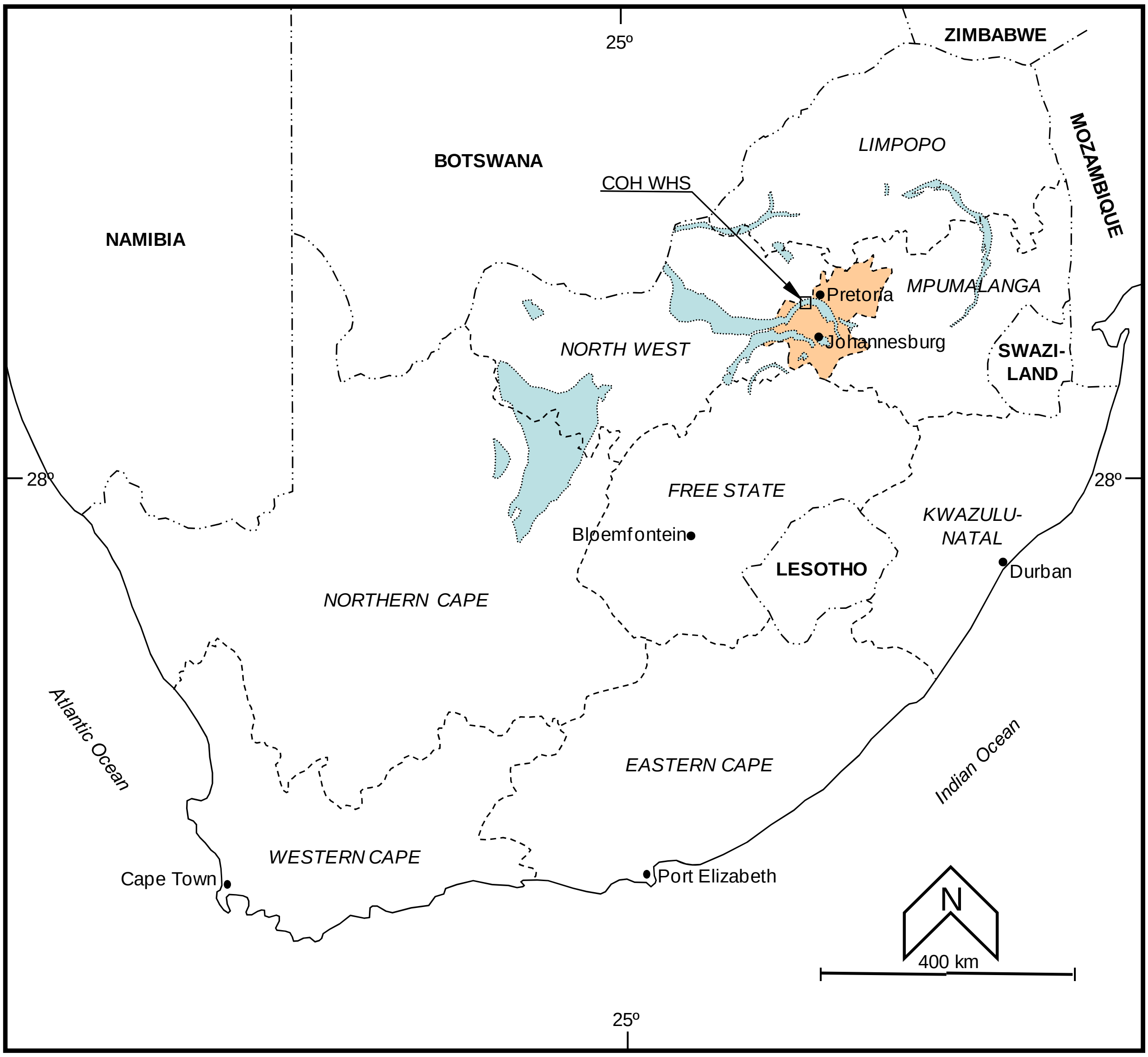

Figure 1 Location of the COH WHS in Gauteng Province (brown shaded area), South Africa, and in relation to the distribution of 'hard' sedimentary carbonate deposits (blue shaded areas) in the South African interior (adapted from Martini and Wilson, 1998)

