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PROJECT TITLE

PILOT IMPLEMENTATION OF A SURFACE WATER AND GROUNDWATER RESOURCES MONITORING PROGRAMME FOR THE CRADLE OF HUMANKIND WORLD HERITAGE SITE

REPORT TITLE

STATUS REPORT FOR THE PERIOD APRIL TO SEPTEMBER 2012

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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. The outcome of this project was captured in a comprehensive situation assessment report dated March 2011, and precipitated the pilot implementation of the proposed water resources monitoring programme for the COH WHS in the period April 2012 to March 2013. This report represents the first status report of the pilot implementation project, and covers the period April to September 2012.

It is clear that an assessment of impacts on the water resources environment of the COH WHS must consider both a holistic view and a specific focus on those resources that are at greatest risk from a wastewater impact. The outcome of the pilot implementation project as documented in this report largely confirms the conceptual hydrophysical and hydrochemical model developed for the COH WHS in the situation assessment report. It has not revealed any major inconsistencies, nor has it exposed significant flaws that might call into question the proposed water resources monitoring programme as originally formulated.

The monitoring data and results reveal the following responses in the water resources environment.

- In the last three hydrological years, the Bloubank Spruit system delivered the 2nd, 3rd and 4th highest runoff in the 40-year historical gauging record of this catchment.

- The re-commencement of uncontrolled raw mine water discharge from the mine area in late-January 2010 triggered an 18-month period of impact (from mid-2010 to late-2011) on the downstream receiving hydrologic environment before returning to 'more normal' pre-2010 conditions.

- Further abatement of the mine water impact on surface water quality commenced in mid-2012 with the commissioning of the immediate AMD intervention measures that witnessed an upgrade of the capacity and efficiency of the high density sludge (HDS) mine water treatment plant.

- Synoptic discharge measurements at two stations in the lower reach of the Riet Spruit confirmed earlier results regarding losses of mine water impacted surface water to the karst aquifer of the Zwartkrans Compartment. Representing allogenic recharge of the karst aquifer, the impact of the poorer quality water on the natural dolomitic groundwater is being manifested much more slowly.

- The impact of allogenic recharge from the losing reach of the Riet Spruit to the karst aquifer of the Zwartkrans Compartment is unequivocally mapped on the basis of elevated salinity and sulphate values in the groundwater. A provisional assessment forecasts arrival of the contamination 'peak' at the Zwartkrans Spring by the end of 2013, by which time the groundwater quality further upstream should already have shown an improvement provided that the immediate AMD intervention measures are maintained.

- The ~3 m rise in the Main Lake water level in Sterkfontein Caves, although unprecedented in modern times, finds support in potentiometric levels across the Zwartkrans Compartment. This level is unlikely to rise further because of the congruence with the channel elevation of the Bloubank Spruit opposite the caves.

- The decline in the Main Lake water level since mid-2012 is expected to continue at a rate of 0.06 m/month, but will remain high as a result of the greater sustained discharge of treated/neutralised mine water associated with the immediate and short-term AMD control and management interventions in the Western Basin.

- The quality of the Main Lake water in Sterkfontein Caves continues to reflect a muted influence from surface water impacted by mine water. This observation alone is sufficient to warrant the vigilance of monitoring the cave water quality.

In conclusion, it is evident from the monitoring data and results that the karst environment of a portion of the Zwartkrans Compartment in the south-western quadrant of the COH WHS has experienced a significant deterioration in groundwater quality. Sulphate levels of as much as ~1300 mg SO_4/L will definitely impact on the potability of groundwater-based water supplies in the area effected. Although the commissioning of the immediate mine water control and management intervention measures in mid-2012 has ameliorated the quality of surface water in the Bloubank Spruit system, the impact on the groundwater environment in the effected portion of the Zwartkrans Compartment will take significantly longer to manifest an improvement.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

~	approximately
>	greater than
<	less than
%	per cent (parts per hundred)
%ile	percentile
°C	degree(s) Centigrade
Δh	change in head
a_h	hydrological year
AMD	acid mine drainage
amsl	above mean sea level
bc	below collar
BRI	Black Reef Incline
bs	below surface
ca.	circa (about)
COH WHS	Cradle of Humankind World Heritage Site
COV	coefficient of variation
DWA	Department of Water Affairs (formerly DWAF; Department of Water Affairs and Forestry)
EC	electrical conductivity
G1	Gold One
HDS	high density sludge
kg	kilogram(s)
km	kilometre(s)
L/d	litre(s) per day
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
MA	Management Authority
meq/L	milliequivalent(s) per litre
mg/L	milligram(s) per litre
mg/s	milligram(s) per second
ML/d	megalitre(s) per day
mm	millimetre(s)
m^3/s	cubic metre(s) per second
Mm^3	million cubic metre(s)
Mm^3/a	million cubic metres per annum
mS/m	milliSiemens per metre
n	count
pp	pages
RU/G1	Rand Uranium/Gold One
SD	standard deviation
SDM	synoptic discharge measurement
TCTA	Trans-Caledon Tunnel Authority
t/d	ton(s) per day
TDS	total dissolved salts
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**). Amongst a number of techno-scientific reports, the project produced a situation assessment of the surface water and groundwater resource environments (Hobbs, 2011a). A substantial amount of new data have become available since the completion of this report. The source of the new data ranges from monitoring activities carried out by various authorities (e.g. Department of Water Affairs, Mogale City Local Municipality) and private entities (e.g. Rand Uranium/Gold One, Nedbank), as well as by the Management Authority through the pilot implementation of the COH WHS water resources monitoring programme. These circumstances require an update of the situation assessment to reflect more recent patterns and trends revealed by the data. Such an update is presented in this report, which combines a situation assessment update with a monitoring report as envisaged in the proposed water resources monitoring programme (Hobbs, 2011b).

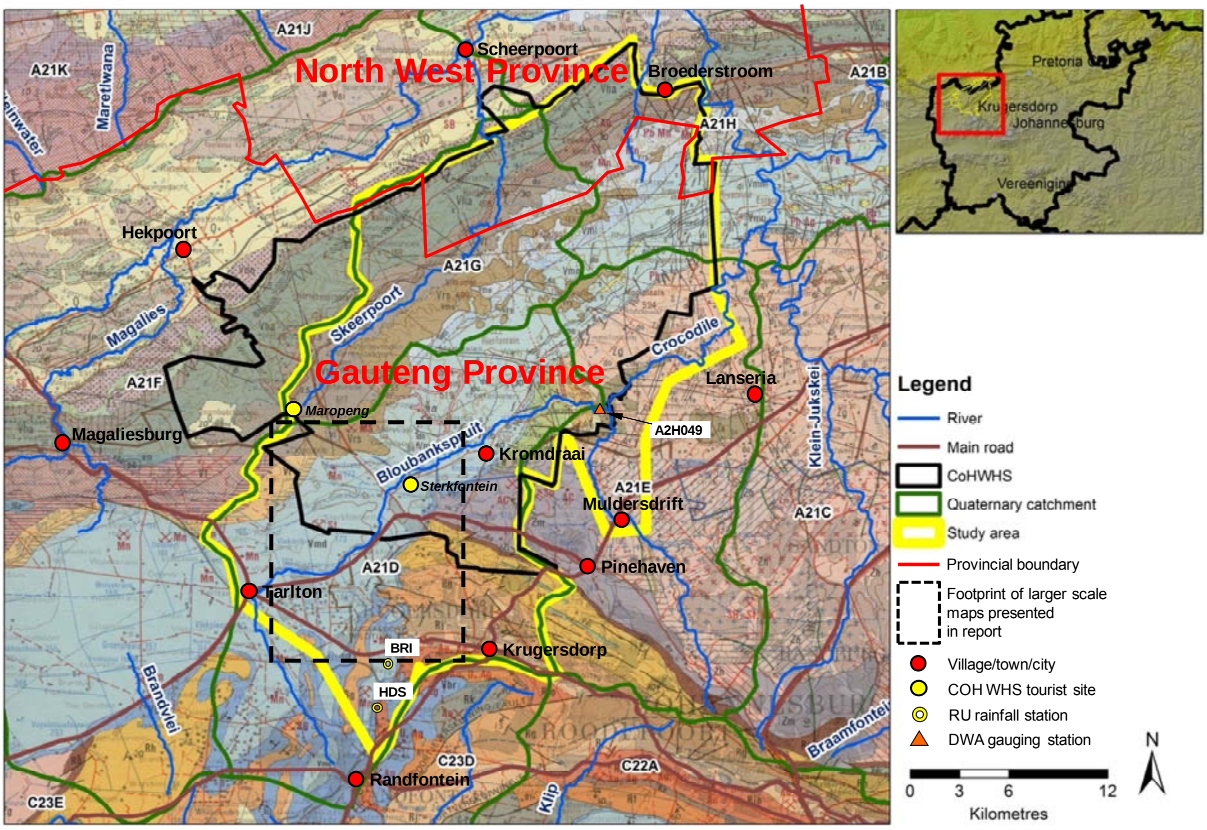


Figure 1 Definition of the study area in regard to the regional geology, surface water drainages, quaternary catchments and other geographic locations for orientation

2 TIMELINE OF KEY EVENTS

It is considered appropriate to contextualise the material presented and discussed in this report in terms of a timeline of key events since the inscription of the COH WHS as a World Heritage Site in 1999. The timeline is presented in **Figure 2**.

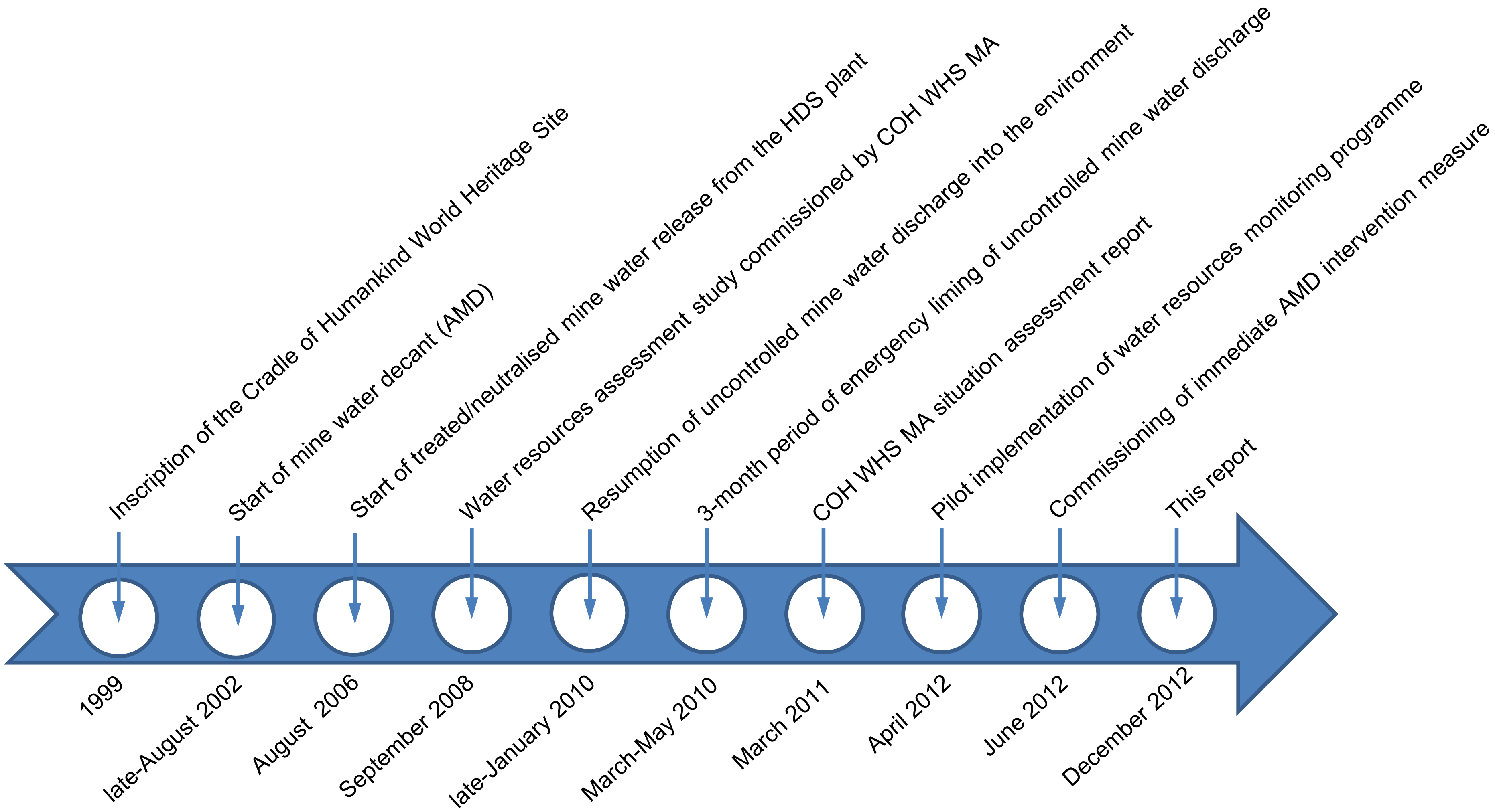


Figure 2 Timeline of events relevant to this report

Landmark events on the timeline (**Figure 2**) are the following and for the stated reasons.

- The water resources situation assessment study commissioned by the COH WHS MA in September 2008. The completion of this study with the publication of its outcomes in March 2011 marks an improved understanding of the surface water and groundwater resources in the COH WHS that (1) provides context for the many and widespread misperceptions regarding impacts on the water resources environment, and (2) informs and supports sound management actions directed at responsible and effective governance of this environment based on an appropriate integrated water resources monitoring programme.

- The resumption of uncontrolled mine water decant in late-January 2010. This triggered a new dynamic in the receiving water resources environment characterised by a dominance of raw mine water over treated/neutralised mine water in the aggregate discharge of AMD from the Western Basin. Although the impact of this event on the surface water environment lasted some 18 months, its impact on the groundwater environment is still unfolding.

- The commissioning in June 2012 of the Department of Water Affairs (DWA) immediate intervention measure implemented by its Implementing Agent, the Trans-Caledon Tunnel Authority (TCTA), to control and manage AMD in the Western Basin. This marks another event horizon that will again alter the dynamic of a mine water impact on the receiving water resources. It has already manifested a positive impact on the surface water environment, but again will take much longer before the groundwater environment responds positively.

3 RAINFALL

The monthly precipitation record for the period October 2008 to September 2012 (**Figure 3**) of the Rand Uranium/Gold One (RU/G1) rainfall stations BRI (named for its location at the Black Reef Incline), and HDS (named for its location at the High Density Sludge plant) (**Figure 1**), reveals the wetter than normal 2009-'10 and 2010-'11 summer rainfall seasons (**Figure 4**). It is evident from **Figure 3** that these circumstances already commenced in October 2009. The rainfall data also confirm the observation (Hobbs, 2011a) that monthly precipitation at station BRI to the north of the continental divide is generally ~14% less than that measured at station HDS on the divide.

4 SURFACE WATER HYDROLOGY

4.1 Physical Hydrology

4.1.1 Surface Water Discharge

The discharge of the Bloubank Spruit system is gauged by the DWA at station A2H049 located ~700 m before its confluence with the Crocodile River (**Figure 1**). The 40-year record provides the monthly discharge statistics presented in **Table 1**. The discharge per hydrological year (a_h) shown in **Figure 5** indicates that last three hydrological years witnessed the 2nd, 3rd and 4th highest runoff (59.1, 50.0 and 44.9 Mm^3 after the 66.9 Mm^3 of the 1977-'78 hydrological year) in the historical record of this catchment. The significance of these circumstances is evident in their impact on the long-term median discharge of the Bloubank Spruit system, which reflects a median value of ~19.3 Mm^3/a for the period 1972-'73 to 2008-'09, and a 15% greater median value of ~22.6 Mm^3/a for the entire record. An analysis of hydrological data (both quantity and quality) must therefore recognise the influence imposed on the long-term data set by the 2009-'10, 2010-'11 and 2011-'12 hydrological years. These circumstances, however, are only due in part to the exceptional rainfall of the 2009-'10 and 2010-'11 summers — the contribution of mine water decant is discussed in **sections 4.2, 4.3** and **5.2**.

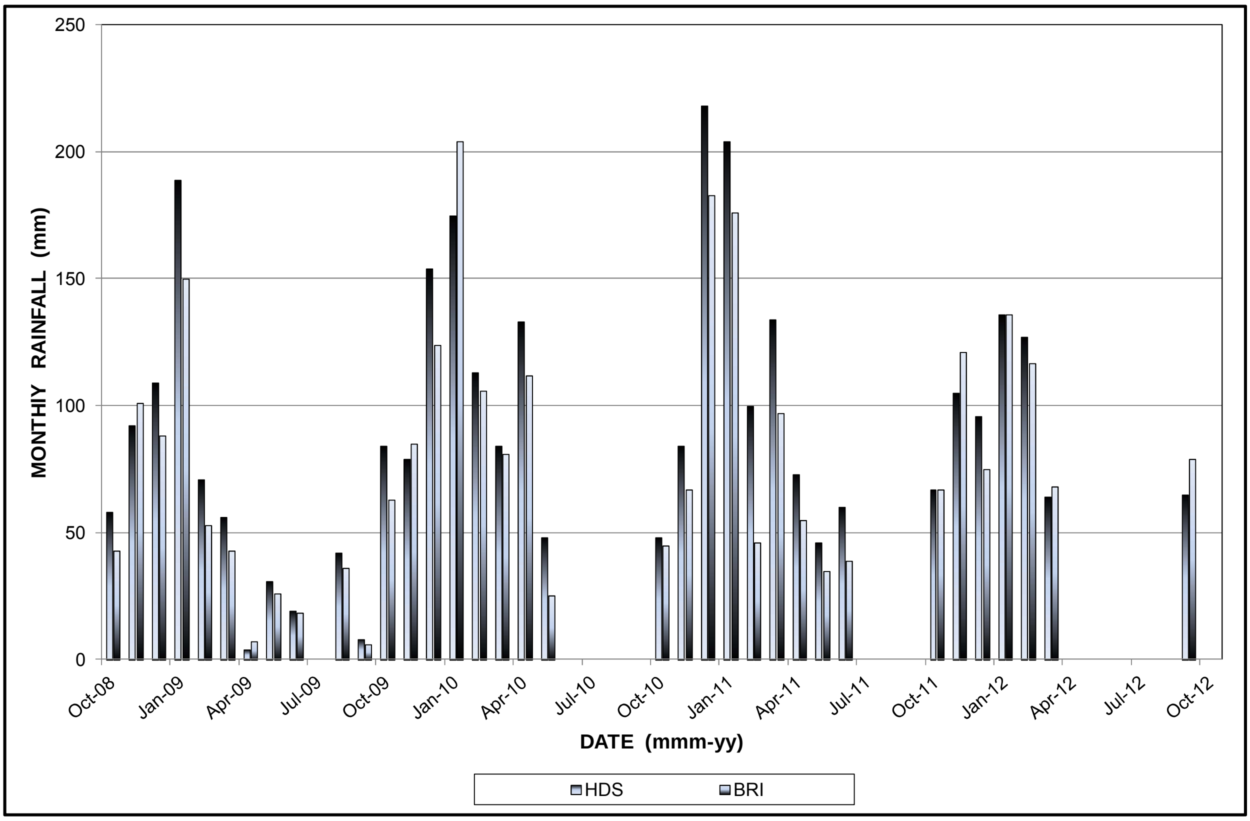


Figure 3 Monthly precipitation recorded at the Rand Uranium/Gold 1 rainfall monitoring stations HDS and BRI in the period October 2008 to September 2012

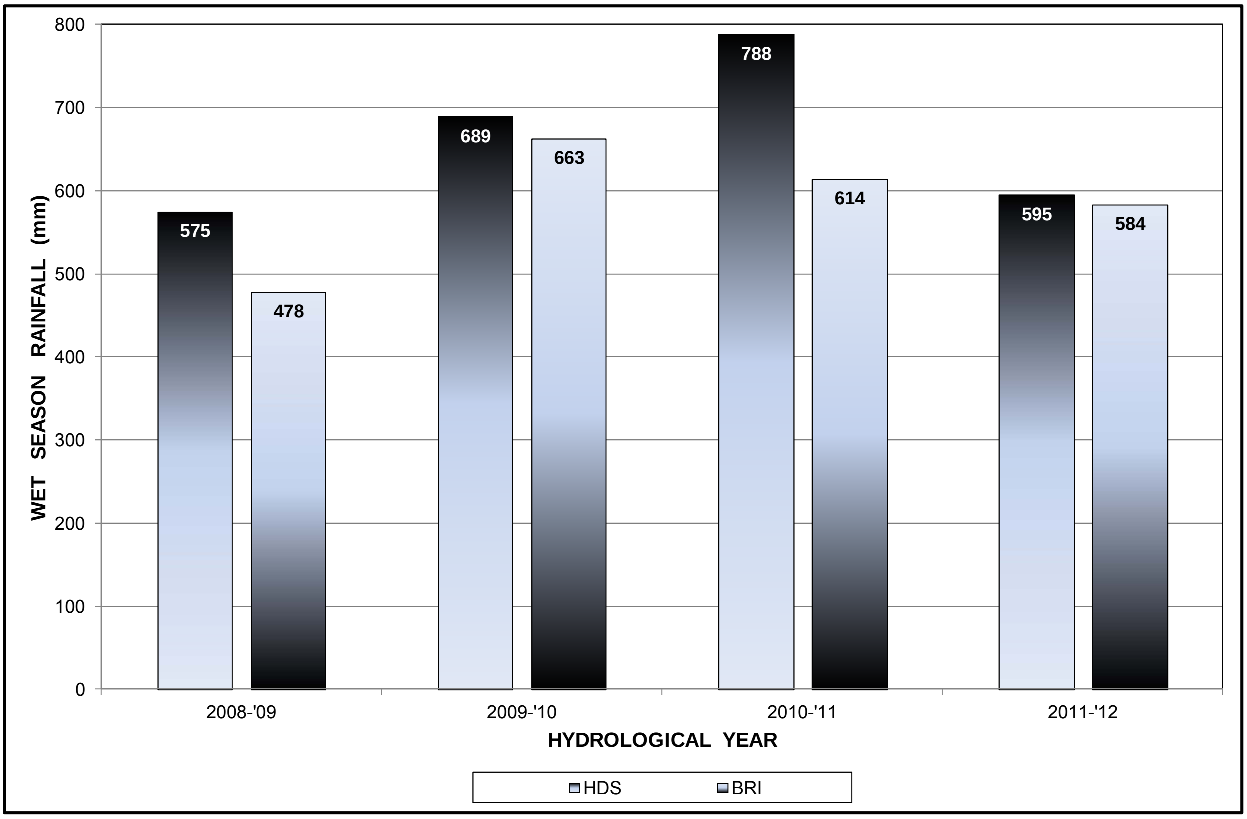
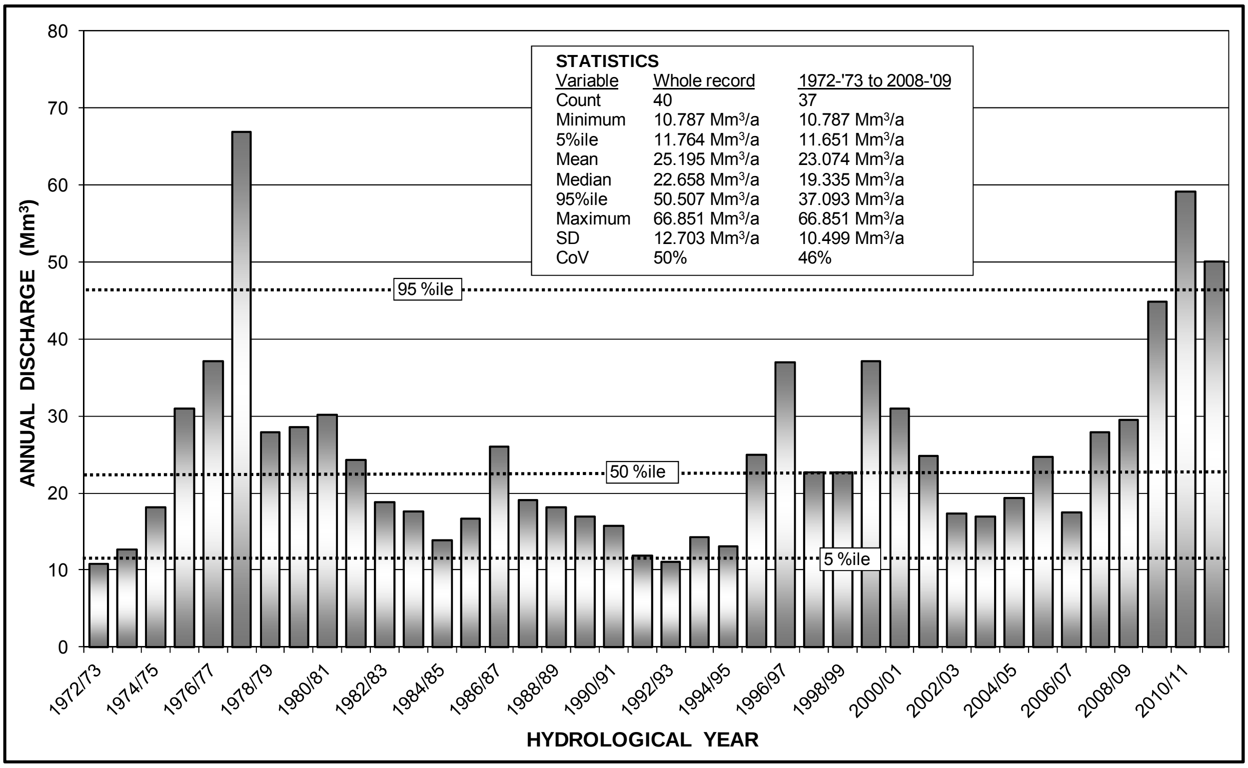


