

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

REPORT TITLE
**SITUATION ASSESSMENT AND STATUS REPORT
FOR THE PERIOD APRIL 2012 TO MARCH 2013**

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DATE
MARCH 2013

REPORT No.
CSIR/NRE/WR/ER/2013/0023/B

PREPARED FOR
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Cradle of Humankind World Heritage Site
Gauteng Tourism Authority
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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 second status report of the pilot implementation project, and covers the full term April 2012 to March 2013. It also presents an updated situation assessment.

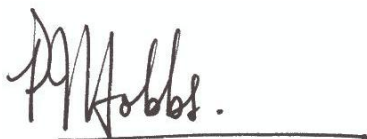
It is clear that an assessment of impacts on the water resources environment of the COH WHS must consider both a holistic view and a specific focus on those resources that are at greatest risk from a wastewater impact. The outcome of the pilot implementation project as documented in this report largely 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 ~0.03 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.
- The municipal wastewater effluent discharged from the Percy Stewart Wastewater Treatment Works continues to manifest an unacceptable bacteriological quality in the downstream receiving reaches of the Bloubank Spruit system. This situation is indefensible given the attention that is directed at AMD as a source of impact on the receiving water resources environment of the COH WHS.
- The mine water discharges have introduced a new set of drivers that have caused a resetting of the natural water resources environment that, in the case of groundwater, is immediately and most evident in the groundwater level (potentiometric) data. It is postulated that this impact will result in higher baseflows (by 10–15%) in the Bloubank Spruit system in the future.

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 ~1 300 mg SO₄/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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CONTENTS

	Page
SUMMARY	i
SYMBOLS, ACRONYMS AND ABBREVIATIONS	v
1 INTRODUCTION, BACKGROUND AND CONTEXT	1
2 TIMELINE OF KEY EVENTS.....	1
3 RAINFALL.....	3
4 SURFACE WATER HYDROLOGY	5
4.1 Physical Hydrology	5
4.1.1 Surface Water Discharge	5
4.1.2 Surface Water Fluxes.....	7
4.2 Chemical Hydrology	12
4.2.1 Tweelopie Spruit and Riet Spruit.....	12
4.2.2 Bloubank Spruit	17
4.3 Salt Load.....	23
4.3.1 Riet Spruit.....	23
4.3.2 Bloubank Spruit	24
5 GROUNDWATER HYDROLOGY	29
5.1 Physical Hydrogeology	29
5.1.1 Groundwater Levels.....	29
5.1.2 Sterkfontein Caves Water Level	34
5.1.3 Groundwater Fluxes.....	35
5.2 Chemical Hydrogeology	37
5.2.1 Monitoring Framework.....	37
5.2.2 Sterkfontein Caves Water Chemistry.....	37
5.2.3 Mine Water Impact	39
6 AUTOMATED MONITORING.....	45
7 CONCLUSIONS	45
8 REFERENCES.....	47

FIGURES

Figure 1	Definition of the study area in regard to the regional geology, surface water drainages, quaternary catchments and other geographic locations for orientation	1
Figure 2	Timeline of events relevant to this report	2
Figure 3	Monthly precipitation at the RU/G1 rainfall monitoring stations HDS and BRI in the period October 2008 to February 2013, also showing the available record for the Sterkfontein Caves station	4
Figure 4	Comparison of total wet season (summer) rainfall at the RU/G1 rainfall monitoring stations HDS and BRI in the past five hydrological years, also showing the available record for the Sterkfontein Caves station.....	4

Figure 5	Correlation of monthly rainfall at Sterkfontein Caves with the RU/G1 record for stations HDS and BRI in the locus of decant.....	5
Figure 6	Graph of Bloubank Spruit annual (a_h) discharge gauged at station A2H049 in the period October 1972 to September 2012.....	6
Figure 7	Long-term monthly hydrograph of the Bloubank Spruit at station A2H049 for the period October 1972 to September 2012.....	7
Figure 8	Locality map of surface water quantity and quality monitoring stations.....	9
Figure 9	Graph of stream flow and losses to the karst aquifer in the lower Riet Spruit valley	10
Figure 10	Correlation of stream flow at stations F11S12 and MRd in the Riet Spruit valley (respective regression lines explained in text and Figure 9), with error bars denoting $\pm 10\%$ at F11S12 (vertical) and $\pm 5\%$ at MRd (horizontal).....	11
Figure 11	Historical Google Earth images showing the development of a ferrous 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 8	11
Figure 12	Pattern of pH values in the Tweelopie Spruit in the period May 2004 to October 2012	12
Figure 13	Pattern of electrical conductivity values in the Tweelopie Spruit in the period May 2004 to October 2012	13
Figure 14	Pattern of SO_4 values in the Tweelopie Spruit in the period May 2004 to October 2012	13
Figure 15	Pattern of Fe values in the Tweelopie Spruit in the period June 2009 to October 2012	14
Figure 16	Pattern of Mn values in the Tweelopie Spruit in the period June 2009 to October 2012	14
Figure 17	Pattern and trend of electrical conductivity of surface water at stations F11S12 and MRd on occasion of the SDMs reported in Table 3	16
Figure 18	Pattern and trend of pH of surface water at stations F11S12 and MRd on occasion of the SDMs reported in Table 3.....	16
Figure 19	Pattern and trend of SO_4 in surface water at stations F11S12 and MRd on occasion of the SDMs reported in Table 3.....	17
Figure 20	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.....	18
Figure 21	Piper diagram of pre-2009–'10 and more recent Bloubank Spruit water chemistry at station A2H049.....	19
Figure 22	Surface water quality sampling sites in the study area	21
Figure 23	Recent temporal pattern of (a) NO_3-N , (b) PO_4-P , (c) COD and (d) faecal coliforms in Bloubank Spruit water at the Nedbank Olwazini Estate	22
Figure 24	Bar graph of surface water TDS load loss to groundwater in the lower reach of the Riet Spruit	23
Figure 25	Bar graph of surface water SO_4 load loss to groundwater in the lower reach of the Riet Spruit	23
Figure 26	Long-term (June 1979 to August 2012) monthly TDS load pattern and trend in the Bloubank Spruit at DWA station A2H049	25
Figure 27	Long-term (June 1979 to August 2012) monthly SO_4 load pattern and trend in the Bloubank Spruit at DWA station A2H049	25
Figure 28	Long-term (June 1979 to August 2012) trend in the SO_4 :TDS ratio at station A2H049	26
Figure 29	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	26
Figure 30	Pattern and trend in the SO_4 concentration at station A2H049 since the start of mine water decant in the Western Basin.....	27
Figure 31	Pattern and trend in the SO_4 :TDS ratio at station A2H049 since the start of mine water decant in the Western Basin	27
Figure 32	Pattern of cumulative monthly TDS load delivered by the Bloubank Spruit system in the long-term	28
Figure 33	Pattern of cumulative monthly SO_4 load delivered by the Bloubank Spruit system in the long-term	29
Figure 34	Graphic comparison of the statistical hydrographic response observed in DWA groundwater level monitoring stations in the period 1985 to 2012 (data from Table 6)	30

Figure 35	Long-term groundwater level response pattern in DWA monitoring boreholes	31
Figure 36	Long-term groundwater level response pattern in Group A boreholes from Figure 35	31
Figure 37	Long-term groundwater level response pattern in Group B boreholes from Figure 35	32
Figure 38	Distribution of DWA monitoring boreholes with groundwater hydrographs (right); arrow denotes principal direction of groundwater flow.....	33
Figure 39	Recent groundwater level response pattern and trend in borehole SF1 that serves as a proxy for the Main Lake water level in Sterkfontein Caves.....	34
Figure 40	Graphical comparison of historical and recent Sterkfontein Caves groundwater chemistry	38
Figure 41	Pattern and trend of sulphate concentration in Sterkfontein Caves lake water	38
Figure 42	Trend of the SO₄:TDS ratio in cave water chemistry since 2001; trendline represents a 2nd order polynomial fit	39
Figure 43	Characterisation of groundwater chemistry in the Zwartkrans Compartment in October 2012	40
Figure 44	Distribution of DWA monitoring boreholes with pH pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow.....	41
Figure 45	Distribution of DWA monitoring boreholes with EC pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow.....	42
Figure 46	Long-term pattern and trend of electrical conductivity (left) and sulphate (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).....	43
Figure 47	Distribution of SO₄ 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	44

TABLES

Table 1	Statistical analysis of Bloubank Spruit monthly discharge data gauged at station A2H049 in the period October 1972 to October 2012.....	5
Table 2	Quantification of stream flow loss rate in the Riet Spruit.....	8
Table 3	Record of salinity and pH measurements made at stations F11S12 and MRd on the occasion of flow gauging measurements (SDMs), also showing derived SO₄ and TDS concentrations	15
Table 4	Statistical analysis of Bloubank Spruit water chemistry data associated with station A2H049 for the period May 1979 to August 2012.....	19
Table 5	Analysis of Bloubank Spruit water nutrient and bacterial content at the NOE property for the period January 2009 to January 2013	20
Table 6	Salient statistics for long-term DWA groundwater level monitoring data	30
Table 7	SDM and load-based calculation of the Zwartkrans Spring discharge on 15 January 2013	35
Table 8	Calculation of groundwater resurgence in the Bloubank Spruit upstream of Zwartkrans Spring on 15 January 2013 using SDMs and salinity-based TDS load values.....	36

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)
cfu	coliform forming units
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 1
HDS	high density sludge
kg	kilogram(s)
km	kilometre(s)
L/d	litre(s) per day
LoD	locus of decant
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
MCLM	Mogale City Local Municipality
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
MPN	most probable number
mS/m	milliSiemens per metre
n	count
pp	pages
RU/G1	Rand Uranium/Gold 1
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, BACKGROUND AND CONTEXT

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 the situation assessment report. These circumstances require an update of the situation and status to reflect more recent patterns and trends revealed by the more recent data. Such an update has previously been reported for the period April to September 2012 (Hobbs, 2012), which combines a situation assessment update with a monitoring report as envisaged in the proposed water resources monitoring programme (Hobbs, 2011b). The situation assessment has been updated further to cover the period October 2012 to March 2013, and is presented in this report which covers the full term of the pilot implementation project, namely April 2012 to March 2013.

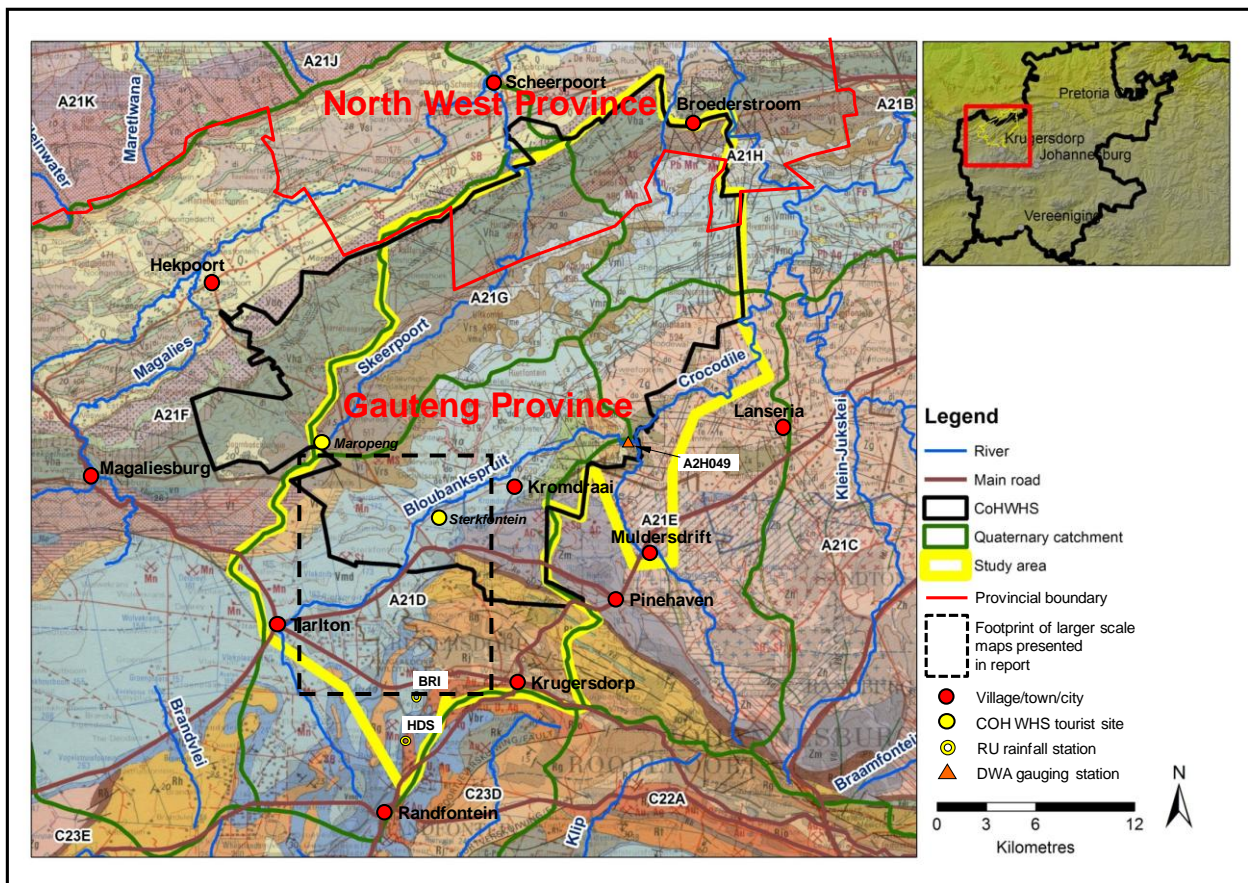


Figure 1 Definition of the study area in regard to the regional geology, surface water drainages, quaternary catchments and other geographic locations for orientation

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**.

