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

FOSSIL SITE HYDROVULNERABILITY ASSESSMENT

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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 COH WHS. In order to successfully achieve this objective, the study included a hydrovulnerability assessment of fossil sites. This was precipitated in part by numerous media reports and public statements that proclaimed the fossil sites in the COH WHS to be under dire threat from acid mine drainage.

The vulnerability of the various fossil sites (and their associated cave systems) in the COH WHS is a particular concern in regard to their hydrologic (surface water) and hydrogeologic (groundwater) settings. 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 surface and subsurface aquatic environment as both a pathway for and receptor of AMD. Although treated municipal wastewater (sewage) effluent also represents an environmental concern and threat to drinking water quality, it is not considered to represent a risk/threat to any fossil site *per se*.

The hydrovulnerability of each fossil site in the COH WHS is examined and discussed in the context of its hydrologic and hydrogeologic settings. The assessment considers both the hydrophysical (e.g. surface water/groundwater interaction, groundwater rest level, etc.) and hydrochemical (mainly water quality) components associated with the respective fossil site settings. The fossil site hydrovulnerability assessment does not address 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 also intersect the water table.

It is concluded that nine of the 14 fossil sites in the COH WHS enjoy 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 enjoys a very high hydrovulnerability. This is due to its position immediately downgradient of the two main sources of poor quality surface water, namely mine water via the Riet Spruit and treated sewage effluent 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 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 Plovers Lake sites enjoy a moderate hydrovulnerability due mainly to a relatively shallow water table. It is apparent, therefore, that the majority of the fossil sites in the COH WHS are not under threat from either changes in groundwater rest level and/or changes in 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.

It is advisable that the fossil sites assigned a very high (Bolt's Farm) or high (Sterkfontein Caves) hydrovulnerability be monitored closely by means of either indirect or direct means. The Bolt's Farm fossil site lends itself to indirect monitoring via a borehole sunk on the property. It is recommended that this borehole be equipped with an automatic recording device (logger) that measures and stores EC, temperature and water level depth readings at a pre-set hourly interval.

The Sterkfontein Caves site lends itself to direct monitoring by tourist guides. Such 'self-monitoring' can be implemented if tourist 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.

In addition, however, a more complete bi-annual (twice a year) water chemistry analysis incorporating major anions and cations together with N and P, selected trace metals (Al, Fe, Mn, Ni and U) and environmental isotopes (^{2}H, ^{3}H and ^{18}O) will be required. Such an arrangement will not only serve the all-important monitoring imperative, but also empower the tourist guides with an additional competency over and above that of a mere guide. Further, it would provide the guides with additional 'first-hand' information that could be communicated to visitors as part of the standard tour guide 'script'.

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 (and even catastrophic) longer term impacts on stygobitic fauna.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DEFINITION OF SYMBOLS, ACRONYMS AND ABBREVIATIONS

~	approximately
>	greater than
<	less than
δ	delta (notation)
%	per cent (parts per hundred)
‰	per mil (parts per thousand)
°E	degree(s) East (longitude)
°S	degree(s) South (latitude)
^{2}H	deuterium
^{3}H	tritium
^{18}O	oxygen-18
AMD	acid mine drainage/discharge
amsl	above mean sea level
bs	below surface
CGS	Council for Geoscience
Cl	chloride
COH WHS	Cradle of Humankind World Heritage Site
EC	electrical conductivity
km	kilometre(s)
m	metre(s)
Ma	million years
ML/d	megalitre(s) per day
mS/m	milliSiemens per metre
p.	page
SO_4	sulphate
TU	tritium unit(s) [1 TU = 1 tritium in 10^{18} hydrogen atoms]
UNESCO	United Nations Educational, Scientific and Cultural Organisation

1 INTRODUCTION

The palaeontology/archaeology of the COH WHS study area (Figure 1) 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 best 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).