Figure 4 Comparison of total wet season (summer) rainfall at the Rand Uranium/Gold 1 rainfall monitoring stations HDS and BRI in the past four hydrological years

Table 1 Statistical analysis of Bloubank Spruit monthly discharge data gauged at station A2H049 in the period October 1972 to October 2012

Variable	Month											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Count (n)	39	38	39	39	40	40	40	39	40	40	39	39
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	0.844	1.037	1.085	0.896	1.028	1.164	0.968	0.946	0.953	0.909	0.798
Mean	1.791	1.773	2.179	2.677	2.552	2.769	2.285	2.180	1.998	1.955	1.833	1.707
Median	1.536	1.660	1.859	2.340	1.934	2.294	1.901	1.797	1.695	1.637	1.513	1.329
95%ile	3.907	2.881	4.540	5.672	5.640	5.854	4.677	4.936	3.673	3.722	3.646	3.526
Maximum	4.272	4.577	5.900	12.079	10.619	9.358	6.081	5.373	5.166	4.754	4.055	4.342
SD	0.929	0.785	1.117	2.031	1.911	1.881	1.247	1.188	0.954	0.899	0.824	0.859
CoV (%)	52	44	51	76	75	68	55	55	48	46	45	50

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



STATISTICS

Variable	Whole record	1972-'73 to 2008-'09
Count	40	37
Minimum	10.787 Mm^3/a	10.787 Mm^3/a
5%ile	11.764 Mm^3/a	11.651 Mm^3/a
Mean	25.195 Mm^3/a	23.074 Mm^3/a
Median	22.658 Mm^3/a	19.335 Mm^3/a
95%ile	50.507 Mm^3/a	37.093 Mm^3/a
Maximum	66.851 Mm^3/a	66.851 Mm^3/a
SD	12.703 Mm^3/a	10.499 Mm^3/a
CoV	50%	46%

Figure 5 Graph of Bloubank Spruit annual (a_h) discharge gauged at station A2H049 in the period October 1972 to September 2012

The instantaneous monthly flow pattern at station A2H049 for the complete record is shown in **Figure 6**. This reveals a comparatively constant lowest value of 0.25 m^3/s. Evident in the hydrograph (**Figure 6**) are distinct recession curves following peak discharge events. 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, but also receives the discharge of other 'lesser' springs (e.g. the Plover's Lake and Aquamine springs) and ephemeral tributaries such as the Honingklip and Tweefontein spruits. These circumstances negate a correlation between spring discharge and rainfall.

A closer inspection of the instantaneous flow data record generated at station A2H049 indicates that the instantaneous daily average flow of 18.6 m^3/s recorded on 16 December 2010 is the second highest in the historical record of gauging at this station. The maximum (highest) daily average flow of 34.3 m^3/s was recorded on 28 January 1978. This observation places in perspective the floods experienced in the Bloubank Spruit in mid-December 2010, and which served as one of the triggers for the Koelenhof fish mortality event that occurred in mid-January 2011 (Hobbs and Mills, 2011). The 1972-'73 to 2008-'09 and the whole record median annual discharge values represent 11-12% of the net capacity (186.4 Mm^3) of Hartbeespoort Dam.

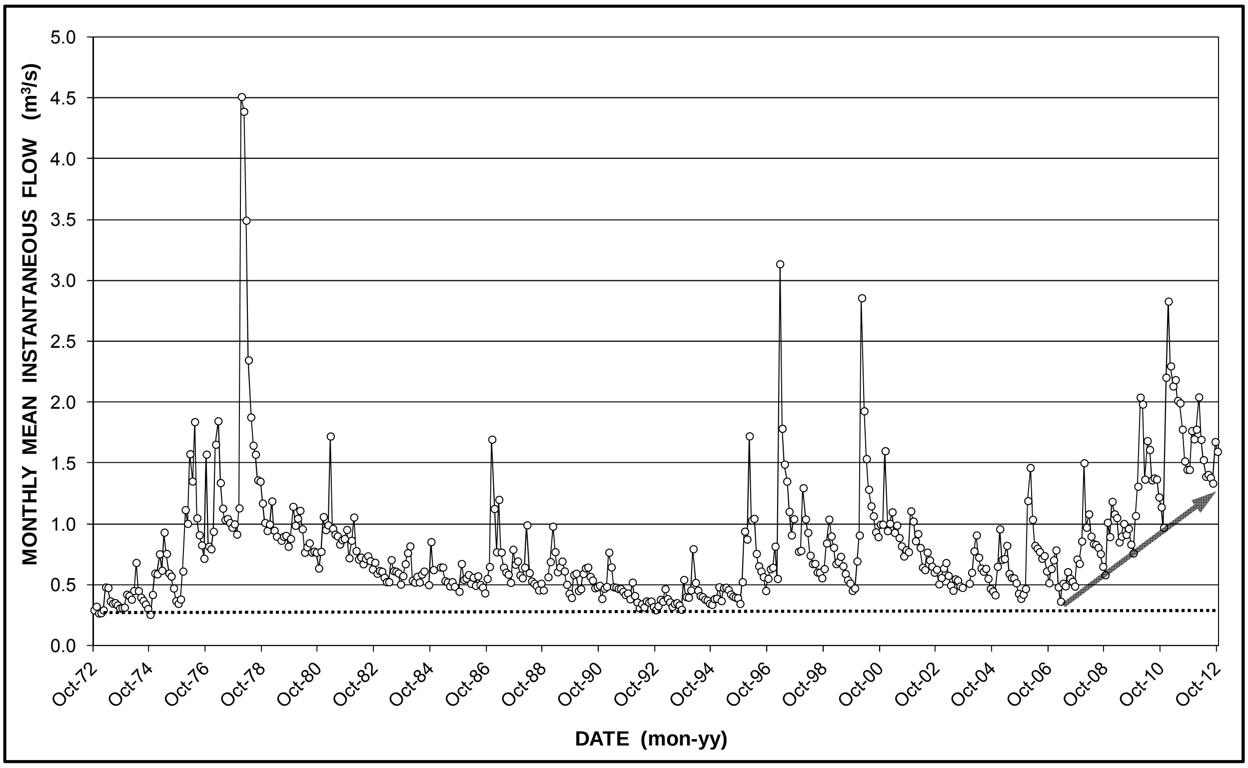


Figure 6 Long-term monthly hydrograph of the Bloubank Spruit at station A2H049 for the period October 1972 to September 2012

4.1.2 Surface Water Fluxes

The interaction between surface water and groundwater is an integral characteristic of karst environments, and is defined by both surface water losses to the subsurface environment and groundwater resurgence in river and stream channels. The allogenic nature of much of the inflowing surface water sources, e.g. mine water from the Western Basin via the Tweelopie Spruit, and municipal wastewater from the Percy Stewart Wastewater Treatment Works (WWTW) via the Blougat Spruit, renders such interaction even more critical for the possible negative impact on the receiving water resources environment in the COH WHS.

In-stream synoptic discharge measurements (SDMs) made on 23 occasions (**Table 2**) at stations F11S12 and MRd (**Figure 7**) further quantify and elucidate the magnitude of surface water loss to the karst aquifer. The results of the SDMs are illustrated in **Figure 8**. Prior to the 2009-'10 summer, site MRd witnessed surface flow only under exceptional discharge conditions[1], when under 'normal' circumstances all of the discharge entering the Riet Spruit via the Tweelopie Spruit was lost primarily to recharge of the karst aquifer before reaching this location. This is exemplified in the measurements recorded on 09 and 22 September 2009 respectively (**Table 2** and **Figure 8**).

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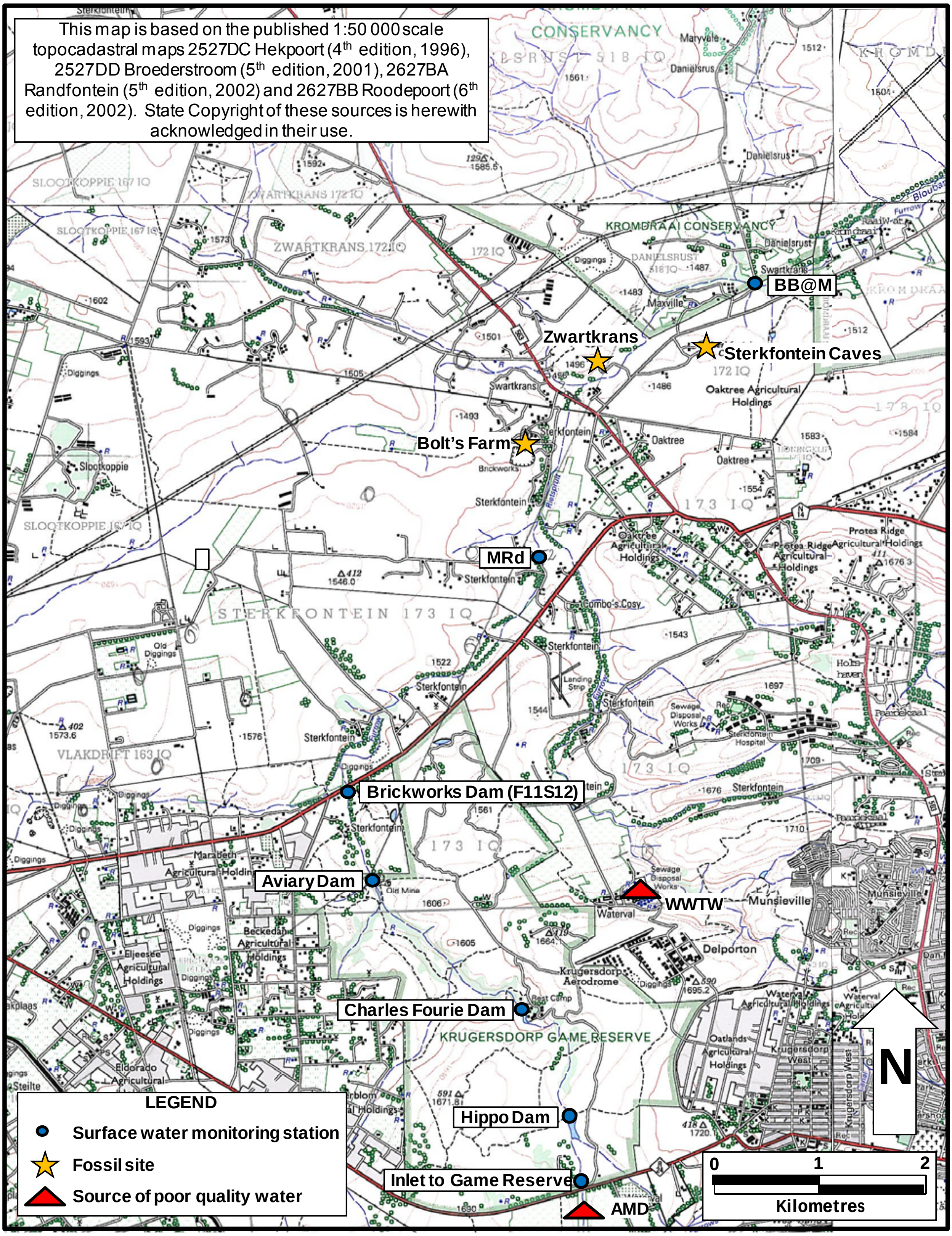
[1] Caused by excessive and uncontrolled AMD overflow from the mining area together with excess surface runoff associated with very high rainfall events.



This map is based on the published 1:50 000 scale topocadastral maps 2527DC Hekpoort (4th edition, 1996), 2527DD Broederstroom (5th edition, 2001), 2627BA Randfontein (5th edition, 2002) and 2627BB Roodepoort (6th edition, 2002). State Copyright of these sources is herewith acknowledged in their use.

Figure 7 Locality map of surface water quantity and quality monitoring stations

Table 2 Quantification of stream flow loss rate in the Riet Spruit

Date	Flow @ F11S12 (ML/d)	Flow @ MRd (ML/d)	Flow Loss (ML/d)	Flow Loss Rate(1) (L/s/km)
09/09/2009	11.9	0	11.9	34
22/09/2009	14.9	0	14.9	43
05/02/2010	35.2	7.3	27.9	81
16/02/2010	31.6	5.7	25.9	75
23/02/2010	26.2	4.0	22.2	64
09/03/2010	32.6	9.4	23.2	67
01/04/2010	40.4	10.3	30.1	87
14/04/2010	25.8	5.7	20.1	58
06/05/2010	43.7	11.7	32.0	93
18/05/2010	35.7	11.0	24.7	71
09/06/2010	32.1	10.5	21.6	63
07/07/2010	29.9	6.2	23.7	69
27/07/2010	31.6	6.5	25.1	73
19/08/2010	25.8	5.3	20.5	59
05/10/2010	13.8	0.4	13.4	39
19/11/2010	22.2	3.4	18.8	54
27/07/2011	31.9	19.4	12.5	36
25/08/2011	28.7	20.0	8.7	25
05/09/2011	22.5	15.9	6.6	19
08/05/2012	21.4	9.6	11.9	34
14/08/2012	22.5	6.8	15.7	45
21/09/2012	24.6	15.5	9.1	26
24/10/2012	16.2	5.7	10.5	30
Count	23	23	23	23
Minimum	11.9	0	6.6	19.1
Mean	27.0	8.3	18.7	54.2
Median	26.2	6.8	20.1	58.0
Maximum	43.7	20.0	32	93.0
SD	8.3	5.6	7.3	21.3
CoV (%)	30.6	67.3	39.1	39.2

(1) Based on a distance of ~4 km between localities

The SDM results presented in **Table 2** and **Figure 8** indicate an absorptive capacity defined by an ingress value of ~14 ML/d (~41 L/s/km). A similar situation is described by Katz et al. (1998; 2004) for sinkhole lakes in the Suwannee and northern Leon counties, respectively, in northern Florida, USA. These lakes overflow when inflow exceeds ~200 L/s (~17 ML/d). Sasowsky and White (1993) describe similar circumstances for the East Fork of the Obey River in north-central Tennessee (USA), reporting that at discharges of <4.5 m^3/s (<389 ML/d) the entire flow of the river disappears into the subsurface.

It is notable that four of the last six determined discharges at the downstream station MRd, namely 19.4, 20.0, 15.9 and 15.5 ML/d measured on 27 July 2011, 25 August 2011, 05 September 2011 and 21 September 2012, respectively, substantially exceed the previous highest measured value of 11.7 ML/d recorded on 06 May 2010 (**Table 2**). Further, four of the six most recently determined surface flow losses between stations F11S12 and MRd equate to the lowest in the record of measurements since flow at station MRd was first recorded in this study. These circumstances suggest that the absorptive capacity of the karst aquifer underlying the losing 4-km reach of the Riet Spruit reached a new equilibrium condition during the 2010-’11 wet season that continued into the 2011-’12 hydrological year.

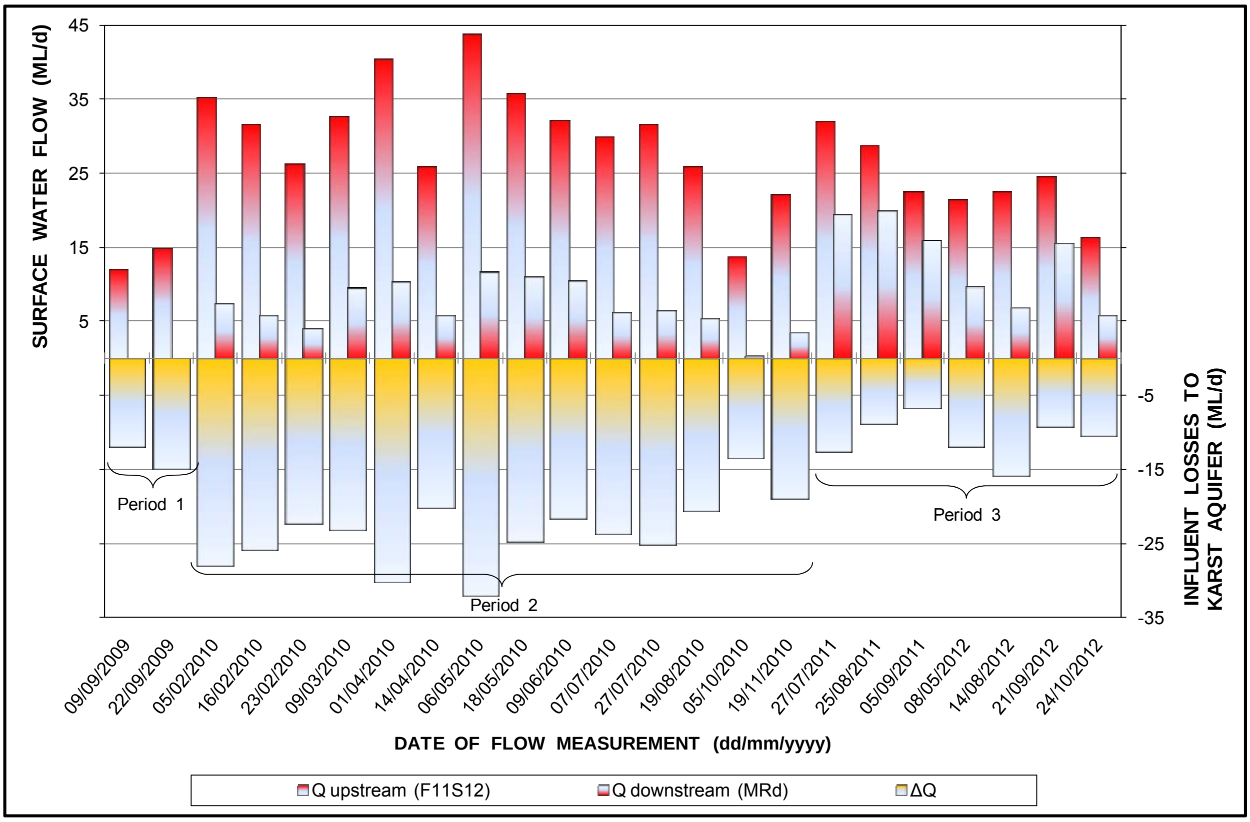


Figure 8 Graphical representation of stream flow and losses to the karst aquifer in the lower Riet Spruit valley

Figure 8 suggests that a threshold flow value exists at the upstream station F11S12, below which all surface flow is lost to the karst aquifer and no flow passes the downstream station MRd. Conversely, flow that exceeds the threshold value at F11S12 results in surface water flow past station MRd. This observation is explored in **Figure 9**, which indicates that the 'threshold' value is in the order of 13-15 ML/d. The linear regression equation for the first 16 measurements ($R^2 = 0.89$) yields a cut-off y-value (for $x = 0$) of ~15 ML/d. The linear regression equation for the first three and last seven measurements ($R^2 = 0.89$) returns a cut-off y-value of ~14 ML/d. The existence of two different regression equations associated with different time periods of a single data set supports the conclusion regarding the change in hydraulic response of the surface and subsurface hydrologic interaction in and below the stream reach in question. The set of historical Google Earth images (**Figure 10**) defined by the imagery dates 22 May 2010, 31 March 2011 and 13 October 2011 provide a possible explanation. These images show the formation of a ferric hydroxide crust in the stream channel sometime between 22 May 2010 and 31 March 2011, that might cause a decrease in streambed permeability.

These analyses lead to the conclusion that the 'absorptive capacity' (and therefore also the 'transmissive capacity') of the epikarst along the ~4-km reach of the Riet Spruit between stations F11S12 and MRd, functions with 100% efficiency at discharges of up to 13-15 ML/d (150-175 L/s). Above this 'threshold', the 'absorptive capacity' is exceeded and more water discharges as surface water flow through the Bloubank Spruit system. Nevertheless, the quality of the influent surface water lost to the karst aquifer in the 2009-'10 and 2010-'11 hydrological years presents a concern that is evaluated and discussed in **section 5.2.3**.