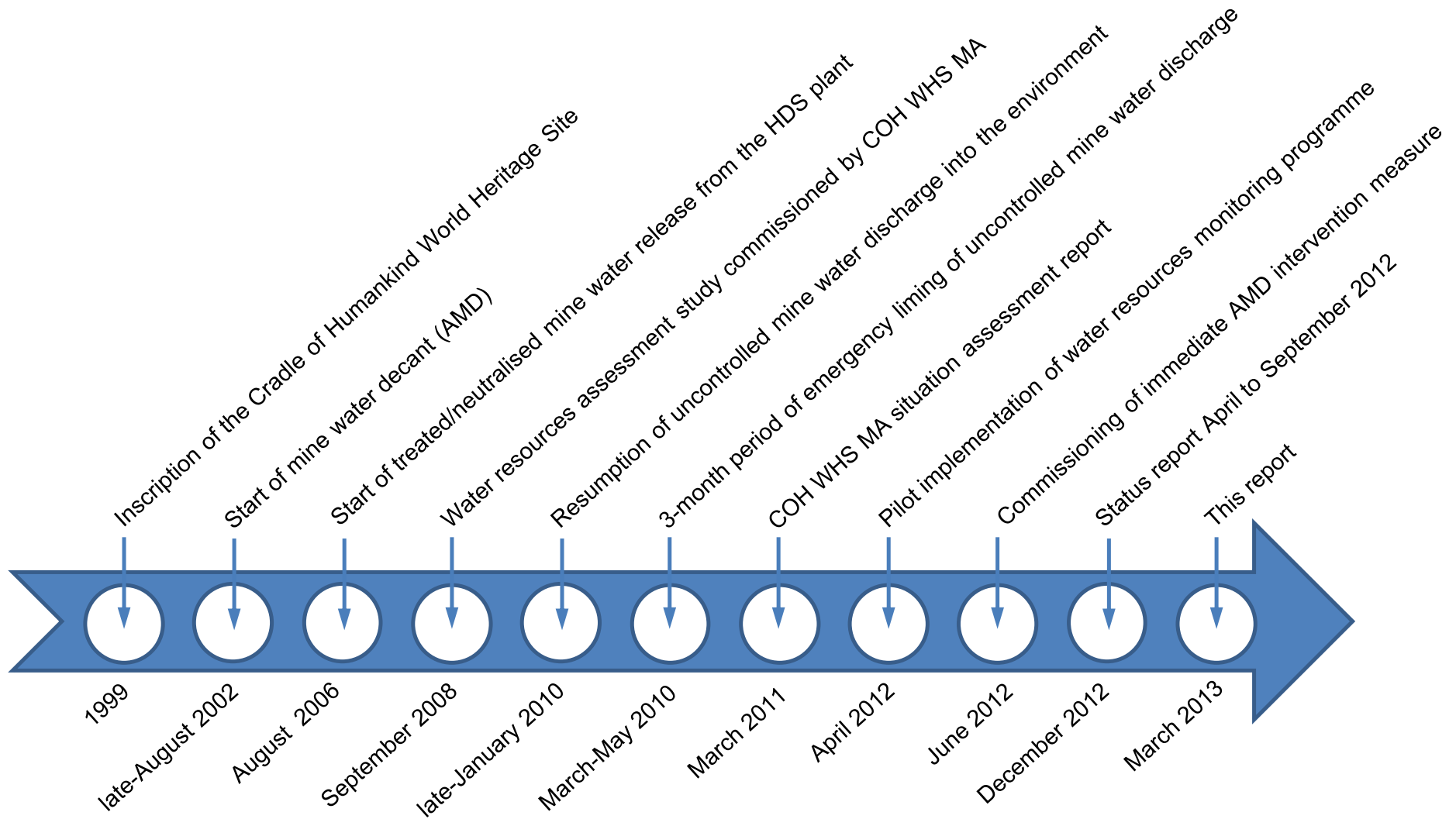


Figure 2 Timeline of events relevant to this report

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.
- The delivery of a status report for the period April to September 2012 (report CSIR/NRE/WR/ER/0088/B dated December 2012) documenting an updated situation assessment and a mid-term evaluation of monitoring data generated in the course of the pilot implementation of a surface water and groundwater resources monitoring programme for the COH WHS.

3 RAINFALL

The monthly precipitation record for the period October 2008 to February 2013 (**Figure 3**) of the Rand Uranium/Gold 1 (RU/G1) rainfall stations BRI and HDS (**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. The updated record suggests a smaller difference of ~11%.

Also shown in **Figure 3** and **Figure 4** are the contemporary rainfall data recorded at the Sterkfontein Caves gauging station by the DWA. Data for the period June 2010 to June 2012 were provided by the DWA. Of particular significance is the exceptional precipitation of 824 mm recorded in the 2010–'11 wet season (**Figure 4**). This confirms the similar result provided by especially the RU/G1 HDS station. An analysis of the common monthly rainfall record ($n = 25$) for all three stations, comparing the Sterkfontein Caves data with (a) the HDS data, (b) the BRI data and (c) the mean of the HDS and BRI data, indicates a best correlation ($R^2 = 0.88$) with the HDS station record (**Figure 5**).

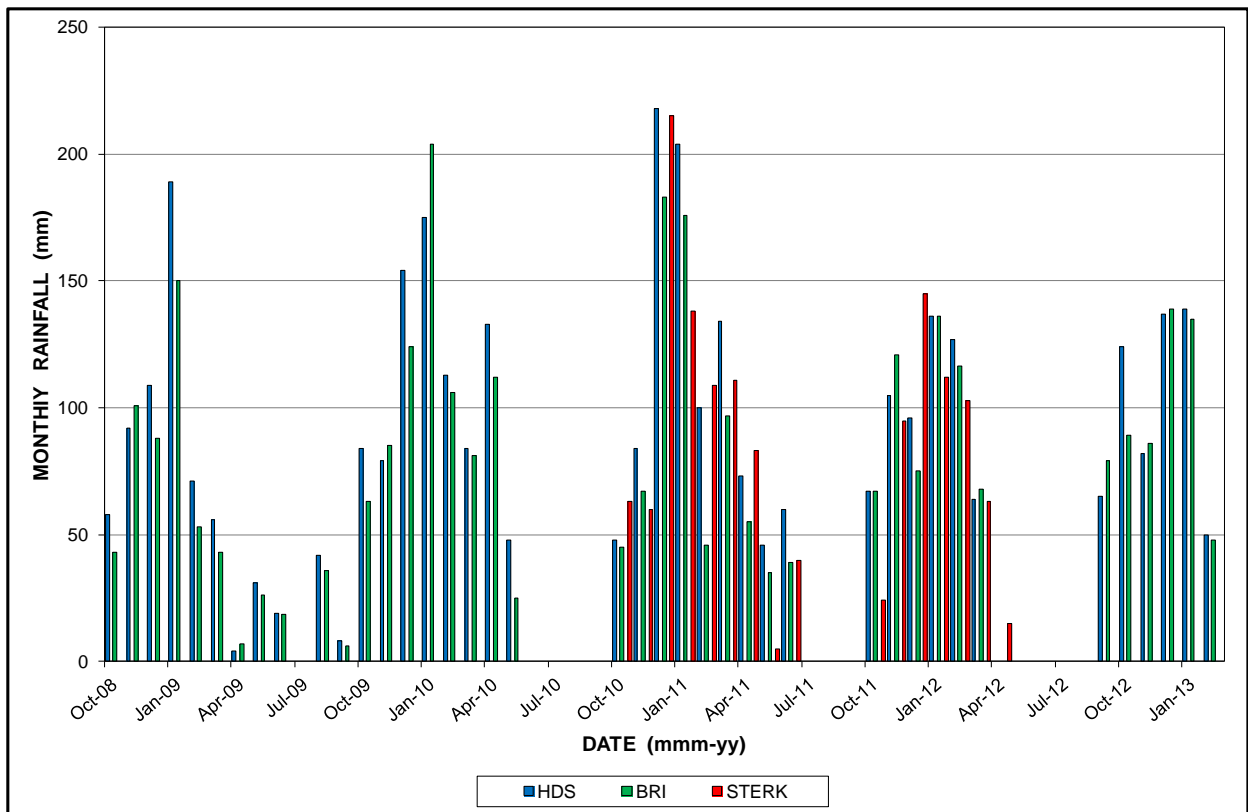


Figure 3 Monthly precipitation at the RU/G1 rainfall monitoring stations HDS and BRI in the period October 2008 to February 2013, also showing the available record for the Sterkfontein Caves station

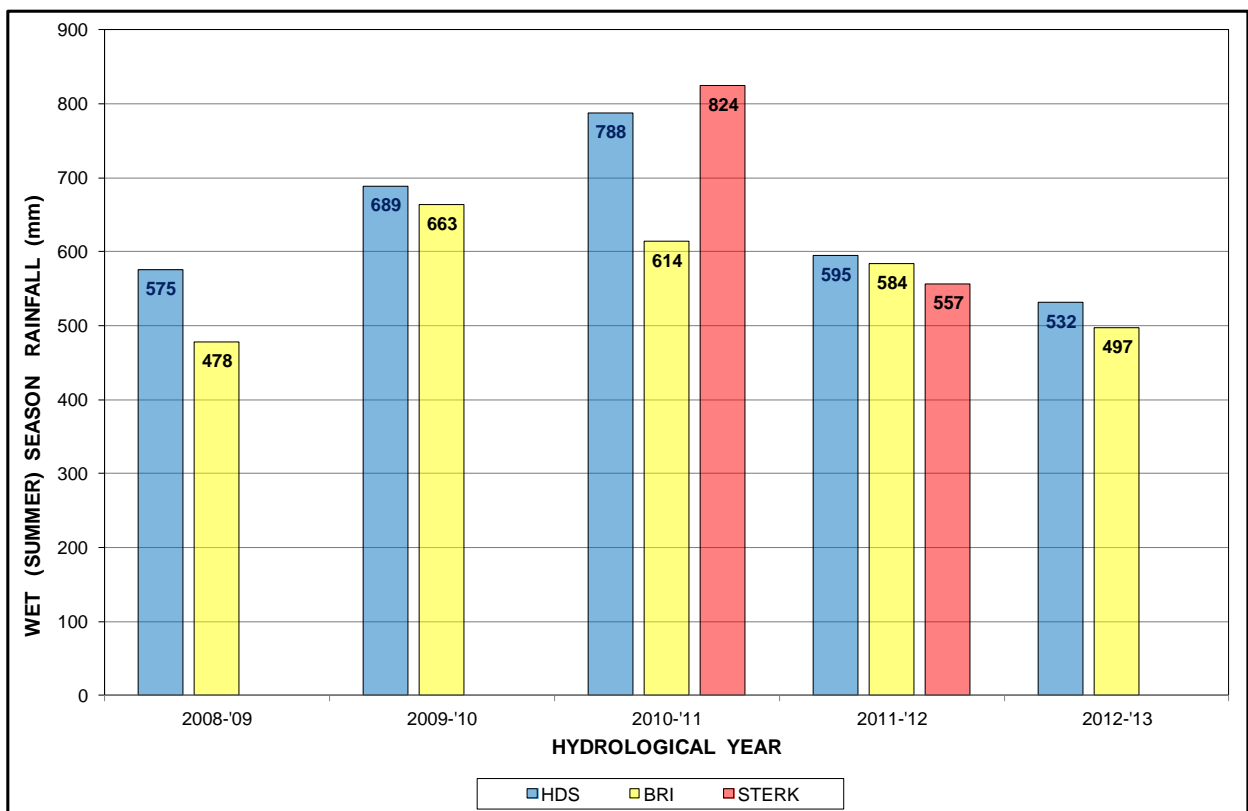


Figure 4 Comparison of total wet season (summer) rainfall at the RU/G1 rainfall monitoring stations HDS and BRI in the past five hydrological years, also showing the available record for the Sterkfontein Caves station