2 Description of the Physical Environment

The watershed that forms the continental divide between the Vaal River system to the south (draining westward to the Atlantic Ocean) and the Limpopo River system to the north (draining eastward to the Indian Ocean), also occupies the highest natural elevation (~1720 m amsl) in the study area. Extending to the north of this divide, the study area 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 orthogonally incised 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, with late-Archaean to early-Proterozoic (~2.5 Ga) dolomite sandwiched between older Randian (2.97-2.78 Ga) sedimentary strata (quartzite) in the south-east and younger Vaalian (2.43-2.22 Ga) sedimentary rocks (mainly quartzite, sandstone and shale) in the north-west (**Figure 2**). Elevation in the COH WHS itself ranges from 1664 m amsl in the south-west to ~1200 m amsl in the north-east.

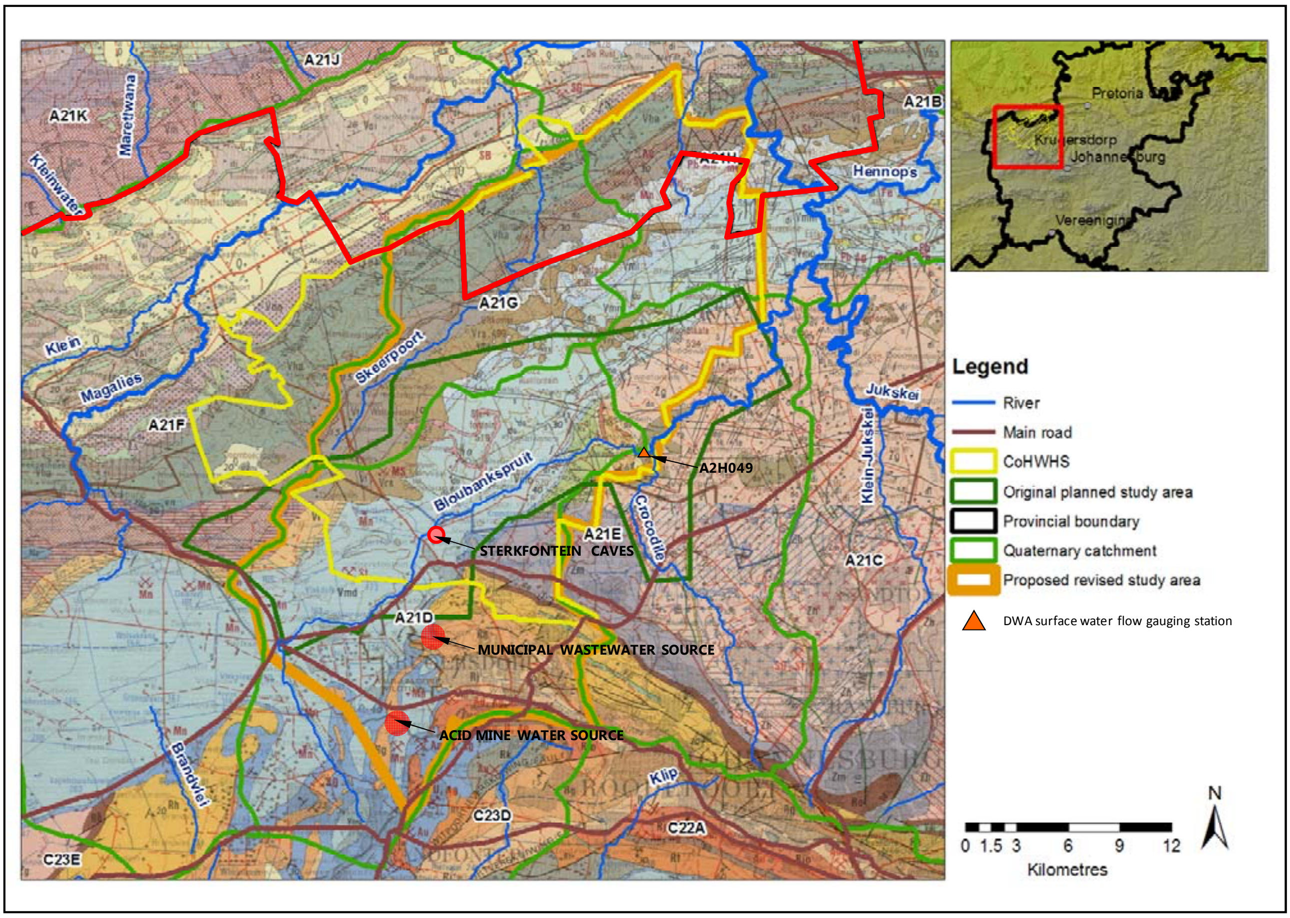

Figure 2 Definition of study area showing salient localities and surface water drainages superimposed on geology as backdrop (dolomite as blue shaded area, flanked by Randian strata to the south-east and Vaalian strata to the north-west)

The study area falls within the warm temperate summer rainfall region that characterises the typical Highveld climate of the north-central South African interior. The mean annual precipitation (MAP) in the study area amounts to ~700 mm/a. The mean annual temperature (MAT) falls in the range 16-18 °C, with daily mean temperatures in the range 20-22 °C in summer (December/January) and 10-12 °C in winter (June/July). The daily mean relative humidity falls in the range 58-60% in winter and 66-68% in summer. The A-pan equivalent mean annual potential evaporation (MAPE) falls in the range 2200-2400 mm (Schulze *et al.*, 1997).

3 Synoptic Overview of Water Resources

Amongst the characteristics unique to karst systems that require focussed study is hydraulic inter-connectivity between surface and subsurface water resources that render these environments highly vulnerable to impacts from surface activities (Vesper, 2008). A conceptual hydrophysical model of the integrated surface water and groundwater environments that accounts for observed