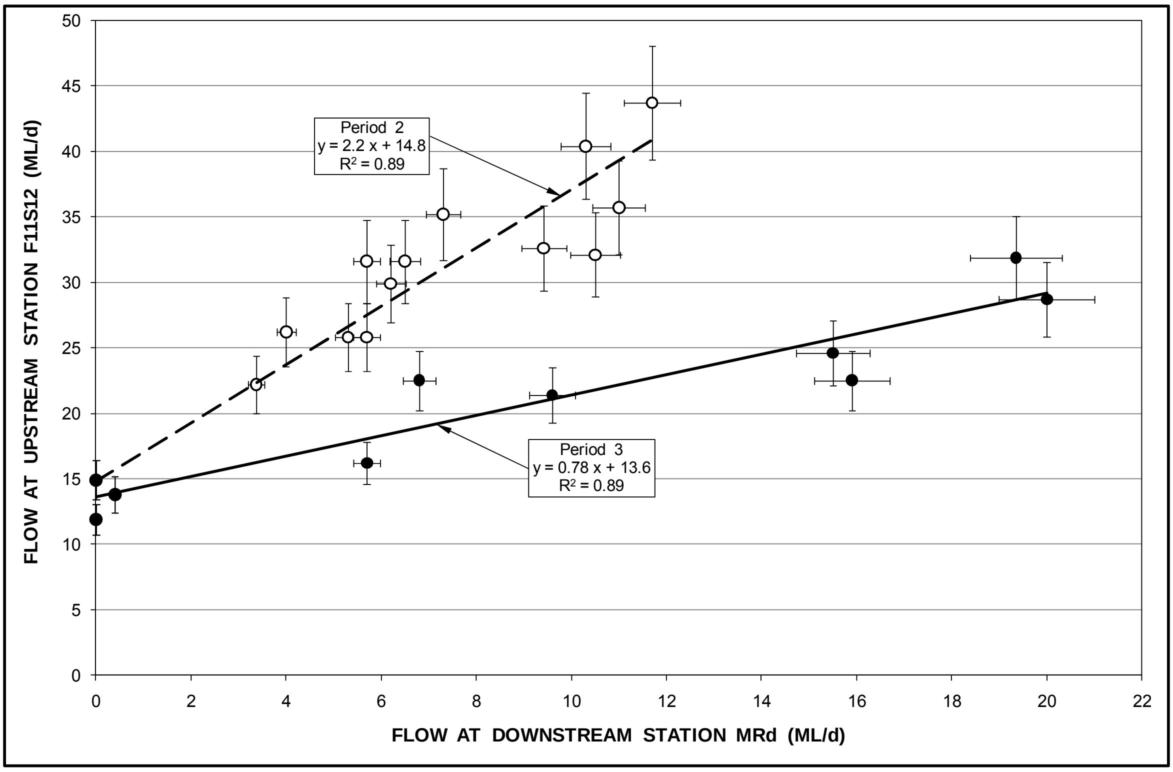


Figure 9 Correlation of stream flow measurements at the upstream (F11S12) and downstream (MRd) monitoring stations in the Riet Spruit valley (respective regression lines explained in text and **Figure 8**), with error bars denoting ±10% at F11S12 (vertical) and ±5% at MRd (horizontal)

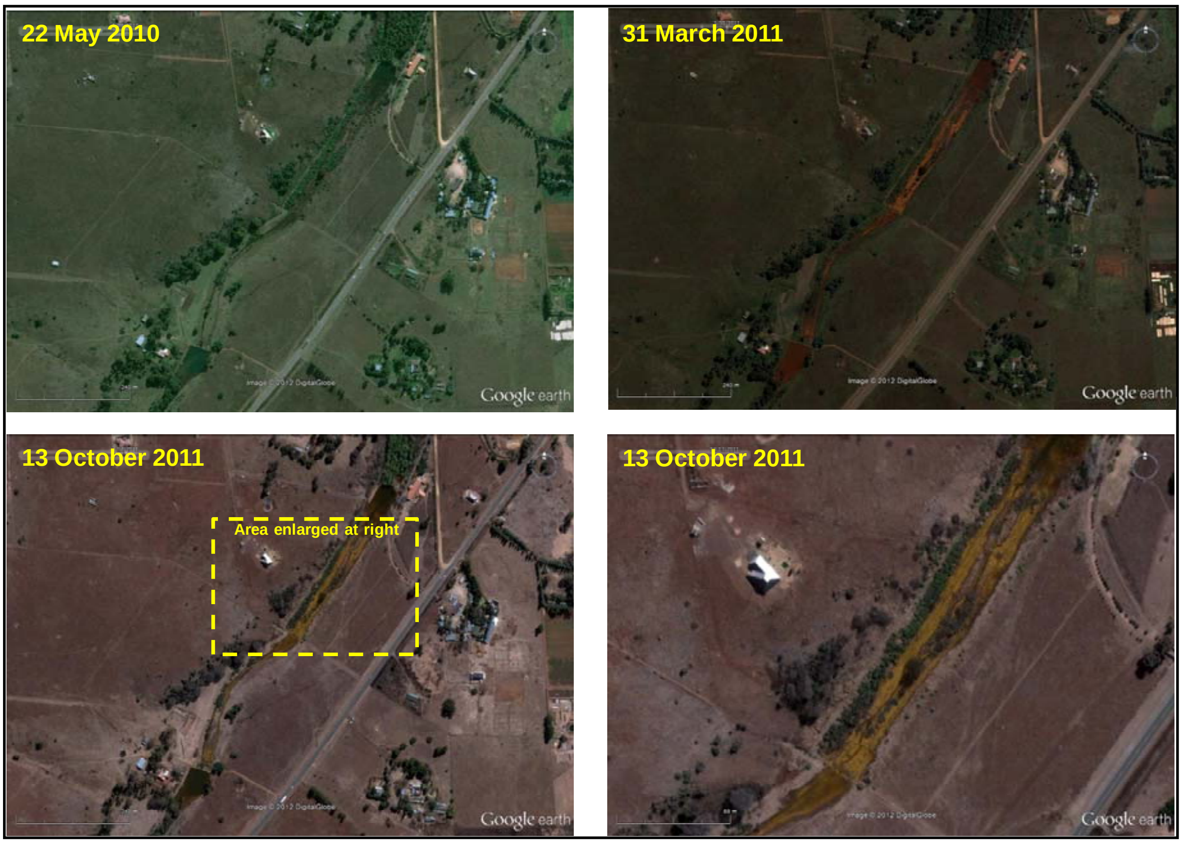


Figure 10 Historical Google Earth images showing the development of a ferric hydroxide crust in the channel of the Riet Spruit sometime between 22 May 2010 and 31 March 2011; stream section located between stations F11S12 and MRD in **Figure 7**

4.2 Chemical Hydrology

4.2.1 Tweelopie Spruit and Riet Spruit

The chemistry of surface water in the Tweelopie Spruit is monitored by RU/G1 at five localities from where it leaves the mine property down to its confluence with the Riet Spruit at Glen Almond north of the Krugersdorp Game Reserve (KGR), a distance of ~6.6 km. These stations are identified in **Figure 7** as (a) the inlet to the KGR, (b) the Hippo Dam, (c) the Charles Fourie Dam, (d) the Aviary Dam and (e) the Brickworks Dam (DWA station F11S12). The weekly monitoring of the variables pH, electrical conductivity (EC) and SO_4 dates back to May 2004. The results of this monitoring, excluding the inlet to the KGR location[2] and the Aviary Dam[3], are presented in **Figure 11** (pH), **Figure 12** (EC) and **Figure 13** (SO_4). The patterns revealed in these graphs indicate the pattern and variation in the respective variable values that are manifested in surface water chemistry through the game reserve over time.

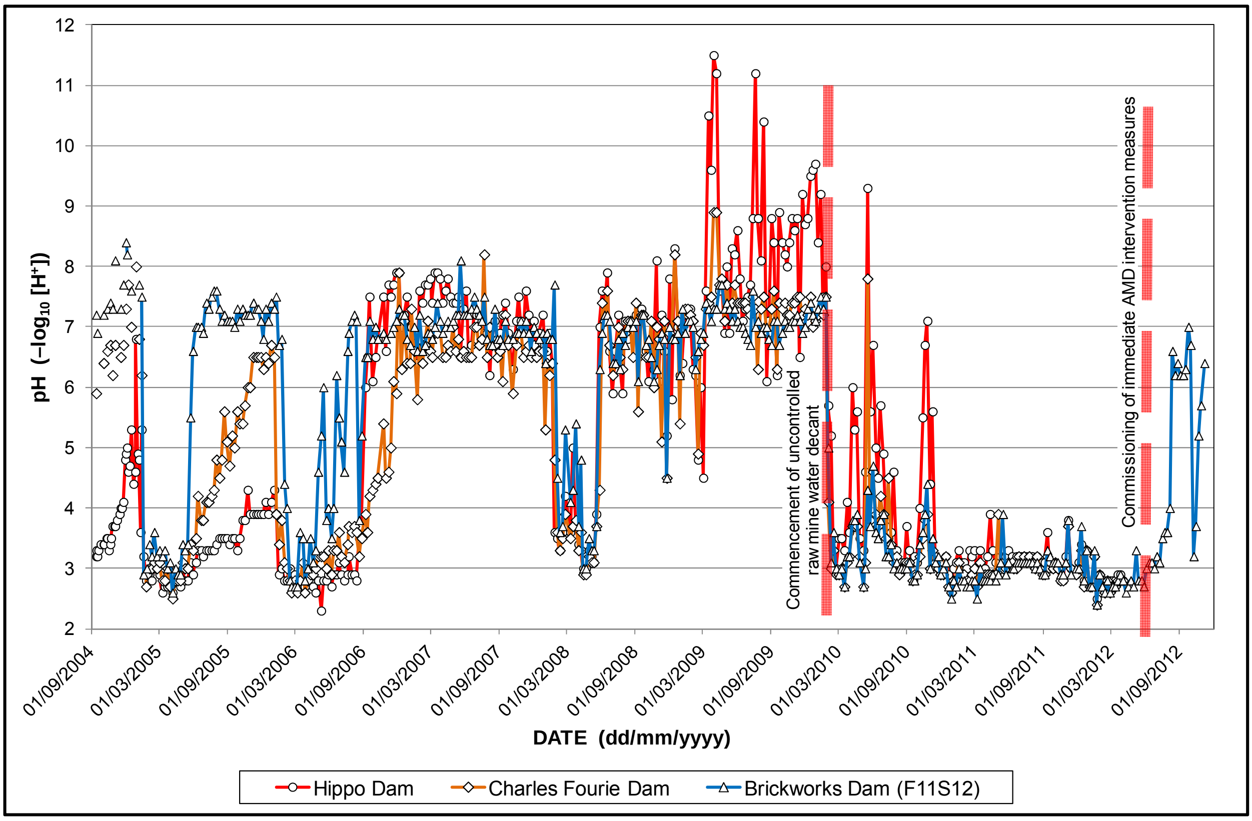


Figure 11 Pattern of pH values in the Tweelopie Spruit in the period May 2004 to October 2012

It is clear from **Figure 11**, and to a lesser extent from **Figure 12** and **Figure 13**, that the severest and most sustained impact of AMD on the receiving surface water environment of the Tweelopie Spruit commenced ca. end-January 2010. This is unequivocally shown in the somewhat shorter record of Fe (**Figure 14**) and Mn (**Figure 15**) values. Prior to this, the gradual 'growth' in impact since 2004 is evidenced by the increasing salinity and sulphate trends up to the recent persistent elevated levels (**Figure 12** and **Figure 13**).

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[2] These data are excluded due to their close proximity to the Hippo Dam, and consideration of the fact that the residence time of this water in the Hippo Dam renders the data for the latter location more representative of the surface water entering the Tweelopie Spruit.

[3] The Aviary Dam is excluded due to the excellent congruence with values obtained at the Brickworks Dam.

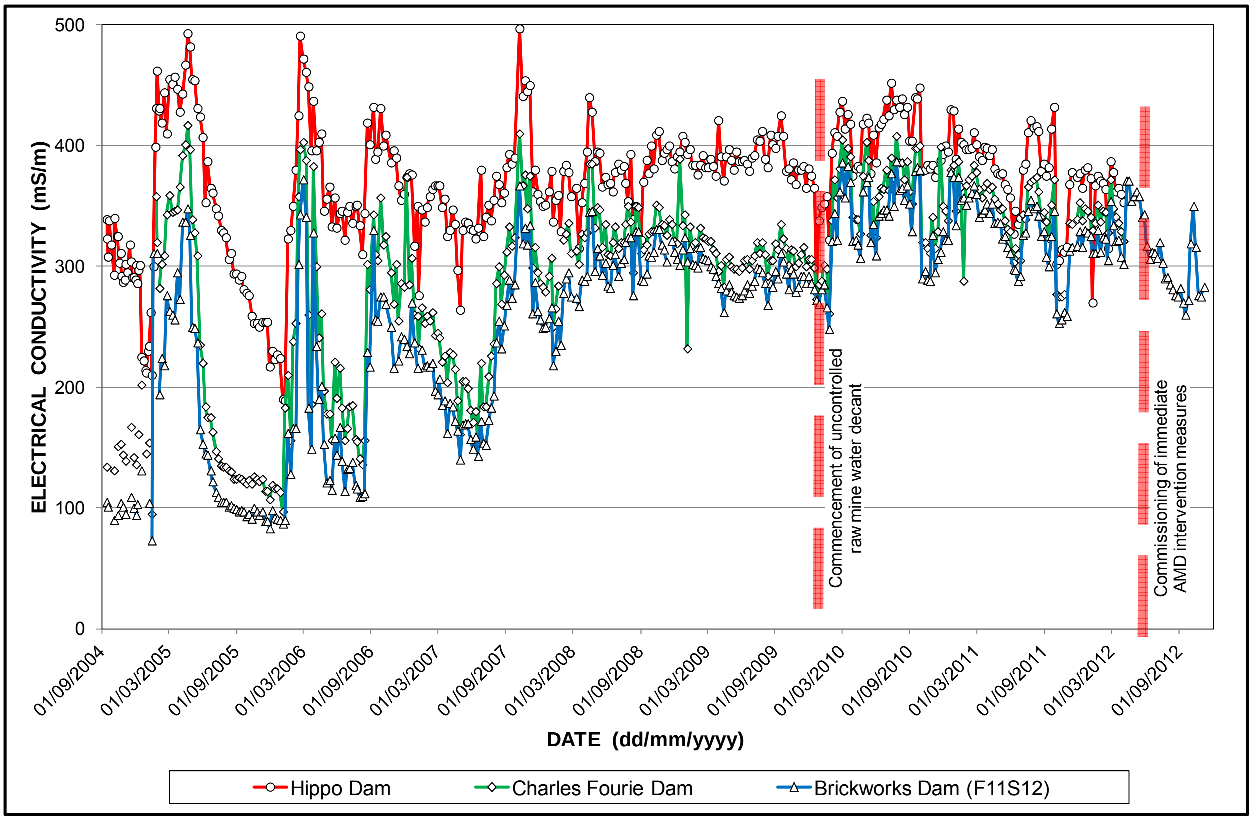


Figure 12 Pattern of electrical conductivity values in the Tweelopie Spruit in the period May 2004 to October 2012

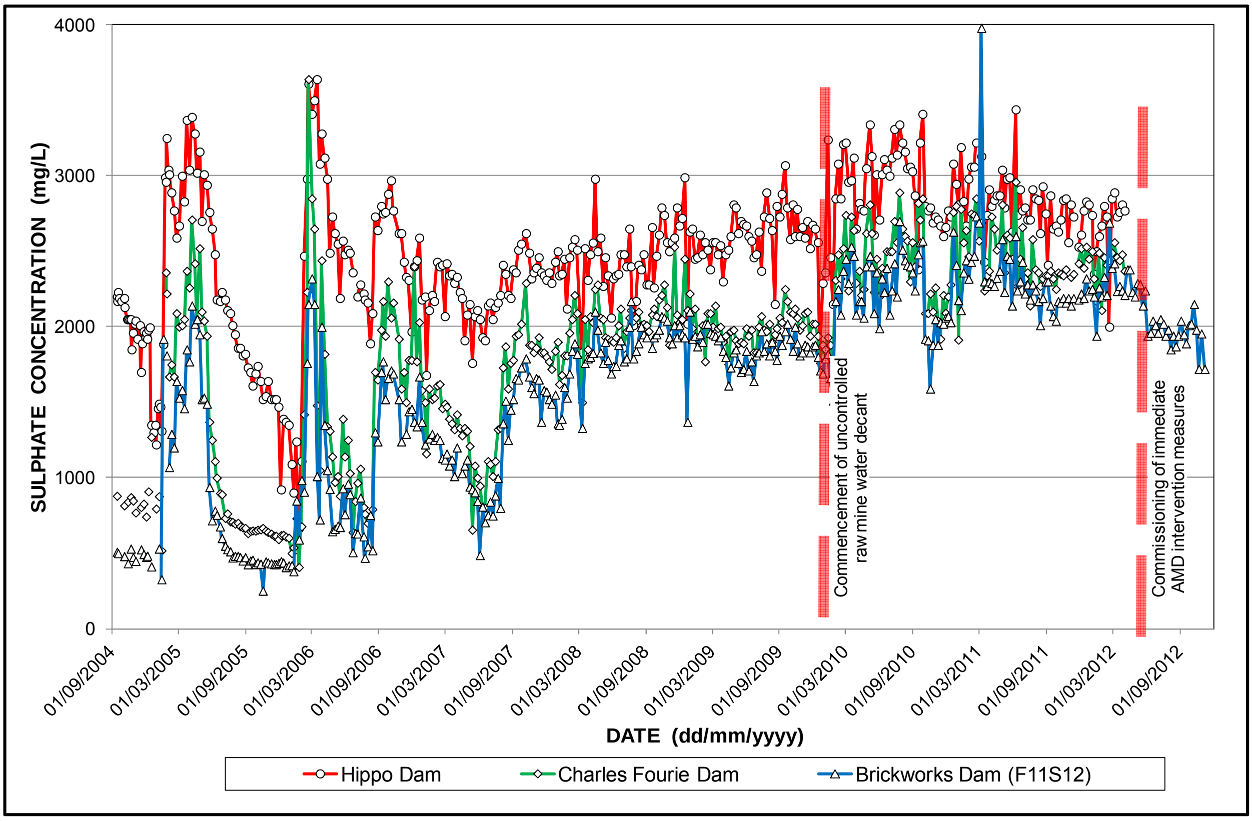


Figure 13 Pattern of SO_4 values in the Tweelopie Spruit in the period May 2004 to October 2012

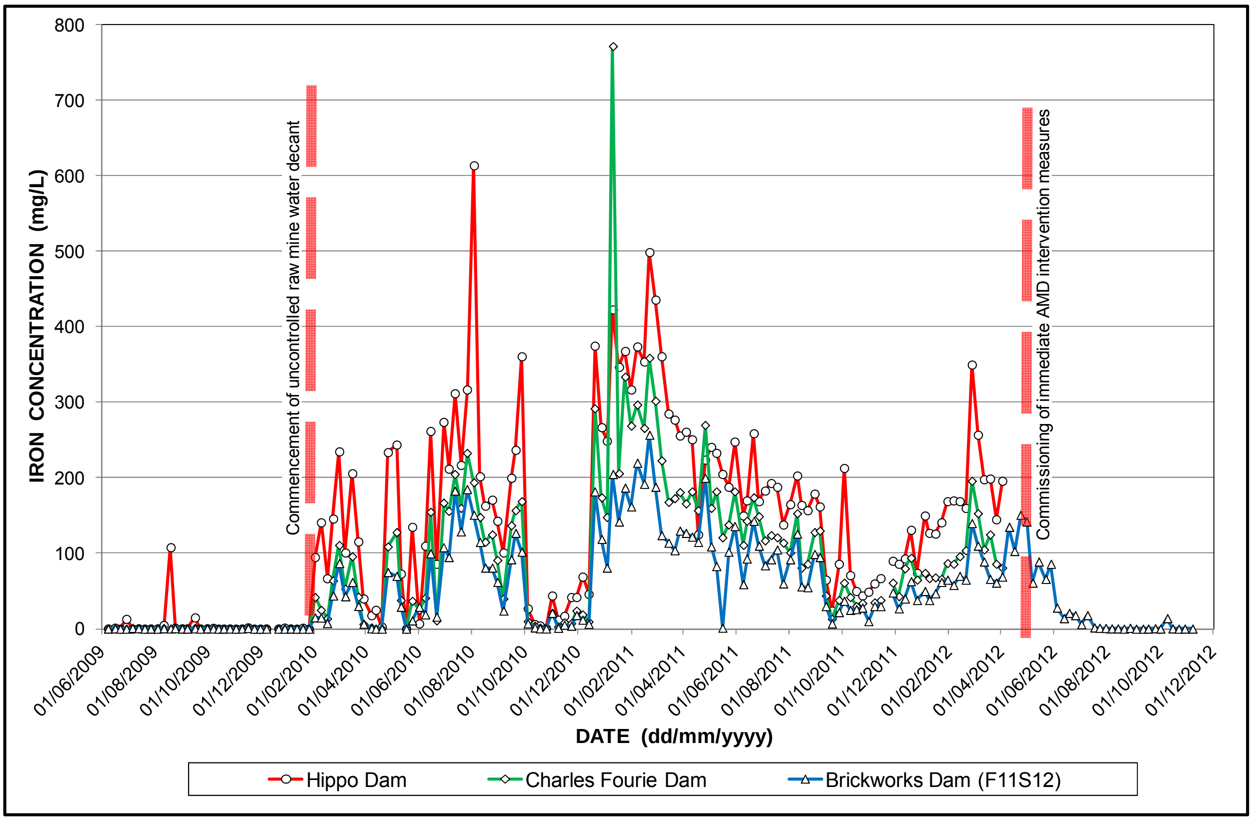


Figure 14 Pattern of Fe values in the Tweelopie Spruit in the period June 2009 to October 2012

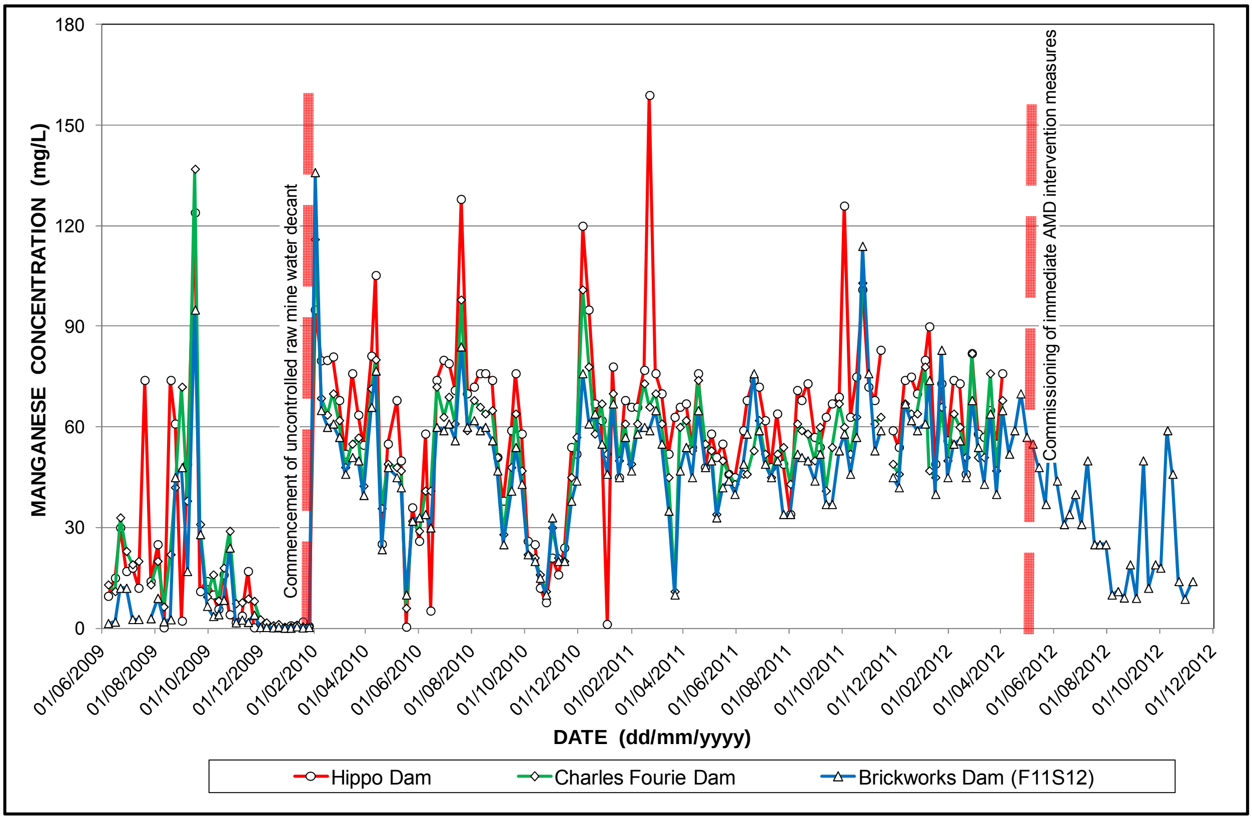


Figure 15 Pattern of Mn values in the Tweelopie Spruit in the period June 2009 to October 2012

The salinity and pH values measured on the occasion of each SDM reported for stations F11S12 and MRd in **Table 2** are graphed in **Figure 16** (EC) and **Figure 17** (pH).