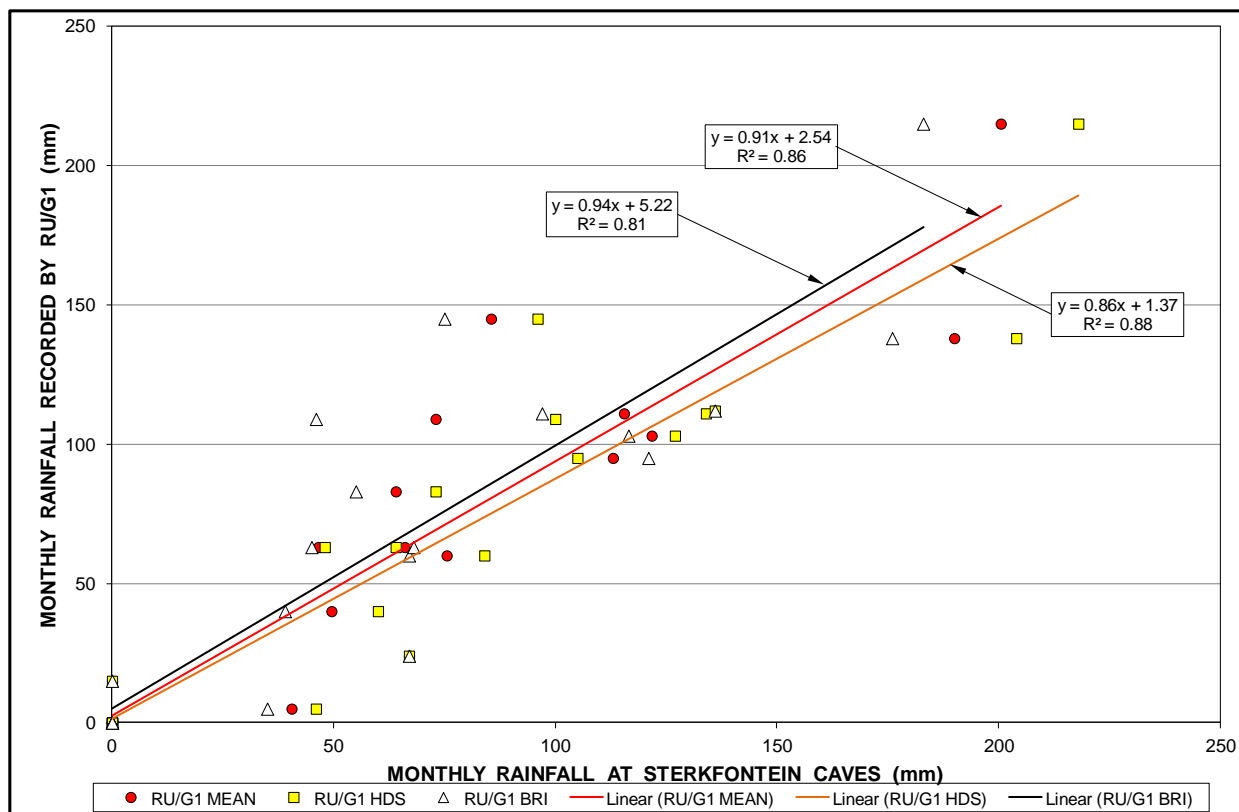


Figure 5 Correlation of monthly rainfall at Sterkfontein Caves with the RU/G1 record for stations HDS and BRI in the locus of decant

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**.

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

The discharge per hydrological year (a_h) shown in **Figure 6** indicates that the last three hydrological years witnessed the 2nd, 3rd and 4th highest runoff (59.1, 50.0 and 44.9 Mm³ after the 66.9 Mm³ 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 Mm³/a for the period 1972–’73 to 2008–’09, and a 15% greater median value of ~22.6 Mm³/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**.

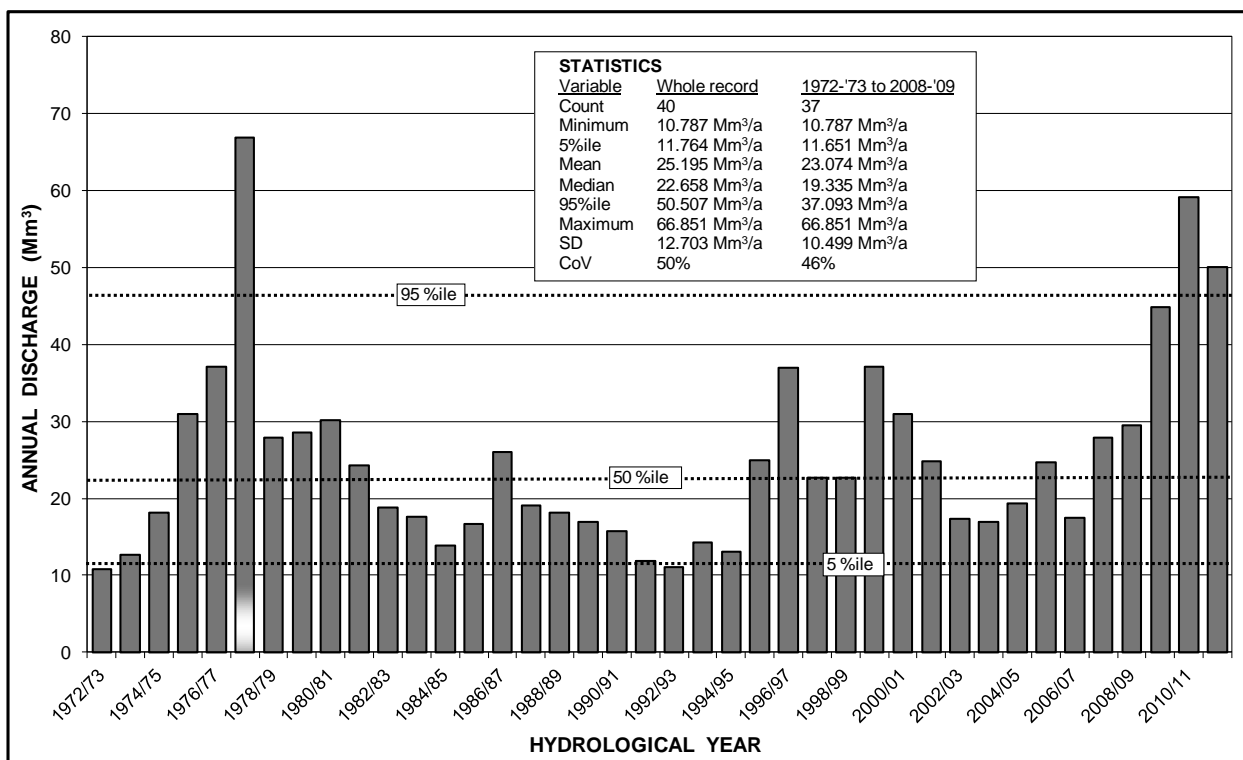


Figure 6 Graph of Bloubank Spruit annual (a_h) discharge gauged at station A2H049 in the period October 1972 to September 2012

The instantaneous monthly flow pattern at station A2H049 for the complete record is shown in **Figure 7**. This reveals a comparatively constant lowest value of 0.25 m³/s. Evident in the hydrograph (**Figure 7**) are distinct recession curves following peak discharge events. Station A2H049, however, is not only located a substantial distance (5–10 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 m³/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 m³/s was recorded on 28 January 1978. This observation places in perspective the floods experienced in the Bloubank Spruit in mid-December 2010 following rainfalls of 106 mm and 95 mm recorded on 16/12/2010 at the Sterkfontein Caves and RU/G1 HDS rainfall stations, respectively. The 1972–’73 to

2008–'09 and the whole record median annual discharge values represent 11–12% of the net capacity (186.4 Mm³) of Hartbeespoort Dam.

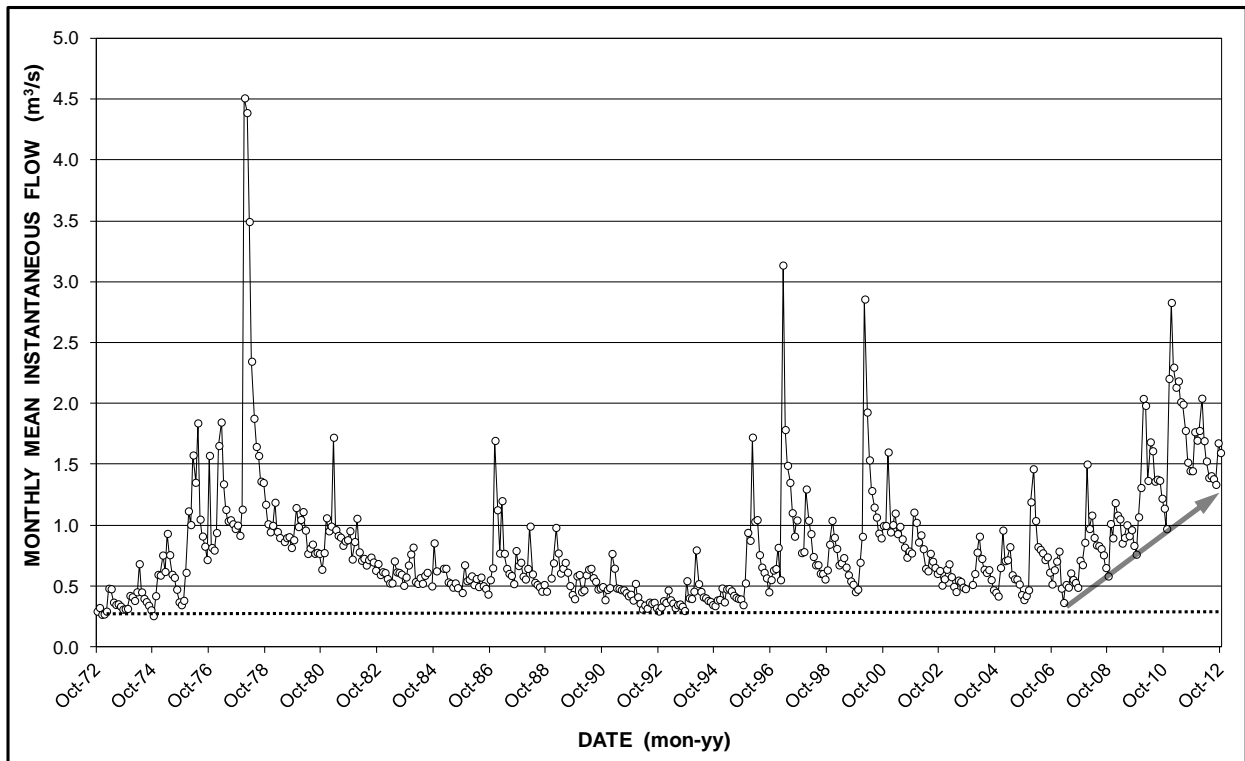


Figure 7 Long-term monthly hydrograph of the Bloubank Spruit at station A2H049 for the period October 1972 to September 2012

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 26 occasions (**Table 2**) at stations F11S12 and MRd (**Figure 8**) further quantify and elucidate the magnitude of surface water loss to the karst aquifer. The results of the SDMs are illustrated in **Figure 9**.

Prior to the 2009–'10 summer, station MRd witnessed surface flow only under exceptional discharge conditions¹, 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 9**).

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

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 ± 1.2	0	11.9	35
22/09/2009	14.9 ± 1.5	0	14.9	44
05/02/2010	35.2 ± 3.5	7.3 ± 0.4	27.9	83
16/02/2010	31.6 ± 3.2	5.7 ± 0.3	25.9	77
23/02/2010	26.2 ± 2.6	4.0 ± 0.2	22.2	66
09/03/2010	32.6 ± 3.3	9.4 ± 0.5	23.2	69
01/04/2010	40.4 ± 4.0	10.3 ± 0.5	30.1	89
14/04/2010	25.8 ± 2.6	5.7 ± 0.3	20.1	60
06/05/2010	43.7 ± 4.4	11.7 ± 0.6	32.0	95
18/05/2010	35.7 ± 3.6	11.0 ± 0.6	24.7	73
09/06/2010	32.1 ± 3.2	10.5 ± 0.5	21.6	64
07/07/2010	29.9 ± 3.0	6.2 ± 0.3	23.7	70
27/07/2010	31.6 ± 3.2	6.5 ± 0.3	25.1	74
19/08/2010	25.8 ± 2.6	5.3 ± 0.3	20.5	61
05/10/2010	13.8 ± 1.4	0.4	13.4	40
19/11/2010	22.2 ± 2.2	3.4 ± 0.2	18.8	56
27/07/2011	31.9 ± 3.2	19.4 ± 1.0	12.5	37
25/08/2011	28.7 ± 2.9	20.0 ± 1.0	8.7	26
05/09/2011	22.5 ± 2.3	15.9 ± 0.8	6.6	20
08/05/2012	21.4 ± 2.1	9.6 ± 0.5	11.9	35
14/08/2012	22.5 ± 2.3	6.8 ± 0.3	15.7	47
21/09/2012	24.6 ± 2.5	15.5 ± 0.8	9.1	27
24/10/2012	16.2 ± 1.6	5.7 ± 0.3	10.5	31
15/01/2013	18.4 ± 1.8	6.4 ± 0.3	12.0	36
14/02/2013	23.0 ± 2.3	7.5 ± 0.4	15.5	46
06/03/2013	20.7 ± 2.1	8.0 ± 0.4	12.7	38
Count	26	26	26	26
Minimum	11.9	0	6.6	19.6
Mean	26.3	8.2	18.1	53.8
Median	25.8	7.1	17.3	51.2
Maximum	43.7	20.0	32	95.0
SD	8.1	5.2	7.1	21.1
CoV (%)	31	64	39	39

(1) Based on a distance of ~3.9 km between localities

The SDM results presented in **Table 2** and **Figure 9** 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 m³/s (<389 ML/d) the entire flow of the river disappears into the subsurface.

It is notable that four of the ten measured discharges at the downstream station MRd in period 3, 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, that eight of the ten period 3 surface flow losses between stations F11S12 and MRd represent the lowest in the record of measurements since flow at station MRd was first recorded. These circumstances suggest that the absorptive capacity of the karst aquifer underlying the losing ~3.9-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.