agreement between rainfall, groundwater recharge, spring discharges, the surface extent of contributing groundwater basins and groundwater drainage patterns facilitates an assessment of the various threats to the water resources environment. Characterisation of the hydrochemistry associated with the different water resource components lends further support and rigour to the conceptual hydrophysical model.

3.1 Surface Water Hydrology

The surface water environment comprises the pristine Skeerpoort River draining quaternary catchment A21G, and the impacted Bloubank Spruit system draining quaternary catchment A21D. Both these systems drain to the ~186 Mm^3 net capacity Hartbeespoort Dam, the former via the Magalies River and the latter via the Crocodile River. This dam is of regional significance for water supply to towns and agriculture.

The Skeerpoort River is fed by karst springs together delivering ~9.5 Mm^3/a of excellent quality dolomitic groundwater. This discharge matches the long-term median annual discharge as gauged over a period of 46 hydrological years (1964-'65 to 2010-'11), and represents ~5% of the net capacity of Hartbeespoort Dam. The Bloubank Spruit system, with a long-term median discharge of ~22.6 Mm^3/a (~12% of the net capacity of Hartbeespoort Dam), receives >4.4 Mm^3/a (>12 ML/d) of poor quality raw and treated (neutralised) mine water and >2.5 Mm^3/a (>6.8 ML/d) of treated municipal sewage effluent in its headwaters upstream of the karst environment. The balance of ~15.7 Mm^3/a (~43 ML/d) is contributed by four karst springs delivering good to excellent quality dolomitic groundwater. It is this drainage and its headwater tributaries, in turn the Riet Spruit and the Tweelopie Spruit, that receive AMD in the form of both raw and neutralised mine water in varying quantities (from 12 to 65 ML/d) depending on temporal hydrologic drivers of mine water decant such as rainfall and recharge. Extending over a distance of ~28 km from the AMD source to the main stem (the Crocodile River), surface water losses to the karst aquifer and gains from karst springs variously characterise the hydraulic and hydrochemical continuum along the ~18 km (~64%) of this flow path that traverses dolomite.