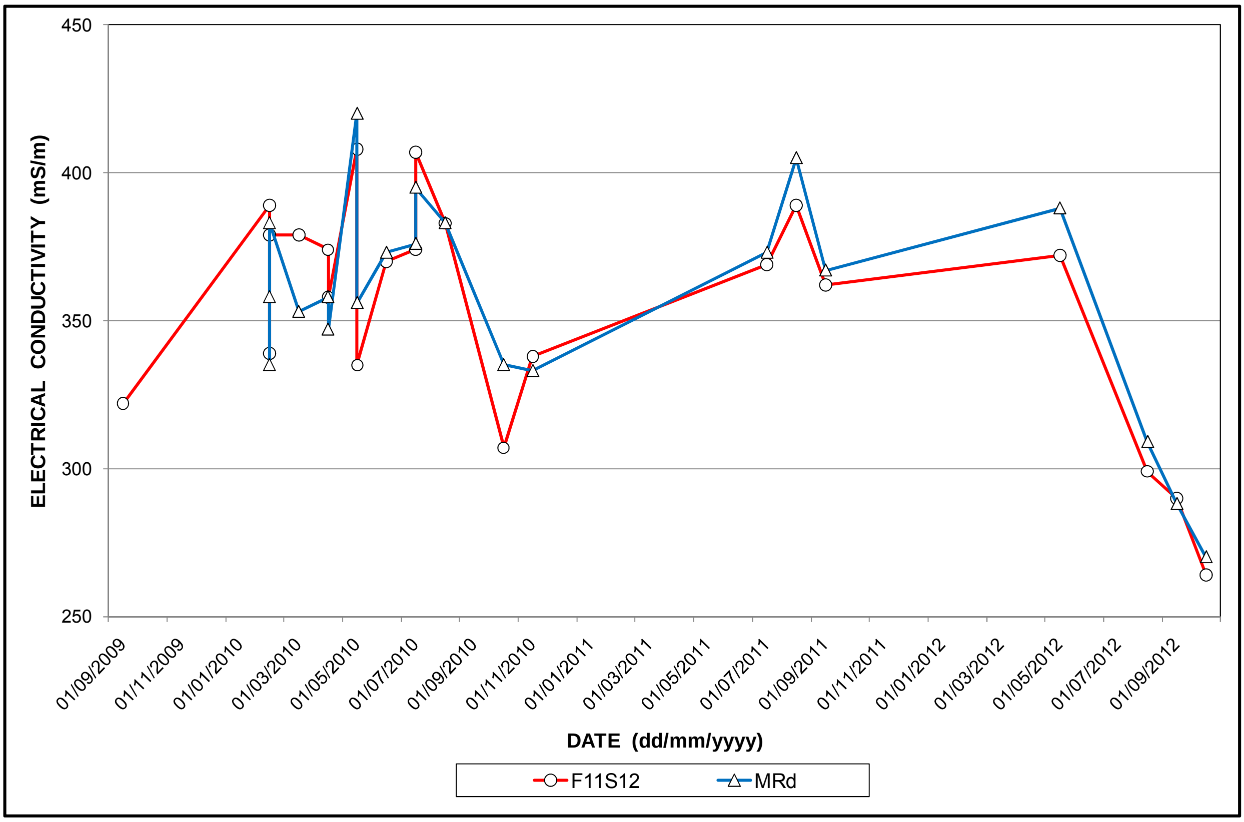


Figure 16 Pattern and trend of electrical conductivity of surface water at stations F11S12 and MRd on occasion of the synoptic discharge measurements reported in **Table 2**

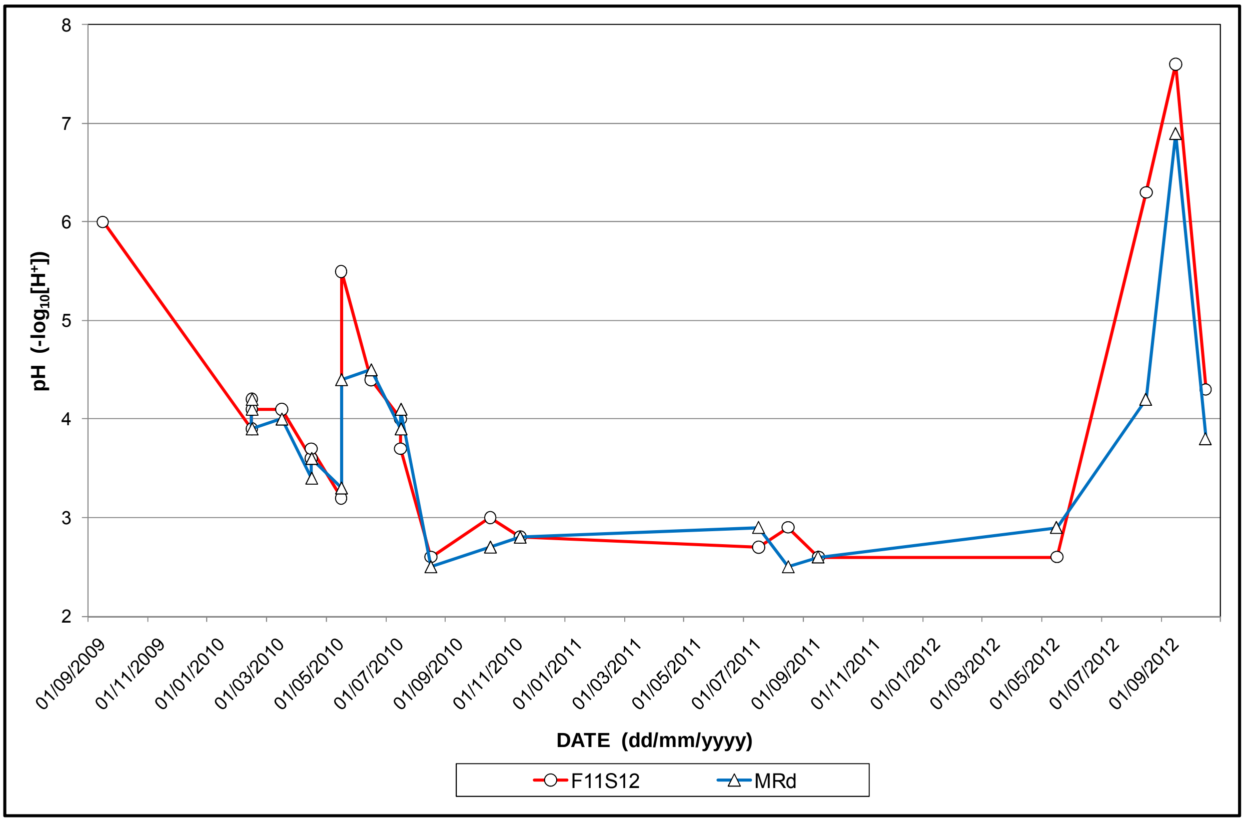


Figure 17 Pattern and trend of pH of surface water at stations F11S12 and MRd on occasion of the synoptic discharge measurements reported in **Table 2**

The EC and pH data reflect the elevated salinity values (>350 mS/m) and low pH values (<3) that characterised the surface water lost to the karst aquifer (**section 4.1.2**) in the period mid-2010 to mid-2012. It is this allogenic recharge that has manifested the mine water imprint on the karst groundwater of the Zwartkrans Compartment (**section 5.2.3**). The very recent positive influence of the immediate AMD control and management intervention measures is evidenced in all of the **Figures 11** to **17**. Whilst this signifies an improvement in the situation in regard to the surface water environment, it will take a while longer to manifest positively on the groundwater environment (**section 5.2.3**).

4.2.2 Bloubank Spruit

Surface water chemistry (quality) is monitored by the DWA at flow gauging station A2H049 at the lower end of the Bloubank Spruit system. A summary of the statistics that characterise this water quality record is presented in **Table 3**. The median and mean electrical balance values afford the analytical results a high degree of confidence. The 95%ile value of 9.7% suggests the increasing inaccuracy of analyses at higher SO_4 concentrations. None of the variables recorded in **Table 3** exceed the respective SANS (2011a) health-related limit where specified. The distinct CaMg-HCO_3 composition of the water as per the whole record data set (**Figure 18a**) again reflects the significant contribution of dolomitic groundwater discharged from the karst aquifer in this catchment.

Table 3 Statistical analysis of Bloubank Spruit water chemistry data associated with station A2H049 for the period May 1979 to August 2012

Variable	**Statistical Parameter**							**SANS (2011a)**(1)
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**SD**	**CoV (%)**	
pH ($-\log_{10}$[H+])	941	7.4	—	8.2	8.5	0.3	4	5.0-9.7
EC (mS/m)	1 046	51.1	59.8	60.3	67.4	6.8	11	<170
TDS (mg/L)	1 046	354.0	433.7	442.2	481.8	51.4	12	<1 200
Ca (mg/L)	863	42.6	53.1	53.5	59.6	7.3	14	n.s.
Mg (mg/L)	861	25.1	32.3	32.4	37.7	4.5	14	n.s.
Na (mg/L)	858	10.0	21.6	21.7	33.1	6.8	31	<200
K (mg/L)	867	0.7	1.9	1.8	3.4	0.9	46	n.s.
Cl (mg/L)	867	19.9	31.7	32.0	40.8	5.9	19	<300
SO_4 (mg/L)	864	65.0	87.3	82.9	110.7	31.7	36	<500
HCO_3 (mg/L)	858	147.6	191.9	197.6	219.3	24.4	13	n.s.
NO_3+NO_2 (mg N/L)	898	2.970	4.531	4.341	6.327	1.751	39	<11
PO_4 (mg P/L)	937	0.005	0.092	0.052	0.316	0.105	115	n.s.
Si (mg/L)	937	5.08	5.99	5.99	6.82	0.82	14	n.s.
Fe (mg/L)	98	0.006	0.030	0.015	0.117	0.049	164	<2
Mn (mg/L)	98	0.001	0.133	0.003	0.157	0.698	526	<0.5
Al (mg/L)	93	0.003	0.050	0.011	0.091	0.220	440	<0.3
EB (%)	815	–1.3	3.6	3.6	9.7	3.9	108	±5
TDS:EC	1045	6.7	7.3	7.2	8.1	0.5	7	n.s.
SO_4:TDS	864	0.16	0.20	0.19	0.24	0.07	34	n.s.

(1) Standard health-related limit for consumption of 2 L/d over 70 years by a 60 kg person
Bold text denotes value exceeds standard limit as described in note (1)

Further inspection of the long-term water quality record is premised on three periods of observation, namely May 1979 to September 2002 (**Figure 18b**), October 2002 to August 2012 (**Figure 18c**), and October 2009 to August 2012 (**Figure 18d**). These periods mark the pre-decant, the whole decant and the recent high volume decant periods, respectively. The y-axis data are plotted to a common scale to facilitate comparison.

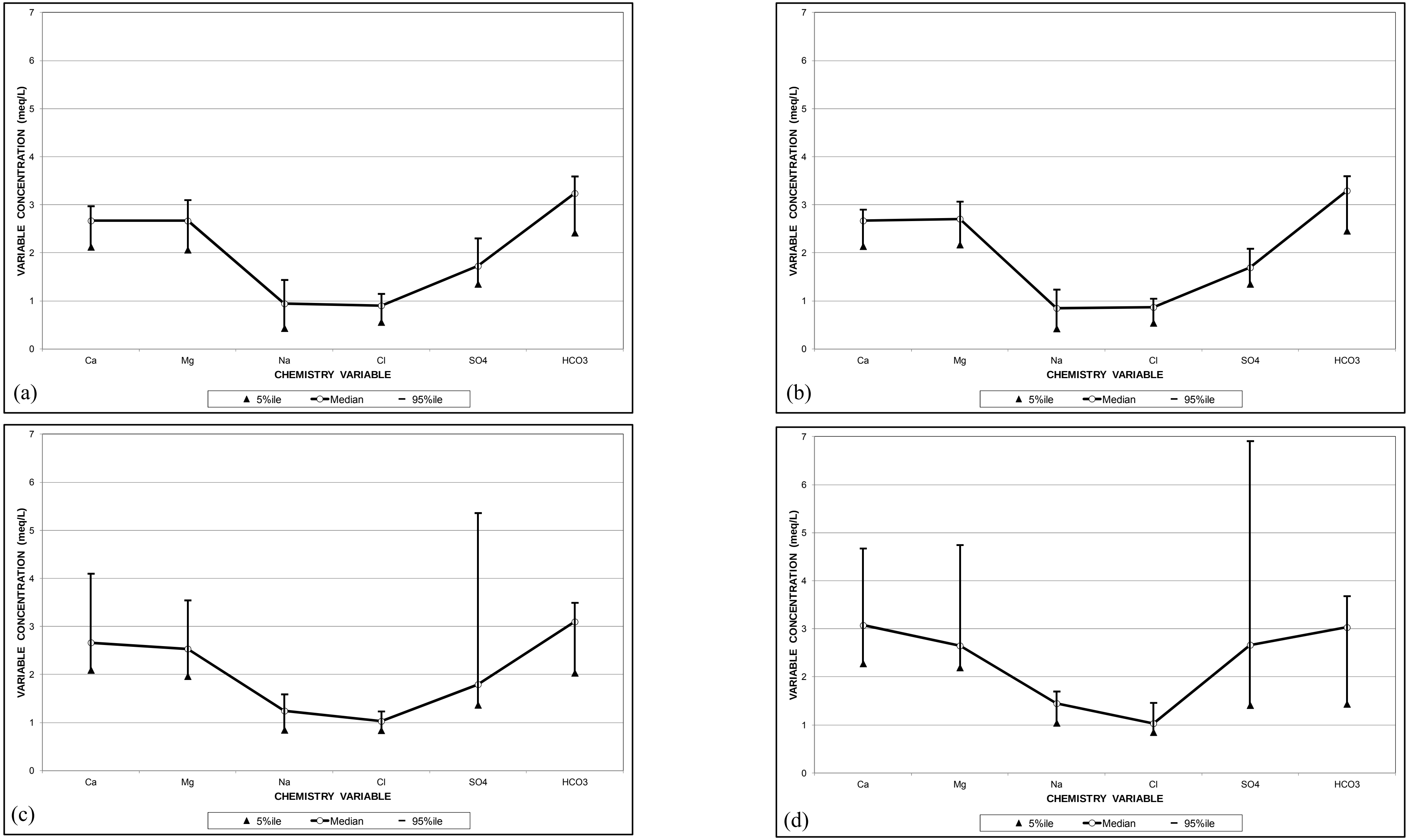


Figure 18 Variability of Bloubank Spruit water major ion chemistry recorded at DWA station A2H049 for (a) the period May 1979 to August 2012, (b) the period May 1979 to September 2002, (c) the period October 2002 to August 2012, and (d) the period October 2009 to August 2012

The data reveal very little difference between the whole record (**Figure 18a**) and the pre-decant period (**Figure 18b**). The decant period, however, reflects notable increases in the median Na and Cl concentrations (**Figure 18c**) compared to the pre-decant and whole period values. These are considered to reflect the municipal wastewater influence on surface water quality. A more subtle AMD influence is evident in the greater variability associated with the SO_4 concentration in the decant period (**Figure 18c**) compared to the pre-decant period. This variability increases even more in the period of greatest impact, i.e. since October 2009 (**Figure 18d**). Slight changes in the Ca and Mg values between the pre-decant and the decant periods are also apparent.

Perhaps the clearest indication of a mine water impact on the chemistry of water discharged by the Bloubank Spruit at station A2H049 is provided by the Piper diagram in **Figure 19**. The shift to the apex of the central diamond field represented by the Ca-SO_4 composition of the February 2011 chemistry is countered by the return to a more 'normal' pre-2009-'10 chemistry in January 2012.

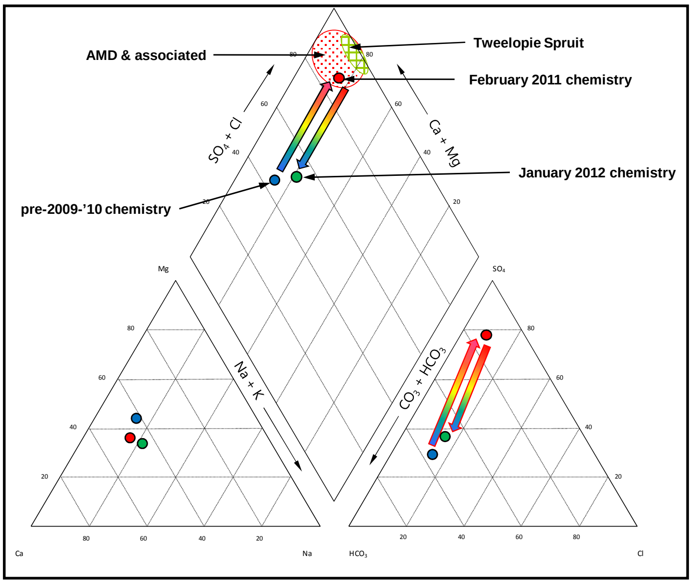
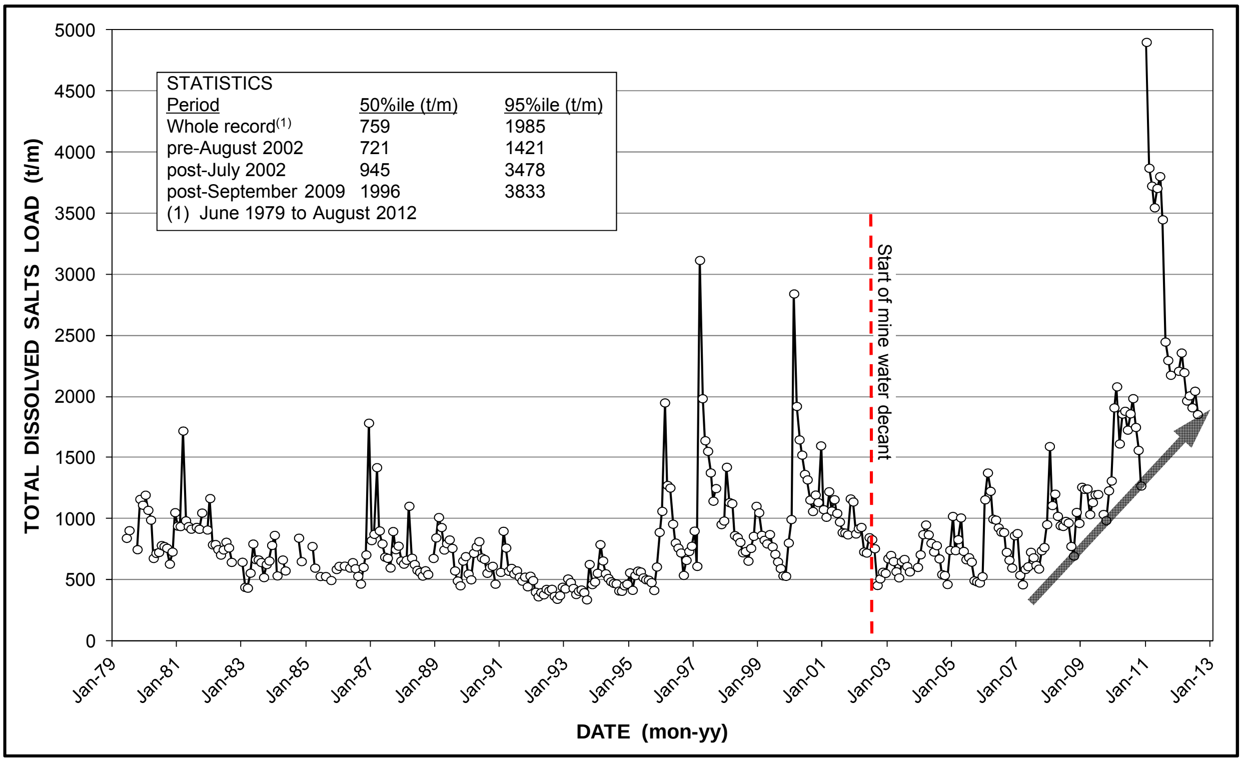


Figure 19 Piper diagram of pre-2009-'10 and more recent Bloubank Spruit water chemistry at station A2H049

4.3 Salt Load

The combination of flow and hydrochemical data affords a re-assessment of the salt load pattern and trend manifested at station A2H049. Such re-assessment is shown for total dissolved salts (TDS) in **Figure 20**, and for sulphate (SO_4) in **Figure 21**. The ratio of SO_4 to TDS illustrated in **Figure 22** similarly reflects the rather dramatic difference between the pre- and post-2009 circumstances precipitated by the resumption of uncontrolled mine water discharge into the Bloubank Spruit system.