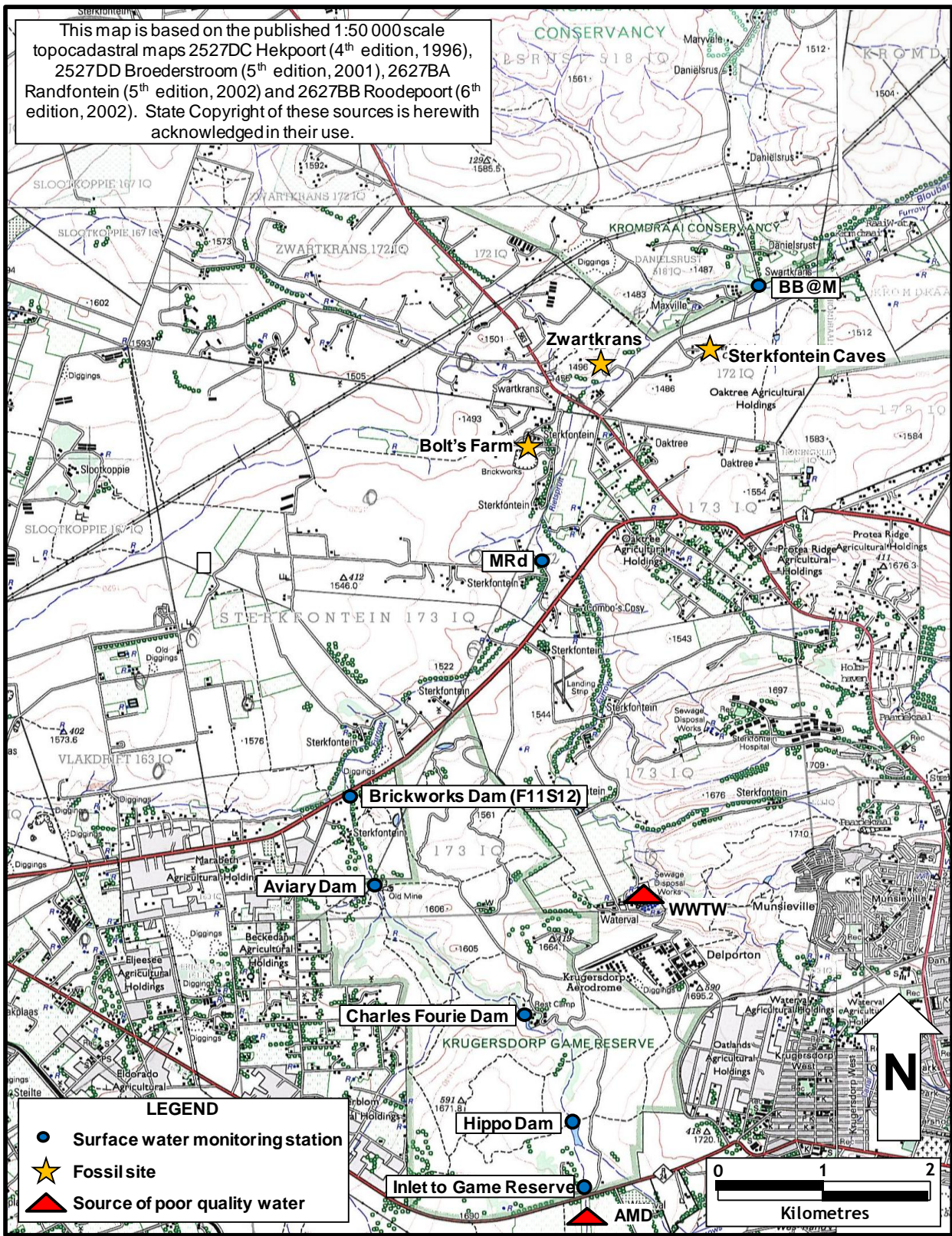


Figure 8 Locality map of surface water quantity and quality monitoring stations

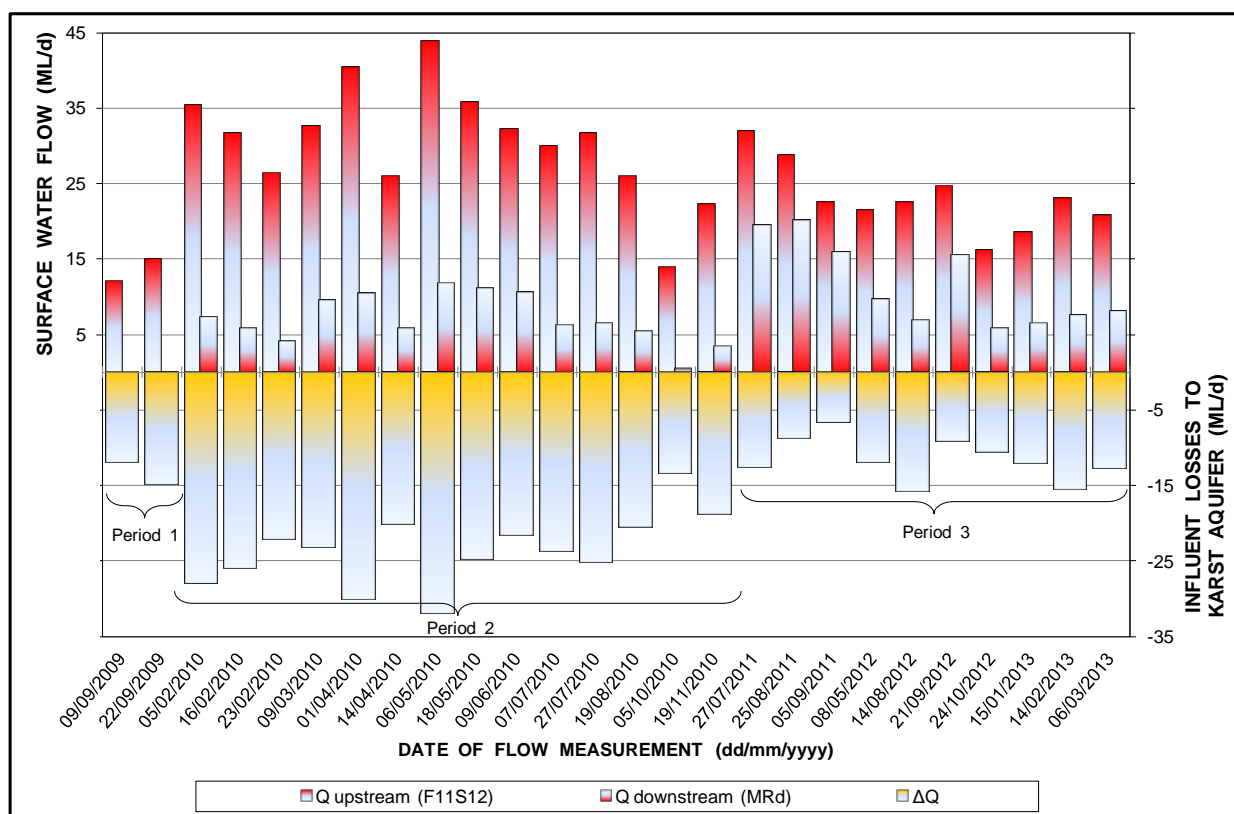


Figure 9 Graph of stream flow and losses to the karst aquifer in the lower Riet Spruit valley

Figure 9 suggests that a threshold flow value exists at station F11S12 below which all surface flow is lost to the karst aquifer, leaving the downstream station MRd dry. Conversely, flow that exceeds the threshold value at F11S12 results in surface water flow past station MRd. This observation is explored in **Figure 10**. The linear regression equation for period 2 yields a cut-off y-value of ~15 ML/d. The similar equation for period 3 returns a value of ~14 ML/d. These flows define the ‘threshold’ value range.

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 11**) 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 ferrous hydroxide crust in the stream channel sometime between 22 May 2010 and 31 March 2011 that might cause a decrease in streambed permeability.

Nevertheless, the analyses lead to the conclusion that the ‘absorptive capacity’ (and therefore also the ‘transmissive capacity’) of the epikarst along the ~3.9-km reach of the Riet Spruit between stations F11S12 and MRd, functions with 100% efficiency at discharges of up to ~15 ML/d (175 L/s). Above this ‘threshold’, the ‘absorptive capacity’ is exceeded. It is the quality of the surface water lost as allogenic recharge to the karst aquifer in the 2009–’10 and 2010–’11 hydrological years that is of particular concern. The circumstances and situation that describe this concern are evaluated and discussed in **section 5.2.3**.

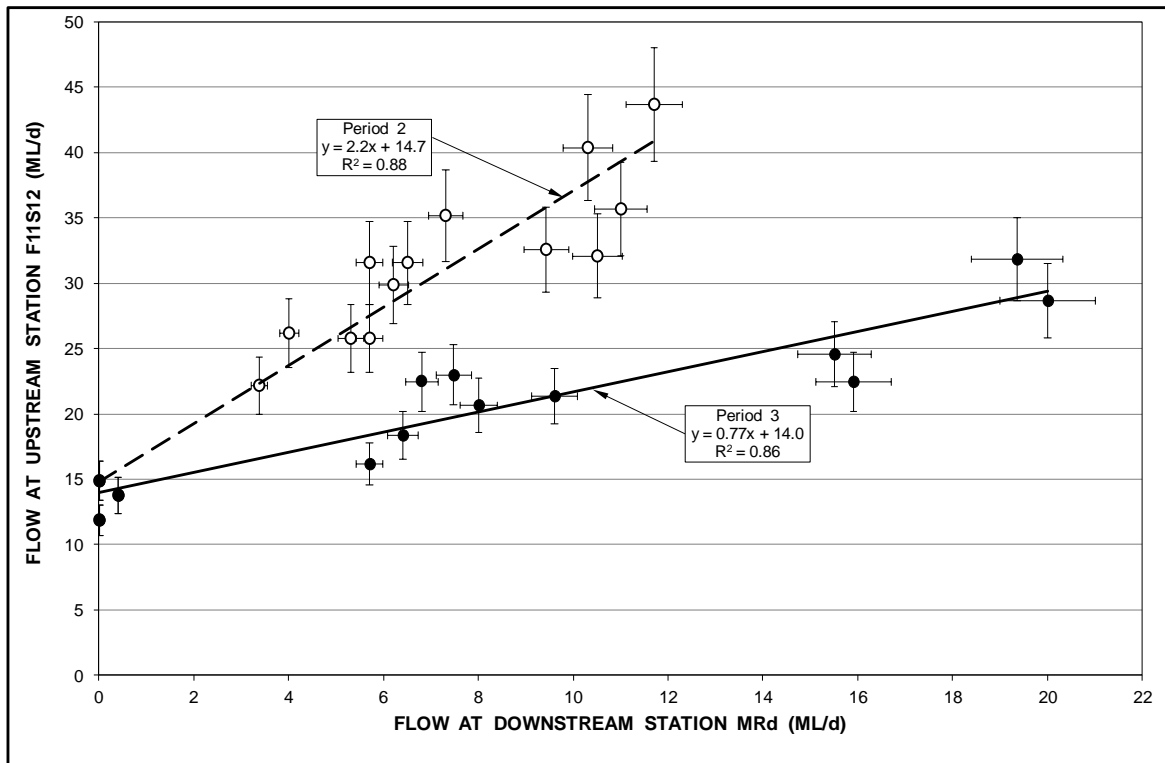


Figure 10 Correlation of stream flow at stations F11S12 and MRd in the Riet Spruit valley (respective regression lines explained in text and **Figure 9**), with error bars denoting $\pm 10\%$ at F11S12 (vertical) and $\pm 5\%$ at MRd (horizontal)

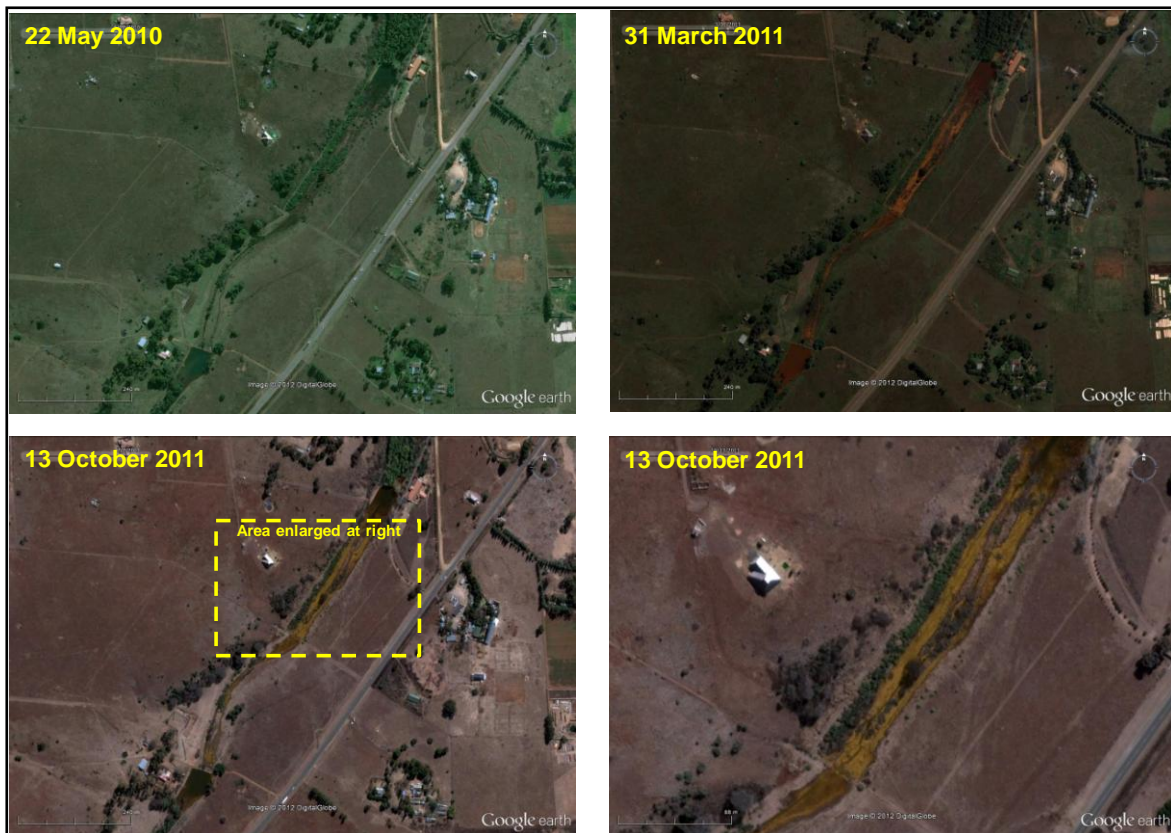


Figure 11 Historical Google Earth images showing the development of a ferrous hydroxide crust in the channel of the Riet Spruit sometime between 22 May 2010 and 31 March 2011; stream section located between stations F11S12 and MRD in **Figure 8**

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 8** 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 SO₄ dates back to May 2004. The results of this monitoring, excluding the inlet to the KGR location² and the Aviary Dam³, are presented in **Figure 12** (pH), **Figure 13** (EC) and **Figure 14** (SO₄). 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. It is clear from **Figure 12**, and to a lesser extent from **Figure 13** and **Figure 14**, 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 15**) and Mn (**Figure 16**) values. Prior to this, the gradual ‘growth’ in impact since 2004 is evidenced by the increasing EC and SO₄ trends up to the recent persistent elevated levels (**Figure 13** and **Figure 14**).