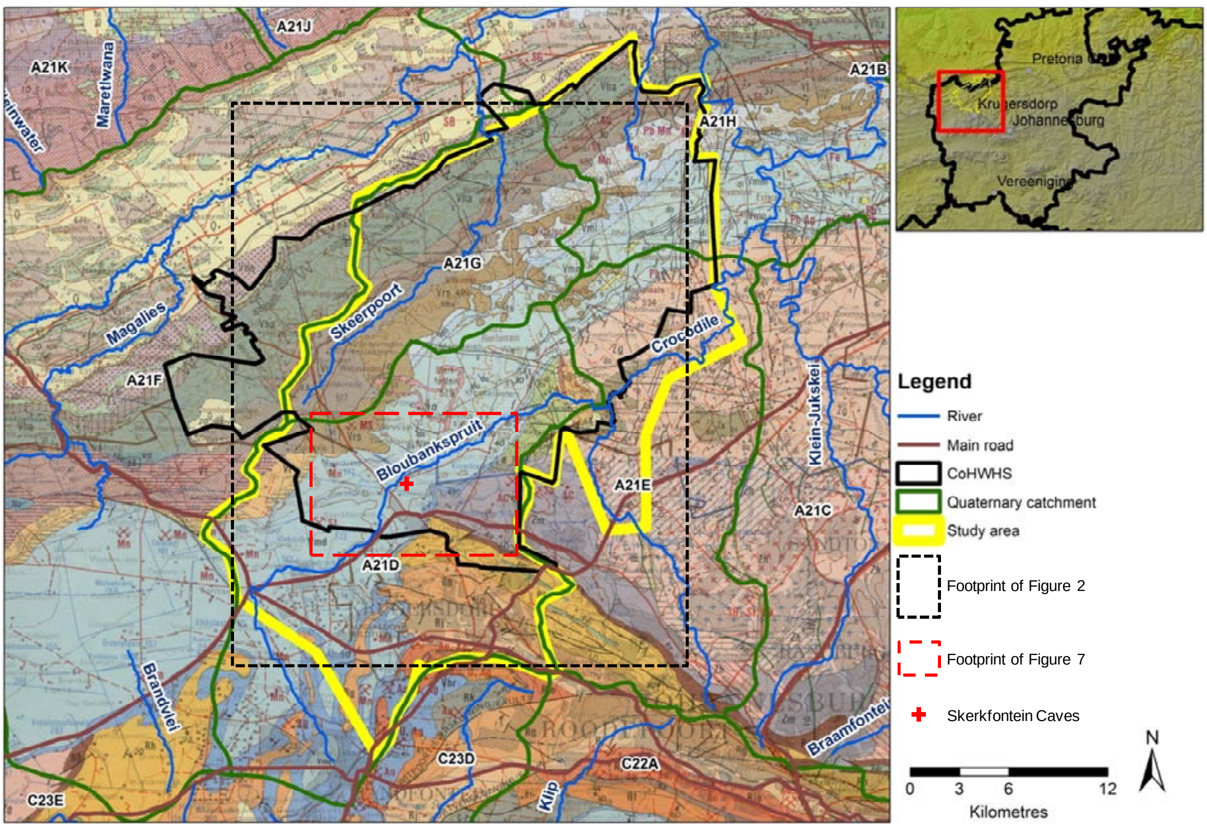

Figure 1. Definition of the study area in regard to the geology, surface water drainages and quaternary catchments in the COH WHS area and environs.

The Sterkfontein site has yielded >500 hominin[1] fossils (Table 1) since the discovery of 'Mrs. Ples' in 1947 (Cooke, 1969). Thirteen fossil sites in the COH WHS (Figure 2) have been declared National Heritage Sites in accordance with the National Heritage Resources Act (Act No. 25 of 1999). These have also been inscribed by UNESCO. The fourteenth and most recent, namely Malapa, has yet to be inscribed, but the significance of this site renders this inevitable.

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

Table 1. Salient hydrologic and hydrogeologic aspects associated with the better-known 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				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				Near-surface & underground	SAAN–0020: internationally recognised 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				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				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				Near-surface & underground	SAAN–0004: known for the excavation of an extinct jackal skull, has the potential for the discovery of hominin fossils
Plovers Lake	25.98°S 27.78°E			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				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			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 teeth and phalanges
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 COH WHS

(1) All coordinates except for Sterkfontein Caves and Wonder Cave truncated to the 2nd decimal in order to protect these sites from unauthorised 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.