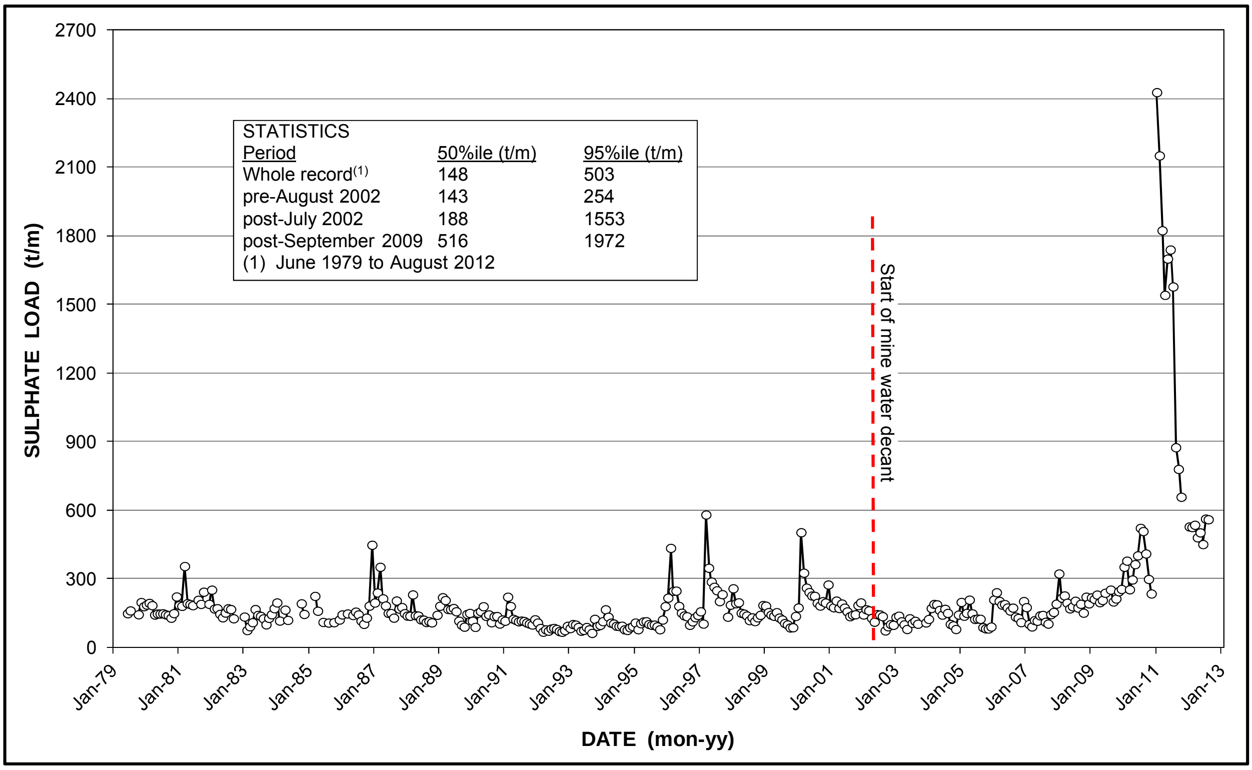
The long-term monthly trend in the TDS load delivered by the Bloubank Spruit (**Figure 20**) and upper reach of the Crocodile River (**Figure 23**) indicate an increasing TDS load (as indicated by the visually inserted arrows) since mid-2002. In the case of station A2H049, the coincidence with the commencement of mine water decant in August 2002 is tenuous and discussed later, whereas the commissioning of Unit 2 of the Driefontein WWTW might explain this observation in regard to station A2H050. The text box in **Figure 20** lists the median and 95%ile values associated with different periods of record. The post-September 2009 period reveals the greatest difference, which is readily attributable to the very high salt loads experienced in the 2010-'11 hydrological year. The magnitude of these loads is also manifested in the 95%ile value of the longer post-July 2002 period. The long-term monthly trend in the SO_4 load delivered by the Bloubank Spruit (**Figure 21**) mimics the TDS load pattern (**Figure 20**) in the most recent period of record. This is unsurprising under circumstances where SO_4 comprises ~62% of the major ion concentration in mine water.


STATISTICS

Period	50%ile (t/m)	95%ile (t/m)
Whole record(1)	759	1985
pre-August 2002	721	1421
post-July 2002	945	3478
post-September 2009	1996	3833

(1) June 1979 to August 2012

Figure 20 Long-term (June 1979 to August 2012) monthly TDS load pattern and trend in the Bloubank Spruit at DWA station A2H049


STATISTICS

Period	50%ile (t/m)	95%ile (t/m)
Whole record(1)	148	503
pre-August 2002	143	254
post-July 2002	188	1553
post-September 2009	516	1972

(1) June 1979 to August 2012

Figure 21 Long-term (June 1979 to August 2012) monthly SO_4 load pattern and trend in the Bloubank Spruit at DWA station A2H049

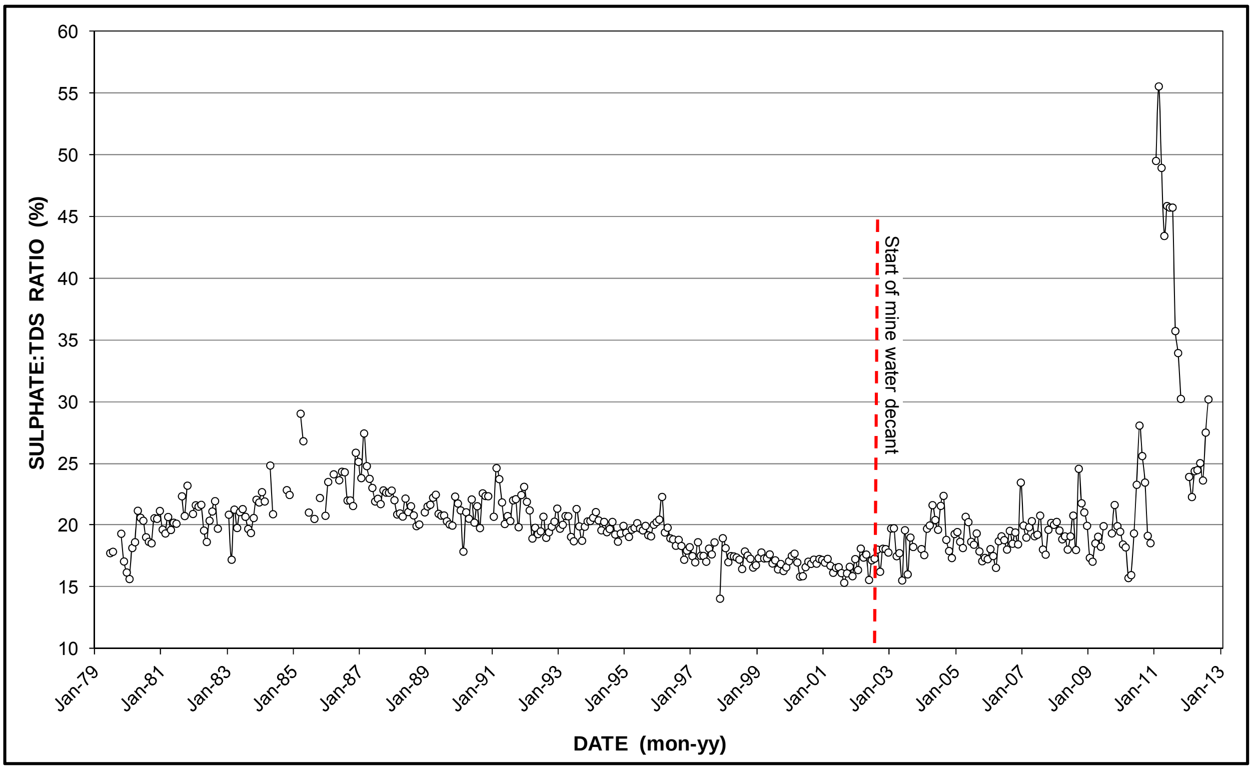


Figure 22 Long-term (June 1979 to August 2012) trend in the SO_4**:**TDS ratio at station A2H049

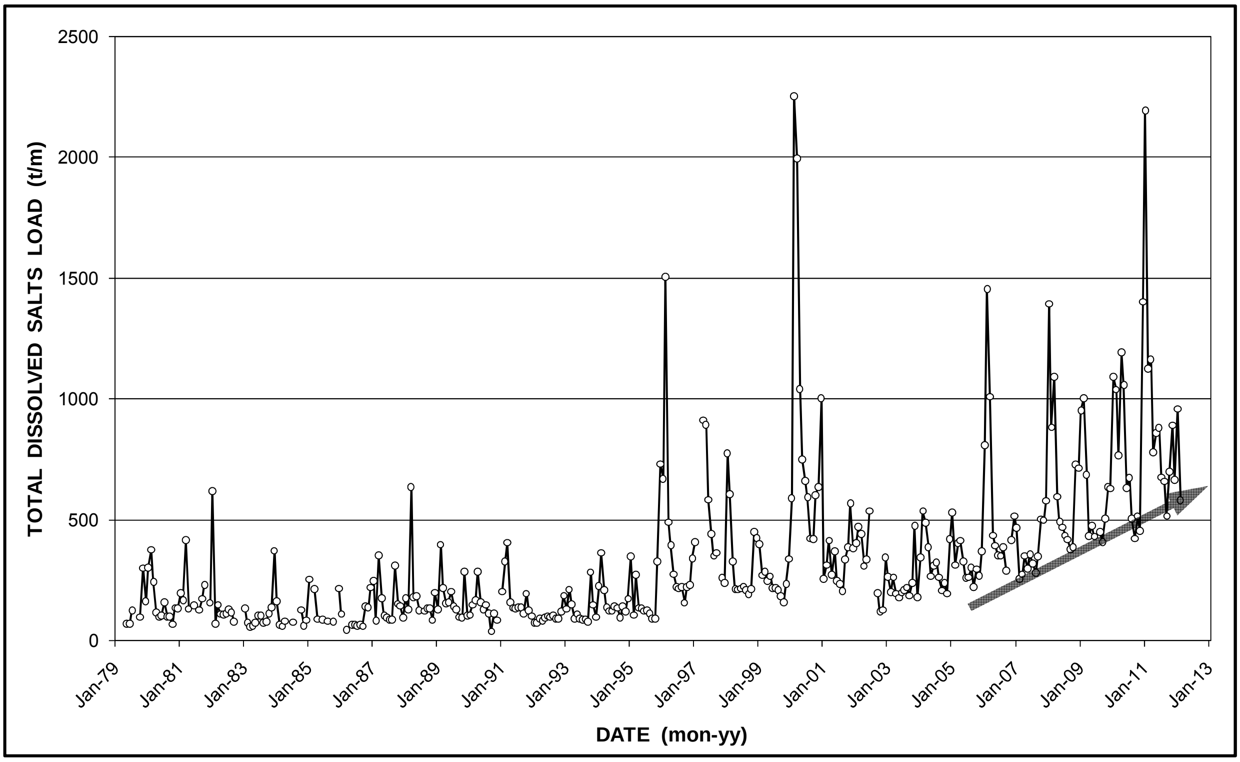


Figure 23 Long-term (May 1979 to August 2012) monthly TDS load pattern and trend in the upper reach of the Crocodile River at DWA station A2H050

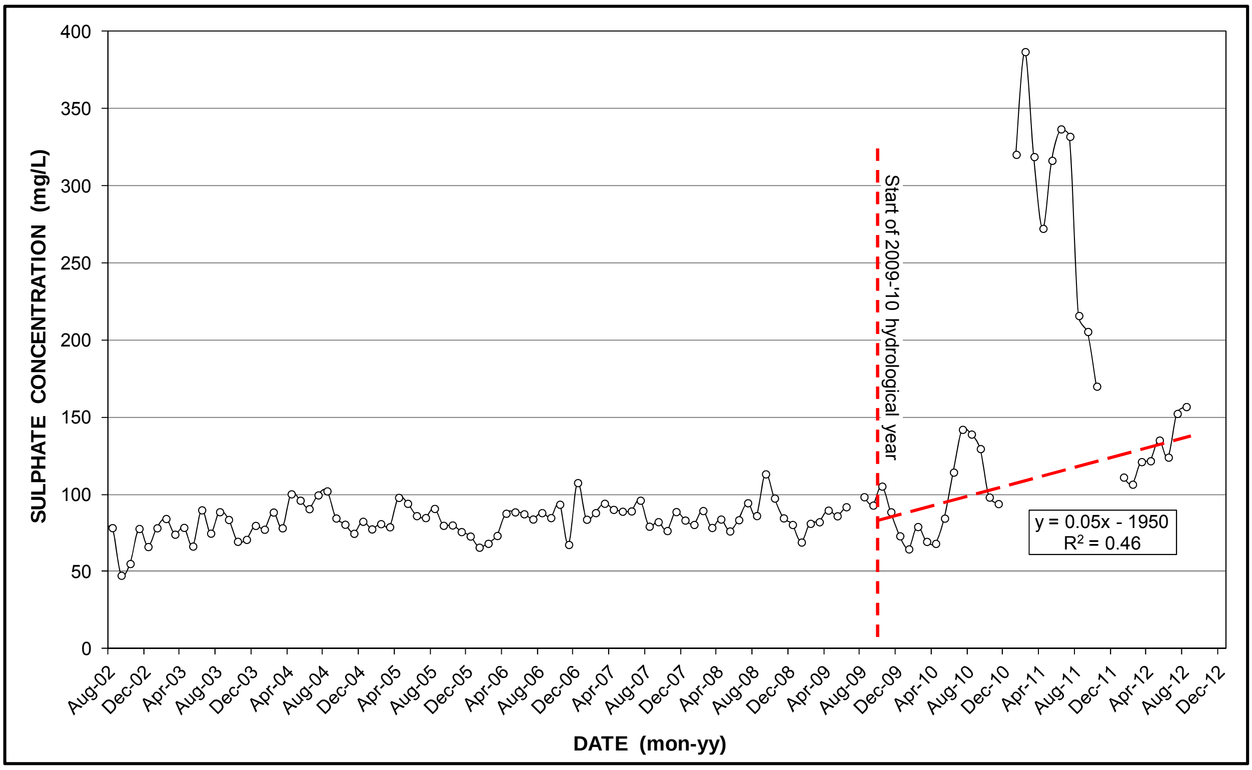


Figure 24 Pattern and trend in the SO_4 concentration at station A2H049 since the start of mine water decant in the Western Basin

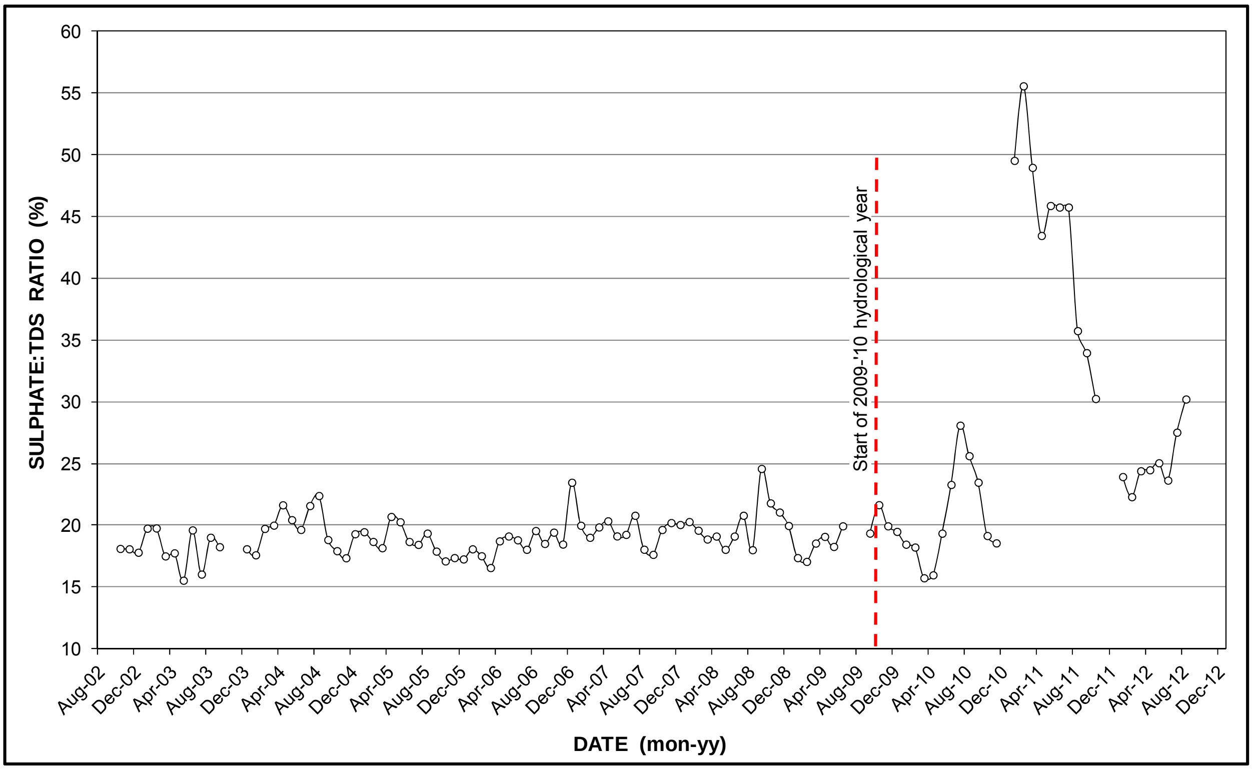


Figure 25 Pattern and trend in the SO_4**:**TDS ratio at station A2H049 since the start of mine water decant in the Western Basin

The SO_4 concentration in the surface water passing station A2H049 (**Figure 24**) shows a return to the recent gradually rising trend since the start of the 2009-'10 hydrological year.

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 22** for the long-term record, and in **Figure 25** for the period since the start of decant.

The closer inspection in **Figure 24** and **Figure 25** of the SO_4 and TDS data recorded at station A2H049 explores the impact of mine water decant in/from the Western Basin on the chemistry of surface water at the downstream end of the Bloubank Spruit system. A linear regression analysis of the data sets since the start of the 2009-'10 hydrological year and that ignores the extreme SO_4 (>150 mg/L) and SO_4**:**TDS (>30) values, indicates a rising trend in both instances. These trends indicate that SO_4 contributes an increasing proportion of the TDS concentration at station A2H049 in the more recent past, which is in contrast to the declining trend that characterises the pre-decant period 1986 to 2001 revealed in **Figure 22**. A possible explanation for the 1986-2001 trend is the greater contribution of dolomitic groundwater, typically very low in SO_4, draining from the Zwartkrans and Krombank compartments following the breaking of the drought that characterised the early 1980s. The preceding (1979-1985) rising SO_4 trend (**Figure 22**) possibly reflects the increasing impact of mine water releases from still active mining operations in the Western Basin at this time. These observations indicate that AMD originating in the Western Basin has had both a historical and recent impact on the surface water (and groundwater) resources in the south-western portion of the study area.

It is since mid-2010 that the recent large and uncontrolled AMD discharges resulted in a significant change in the chemical composition of surface water leaving the Bloubank Spruit system. This confirms that a significantly greater mine water component, and in particular raw mine water, characterised the surface water chemistry in the middle and lower reaches of the Bloubank Spruit system than before mid-2010. This impact had dissipated by early-2012 with a return to 'normal' values, as confirmed by salinity values of 125 and 99 mS/m recorded on 23 February 2012 and 16 May 2012 in the upper reach of the Bloubank Spruit near Sterkfontein Caves. Exploring the effects of the more recent large AMD discharges during the 2009-'10 and 2010-'11 rainfall seasons in the context of the long-term TDS and SO_4 loads delivered by the Bloubank Spruit system is attempted in **Figure 26** and **Figure 27**.

The cumulative TDS load (**Figure 26**) in the pre-January 2010 period suggests a slight change in slope ca. January 1996. This change, although interesting, is not considered significant enough to warrant more detailed inspection in this study. Support for this consideration is provided by the cumulative SO_4 load (**Figure 27**), which indicates that a single regression line through the pre-January 2010 data provides an equally good fit (R^2 = 0.99), even though a similar slight change in slope ca. January 1996 is evident. More significant is the sharper change in slope post-January 2010, and most dramatically (especially in the case of SO_4) post-January 2011. These are unequivocal manifestations of the impact of AMD on the surface water chemistry delivered by the Bloubank Spruit system. Less evident in these graphs is the decreasing trend that characterises the end of the record period. Later data are expected to confirm a 'return to more normal' conditions.

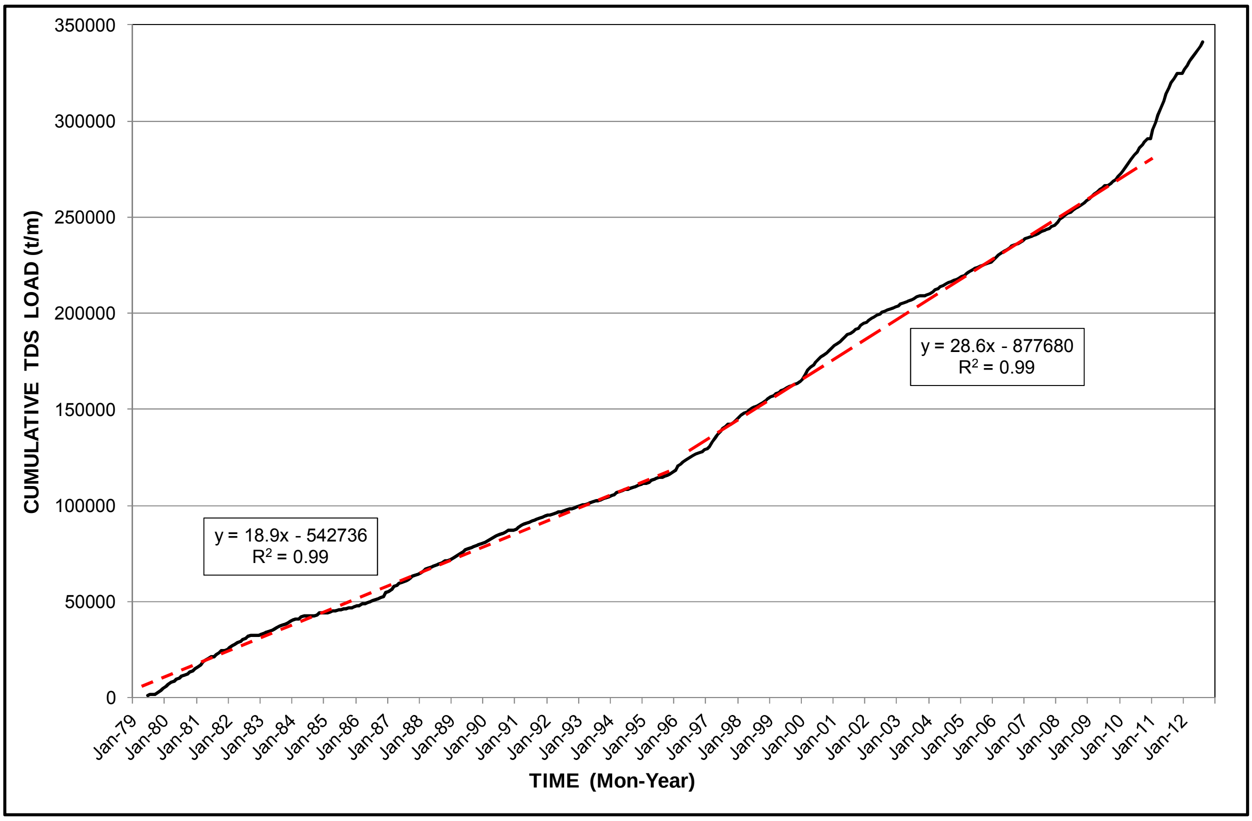


Figure 26 Pattern of cumulative monthly TDS load delivered by the Bloubank Spruit system in the long-term