3.2 Groundwater Hydrology

The groundwater environment comprises ten dolomitic compartments, two of which are subdivided into subcompartments. The recognition of these compartments is based on available mapped geological information supplemented with airborne geophysical survey data and verified on the basis of groundwater level measurements sourced from existing boreholes and spring elevations. Most of the compartments are drained by springs with known hydrochemistries and, in many instances, discharges quantified for the first time by this study. The aggregate discharge of eight enumerated karst springs each delivering >20 L/s (up to ~300 L/s), amounts to 25.2 Mm^3/a (~800 L/s or 69.1 ML/d). This equates to ~14% of the net capacity of Hartbeespoort Dam, and reflects the important contribution of good to excellent quality dolomitic groundwater rising mainly in the COH WHS, to the water budget of the wider region. Numerous other lower yielding (typically <2 L/s) springs exist, but have not been considered in this aggregation. A correlation between spring discharge, basin catchment area, spring water chemistry and rainfall recharge is demonstrated for most of the compartments. This has provided an improved understanding of groundwater flow patterns especially in regard to the karst formations, and which forms the basis for a plausible conceptual hydrologic and hydrogeologic model of the water resources environment in the COH WHS.

The very wet 2009-'10 and 2010-'11 summers resulted in the exceptional recharge of groundwater resources in the study area. Water balance calculations indicate that ~17 ± 5% of the mean annual precipitation (MAP) provides a reasonable estimate of recharge from rainfall. A rise in groundwater rest levels by ~3 m on average, also observed in the Sterkfontein Caves water level (Hobbs, 2011a), reflects these circumstances (**Figure 3**). This and greater water level rises (by as much as ~5 m) are attributed to allogenic recharge associated with the infiltration of surface water contributed in the form of mining and municipal wastewater effluent from upstream non-karst areas, as well as naturally-derived autogenic recharge. The allogenic recharge 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.

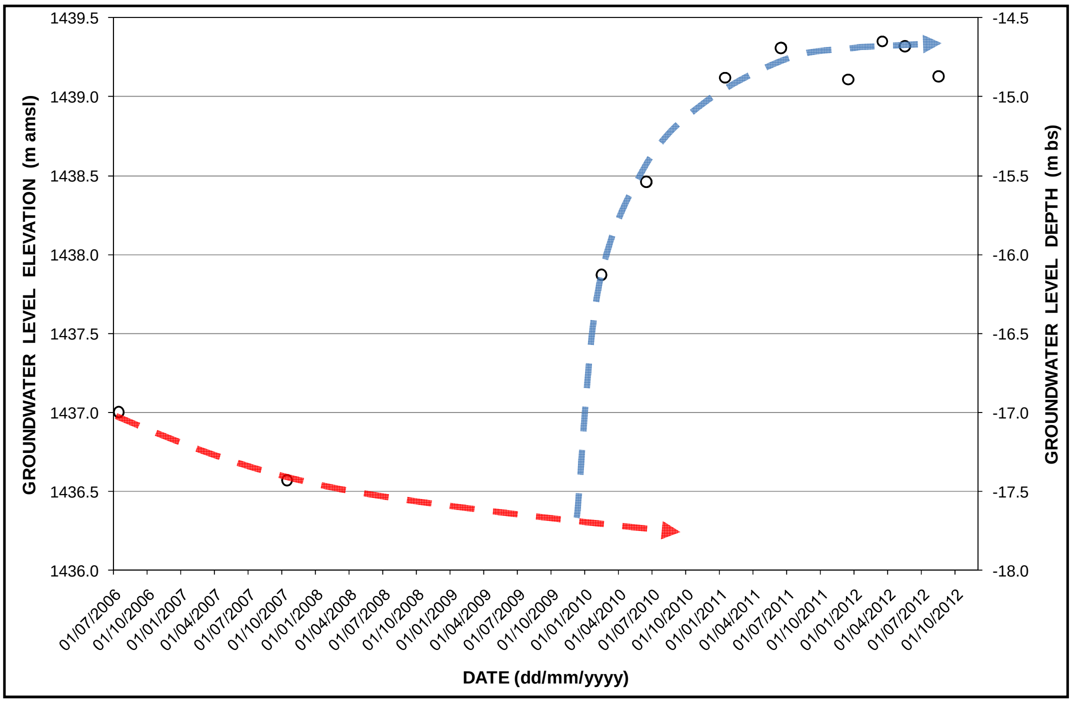

Figure 3 Groundwater level response in a borehole that serves as a proxy for the Sterkfontein Caves main lake water level