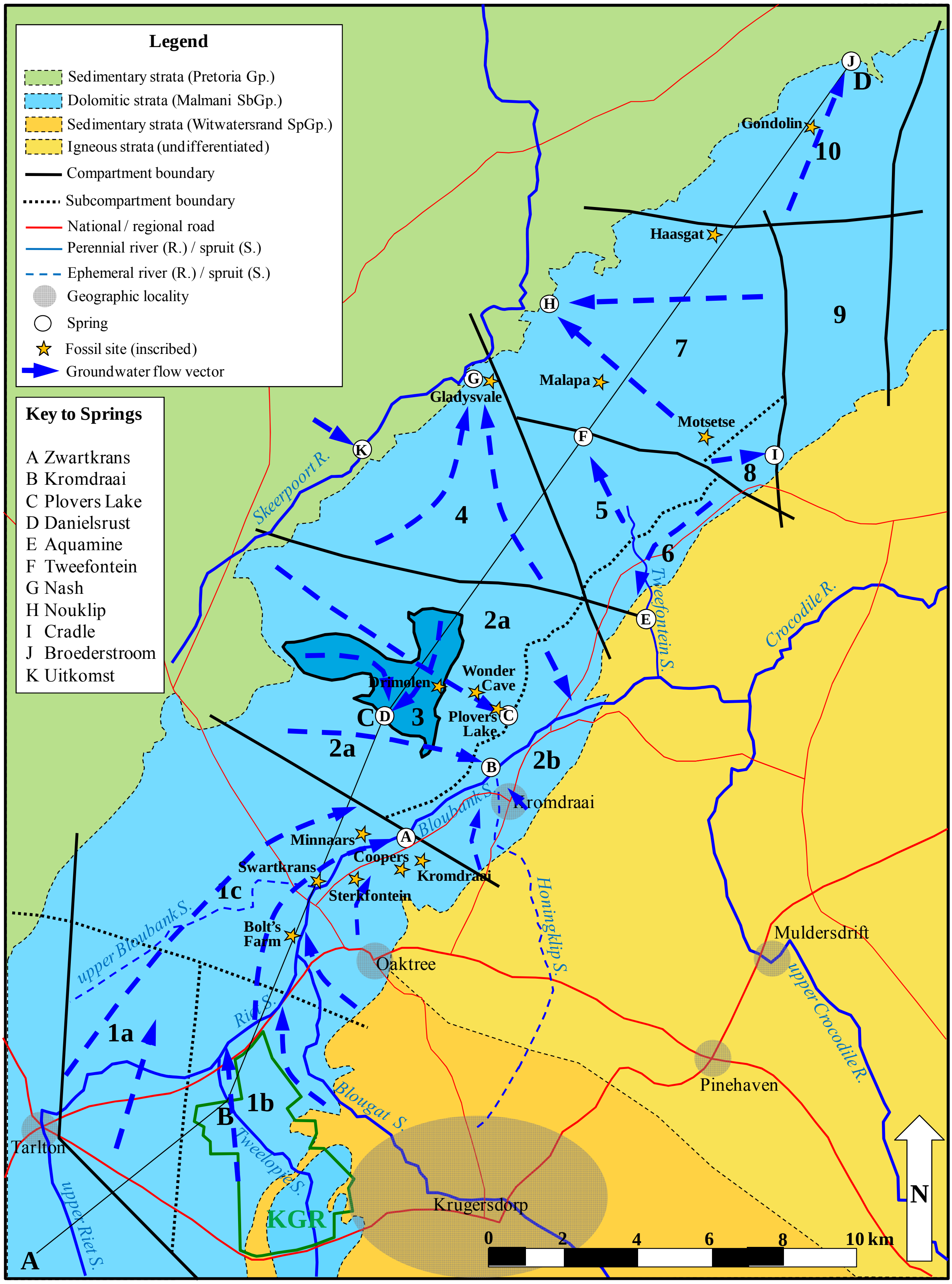

Figure 2. Location of fossil sites in relation to the compartments/subcompartments and their associated drainage patterns and dolomitic springs that form the hydrologic and hydrogeologic framework in the study area. Nos. 1a through 10 identify compartments/subcompartments as per key to Figure 9.

Many fossil-bearing deposits and sites of palaeontological, archaeological, historical and cultural heritage importance (both categorised and uncategorised) 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).

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). 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 Management Authority (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[2] fossil sites in the COH WHS are summarised in Table 1. The observation that the geographic footprint of groundwater compartments (e.g. the Diepkloof Compartment in Table 1) 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 1 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 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 Council for Geoscience (CGS, undated) reports that in all instances in the COH WHS, the important palaeontological finds are located within the top 10 m of the 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, this places the 'Little Foot' site at an elevation of ~1460 m amsl, some 22 m above the current cave water level of ~1438 m amsl. The Malapa cave system, recognised as the most recently discovered fossil site, understandably suffers from a relative paucity of information.

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

2 FOSSIL SITE HYDROVULNERABILITY ASSESSMENT

The vulnerability of the various cave systems in the COH WHS is a particular concern in regard to their hydrologic and hydrogeologic settings. The hydrovulnerability of each fossil site (and its associated cave system) is examined and discussed in the context of these settings in the sections hereunder. The assessment considers both the physical (e.g. surface water/groundwater interaction, groundwater rest level, etc.) and chemical (water quality) components associated with the respective fossil site settings. The outcome is summarised in Table 2, and illustrated schematically in Figure 3.

Table 2. 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)	Hydro-vulnerability
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
Plovers 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	~1350	~1365	0	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.

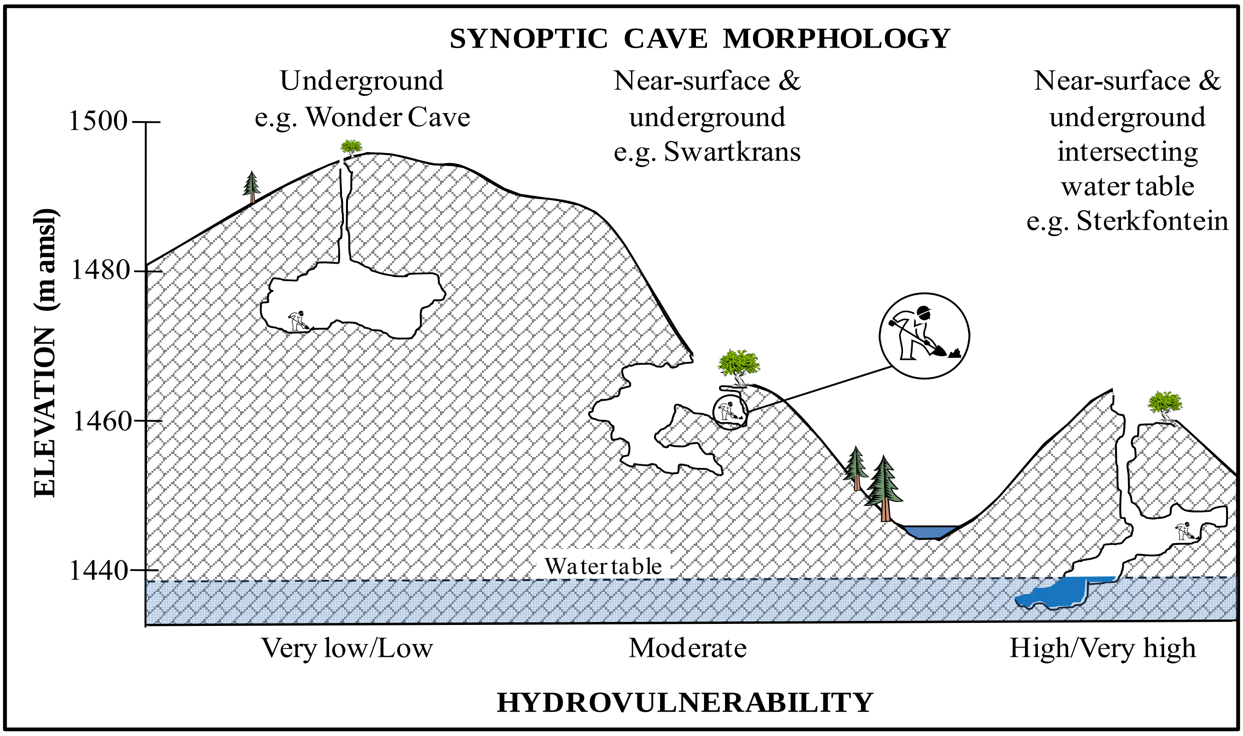

Figure 3. Schematic diagram illustrating the link between synoptic cave morphology and hydrovulnerability as applied to fossil sites in the COH WHS.