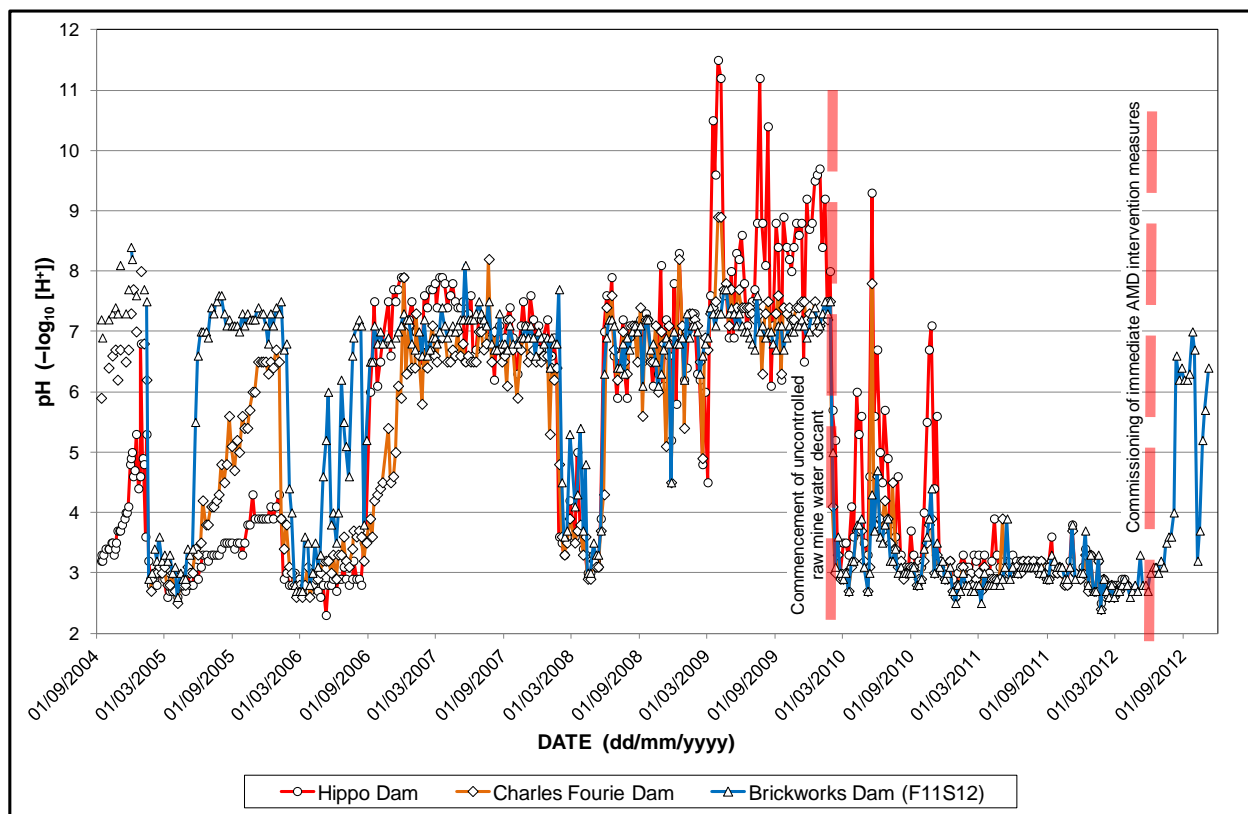


Figure 12 Pattern of pH values in the Tweelopie Spruit in the period May 2004 to October 2012

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.

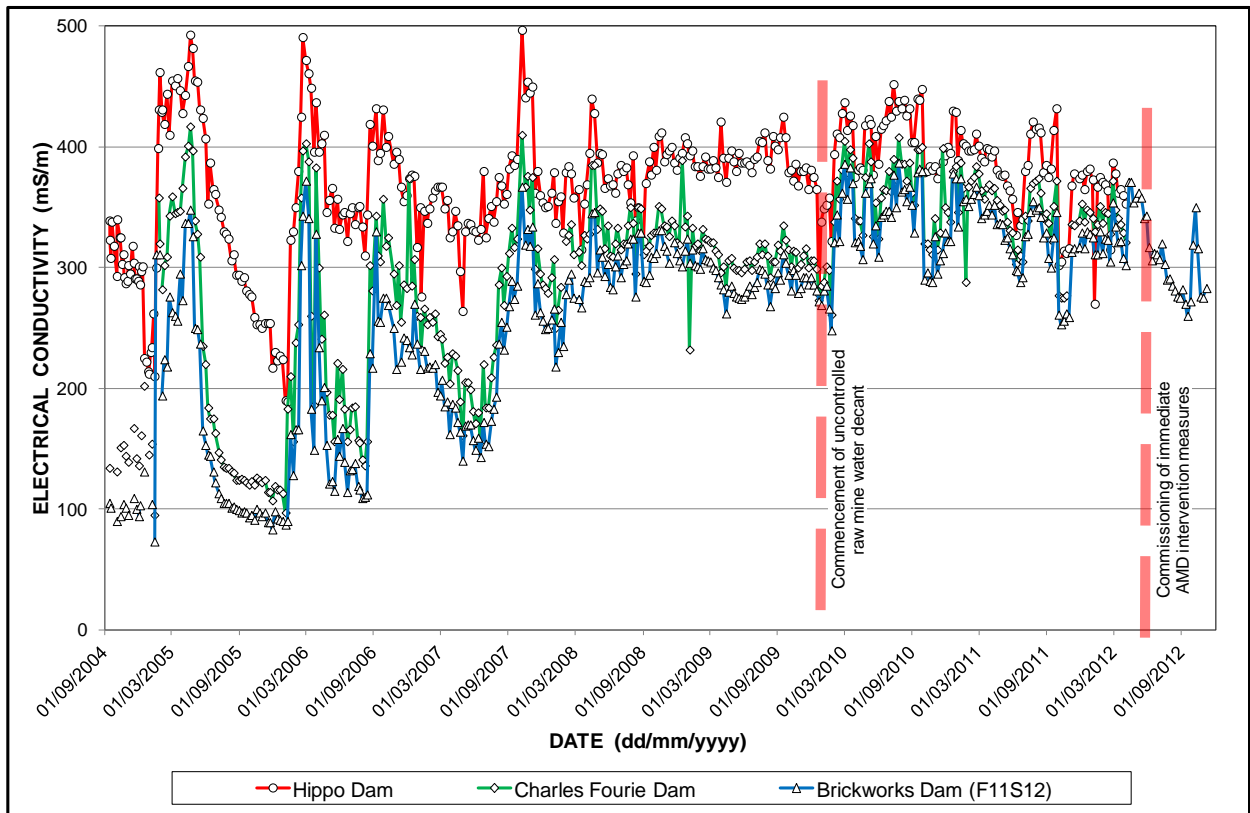


Figure 13 Pattern of electrical conductivity values in the Tweelapie Spruit in the period May 2004 to October 2012

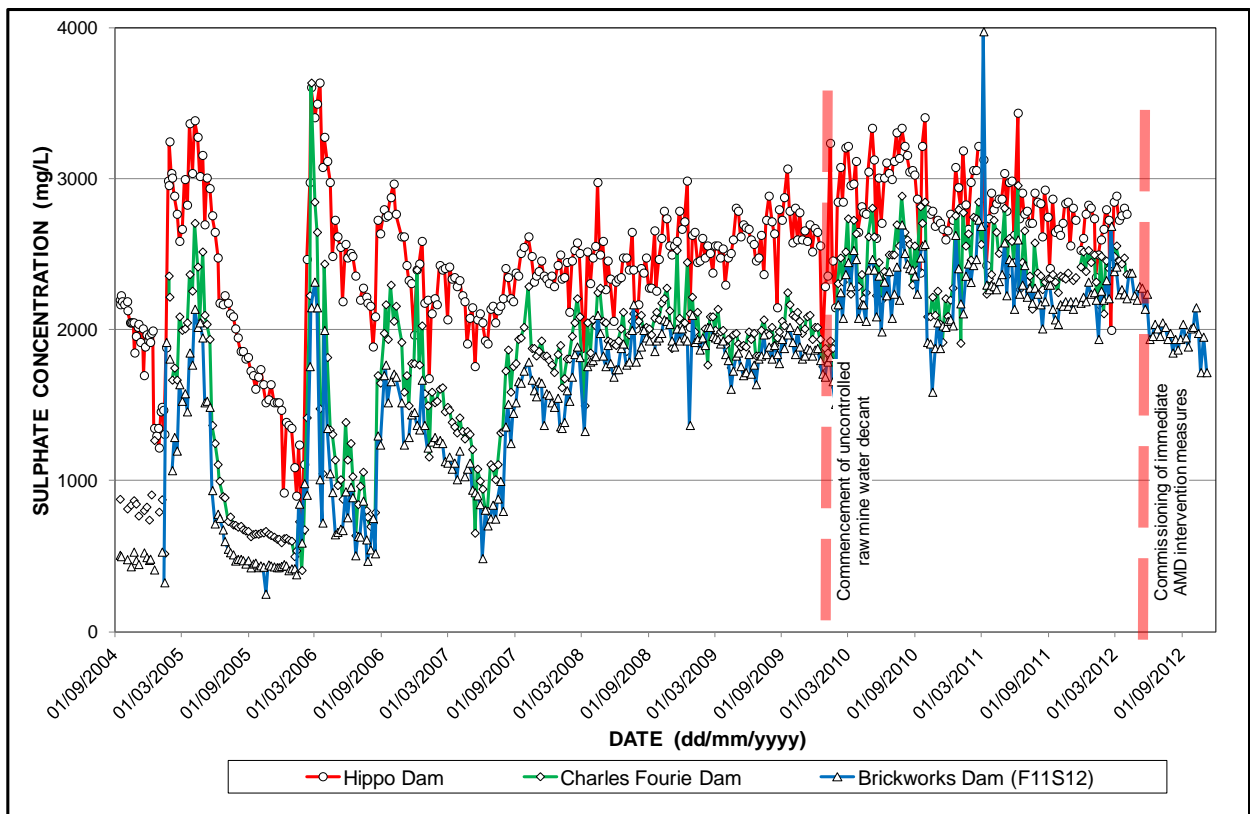


Figure 14 Pattern of SO₄ values in the Tweelapie Spruit in the period May 2004 to October 2012

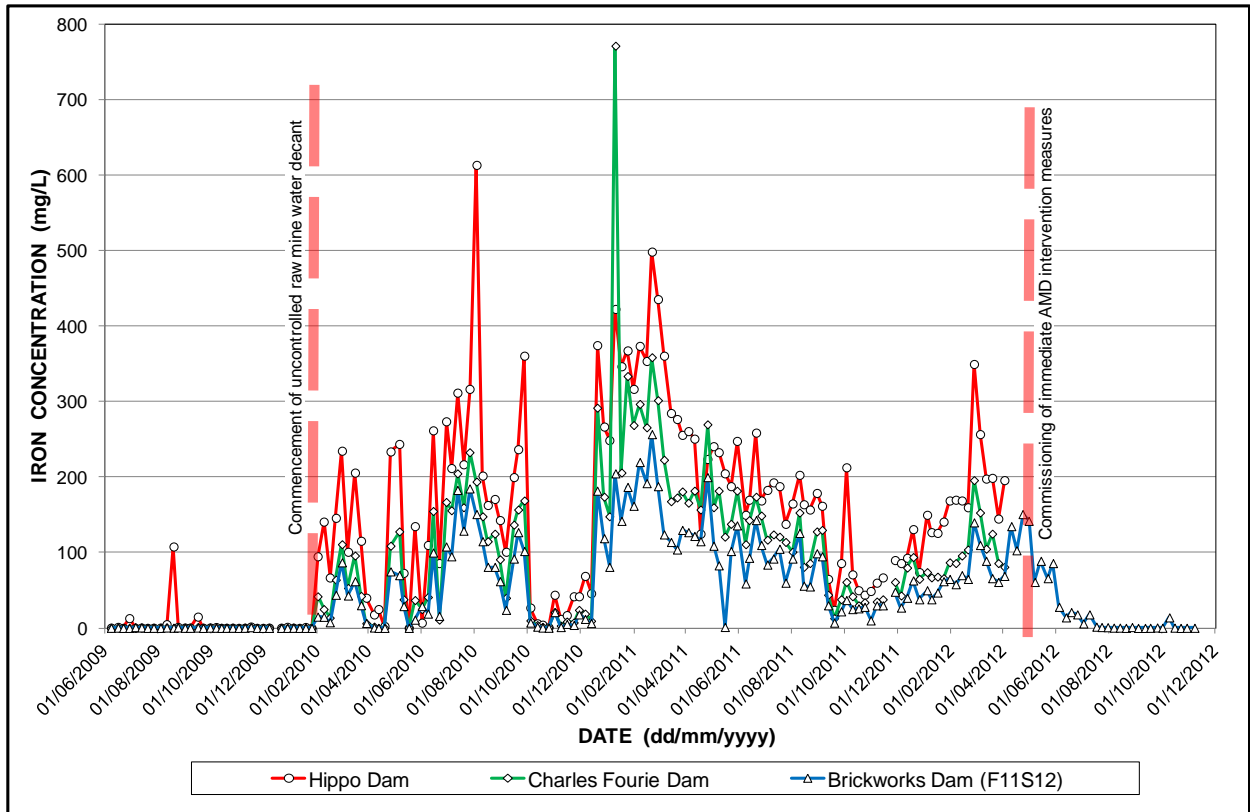


Figure 15 Pattern of Fe values in the Tweelopie Spruit in the period June 2009 to October 2012