4 Characterisation of Wastewater Impacts

4.1 Surface Water Environment

The prominence of AMD as a pernicious environmental pollution threat necessarily focuses attention on this wastewater impact. Weekly monitoring of downstream surface water chemistry by the mines under a directive issued by the DWA has provided voluminous data on the impact of mine water in the receiving drainages. The focus of this monitoring has been on the Tweelopie Spruit, the first drainage to receive mine water, down to its confluence with the Riet Spruit a distance of ~6.5 km from the locus of raw mine water decant and neutralised mine water discharge. The monitoring suite common to all stations comprises the variables pH, electrical conductivity (EC), sulphate (SO_4), iron (Fe) and manganese (Mn). Typical values for these variables vary according to the proportion of raw mine water (RMW) to treated/neutralised mine water (NMW) leaving the mine area. This proportion varies depending on whether active decant is greater or less than the high density sludge (HDS) mine water treatment plant capacity, which was ~12 ML/d prior to the current upgrading of the plant. At the end of the Tweelopie Spruit and for RMW>NMW, pH is ~3, EC is ~350 mS/m, SO_4 is ~2500 mg/L, Fe is ~100 mg/L and Mn is ~60 mg/L. For RMW<NMW, pH is ~7, EC is ~300 mS/m, SO_4 is ~2000 mg/L, Fe is ~1 mg/L and Mn is ~10 mg/L at this location. The dominance of SO_4 in the chemical composition of raw mine water (typically ~65% of TDS) serves as an indicator variable of this water throughout the receiving surface water environment (Hobbs, 2011b).

The municipal wastewater effluent discharged from the Percy Stewart WWTW enters the Bloubank Spruit via the Blougat Spruit. This river drains the urban and industrial area that forms the north-western portion of the Mogale City Local Municipality. Available data from the mandatory discharge quality monitoring programme indicates typical mean nutrient ‘end-of-pipe’ concentrations of 6.2 mg NO_3-N/L, 26 mg NH_4-N/L, 5 mg PO_4-P/L and 118 mg COD/L. For comparison with the mine water quality reported above, this water is characterised by a pH of ~7.2, a salinity of ~100 mS/m, a SO_4 of ~200 mg/L, Fe of 0.68 mg/L and Mn of 0.9 mg/L, with an *E. coli* count of 30 000 per 100 mL. The municipal wastewater effluent threat therefore relates to the bacteriological contamination and nutrients contributed by this source, and the influence on the trophic status of the surface water environment. This is especially relevant in regard to the hypertrophic Hartbeespoort Dam, a condition that dates back to the 1970s (Zohary *et al.*, 1988).

At the bottom end of the Bloubank Spruit, instantaneous discharge is recorded at DWA gauging station A2H049, and the water chemistry determined less frequently (on average monthly) for a number of variables. At this position in the Bloubank Spruit system, both the long-term median discharge of ~22.6 Mm^3/a and the long-term characteristic CaMg-HCO_3 chemical composition of the water reflect the moderating influence of the perennial and comparatively constant groundwater contribution of ~15.7 Mm^3/a (~43 ML/d) from karst springs. These circumstances are reflected in the long-term pattern and trend of TDS and SO_4 loads passing station A2H049, as is the mine water impact on this pattern in the most recent two hydrological years **(Figure 4**). Also evident is the very recent return of the pattern to more "normal" pre-2009-'10 conditions, more clearly illustrated in **Figure 5**. These circumstances are explained by circumstances where prior to 2009-'10, the proportion of RMW to NMW leaving the mine property was 1:5 or greater, whereas in the 2009-'10 and 2010-'11 hydrological years this proportion was on occasion as much as 5:1.