2.1 Bolt's Farm

Located immediately to the north of the Riet Spruit in the Oaktree Agricultural Holdings area, this terrain comprises numerous fossil sites and caves distributed over a reasonably wide area. At least one cave in this system, accessed via a portal in the western sidewall of Sterkfontein Quarry, intersects the water table. On the other hand, those fossil sites that occupy higher elevations in this landscape (>1490 m amsl), are located at least 40 m above the ambient water table.

It has been shown 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 last some three years. 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 'complex' 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 considered 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 (boreholes) CSIR8, CSIR9, GB2 and SCH1 (Figure 7) 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 4).

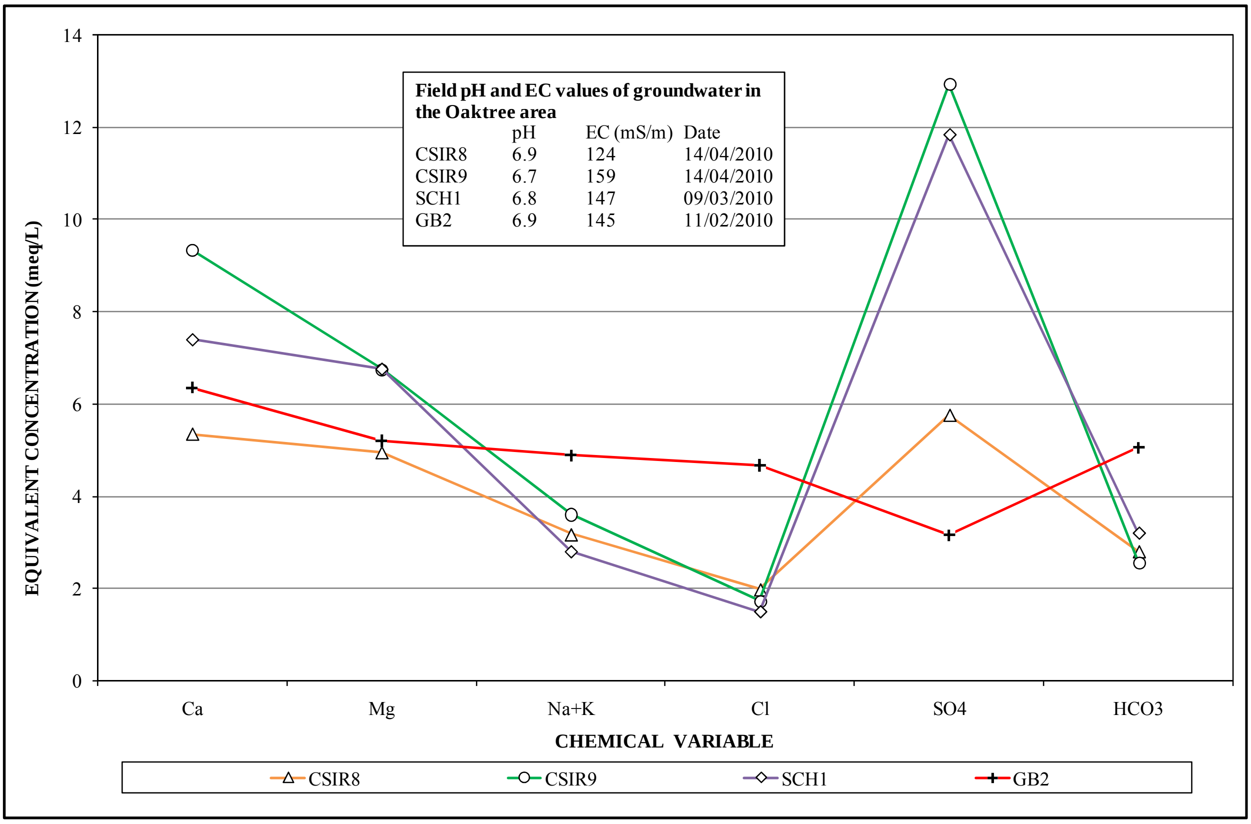

Figure 4. Comparison of severely impacted groundwater chemistry in the Oaktree area.

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, are considered to exhibit a **very high vulnerability** to both groundwater level fluctuations and water quality. However, recognition of the fact that a number of the fossil sites in this area occupy surface elevations >40 m above the ambient water table should also temper this rating. Mitigation measures to lessen the vulnerability of this fossil site 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 medium- to long-term measure.

2.2 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 will be excessive (Hobbs, 2008). For example, an analysis of groundwater level fluctuations in boreholes occupying a similar hydrogeologic position in the Groenkloof Nature Reserve area of the East Fountains Compartment of the Tshwane karst aquifer, indicate a maximum long-term fluctuation of <3 m (Hobbs, 2004). The recent quality of the groundwater passing beneath this fossil site is represented by that shown in Figure 5 for stations NR1, MB1, SC1 (Sterkfontein Caves) and ZWSp (Zwartkrans Spring) (Figure 7).