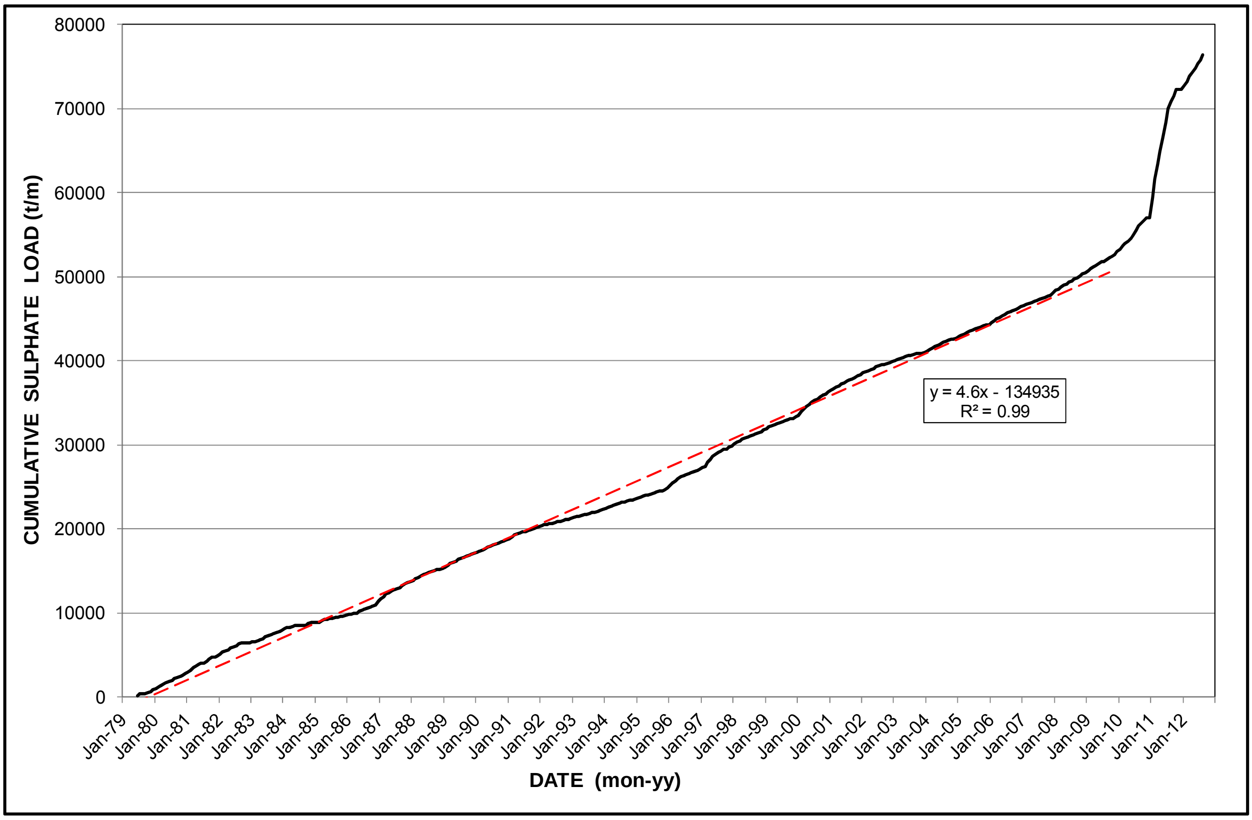


Figure 27 Pattern of cumulative monthly SO_4 load delivered by the Bloubank Spruit system in the long-term

5 GROUNDWATER HYDROLOGY

5.1 Physical Hydrogeology

5.1.1 Groundwater Levels

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 4**. A graphical representation of the information is shown in **Figure 28**. An analysis of the %ile Δh data yields a 25%ile value of 3.7 m, a median value of 4.6 m, and a 75%ile value of 6.8 m. Most of these graphs are compared in **Figure 29**.

Table 4 Salient statistics for long-term DWA groundwater level monitoring data

Station	**Groundwater Rest Level (m bc)**							**Record Period(1)**
	n	**5%ile**	**Mean**	**Median**	**95%ile**	**Max Δh(2)**	**%ile Δh(3)**	
A2N0580	264	–59.96	–54.65	–54.40	–51.00	11.13	8.96	05/1985-05/2012
A2N0582	210	–42.91	–40.11	–40.15	–35.77	8.53	7.14	05/1985-12/2010
A2N0583	211	–45.56	–45.00	–45.02	–44.44	–1.84	1.13	05/1985-05/2012
A2N0584	235	–28.11	–26.06	–26.51	–21.81	7.93	6.29	05/1985-05/2012
A2N0586	265	–28.70	–26.63	–27.25	–21.74	8.49	7.11	05/1985-05/2012
A2N0589	169	–29.90	–28.89	–28.97	–27.92	3.85	1.98	05/1985-06/2010
A2N0590	165	–36.48	–34.97	–35.32	–32.17	5.53	4.32	05/1985-05/2012
A2N0592	255	–78.56	–77.26	–77.43	–74.10	5.75	4.45	06/1985-05/2012
A2N0594	183	–74.41	–72.79	–72.80	–70.86	4.91	3.55	01/1985-09/2008
A2N0598	89	–63.32	–58.76	–58.84	–53.53	12.17	9.79	07/1985-05/2010
A2N0600	184	–25.40	–24.21	–24.44	–21.47	4.58	3.93	04/1989-05/2012
A2N0602	210	–55.99	–54.61	–54.95	–51.42	5.88	4.57	06/1987-05/2012
A2N0605	194	–63.67	–62.59	–62.79	–60.78	4.09	2.89	04/1989-05/2012
A2N0606	53	–69.53	–67.03	–67.00	–64.64	5.11	4.90	08/1989-05/2012
A2N0607	146	–70.82	–67.41	–67.25	–64.40	7.82	6.42	10/1993-05/2012

(1) From month of first measurement to month of most recent available measurement as at June 2012 update from DWA; shaded rows (except caption row) denote stations no longer in service

(2) Difference between minimum and maximum values (not shown in this table)

(3) Difference between the 5%ile and 95%ile values

The comparison in **Figure 29** 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 reflects the location of these groupings in two different compartments/subcompartments. These groupings are produced separately in **Figure 30** (Group A) and **Figure 31** (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.

The unprecedented rise in the groundwater level observed in stations A2N0584 and A2N0586 since late-2007 (**Figure 31**) reflects the impact of exceptional recharge associated with raw and/or treated mine water being lost from the lower reach of the Riet Spruit (**section 4.1.2**). Both these stations are located in proximity to the Riet Spruit (**Figure 36**). These circumstances were precipitated by the 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. The additional contribution of raw mine water to this discharge in the much wetter 2009-'10 and 2010-'11 rainy seasons has, on occasion, increased the artificial flow in this drainage to >60 ML/d.

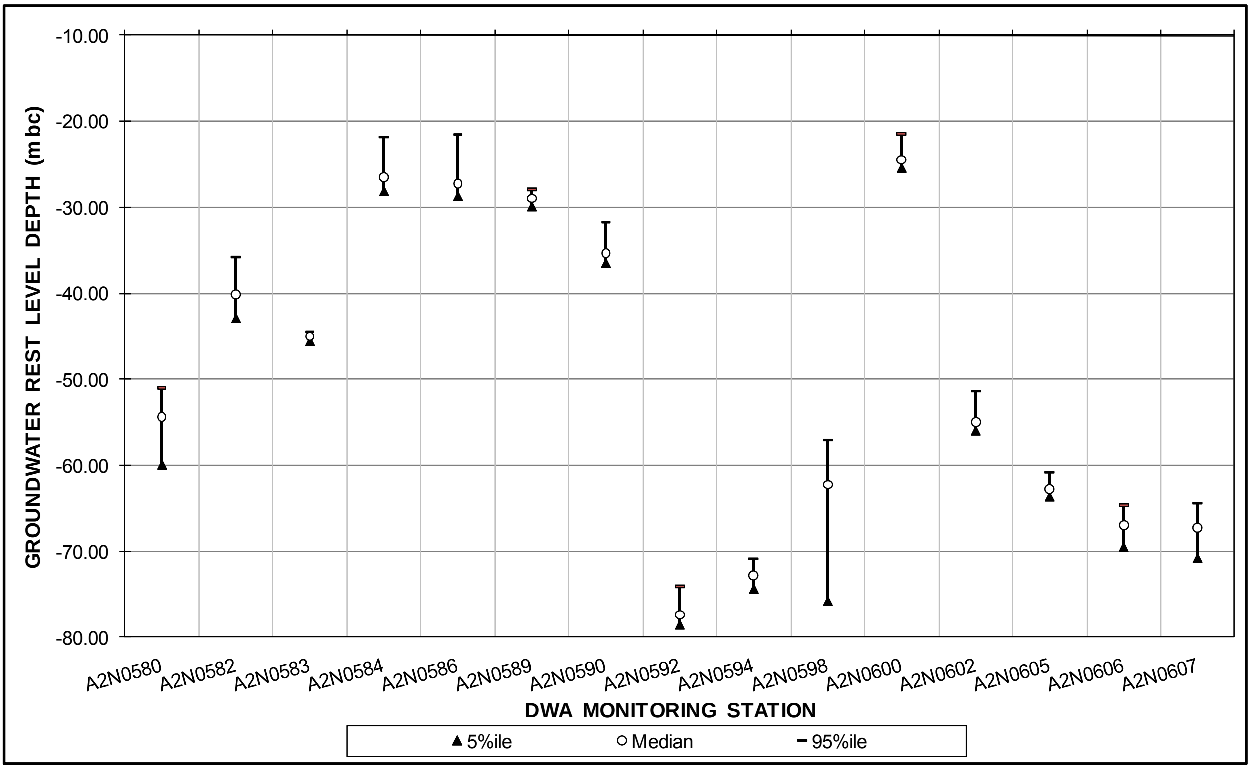


Figure 28 Graphic comparison of the statistical hydrographic response observed in DWA groundwater level monitoring stations in the period 1985 to 2012 (data from **Table 4**)

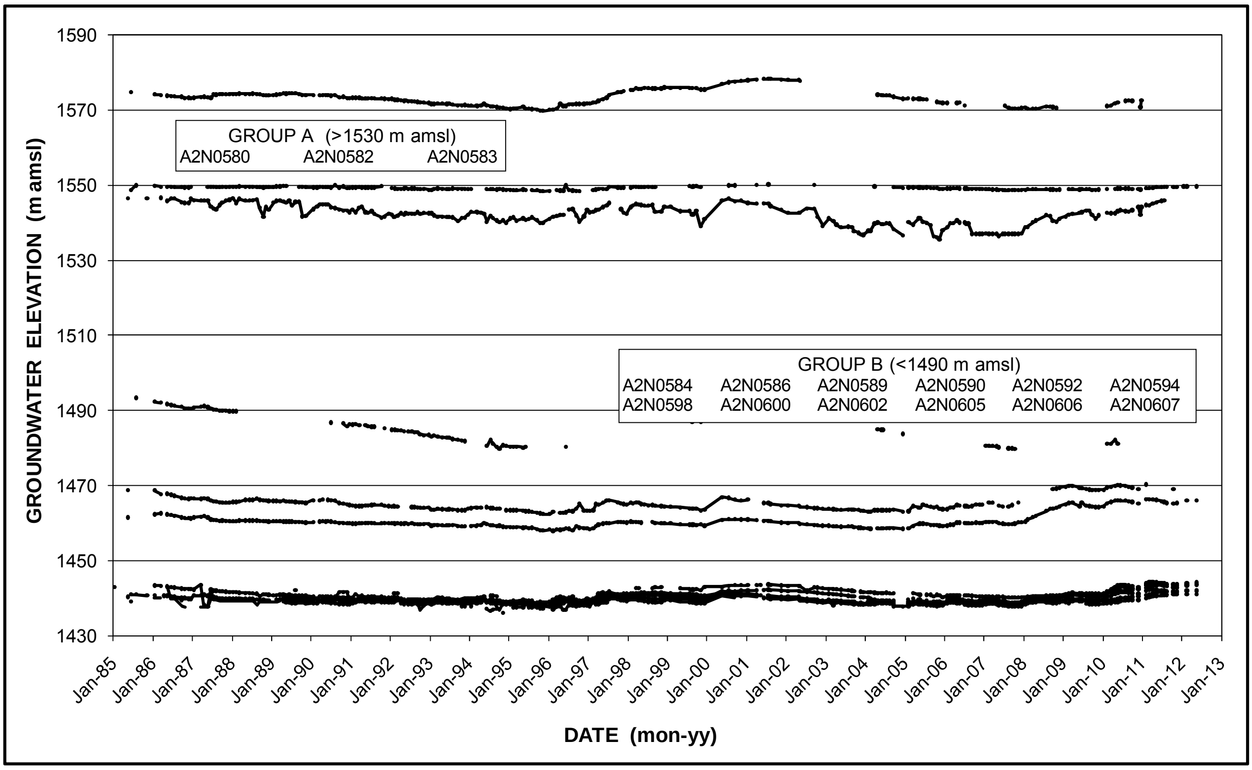


Figure 29 Long-term groundwater level response pattern in DWA monitoring boreholes

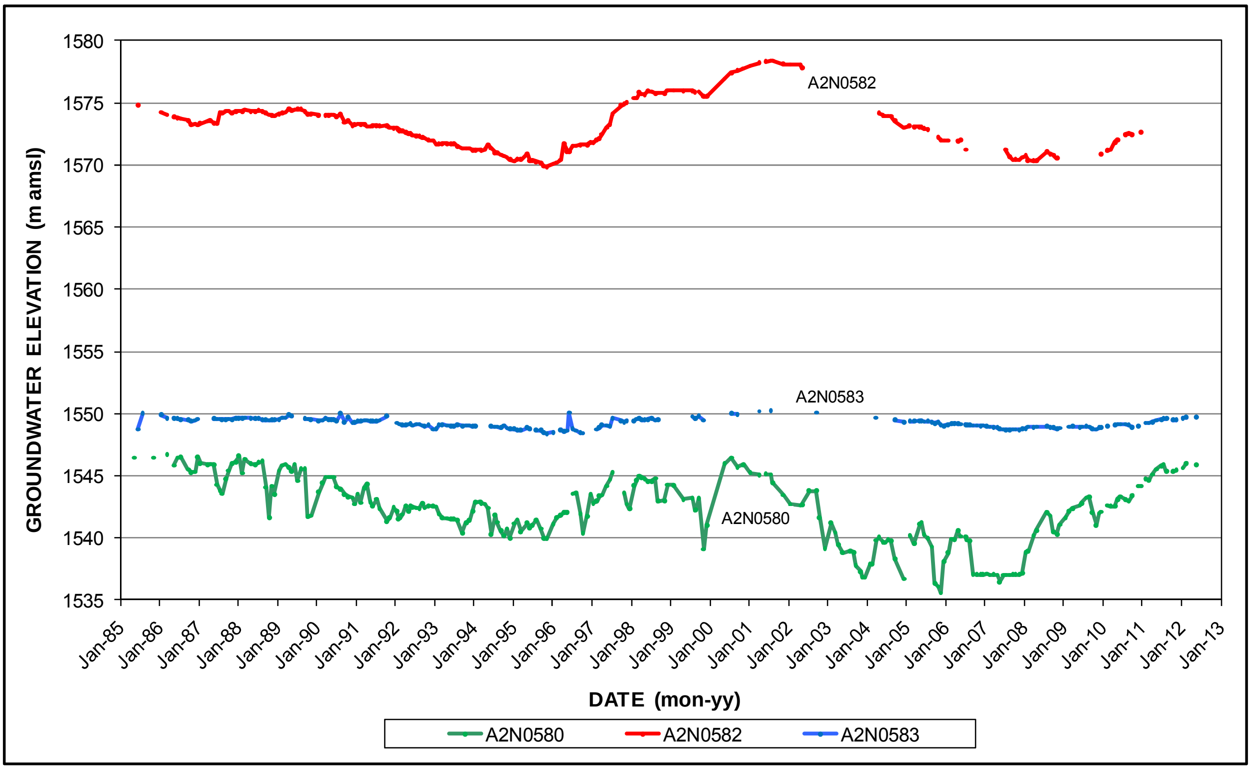


Figure 30 Long-term groundwater level response pattern in Group A boreholes from **Figure 29**

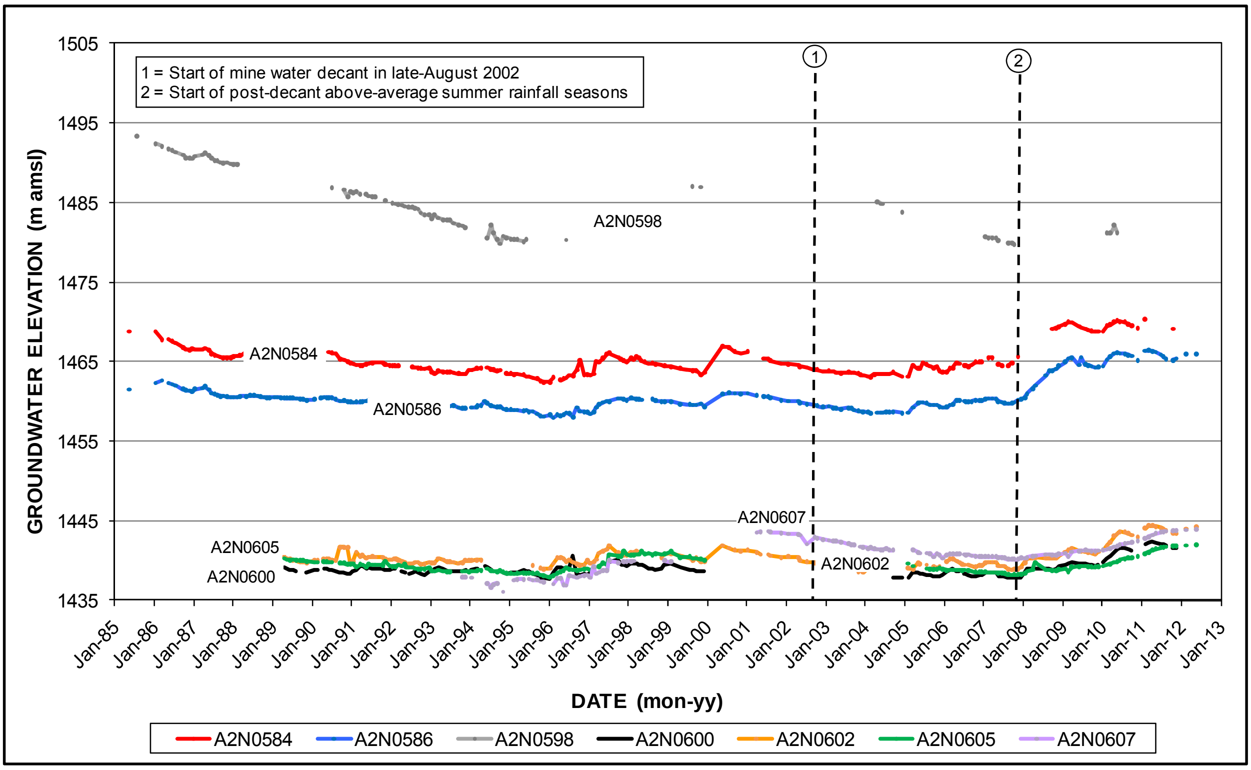


Figure 31 Long-term groundwater level response pattern in Group B boreholes from **Figure 29**

5.1.2 Sterkfontein Caves Water Level

The international significance of Sterkfontein Caves as the flagship fossil site in the COH WHS focuses attention on any perceived impact on this site. It is common cause that a recent substantial rise in the cave water level has caused Maropeng āAfrika (the authority responsible for managing the tourist component of the site) to reroute the tourist path through the caves to successively higher elevations. Against this background, the circumstances that inform this phenomenon warrant separate discussion.

In sympathy with the observed rise in water levels in the Zwartkrans Compartment in the more recent past (**section 5.1.1**), a similar response is observed in the Sterkfontein Caves. In mid-May 2010, cave 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 February 2010 and June 2010 (**Figure 32**), and the ~0.4 m rise in borehole MB1 at the Makiti Wedding and Conference Centre between February 2010 and May 2010. The associated trend is shown in **Figure 32**, and suggests that the cave lake water level might have started rising in mid-2009. A water level measurement in borehole SF1 on 14 January 2011 indicated a further rise of ~0.7 m since June 2010, for a total rise of ~2.6 m between October 2007 and January 2011, increasing to ~2.8 m with a further rise of ~0.2 m being manifested in the 5-month period January 2011 to June 2011. More recent measurements reflect the consistent decline in the Main Lake water level.

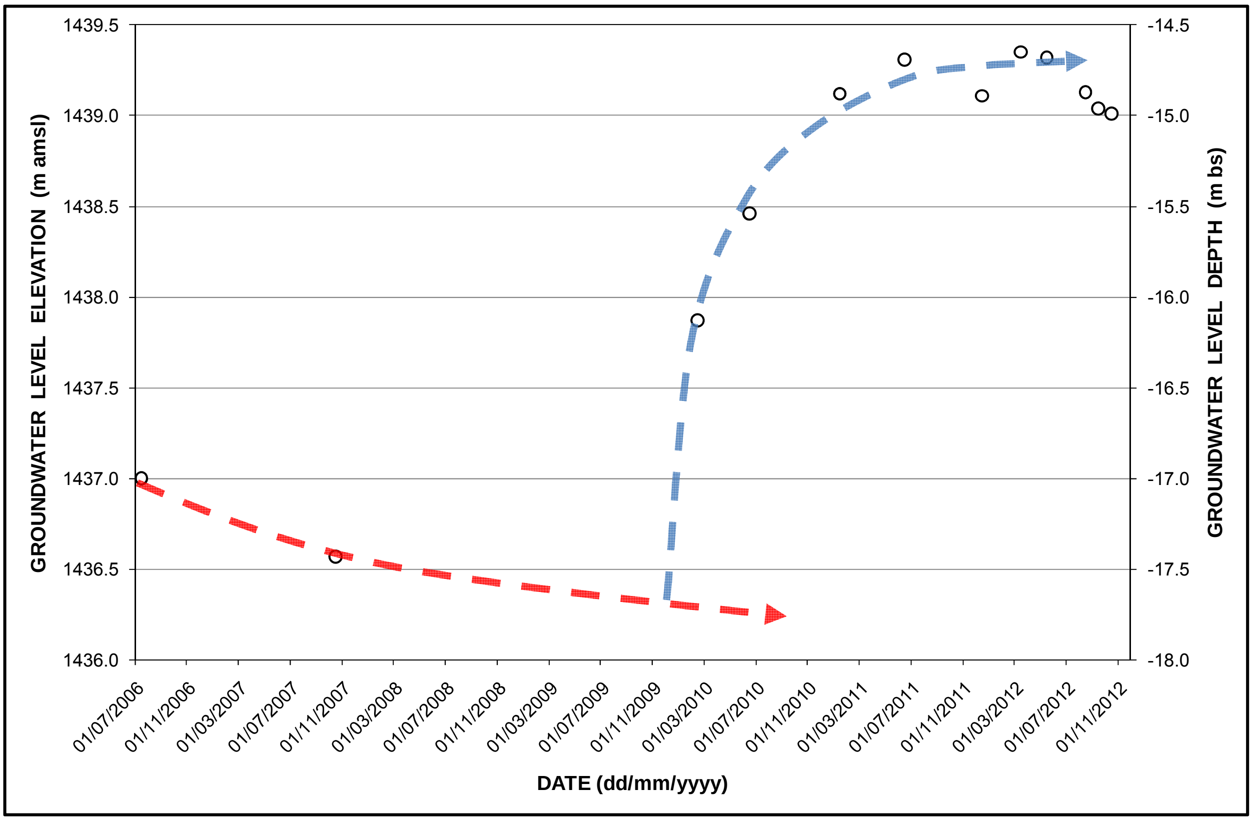


Figure 32 Recent groundwater level response pattern and trend in borehole SF1 that serves as a proxy for the Main Lake water level in Sterkfontein Caves

The 'maximum' elevation of ~1439.3 m amsl (**Figure 32**) approaches the ~1440 m amsl assigned to the Bloubank Spruit channel to the north of the caves. This suggests that the cave water level reaches equilibrium at an elevation of just below 1440 m amsl (equivalent to a depth of ~14.5 m below surface at borehole SF1) when the karst water table intersects the stream channel of the Bloubank Spruit located to the north. If so, then the maximum possible rise of ~3 m agrees well with the zone of perceived most aggressive carbonate re-solution that defines the more recent speleogenetic evolution of the cave system as observed by Martini et al. (2003). The four most recent measurements in borehole SF1 (**Figure 32**) indicate a rate of decline of 0.06 m/month in the period May 2012 to October 2012. This is similar to that observed in the historical record of the Main Lake water level itself (Hobbs, 2011a).