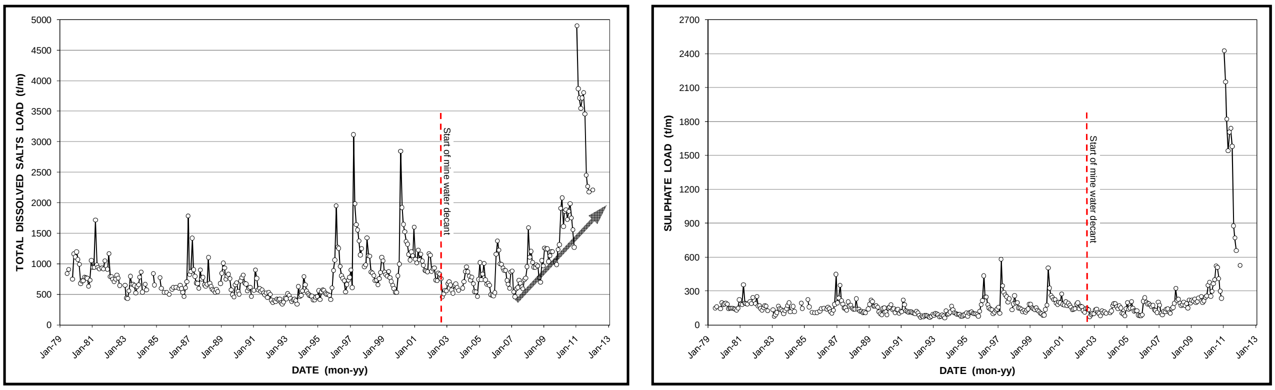

Figure 4 Long-term TDS (left) and SO_4 (right) load pattern and trend in Bloubank Spruit surface water at bottom end of sytem

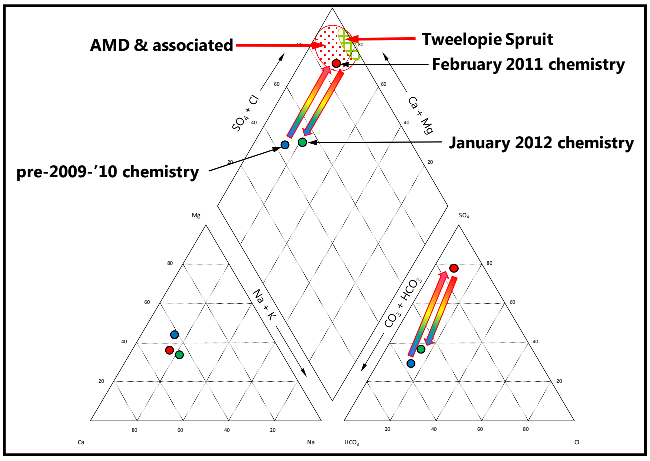

Figure 5 Hydrochemical characterisation of Bloubank Spruit surface water at bottom end of system over time, showing the characteristic fields that define AMD-impacted water

Expressed in terms of long-term median annual total dissolved salt (TDS) load contributions, the Skeerpoort River and Bloubank Spruit deliver in the order of 2350 and 8560 tons of total dissolved salts respectively to Hartbeespoort Dam. Concern for the recent presence of a significant mine water component in surface water discharge is somewhat mitigated by the upgrading of the HDS mine water treatment plant to more efficiently neutralise raw mine water in greater volumes (up to 30 ML/d) prior to its release into the environment. This intervention forms part of the immediate and short-term intervention recommended in the report (DWA, 2011b) to the Inter-Ministerial Committee (IMC) on AMD. The historical persistence of poor bacteriological quality associated with surface water in the Bloubank Spruit (as reflected in very high *E. coli* values of >3000 counts/100 mL) represents a significant threat to the ‘fitness for use’ of this resource.

4.2 Groundwater Environment

The magnitude of AMD impact on the karst groundwater chemistry is considerably more muted than its impact on surface water chemistry. This is reflected in pH values of >6.4, salinity values of ~300 mS/m and SO_4 values of ~2000 mg/L in groundwater sourced from boreholes in closest proximity to the losing drainage. These values improve within a few hundred meters, where pH values of >7, salinity values of <200 mS/m and SO_4 values of <600 mg/L are typical. For example, the Zwartkrans Spring water chemistry, which reflects the integrated impact of all contamination entering the dolomitic compartment drained by this geosite, continues to reflect a pH of 7.2, a salinity of 92 mS/m and a SO_4 concentration of ~260 mg/L. Clearly, therefore, the receiving karst hydrosystem continues to manifest a remarkable resilience to and assimilatory influence on the contamination threat posed by AMD.