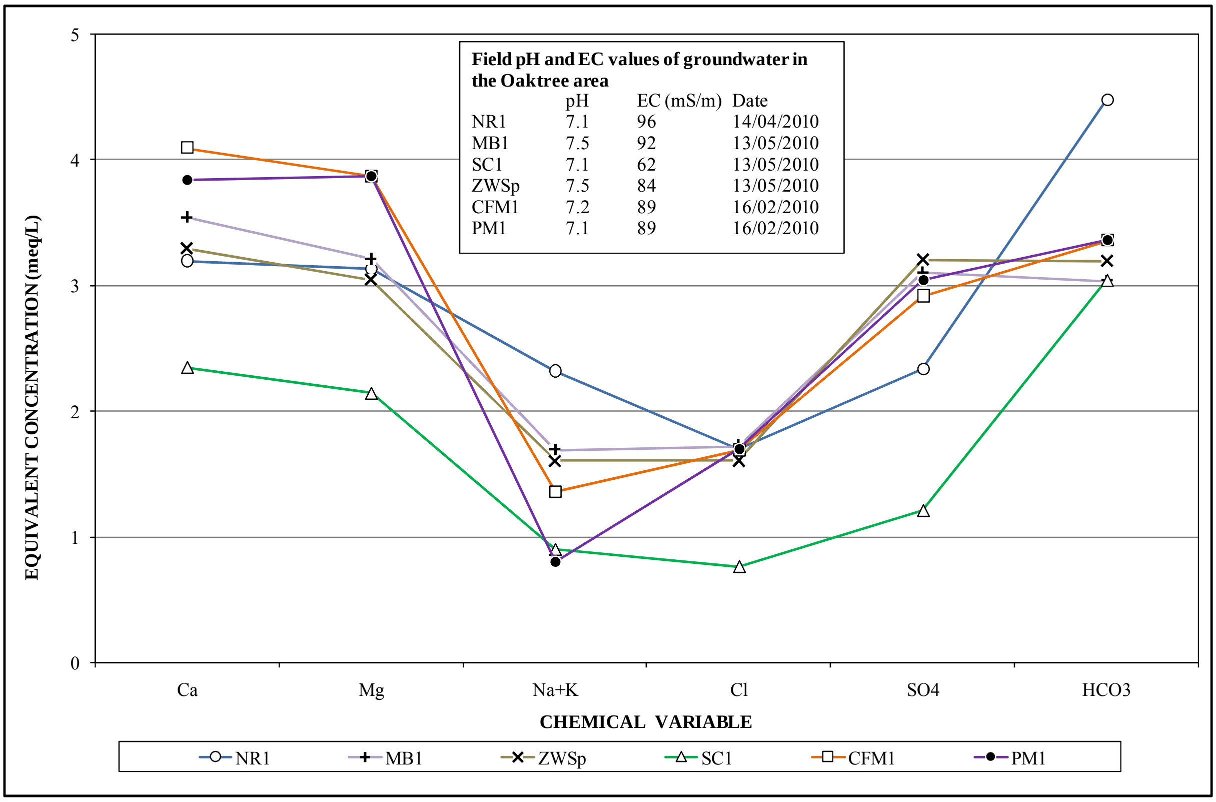

Figure 5. Comparison of moderately impacted groundwater chemistry in the Oaktree area.

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 2).

2.3 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. 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 following historical observations.

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 (Figure 6). The record 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, 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 in the north-eastern corner of the property between 17/02/2010 and 09/06/2010, and the ~0.4 m rise in borehole MB1 on the Makiti Wedding and Conference Centre property between 18/02/2010 and 13/05/2010. A water level measurement in borehole SF1 (Figure 7) on 14/01/2011 indicated a further rise in water level of ~0.7 m since 09/06/2010. The cave water level has therefore experienced an average rate of rise of ~0.12 m per month (1.3 m in 11 months) in the past year or so. 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.

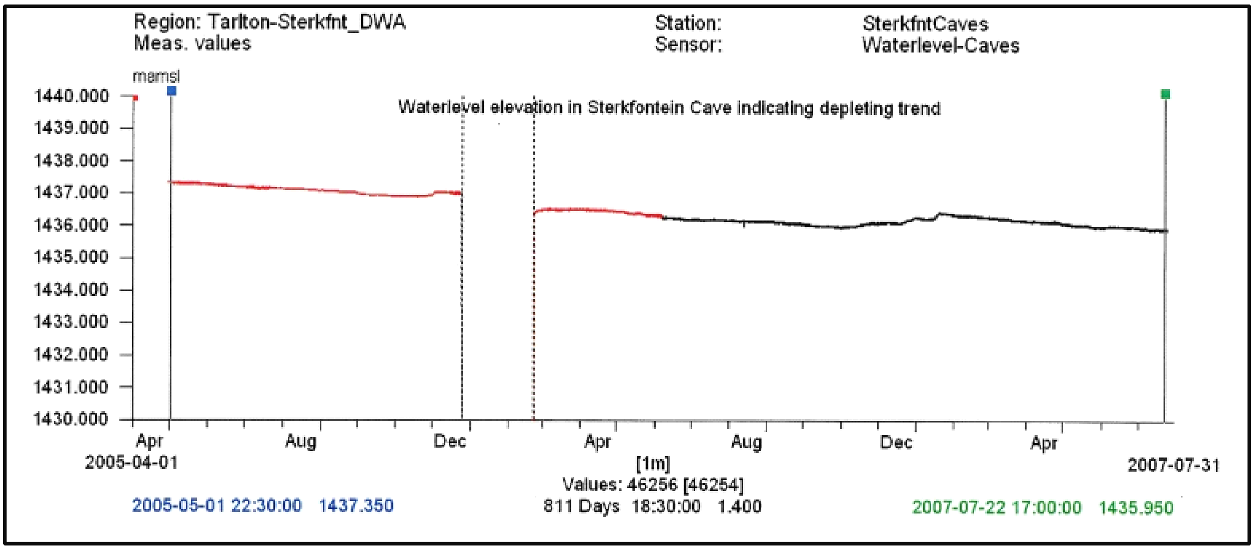

Figure 6. Continuous groundwater level response pattern in Sterkfontein Cave over a period of 27 months. (Use of image courtesy of E. van Wyk, DWA).