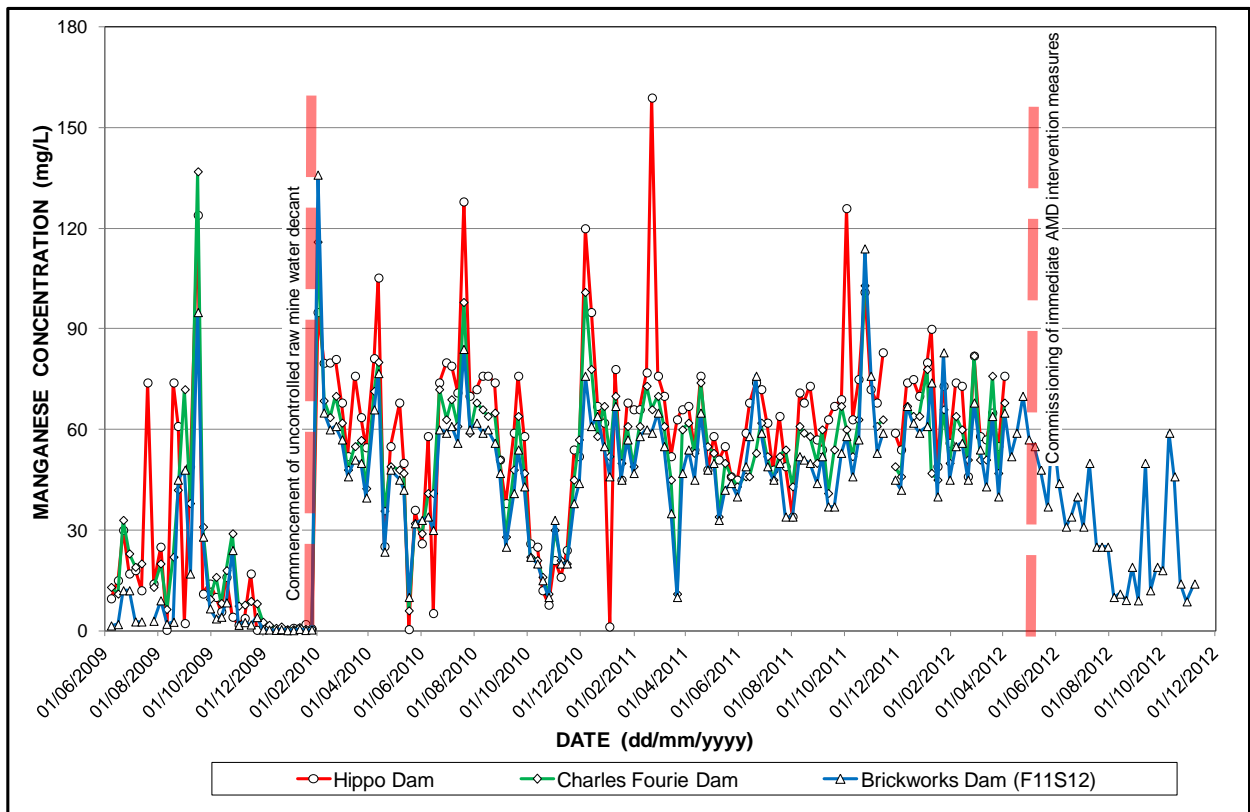


Figure 16 Pattern of Mn values in the Tweelopie Spruit in the period June 2009 to October 2012

The salinity, pH and SO₄ values measured (and derived in the case of SO₄) on the occasion of each SDM reported for stations F11S12 and MRd in **Table 3** are graphed in **Figure 17** (EC), **Figure 18** (pH) and **Figure 19** (SO₄). 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. Similarly, **Figure 19** reflects the elevated SO₄ levels (>2 000 mg/L) in this water. The correlation between EC and SO₄ derived from the large RU/G1 data set for the Brickworks Dam (F11S12) monitoring station (see **Figure 13** and **Figure 14**) allows for the derivation of SO₄ values in **Table 3**. 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 **Figure 12** to **Figure 25**. 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**).

Table 3 Record of salinity and pH measurements made at stations F11S12 and MRd on the occasion of flow gauging measurements (SDMs), also showing derived SO₄ and TDS concentrations

Date	Station F11S12				Station MRd			
	EC (mS/m)	SO ₄ ⁽¹⁾ (mg/L)	TDS ⁽²⁾ (mg/L)	pH (-log ₁₀ [H ⁺])	EC (mS/m)	SO ₄ ⁽¹⁾ (mg/L)	TDS ⁽²⁾ (mg/L)	pH (-log ₁₀ [H ⁺])
22/09/2009	322	2 089	2 479	6.7				
05/02/2010	389	2 586	2 997	3.9	358	2 358	2 759	4.1
16/02/2010	339	2 215	2 610	4.2	335	2 186	2 581	4.2
23/02/2010	379	2 510	2 918	4.1	383	2 538	2 948	3.9
09/03/2010	379	2 510	2 918	4.1	353	2 320	2 720	4.0
01/04/2010	374	2 472	2 878	3.6	358	2 358	2 759	3.4
14/04/2010	358	2 355	2 757	3.7	347	2 274	2 672	3.6
06/05/2010	408	2 724	3 142	3.2	420	2 813	3 234	3.3
18/05/2010	335	2 185	2 580	5.5	356	2 340	2 741	4.4
09/06/2010	370	2 444	2 849	4.4	373	2 466	2 872	4.5
07/07/2010	374	2 473	2 880	4.0	376	2 488	2 895	3.9
27/07/2010	407	2 717	3 134	3.7	395	2 628	3 042	4.1
19/08/2010	384	2 547	2 957	2.6	335	2 185	2 580	2.7
05/10/2010	307	1 979	2 364	3.0	383	2 540	2 949	2.5
19/10/2010	314	2 030	2 418	3.6	326	2 119	2 510	3.1
19/11/2010	338	2 207	2 603	2.8	333	2 171	2 564	2.8
18/12/2010	416	2 783	3 203	2.7	376	2 488	2 895	3.0
27/07/2011	369	2 436	2 841	2.7	373	2 466	2 872	2.9
25/08/2011	389	2 584	2 995	2.9	405	2 702	3 119	2.5
05/09/2011	362	2 385	2 787	2.6	367	2 421	2 826	2.6
08/05/2012	372	2 458	2 864	2.6	388	2 576	2 988	2.9
14/08/2012	299	1 920	2 302	6.3	309	1 993	2 379	4.2
21/09/2012	290	1 853	2 233	7.6	288	1 838	2 218	6.9
24/10/2012	264	1 661	2 033	4.3	270	1 706	2 079	3.8
15/01/2013	282	1 794	2 171	6.6	283	1 802	2 179	4.9
14/02/2013	274	1 735	2 110	7.0	277	1 757	2 133	6.4
06/03/2013	244	1 514	1 879	6.9	241	1 492	1 856	6.6
Count	26	26	26	26	26	26	26	26
Minimum	244	1 514	1 879	2.6	241	1 492	1 856	2.5
Mean	347	2 272	2 670	4.2	346	2 270	2 668	3.9
Median	366	2 410	2 814	3.8	357	2 349	2 750	3.9
Maximum	416	2 783	3 203	7.6	420	2 813	3 234	6.9
SD	48	356	371	1.5	45	334	348	1.2
CoV (%)	14	16	14	37	13	15	13	31

(1) $SO_4 = 7.38 * EC - 287$ to derive a theoretical representative SO₄ value

(2) $EC * 7.7$ to derive a theoretical representative TDS value

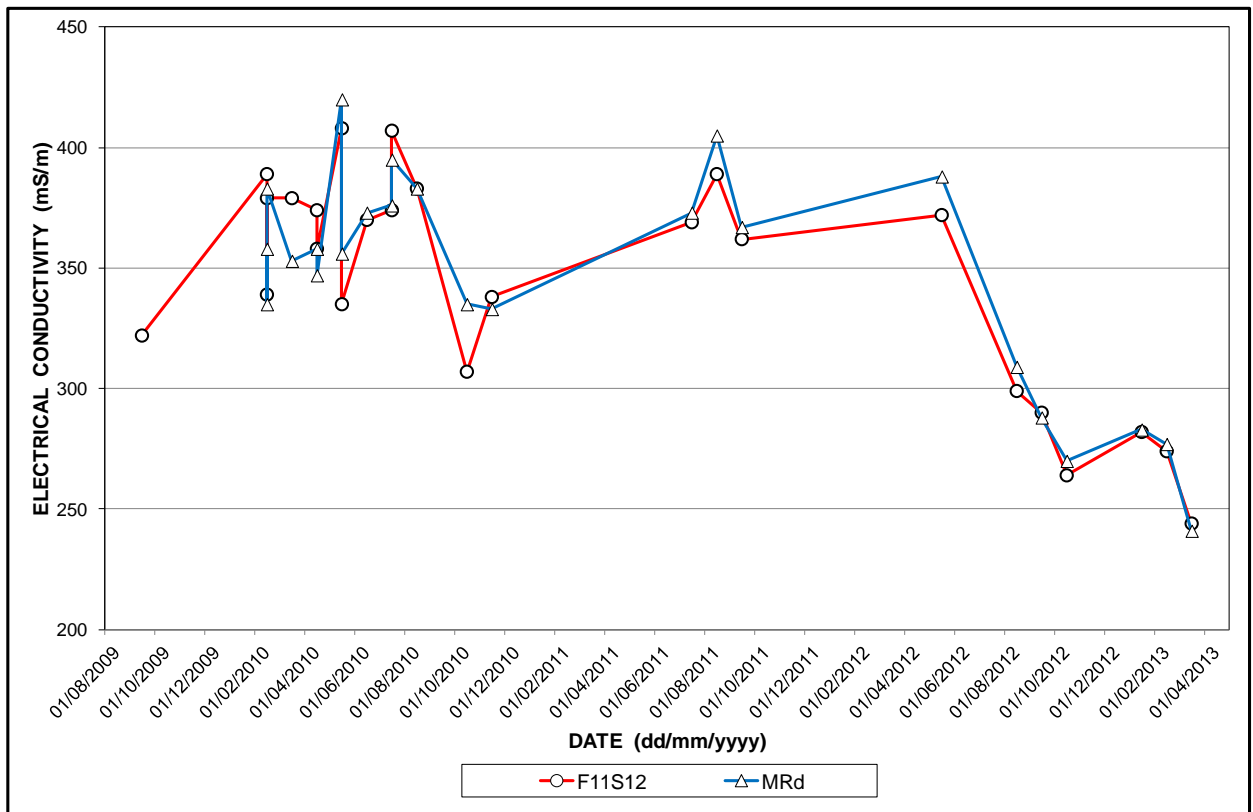


Figure 17 Pattern and trend of electrical conductivity of surface water at stations F11S12 and MRd on occasion of the SDMs reported in **Table 3**