Nevertheless, it is postulated that the Main Lake will maintain a high water level into the future because of sustained above-normal discharge in the upper tributaries of the Bloubank Spruit, and associated allogenic groundwater recharge in the Zwartkrans Compartment. This is premised on the greater sustained discharge of treated/neutralised mine water associated with the immediate and short-term AMD control and management interventions in the Western Basin (DWA, 2011).

5.1.3 Groundwater Fluxes

The surface water fluxes (gains and losses) discussed in **section 4.1.2** necessarily impact on the groundwater environment. This impact is manifested as groundwater resurgence at springs and in river and stream channels in the lower (discharge) reaches of groundwater basins. This is most pertinent in regard to the Zwartkrans Compartment, where allogenic recharge associated primarily with the mine water has manifested an unprecedented volumetric addition to the quantity of water in this aquifer.

Under circumstances where the Zwartkrans Spring represents the most obvious and identifiable groundwater discharge feature, and historical attention has necessarily focussed on determining its yield, the surface discharge characteristics of the Bloubank Spruit upstream and downstream of this feature have largely been ignored. The recognition by Hobbs (2011a) of groundwater resurgence in the stream channel upstream of the spring, indicating an additional groundwater outflow component over and above that of the spring, has focussed attention on quantifying both the spring and groundwater resurgence loss components.

A set of SDMs carried out upstream and downstream of the Zwartkrans Spring on 16 May 2012 provided an opportunity to establish the flow of the spring. The data presented in **Table 5** describe the results obtained.

Table 5 Calculation of the Zwartkrans Spring discharge on 16 May 2012 using TDS load values

Flow Location		**Field EC (mS/m)**	**TDS [*C*] (mg/L)**	**Discharge [*Q*]**		**Salt (TDS) Load**	
				(L/s)	**(ML/d)**	**mg/s** [=Q_X•C_X]	**t/d**
Downstream	Stream	94	658(1) [=C_D]	~631(2) [=Q_D]	54.5	415 198	35.9
	A-furrow	94	658(1) [=C_F]	Negligible [=Q_F]			
Upstream		99	693(1) [=C_U]	~306(2) [=Q_U]	26.4	212 058	18.3
Calculated difference in salt load						203 140	17.6
Zwartkrans Spring		92	644(1) [=C_S]	~325(3) [=Q_S]	28.1	209 300	18.1

(1) EC * 7.0 used as a proxy to derive a theoretical TDS value
(2) Synoptic discharge measurement (SDM) value
(3) Derived value from the difference of the SDM values

The veracity of the flow measurements given in **Table 5** is interrogated on the basis of a mass balance calculation as follows:

$$Q_S = [(Q_D \bullet C_D) - (Q_U \bullet C_U)]/C_S = [415\ 198 - 212\ 058]/644 = 315 \text{ L/s}$$

The derived spring discharge value of 325 L/s (Q_S, **Table 5**) is encouragingly close to the mass balance calculated value of 315 L/s. The difference of 10 L/s is readily accounted for by the negligible flow in the A-furrow (Q_F) which, if added to the downstream flow (Q_D) and assuming an EC value (C_F) of 94 mS/m, returns a mass balance calculated value of 327 L/s for the Zwartkrans Spring (Q_S).

As postulated by Hobbs (2011a), however, the Zwartkrans Spring does not represent the only outlet of the Zwartkrans Compartment, i.e. it is not the sole source of groundwater discharge. There is sufficient evidence to indicate that a significant proportion of the observed groundwater contribution to surface flow derives from effluent conditions in the stream channel upstream of the spring. It is quite plausible that the magnitude of this contribution (~90 L/s/km of stream reach) exceeds that of the spring itself. Given a gaining stream reach length of at least 400 m between the 'upstream' SDM position and the spring, groundwater resurgence could amount to at least ~40 L/s. Subtracting this from the spring discharge of 325 L/s reduces the spring yield to 285 L/s, which is in reasonable agreement with earlier reported spring flow values (e.g. Bredenkamp et al., 1986; Hobbs, 2011a). Nevertheless, the SDM locations upstream and downstream of the spring are still deemed too far apart to provide the requisite accuracy for each of the loss components. Further SDMs more closely bracketing the Zwartkrans Spring will be carried out to achieve greater confidence in this regard.

5.2 Chemical Hydrogeology

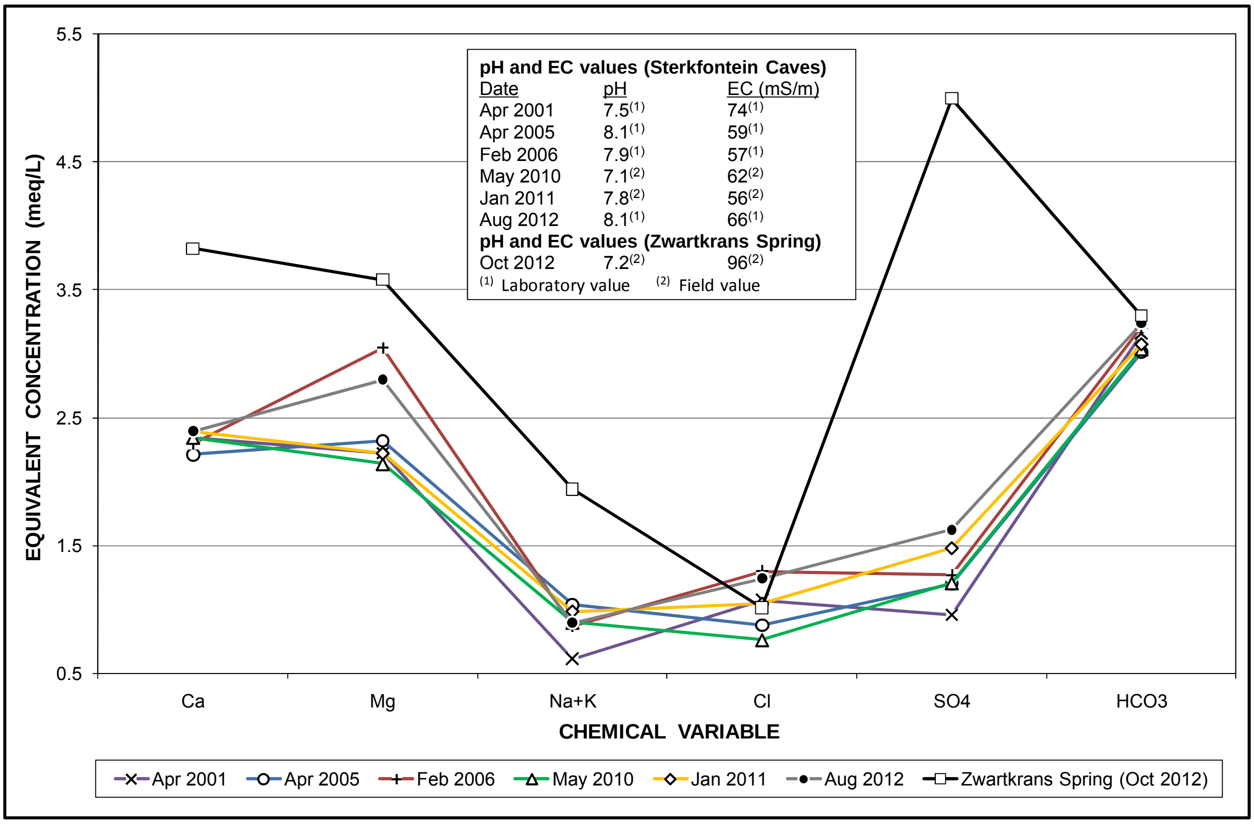
5.2.1 Monitoring Framework

The DWA groundwater monitoring programme in the south-western portion of the study area was substantially expanded with the establishment of an additional 13 monitoring boreholes in late-2010. These stations (identified by the alpha-numeric code GP003##) supplement the 13 stations (identified by the alpha-numeric code A2N0###) that are the legacy of the mid-1980 DWA study (Bredenkamp et al., 1986) in the region. The distribution of this monitoring network is shown in **Figure 36** and **Figure 37**. Whereas the older stations support a quasi-continuous monitoring record dating back to 2003, the record of the newer stations commences in March 2011. It is the product of this monitoring that forms the basis for evaluating the mine water impact on the karst groundwater resources of the Zwartkrans Compartment. It is also important to recognise that the focal area in this regard represents <25% of the COH WHS footprint (~52 000 ha). This information is supplemented with data generated by the COH WHS MA monitoring programme for the entire study area.

5.2.2 Sterkfontein Caves Water Chemistry

It might be expected that if the water level rise in Sterkfontein Caves is attributable to allogenic recharge driven mainly by acid mine drainage, then this would also be reflected in the cave water chemistry. An assessment of available groundwater chemistry data for the karst hydrosystem shared by the caves, provides the following insight.

Holland and Witthüser (2009) report SO_4 and Cl concentrations of 154 and 55 mg/L respectively for groundwater sourced ca. 2006 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 in the upstream Oaktree area (Hobbs and Cobbing, 2007), and raise concern for the quality of the cave water. Fortunately a comparison of cave water chemistry over time is provided by the analyses of April 2001 (from Rand Uranium records), April 2005 (from DWA records), February 2006 (from Harmony Gold records), May 2010 (from CSIR records), and January 2011 and August 2012 (from Maropeng āAfrika records). This comparison is made in **Figure 33** which also shows the October 2012 composition of Zwartkrans Spring water. The similar CaMg-HCO$_3$ chemical composition of the cave waters (including the two most recent records) is readily apparent. The sharp contrast of the cave water chemistry with the Ca-SO$_4$ composition of the Zwartkrans Spring water is equally evident.



pH and EC values (Sterkfontein Caves)

Date	pH	EC (mS/m)
Apr 2001	7.5(1)	74(1)
Apr 2005	8.1(1)	59(1)
Feb 2006	7.9(1)	57(1)
May 2010	7.1(2)	62(2)
Jan 2011	7.8(2)	56(2)
Aug 2012	8.1(1)	66(1)
pH and EC values (Zwartkrans Spring)		
Oct 2012	7.2(2)	96(2)

(1) Laboratory value (2) Field value

Figure 33 Graphical comparison of historical and recent Sterkfontein Caves groundwater chemistry

Closer inspection of the data indicate that the SO$_4$ concentration in the cave water has increased by ~70% from 46 mg/L in April 2001 to 78 mg/L in August 2012 (**Figure 34**). It has been shown by Hobbs (2011a) that SO$_4$ comprises ~62% of the TDS concentration associated with Western Basin mine water, ~19% of the TDS typical of surface water in the receiving downstream environment, and ~2% in the case of pristine karst groundwater. The SO$_4$**:**TDS ratio value therefore serves as an indicator of a mine water presence in receiving water resources.

An evaluation of the SO$_4$**:**TDS ratio associated with the cave water chemistry returns the trend illustrated in **Figure 35**. The increasing trend from ~13% to ~18% approaches a value that characterises more recent surface water chemistry in the Bloubank Spruit. This provides a clear indication of a surface water influence on the cave water chemistry. Given the previously demonstrated evidence of a mine water impact on the surface water chemistry of the Bloubank Spruit system (**section 0**), the corollary transposes a muted mine water impact also on the cave water chemistry.

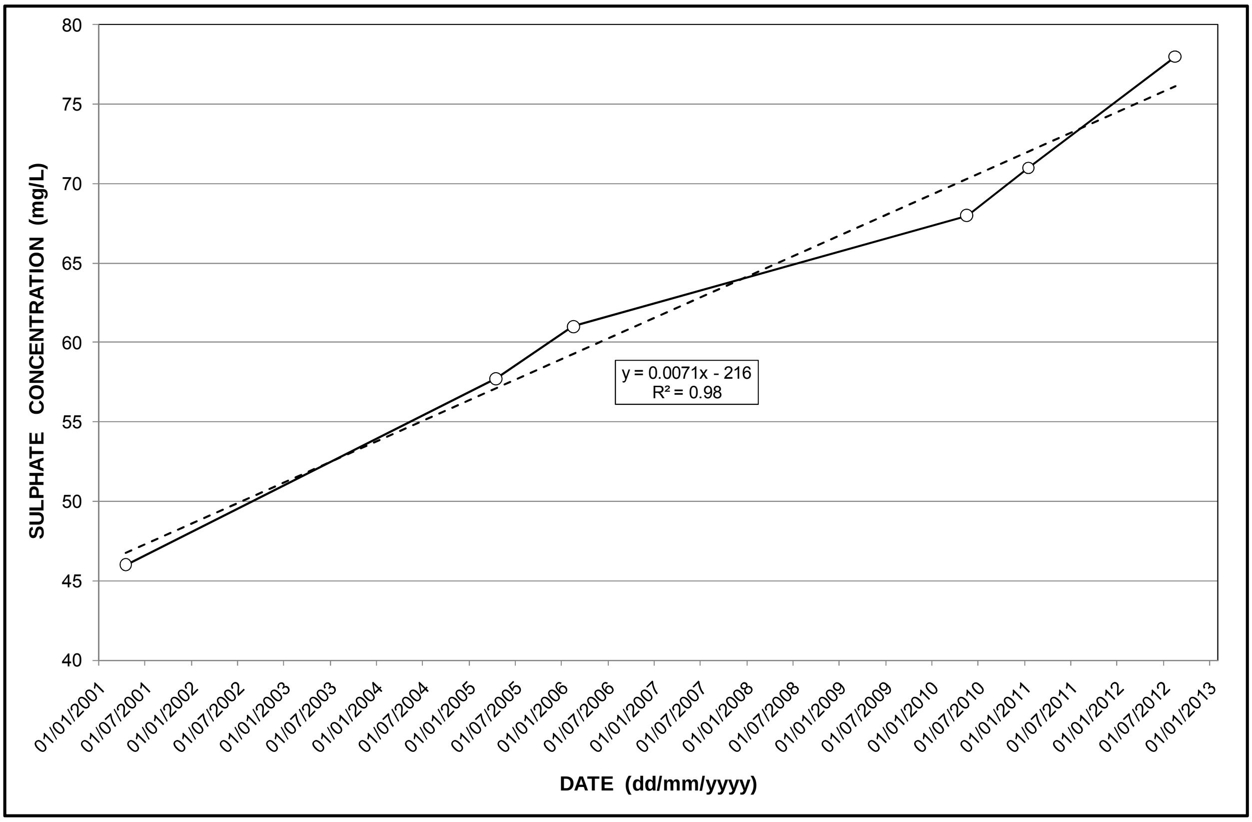


Figure 34 Pattern and trend of sulphate concentration in Sterkfontein Caves lake water

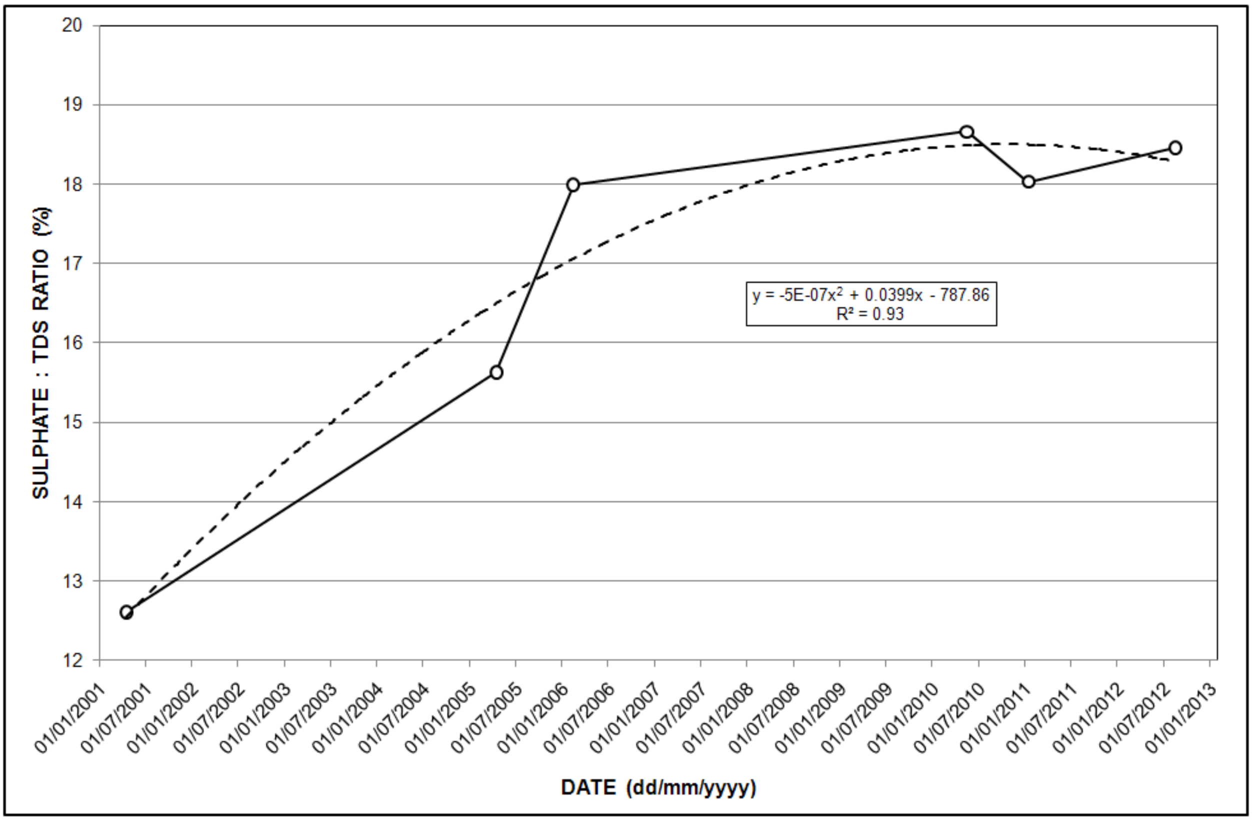


Figure 35 Trend of the SO_4:TDS ratio in cave water chemistry since 2001; trendline represents a 2nd order polynomial fit

5.2.3 Mine Water Impact

The groundwater chemistry data generated by the monitoring programme in the Zwartkrans Compartment provides an indication of the extent and magnitude of the mine water impact on the karst aquifer in this portion of the COH WHS. This is illustrated in **Figure 36** and **Figure 37** with the aid of bar graphs for the chemical variables pH and electrical conductivity (EC) respectively.

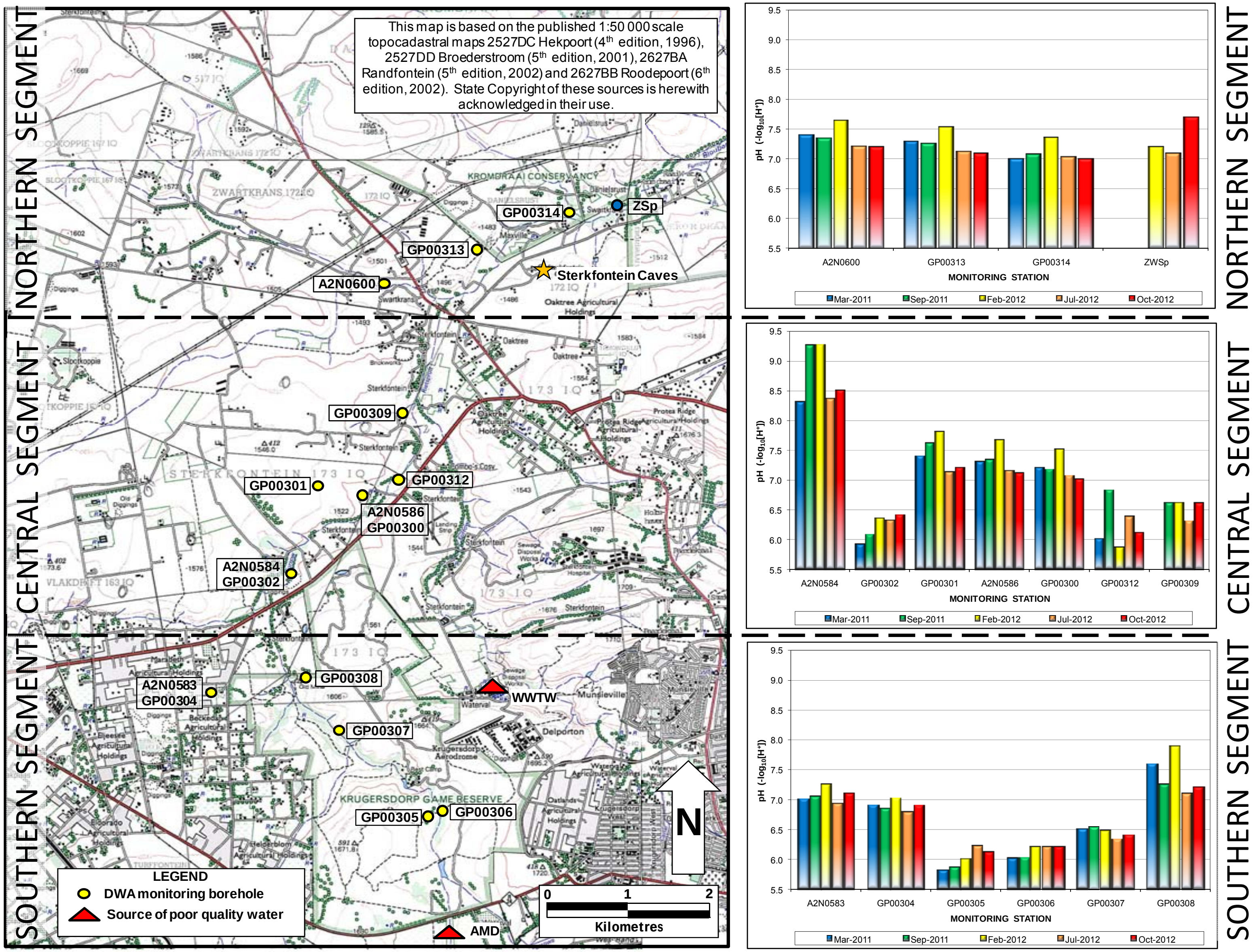
The bar graphs in **Figure 36** reflect the general progressive decrease in pH from south to north within the central and northern segments. This pattern is reflected both in the individual stations and in a spatial context, although the latter is heavily influenced by proximity to the influent (losing) reach of the Riet Spruit in the central segment.