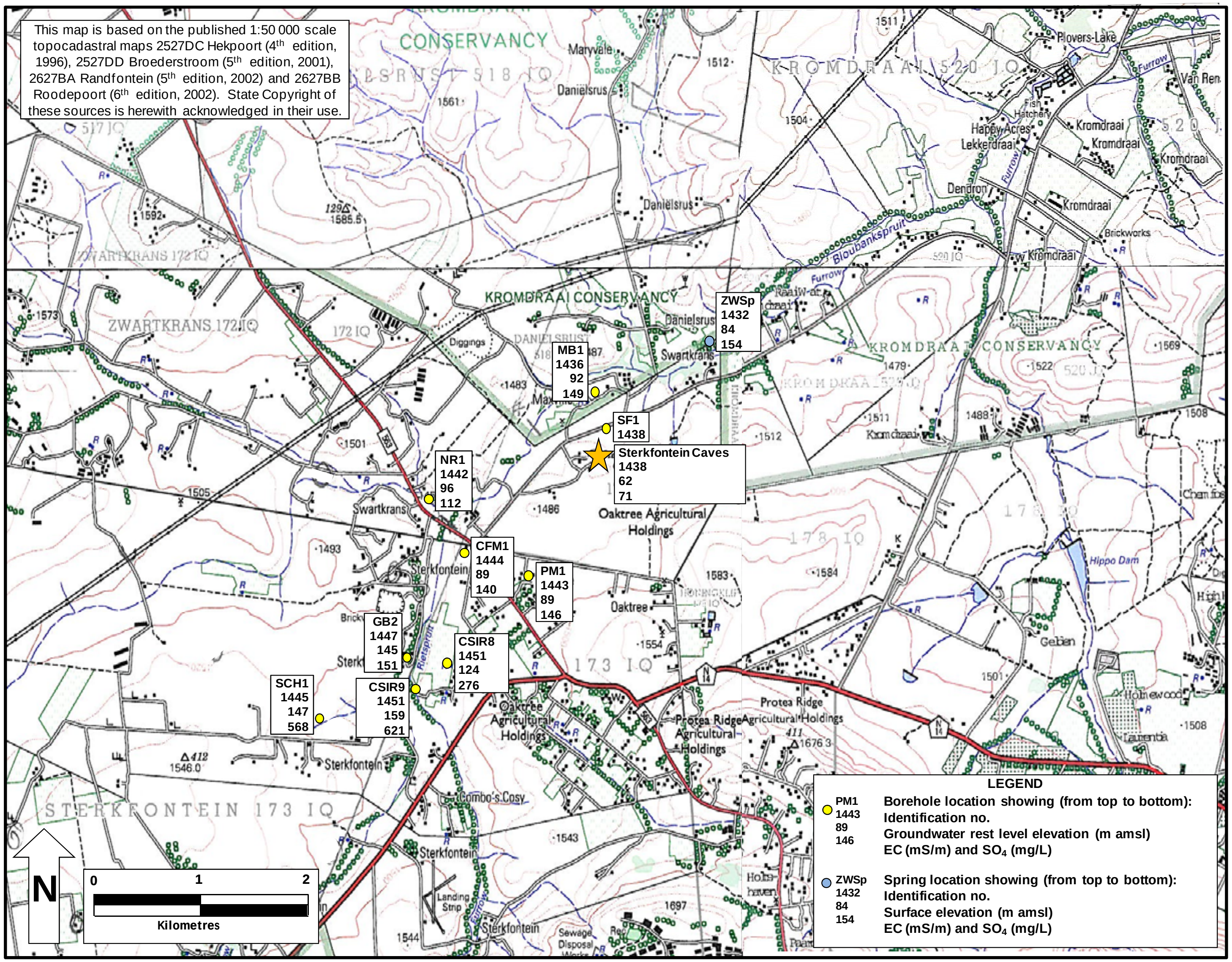

Figure 7. Locality map of geosites in the Oaktree area and Sterkfontein Caves environs referenced in this report.

The chemistry of the cave water reflects a composition that is similar to that determined for station NR1 (Figure 5). As such, it represents the situation already described for the Swartkrans fossil site (section 2.2). 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 (recent EC = 62 and 56 mS/m, Figure 8) of the geosites sourced for groundwater samples in the Oaktree area. This observation suggests that the site does not lie in the main flowpath of groundwater discharge toward the Zwartkrans Spring. Further support for this hypothesis is provided by the comparison of earlier cave water chemistry (provided by the April 2005 analysis from the DWA records) with the most recent (provided by the May 2010 and January 2011 analyses) of this study. This comparison is made in Figure 8, which also shows the May 2010 analysis result for Zwartkrans Spring water for further comparison. Notable are (a) the very similar compositions of the two Sterkfontein Caves water samples, (b) the similar cave water EC values, and (c) the different Zwartkrans Spring water composition with its EC value of 84 mS/m (even though these sources are located reasonably close together in the same compartment).