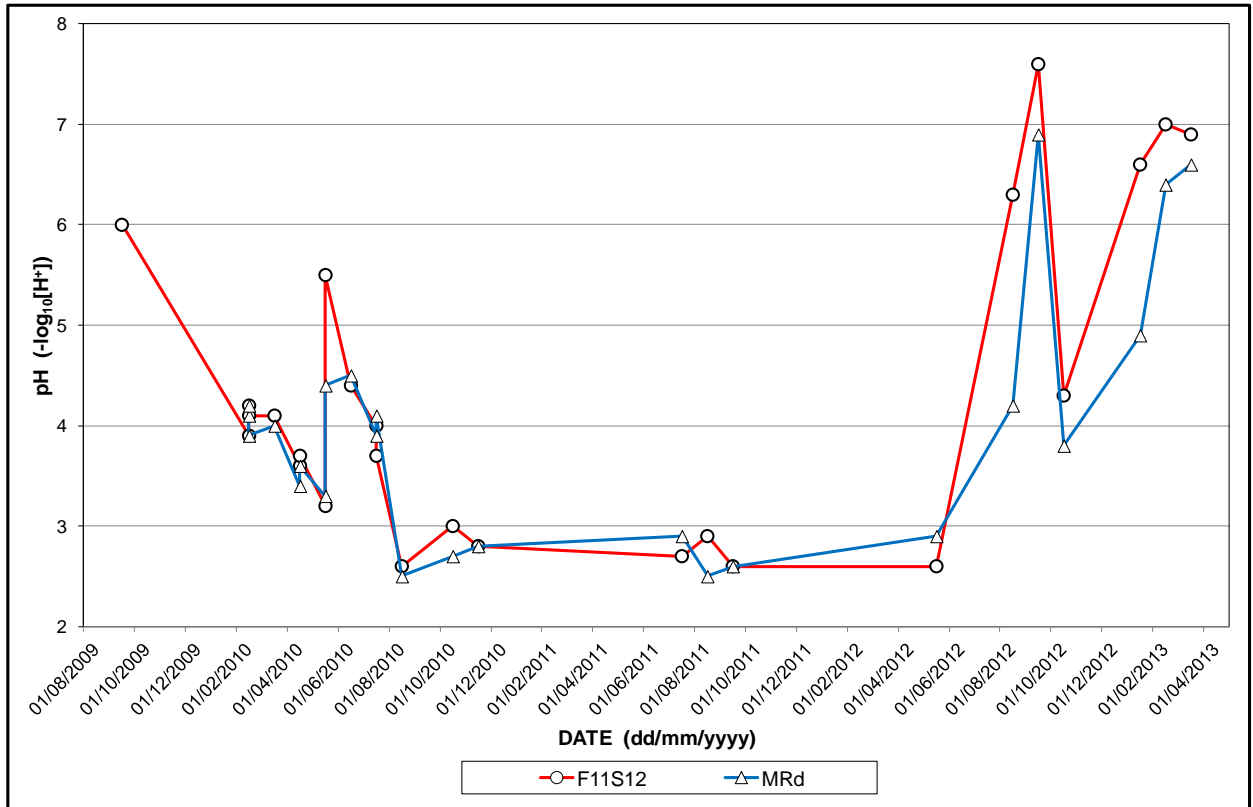


Figure 18 Pattern and trend of pH of surface water at stations F11S12 and MRd on occasion of the SDMs reported in **Table 3**

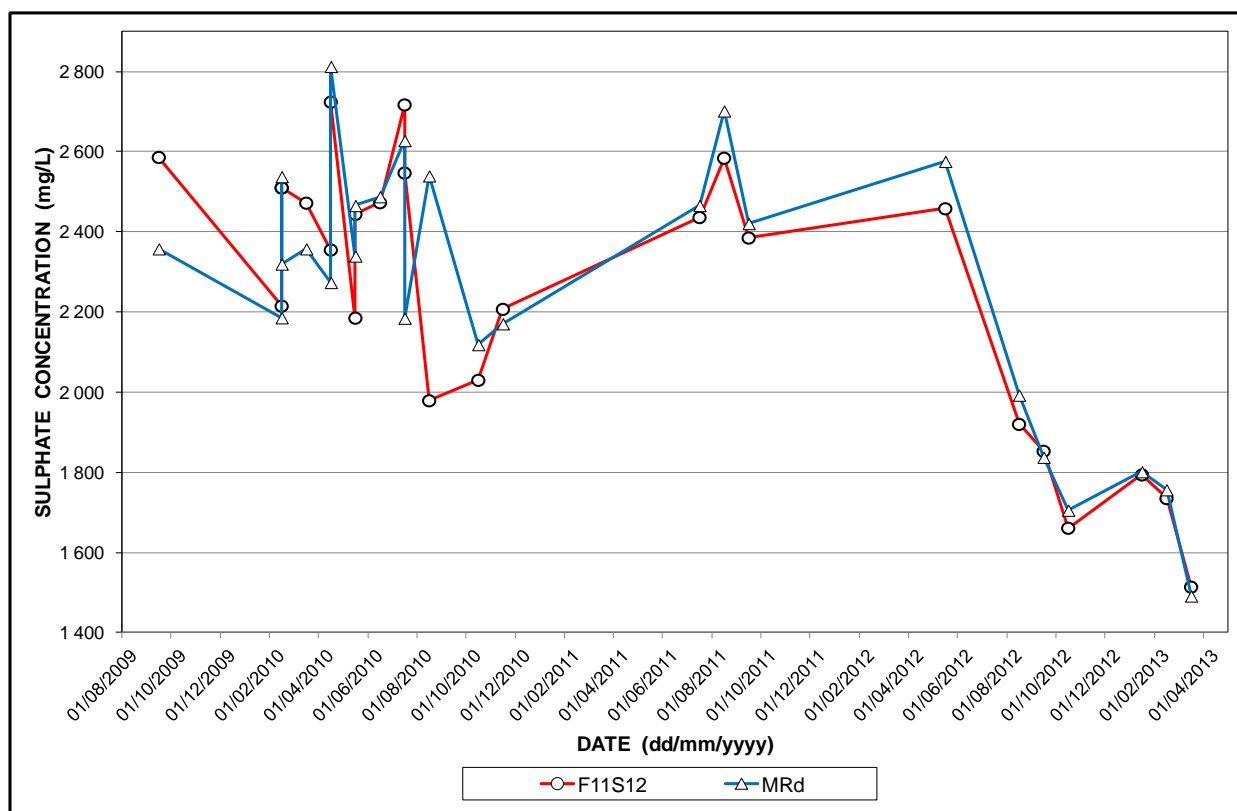


Figure 19 Pattern and trend of SO_4 in surface water at stations F11S12 and MRd on occasion of the SDMs reported in **Table 3**

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 4**. 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 4** 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 20a**) reflects the significant contribution of dolomitic groundwater discharged from the karst aquifer in this catchment. The data reveal very little difference between the whole record (**Figure 20a**) and the pre-decant period (**Figure 20b**). The decant period, however, reflects notable increases in the median Na and Cl concentrations (**Figure 20c**) 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 20c**) compared to the pre-decant period. This variability increases even more in the period of greatest impact, i.e. since October 2009 (**Figure 20d**). Slight changes in the Ca and Mg values between the pre-decant and the decant periods are also apparent. Further inspection of the long-term water quality record is premised on three periods of observation, namely May 1979 to September 2002 (**Figure 20b**), October 2002 to August 2012 (**Figure 20c**), and October 2009 to August 2012 (**Figure 20d**). 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.

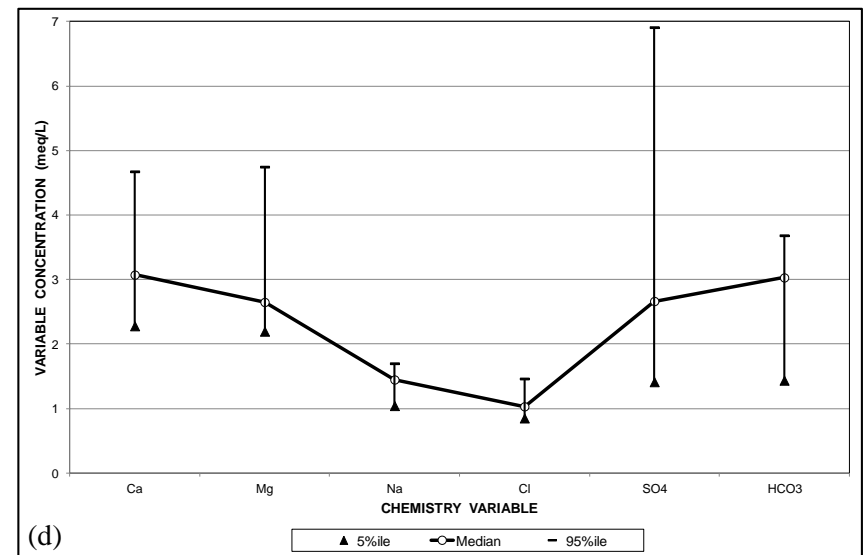
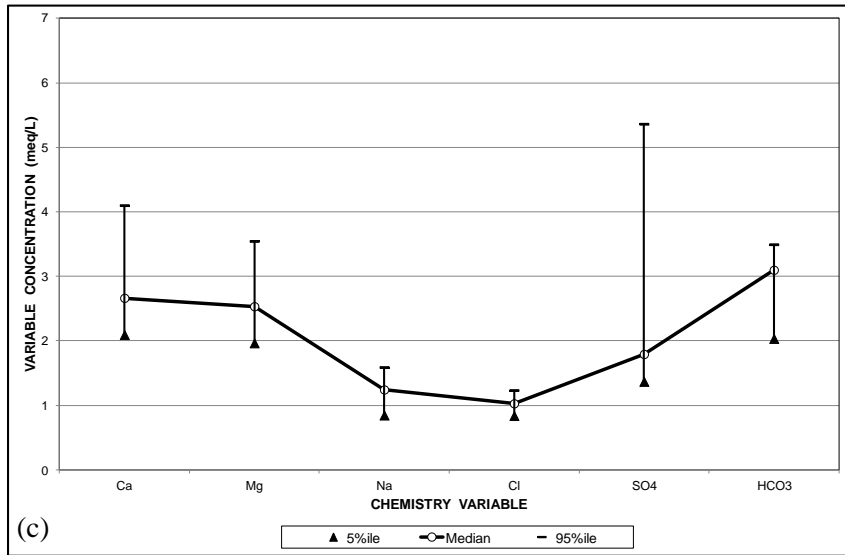
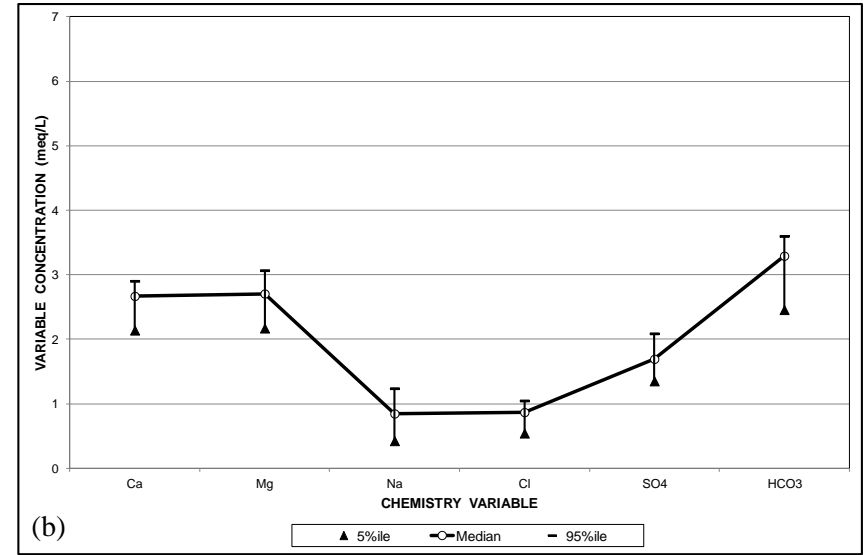
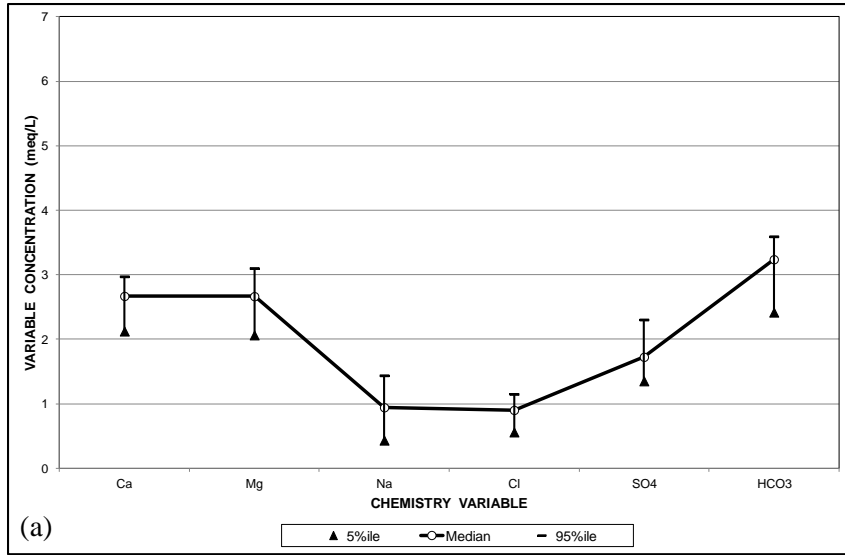


Figure 20 Variability of Bloubank Spruit water major ion chemistry recorded at DWA station A2H049 for (a) the period May 1979 to August 2012, (b) the period May 1979 to September 2002, (c) the period October 2002 to August 2012, and (d) the period October 2009 to August 2012

Table 4 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	1 045	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)

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 21**. The shift to the apex of the central diamond field represented by the Ca-SO₄ composition of the February 2011 chemistry is countered by the return to a more ‘normal’ pre-2009–’10 chemistry in January 2012.