The bar graphs in **Figure 37** similarly reflect the general progressive increase in salinity from south to north within the central segment. In the northern segment, however, the spatial trend is a declining one, even though all of the stations individually reflect an increase in salinity. The significant influence exerted by proximity to the Riet Spruit in the central segment is again evident. As in the case of pH (**Figure 36**), this influence is least at the southern margin (stations A2N0583 and GP00302), and increases down-gradient to station GP00309. This pattern reflects the north to north-easterly flow path followed by the allogenic recharge of mine water in the karst aquifer.

The historical pattern and trend of groundwater salinity and sulphate concentrations in proximity to the losing reach of the Riet Spruit is reflected in the longer term monitoring data associated with stations A2N0584, A2N0586 and A2N0600. These are presented in **Figure 38**, and again reveal the comparatively recent increase in EC and SO_4 concentration levels.

The postulated commencement of the rise in concentrations ca. September 2008 is based on the SO_4 response at station A2N0584 located the furthest upstream along the Riet Spruit. It might be expected that a response at the downstream stations (especially A2N0600) would manifest later because of slower travel times in the subsurface. The variable of concern is SO_4, which exceeds the SANS (2011a) standard health-related limit of 500 mg/L (**Table 3**) in all three instances.

A Piper diagram that characterises the groundwater chemistry in the Zwartkrans Compartment in October 2012 (**Figure 39**) clearly reflects the mine water impact at all but one of the monitoring stations. The distribution of SO_4 concentrations associated with the stations represented in **Figure 39** is shown in **Figure 40**, and provides an indication of the footprint of this impact. The distribution pattern evident in the central diamond field of **Figure 39** reflects a diminishing impact from top (station GP00312) to bottom (station ZSp) which describes a vector from upstream to downstream as illustrated by the flow path that describes allogenic recharge in **Figure 40**. Also evident in **Figure 39** is the position of the A2N0594 sample that characterises nearly pristine karst groundwater. **Figure 40** shows that this station is located in the upper reaches of the Zwartkrans Compartment within the flow path that describes autogenic recharge.



This map is based on the published 1:50 000 scale topocadastral maps 2527DC Hekpoort (4th edition, 1996), 2527DD Broederstroom (5th edition, 2001), 2627BA Randfontein (5th edition, 2002) and 2627BB Roodepoort (6th edition, 2002). State Copyright of these sources is herewith acknowledged in their use.

Figure 36 Distribution of DWA monitoring boreholes with pH pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

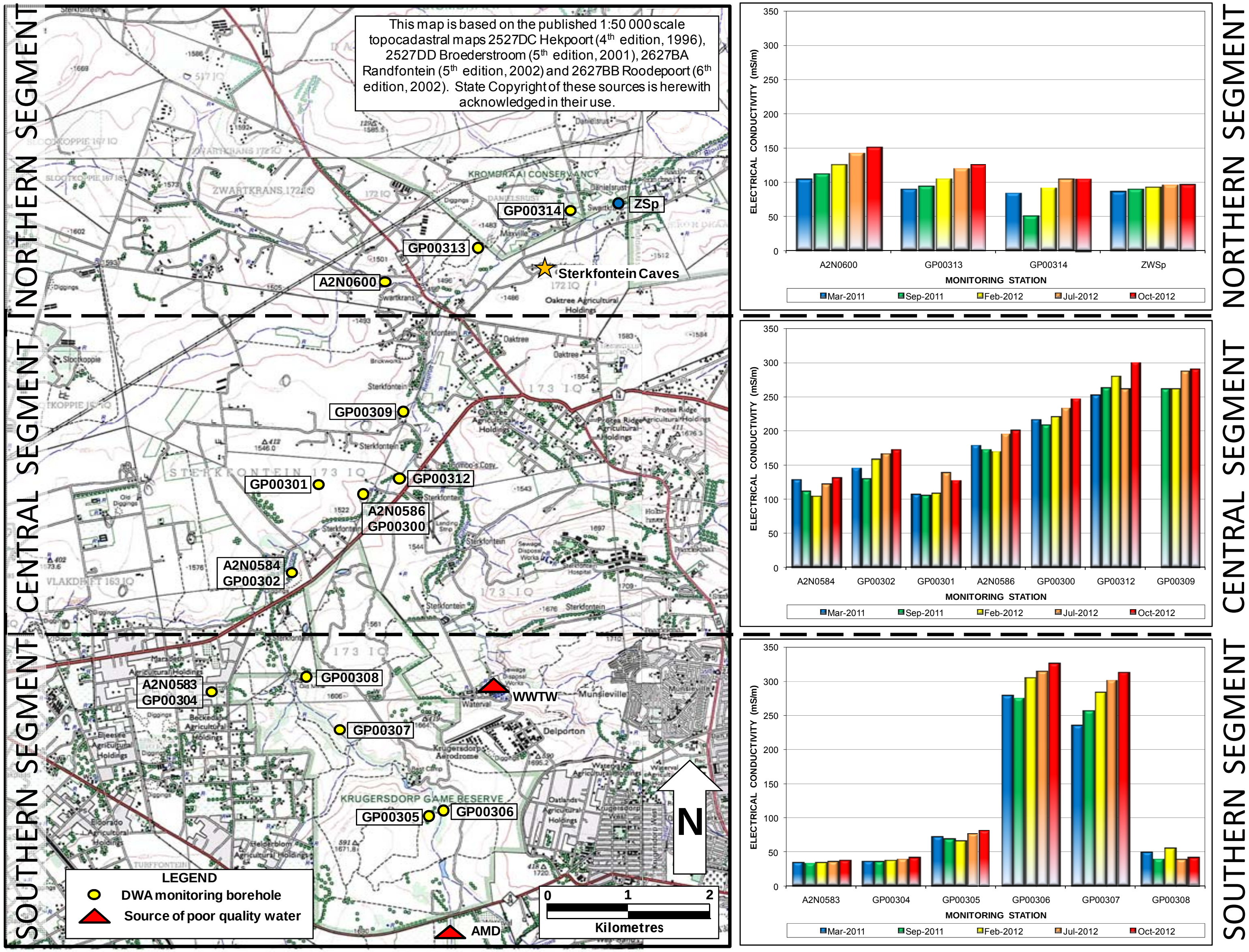


Figure 37 Distribution of DWA monitoring boreholes with EC pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

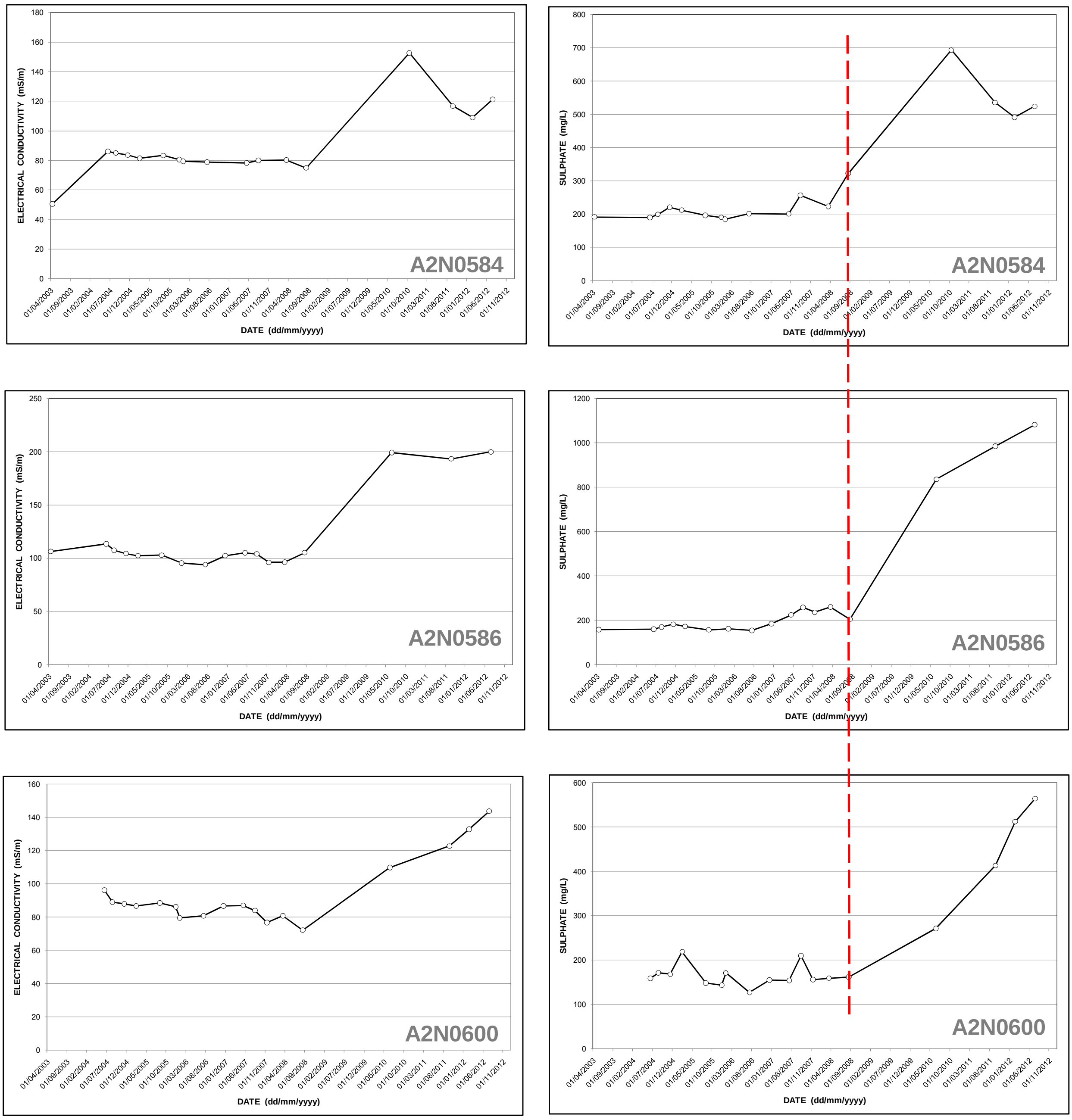


Figure 38 Long-term pattern and trend of electrical conductivity (at left) and sulphate (at right) in karst groundwater from DWA monitoring stations A2N0584, A2N0586 and A2N0600; note common time scales and postulated commencement of rise in concentrations (vertical pecked line)

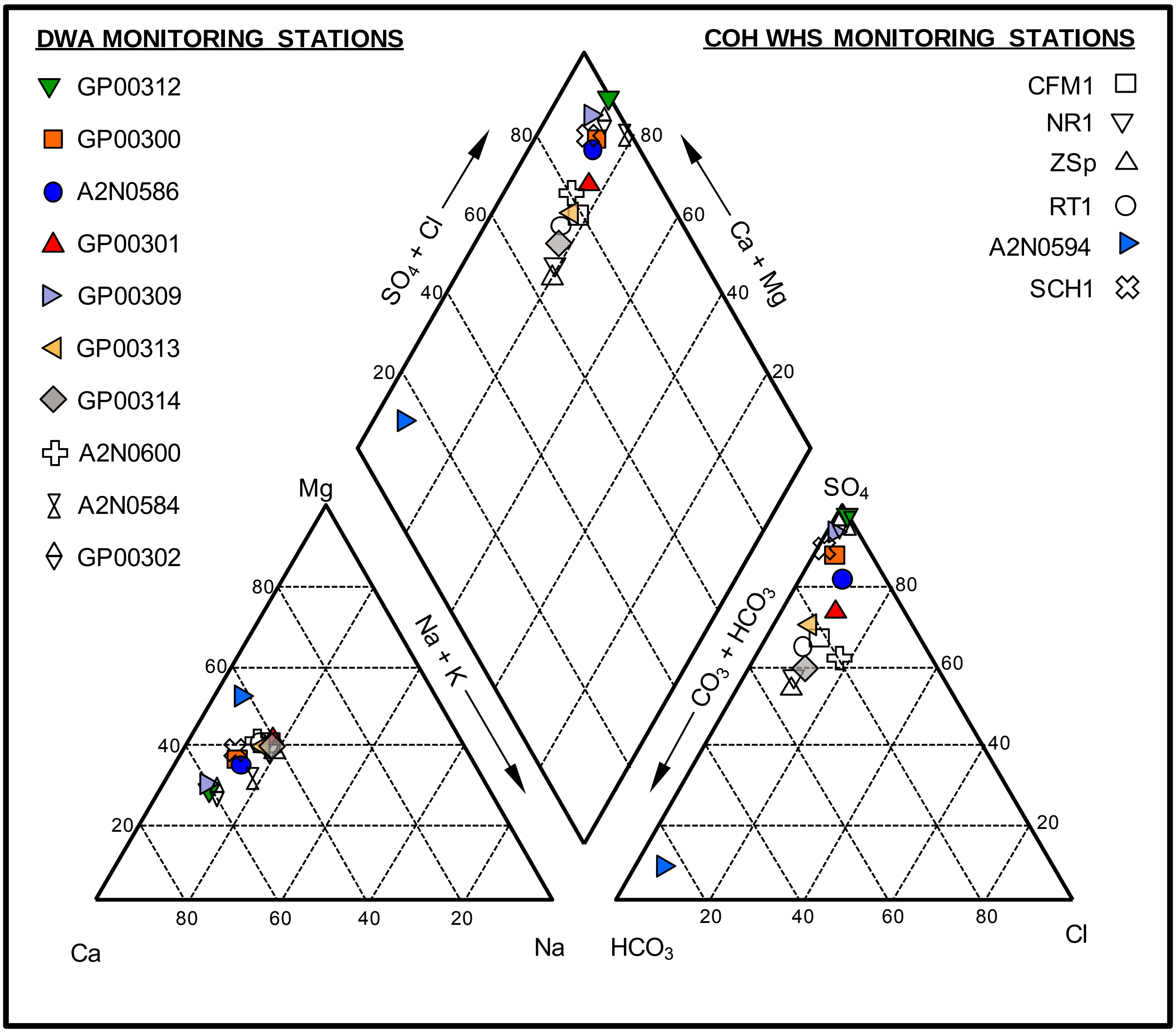


Figure 39 Characterisation of groundwater chemistry in the Zwartkrans Compartment in October 2012

6 REMOTE MONITORING

The DWA has equipped a number of their monitoring boreholes with water level and field chemistry (salinity and temperature) sensors for the near real-time remote monitoring of these variables. Although installed, the sensors need to be calibrated and programmed, whereafter the captured data will be transmitted wirelessly to the DWA Head Office in Pretoria.

The DWA has also been requested to install a conductivity sensor in a stilling well adjacent to the Zwartkrans Spring. Monitoring of the groundwater salinity at this position will track the transit of the mass solute associated with the migration of mine water impacted karst groundwater exiting the Zwartkrans Compartment.

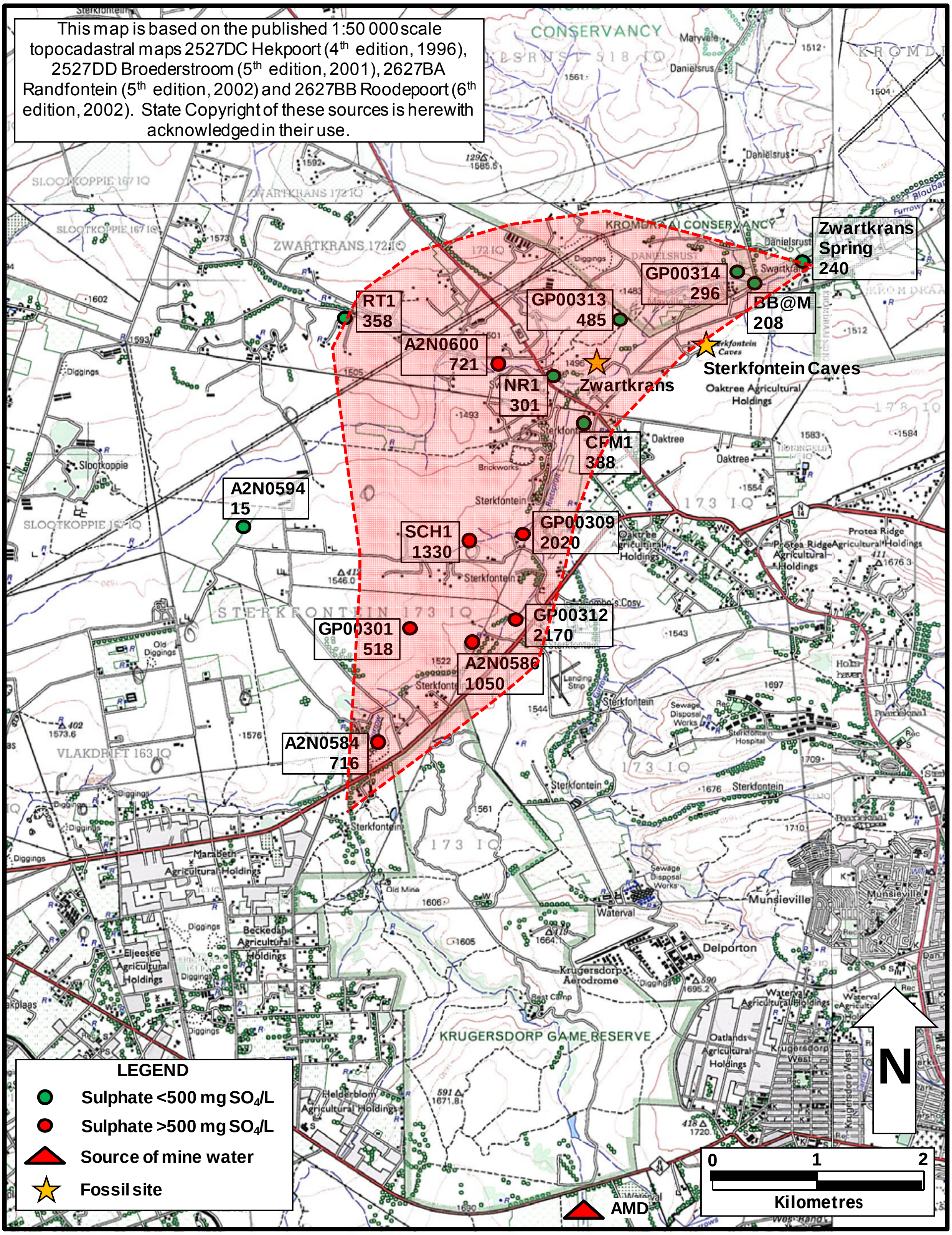


Figure 40 Distribution of SO_4 concentrations in groundwater of the Zwartkrans Compartment in October 2012, also showing the principal vectors of allogenic recharge (brown arrow), autogenic recharge (blue arrow) and the postulated footprint (shaded area) of a mine water impact on the karst aquifer

7 CONCLUSIONS

It is clear that an assessment of impacts on the water resources environment of the COH WHS must consider both a holistic view and a specific focus on those resources that are at greatest risk from a wastewater impact. The outcome of the pilot implementation project as documented in this report largely confirms the conceptual hydrophysical and hydrochemical model developed for the COH WHS in the situation assessment report. It has not revealed any major inconsistencies, nor has it exposed significant flaws that might question the proposed water resources monitoring programme as originally formulated.

The monitoring results reveal the following responses in the water resources environment to drivers/stressors such as rainfall, effluent wastewater discharge, autogenic and allogenic recharge of the karst groundwater system, and groundwater discharge.

- In the last three hydrological years, the Bloubank Spruit system delivered the 2nd, 3rd and 4th highest runoff (59.1, 50.0 and 44.9 Mm^3 respectively), after the 66.9 Mm^3 of the 1977-'78 hydrological year, in the 40-year historical gauging record of this catchment.

- The re-commencement of uncontrolled raw mine water discharge from the mine area in late-January 2010 triggered an 18-month period of impact (from mid-2010 to late-2011) on the downstream receiving hydrologic environment before returning to 'more normal' pre-2010 conditions.

- Further abatement of the mine water impact on surface water quality commenced in mid-2012 with the commissioning of the immediate AMD intervention measures that witnessed an upgrade of the capacity and efficiency of the high density sludge (HDS) mine water treatment plant.

- Synoptic discharge measurements at two stations in the lower reach of the Riet Spruit confirmed earlier results regarding losses of mine water impacted surface water to the karst aquifer of the Zwartkrans Compartment. Representing allogenic recharge of the karst aquifer, the impact of the poorer quality water on the natural dolomitic groundwater is being manifested much more slowly because of factors (amongst others) such as (a) the considerably lower groundwater flow rates, (b) dispersion and diffusion effects in the subsurface, and (c) geochemical and biogeochemical reactions between different quality groundwaters.

- The impact of allogenic recharge from the losing reach of the Riet Spruit to the karst aquifer of the Zwartkrans Compartment is unequivocally mapped on the basis of elevated salinity and sulphate values in the groundwater. These values represent the site and time specific values in a changing continuum that defines the transit of the plume of groundwater with a mine water signature moving through the karst aquifer. Where each sampling station lies within this continuum, i.e. ahead of an approaching maximum value, at or near the maximum value or behind a departing contamination 'peak' is as yet undecipherable from the available data. A provisional assessment forecasts arrival of the contamination 'peak' at the Zwartkrans Spring by the end of 2013, by which time the groundwater quality further upstream should already have shown an improvement provided that the immediate AMD intervention measures are maintained.

- The ~3 m rise in the Main Lake water level in Sterkfontein Caves, although unprecedented in modern times, finds support in potentiometric levels across the Zwartkrans Compartment. The rise also agrees well with the zone of perceived most aggressive carbonate re-solution that defines the more recent (<2 Ma) speleogenetic evolution of the cave system. This level is unlikely to rise further because of the congruence with the channel elevation of the Bloubank Spruit opposite the caves.

- The decline in the Main Lake water level since mid-2012 is expected to continue at a rate of 0.06 m/month, but will remain high as a result of the greater sustained discharge of treated/neutralised mine water associated with the immediate and short-term AMD control and management interventions in the Western Basin.

- The quality of the Main Lake water in Sterkfontein Caves continues to reflect a muted influence from surface water impacted by mine water. This observation alone is sufficient to warrant the vigilance of monitoring the cave water quality.

In conclusion, it is evident from the monitoring data and results that the karst environment of a portion of the Zwartkrans Compartment in the south-western quadrant of the COH WHS has experienced a significant deterioration in groundwater quality. Sulphate levels of as much as ~1300 mg SO_4/L will definitely impact on the potability of groundwater-based water supplies in the area effected. Although the commissioning of the immediate mine water control and management intervention measures in mid-2012 has ameliorated the quality of surface water in the Bloubank Spruit system, the impact on the groundwater environment in the effected portion of the Zwartkrans Compartment will take significantly longer to manifest an improvement.

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