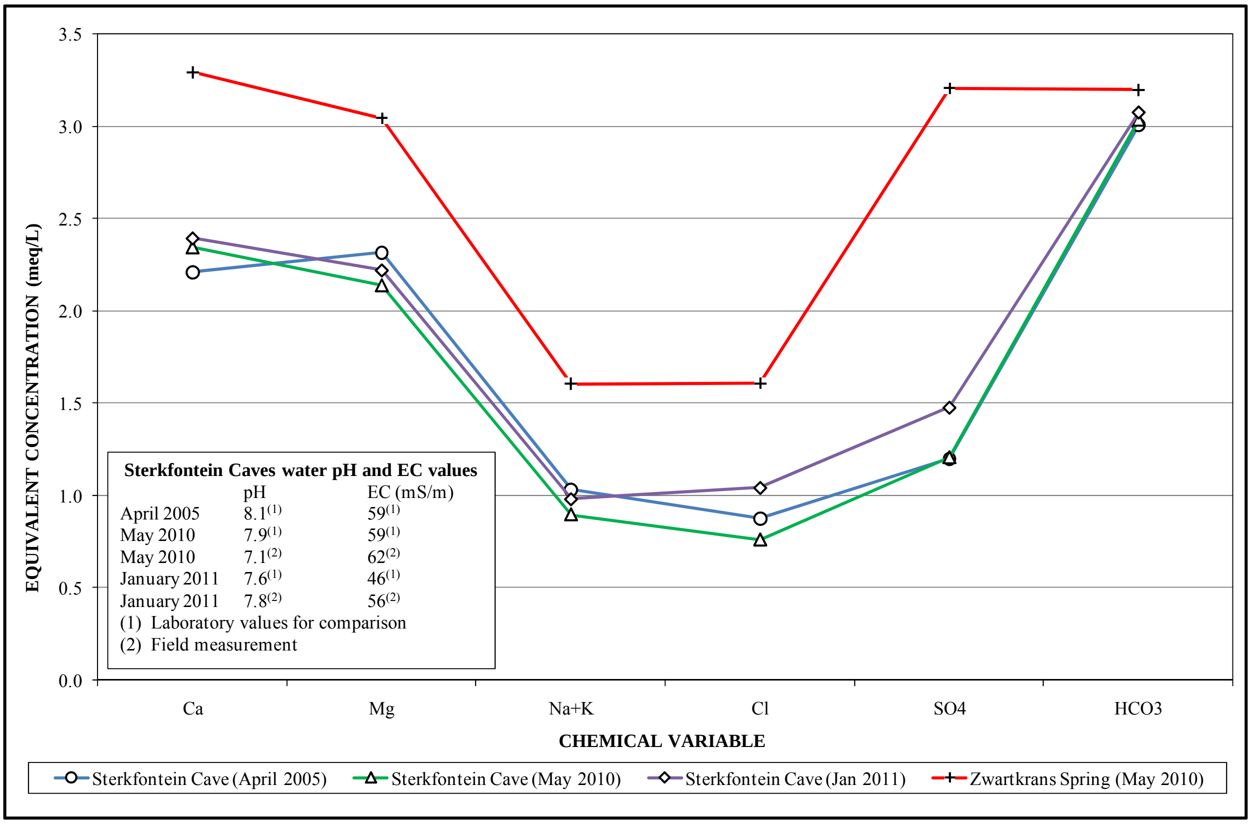

Figure 8. Comparison of historical and recent Sterkfontein Caves water chemistry with recent Zwartkrans Spring water chemistry.

Equally supportive of the hypothesis are the results of stable isotope analyses carried out on cave water and Zwartkrans Spring water in the recent past. These data are compared in the following tabulations, and indicate very little difference in the span of one year between analyses. A comparison of the May 2009 cave water tritium (^{3}H) value with that obtained in July 2009 for the Zwartkrans Spring reflects a significant difference of 1.1 ± 0.3 TU. The higher value associated with the spring water indicates that this source delivers a younger groundwater than that which is represented by the cave water.

Sterkfontein Caves

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

Zwartkrans Spring

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

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 1). 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 compromised 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. Nevertheless, a **high vulnerability** is assigned to this fossil site (Table 2).

2.4 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.

2.5 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 enjoys a similar measure of protection against hydrogeologic risks as Coopers, and accordingly enjoys a similarly **low vulnerability**.

2.6 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 1) 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.

2.7 Plovers Lake

Occupying a lowest surface elevation of ~1430 m amsl, the proximity of this fossil site to the Plovers 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,
- 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 represents a typically pristine karst water chemistry, and
- the largely natural landscape and low risk land use activities that characterise the Kromdraai Subcompartment provide good assurance against the deterioration of groundwater quality.

2.8 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[3]), 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**.

2.9 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 2 and Figure 9), 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**.

2.10 Gladysvale

The Gladysvale (Uitkomst) fossil site in the John Nash Nature Reserve extends to a depth of ~65 m below surface[4], which places the base of the cave system below the elevation (~1360 m amsl) of the Nash Spring. The fossil site and spring are located a distance of ~800 m apart in the Uitkomst Compartment. 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

[3] Sourced 28/06/2010 at http://www.southafrica.net/sat/content/en/us/full-article?oid=10034&sn=Detail&pid=7014.

[4] Based on a Jpeg image sourced at http://en.wikipedia.org/wiki/File:Gladysvale4.jpg on 17/05/2010.

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, as revealed by an EC of 25 mS/m. Further, the largely natural landscape and low risk land use activities that characterise 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. Accordingly, this fossil site is assigned a **low vulnerability**.

2.11 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 characterise 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. Accordingly, this fossil site is assigned a **very low vulnerability**.

2.12 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**.

2.13 Gondolin

This fossil site is located near the north-eastern extremity of the COH WHS (Figure 2). Situated in the Broederstroom Compartment, it occupies an elevation that is placed >40 m above the ambient groundwater rest level. This compartment is drained primarily by the Broederstroom Spring located at an elevation of ~1281 m amsl. Identified as a near-surface feature (Table 1), this fossil site is assigned a **very low vulnerability**.

2.14 Malapa

The Malapa Cave system occupies a surface elevation of ~1440 m amsl, 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. This observation matches field observations by T. Abiye and P. Dirks (T. Abiye, personal communication) regarding the depth of a vertical shaft (aven) located near this fossil site. Accordingly, the site is assigned a **very low vulnerability**.