It has been established that <30% (~15 600 ha) of the karst aquifer in the COH WHS is under threat from AMD. Even within this limited area, the threat ranges from high to non-existent depending on where in the karst system the threat is evaluated. As might be expected, the impact is most apparent in close proximity to the losing river section, and dissipates with distance away from the line source of allogenic recharge.

The municipal wastewater effluent threat represents a concern also for the karst water resources and the impact on the bacteriological quality of this groundwater. This threat is compounded by nutrients contributed from intensive irrigated agriculture in the Oaktree area upstream of Sterkfontein Caves. These impacts are held accountable for the nitrate concentration of ~10 mg N/L associated with the Zwartkrans Spring water. The Sterkfontein Caves water similarly contains ~8 mg N/L, but a phosphorus concentration of <0.2 mg P/L. The 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 concentration, provided the current hydrochemical conditions prevail. Assurance in this regard can be obtained from a regular biomonitoring programme (as described by Culver and Sket, 2002) that target stygobitic fauna.

5 Fossil Site Hydrovulnerability Assessment

A fossil site hydrovulnerablity assessment indicates that nine of the 14 fossil sites in the COH WHS (**Figure 6**) reflect a very low or low vulnerability because of their location (a) in groundwater compartments that are hydrogeologically separated from those where the contaminated water impact is a threat, 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, Minnaar’s and Plover’s Lake sites reflect a moderate vulnerability.

From this assessment 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 the result of mine water, treated sewage effluent or agricultural return water ingress. The more vulnerable sites are targeted for closer monitoring.

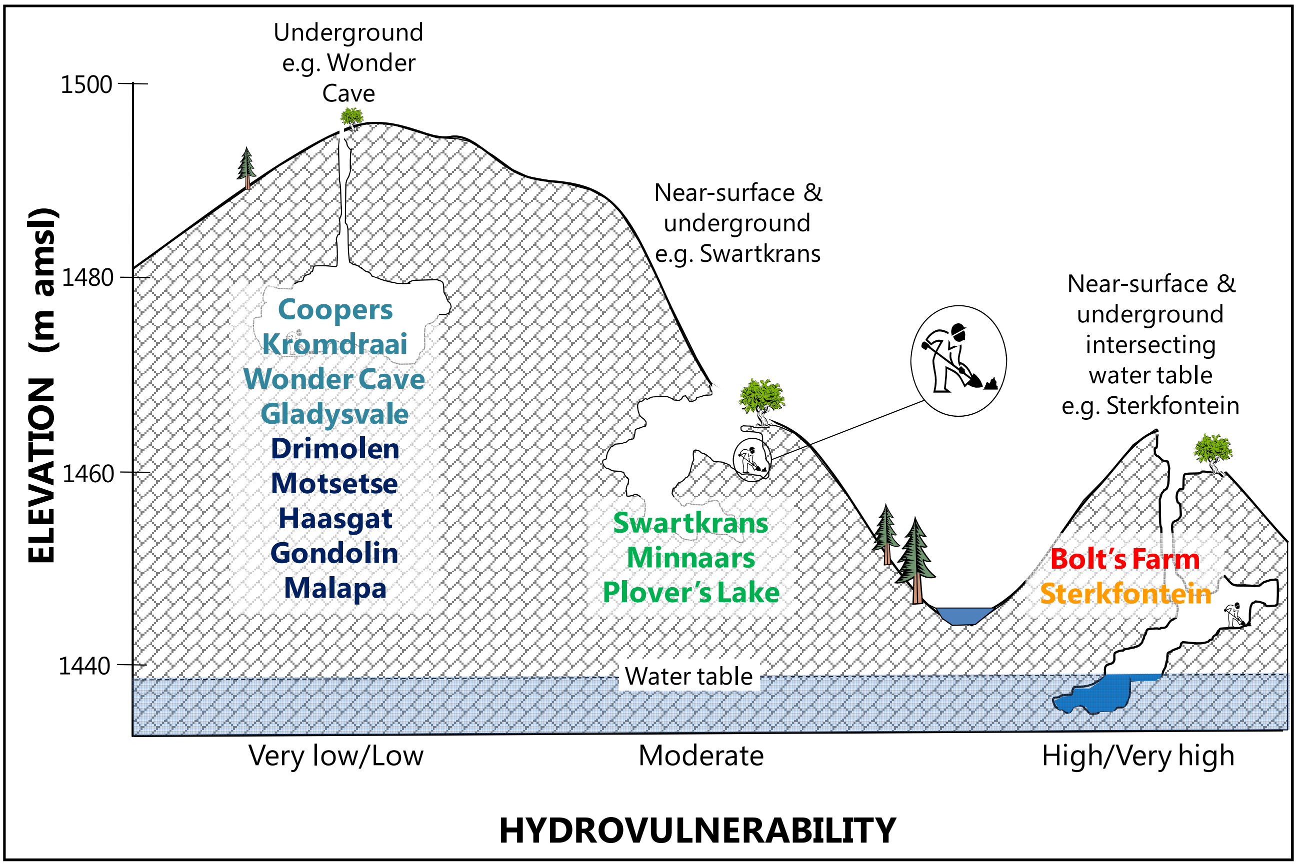

Figure 6 Schematic illustration of the hydrovulnerability assessment of the 14 recognised fossil sites in the COH WHS

6 General Discussion

The interaction between acidic mine water and municipal wastewater effluent in a receiving subsurface karst aquifer is extremely poorly understood. The Obey River Basin in north-central Tennesee (USA) is one location where such interaction has been studied (Sasowsky and White, 1993; Webb and Sasowsky, 1994; Sasowsky *et al.*, 1995). The mixing of these two sources of allogenic recharge in a naturally neutralising karst environment has been occurring by default in the south-western portion of the COH WHS for at least a decade. The default arises from an inability (up until quite recently) to contain the growing contribution of an acidic mine water input, and an inability on the part of a local authority to properly operate and maintain a wastewater treatment works under the pressure exerted by rapidly expanding urban residential and industrial development.

The literature provides numerous studies that discuss the application of bioremediation techniques in mitigating the negative impacts of acid mine drainage at a laboratory scale (e.g. Omoike and Vanloon, 1999; Johnson and Younger, 2006; McCullough, 2008; McCullough *et al.*, 2008; Strosnider and Nairn, 2010; Strosnider *et al.*, 2011). These studies have demonstrated that concentrations of various trace metals including Al, As, Cd, Cr, Fe, Pb, V and Zn reduce significantly when incubated in a mixture of acid mine water and municipal wastewater. The COH WHS provides a natural laboratory to study these interactions at a meso- to macroscopic scale.

The chemistry of groundwater sourced from boreholes in the nexus of AMD and municipal wastewater effluent convergence is devoid of the trace metal concentrations (for given detection limits) of metals such as Al, Co, Mn, Ni, U and Zn delivered by the AMD. Similarly, the nutrients (especially phosphorus) delivered by the municipal wastewater effluent are not evident in this groundwater. These observations suggest that bacterial sulphate reduction (BSR) might be occurring in this portion of the karst aquifer, where the organic matter associated with the municipal wastewater serves as the driving reductant resulting in the comparatively low SO_4 and trace metal concentrations in the karst groundwater. In essence, the mixing of the 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 phosphorus 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 utilise to generate alkalinity and precipitate metals as sulphides.

7 Conclusion

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. The greater understanding of surface and subsurface hydrologic interaction 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. This understanding indicates that the groundwater resources of <30% of the WHS are at risk of AMD and municipal wastewater effluent. It also serves to focus water resources monitoring activities in the area where it matters most, and informs an assessment of the relative risk to fossil sites from anthropogenic impacts on the water resources environment.

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 concern under circumstances where much of this discharge has been attributable to abnormally high acid mine drainage volumes. These circumstances intensify the focus on the immediate and short-term AMD intervention measures currently being implemented in the Western Basin.

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