3 DISCUSSION

The fossil site hydrovulnerability assessment is further illustrated in Figure 9, which shows the fossil site locations in relation to the hydrologic and hydrogeologic framework as defined for the study area.

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.

It is important to note that the fossil site risk assessment does not address 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.

4 CONCLUSIONS

It is concluded that nine of the 14 fossil sites in the COH WHS enjoy 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 enjoys a very high hydrovulnerability. This is due to its position immediately downgradient 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 must be tempered to some extent by recognizing that a number of the 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 Plovers Lake sites enjoy a moderate hydrovulnerability. This is mainly due to a relatively shallow (5 to 25 m bs) water table.

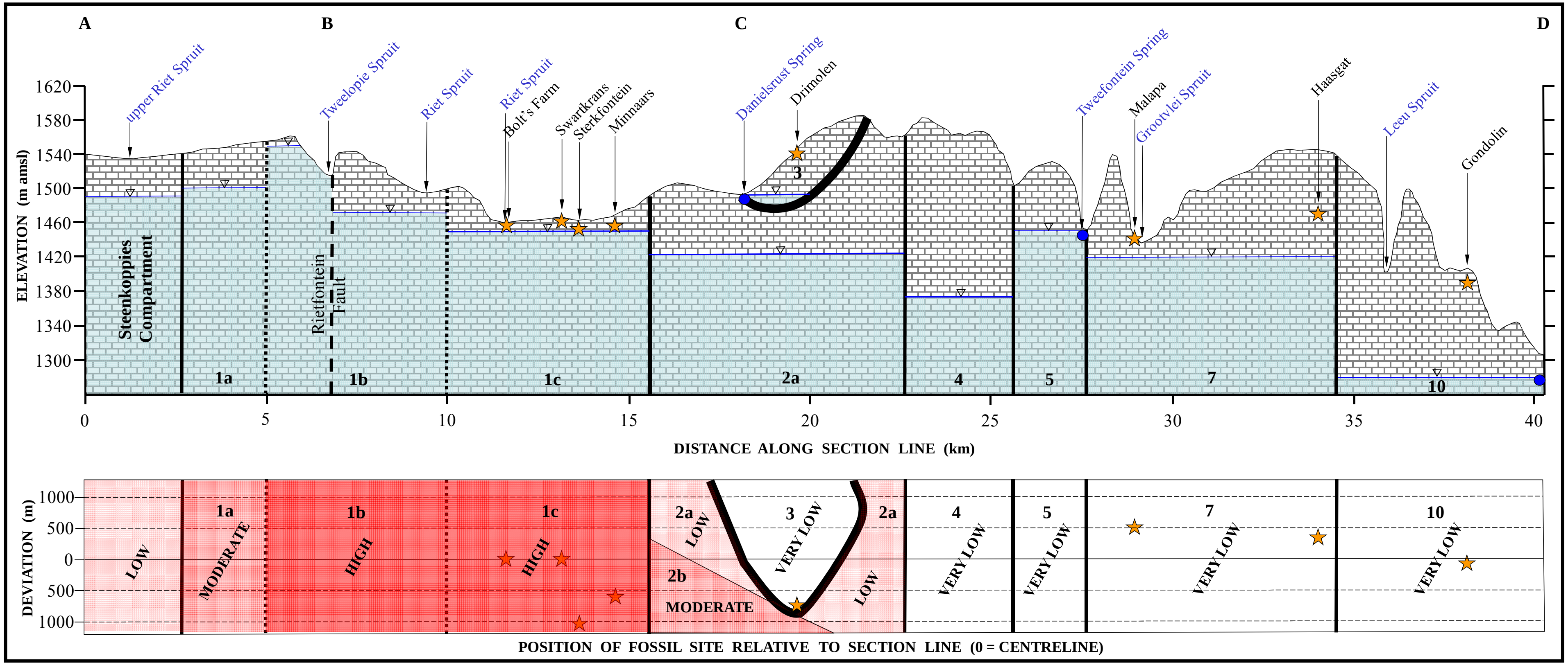

Figure 9. Cross-section (top) through the karst aquifer from south-west to north-east (see Figure 2) illustrating the position of fossil sites within ~1 km of the section line in relation to the hydrogeology at each site, and plan view (bottom) showing the measure of fossil site deviation from the centreline (expressed as metres normal to the latter) and the relative risk to the compartment/subcompartment from polluted water.

[Note: The fossil site elevations shown in the cross-section reflect approximately the surface elevations given in Table 2, 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.]

Key to compartments/subcompartments:

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

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 identified and are earmarked for specific monitoring activities.

5 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 a borehole sunk on the property. It is recommended that this borehole be equipped with an automatic recording device (logger) that measures and stores EC, temperature and water level depth readings at a pre-set hourly interval.

The Sterkfontein Caves site lends itself to direct monitoring by tourist guides. Such 'self-monitoring' can be implemented if tourist guides are tasked to routinely (daily?) 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.

Such an arrangement will not only serve the all-important monitoring imperative, but also empower the tourist guides with an additional competency over and above that of a mere guide. Further, it would provide the guides with additional 'first-hand' information that could be communicated to visitors as part of the standard tour guide 'script'.

In addition, however, a more complete bi-annual (twice a year) water chemistry analysis incorporating major anions and cations together with N and P, selected trace metals (Al, Fe, Mn, Ni and U) and environmental isotopes (^{2}H, ^{3}H and ^{18}O) will be required. This sampling frequency might be increased to quarterly should the "high frequency" field monitoring by tourist guides indicate a change in chemical field variable(s) that warrants such action.

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.

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