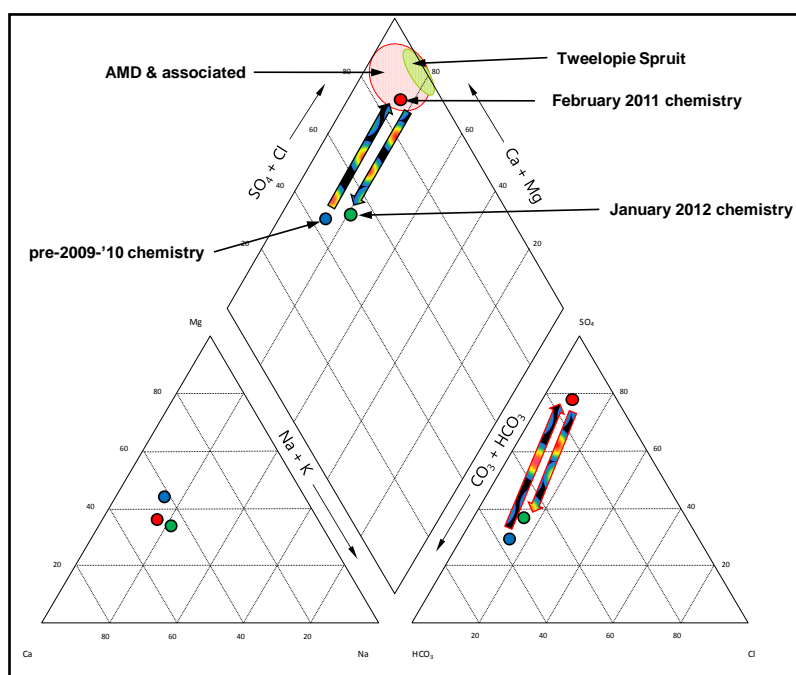


Figure 21 Piper diagram of pre-2009–’10 and more recent Bloubank Spruit water chemistry at station A2H049

The surface water quality monitoring carried out at the Nedbank Olwazini Estate complex (station NOE in **Figure 22**) provides a valuable ‘reference’ of bacteriological water quality in the lower reaches of the Bloubank Spruit. This is particularly relevant under circumstances where discharge quality data for the Mogale City Local Municipality (MCLMs) Percy Stewart Wastewater Treatment Works (WWTW) and the DWAs water quality data for upstream monitoring stations are unavailable. The NOE monitoring has further significance for its location in proximity to where the Bloubank Spruit drainage leaves the dolomitic environment and traverses older strata down to its confluence with the Crocodile River. Unlike the water chemistry record for station A2H049, therefore, the NOE water chemistry record represents almost exclusively that of water which drains the karst portion of the catchment, discounting the ephemeral discharge of the Honingklip Spruit tributary.

The pH values and nutrient (NO₃-N, PO₄-P and COD) and bacterial concentrations in Bloubank Spruit water at the upstream and downstream ends of the NOE complex in the period January 2009 to January 2013 (4 years) are given in **Table 5**. The temporal pattern of the nutrient and bacterial variables is illustrated in **Figure 23**.

It is concerning that the faecal coliform count as far downstream as the NOE property continues to reflect elevated concentrations even at the 1%ile level (**Table 5**). The association of higher faecal coliform concentrations with rainfall is evident in **Figure 23d**. This observation suggests that significant municipal wastewater impacts on surface water bacteriological quality are driven by rainfall.

The mean and median faecal coliform values of 617 and 320 cfu/100 mL respectively (**Table 5**), are compared to February 2013 *E. coli* levels of 980 and 1 553 MPN/100 mL obtained at the stations BG@N14 and BB@M located further upstream (**Figure 22**). The lower NOE values fit the decreasing pattern associated with ‘distance from source’ reported by Hobbs (2011a). Nevertheless, the results indicate a severe non-conformance of faecal coliforms (and therefore almost certainly also *E. coli*) in regard to potable, animal and recreational use at the NOE position in the Bloubank Spruit system. This situation undoubtedly worsens progressively with distance upstream.

Table 5 Analysis of Bloubank Spruit water nutrient and bacterial content at the NOE property for the period January 2009 to January 2013

Variable	Statistical Parameter								SANS (2011a) ⁽¹⁾	TWQR ⁽²⁾ TWQR ⁽³⁾
	n	1%ile	5%ile	Mean	Median	95%ile	SD	CoV (%)		
pH ⁽⁴⁾ (-log ₁₀ [H ⁺])	45	—	7.5	—	8.1	8.6	0.3	4	5.0–9.7	—
NO ₃ (mg N/L)	45	—	4.0	7.8	7.1	14.7	3.3	43	<11	—
O-PO ₄ (mg P/L)	45	—	0.1	0.4	0.3	0.8	0.3	72	n.s.	—
COD (mg/L)	37	—	9	64	53	174	51	80	n.s.	—
Faecal coliforms (cfu/100 mL)	45	38	53	617	320	1 878	909	147	≤10 in 1% of samples	<200 ⁽²⁾ <130 ⁽³⁾

(1) Standard health-related limit for consumption of 2 L/d over 70 years by a 60 kg person

(2) Target Water Quality Range for livestock watering as per DWAF (1996a)

(3) Target Water Quality Range for recreational water use as per DWAF (1996b)

(4) Laboratory values

Bold text denotes value exceeds standard limit as described in note (1)

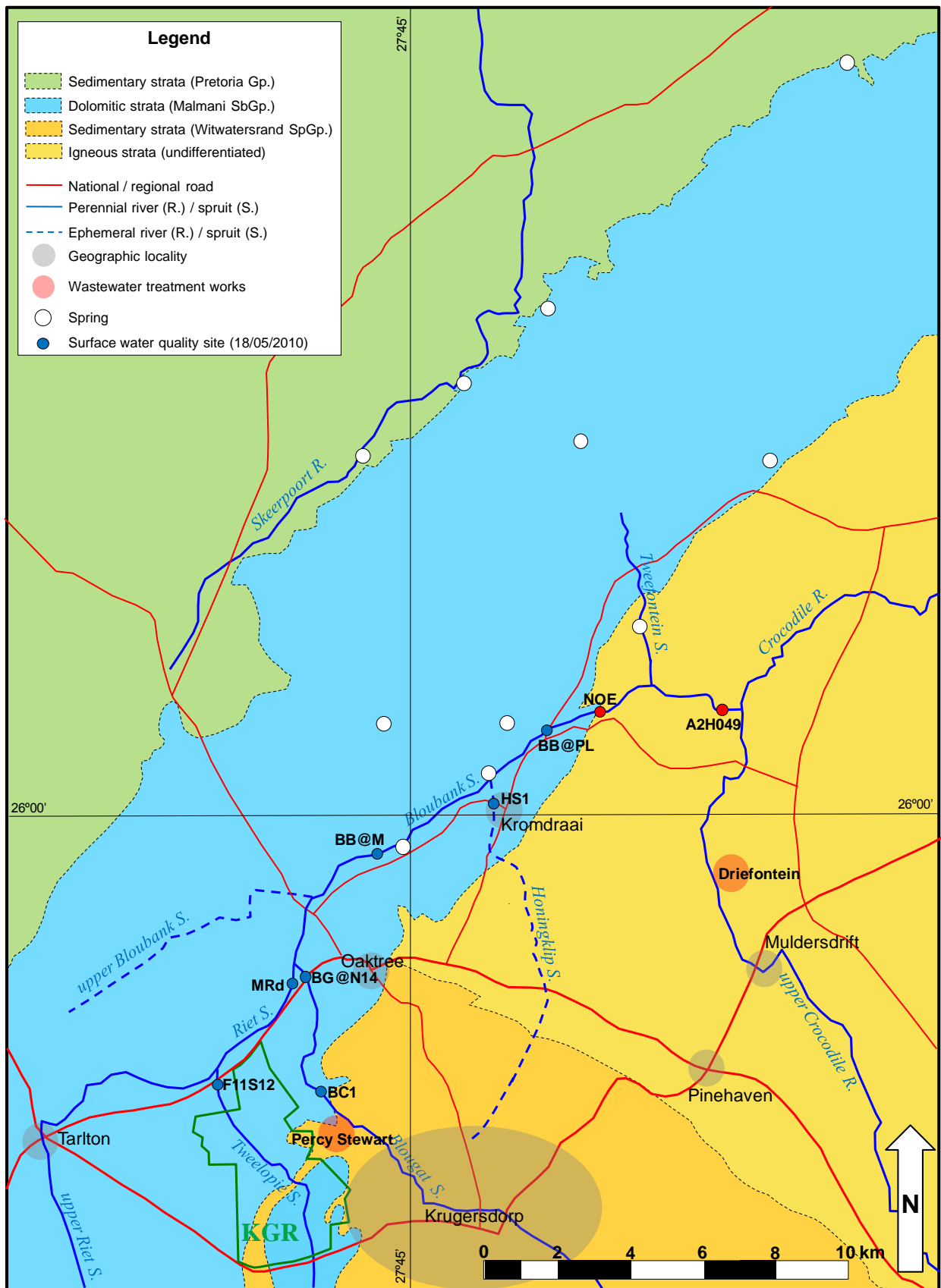


Figure 22 Surface water quality sampling sites in the study area

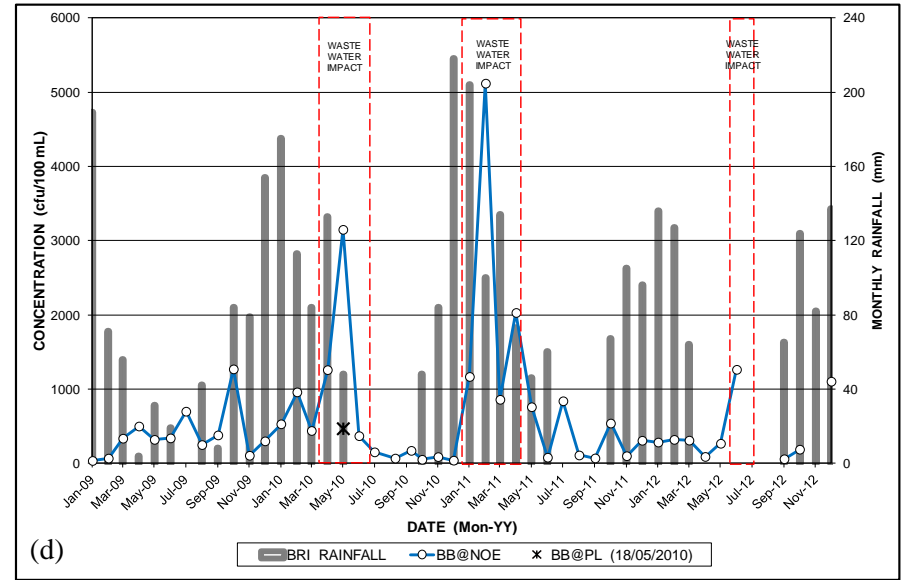
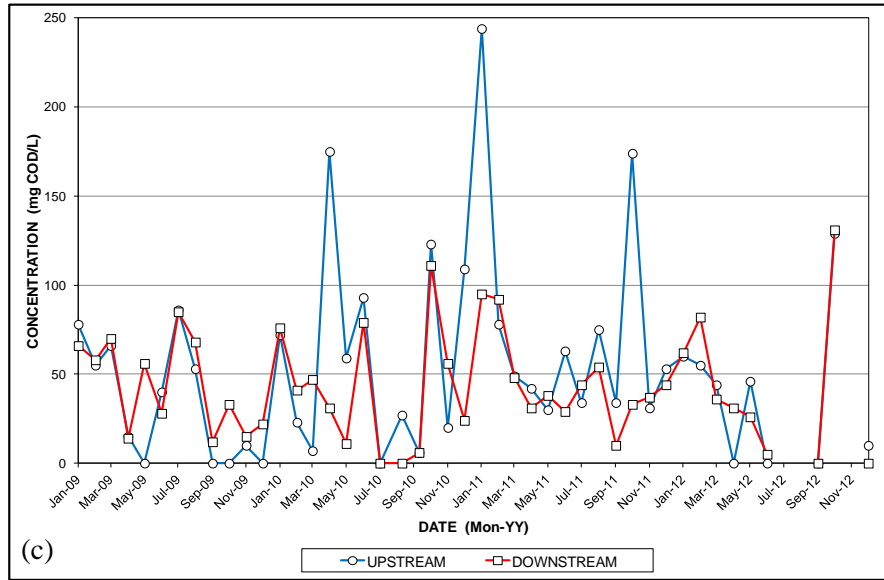
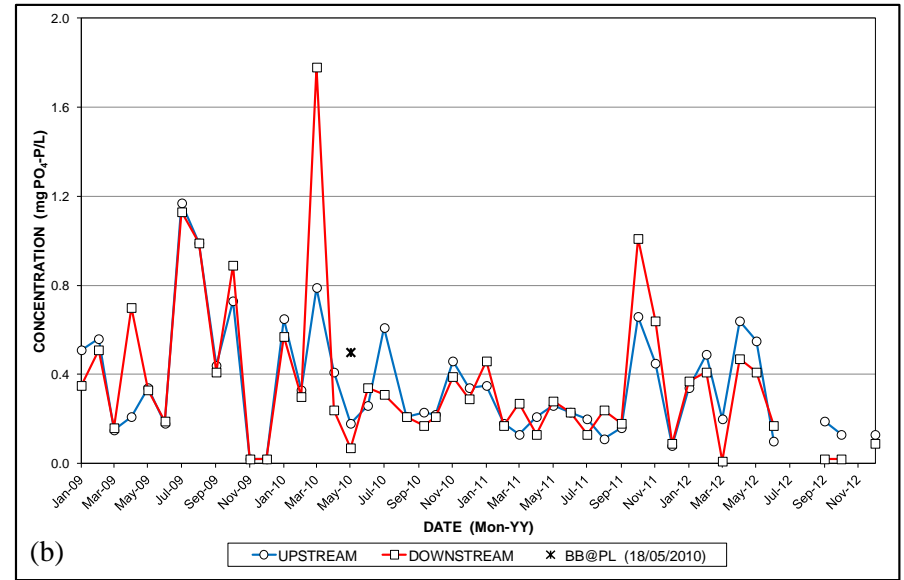
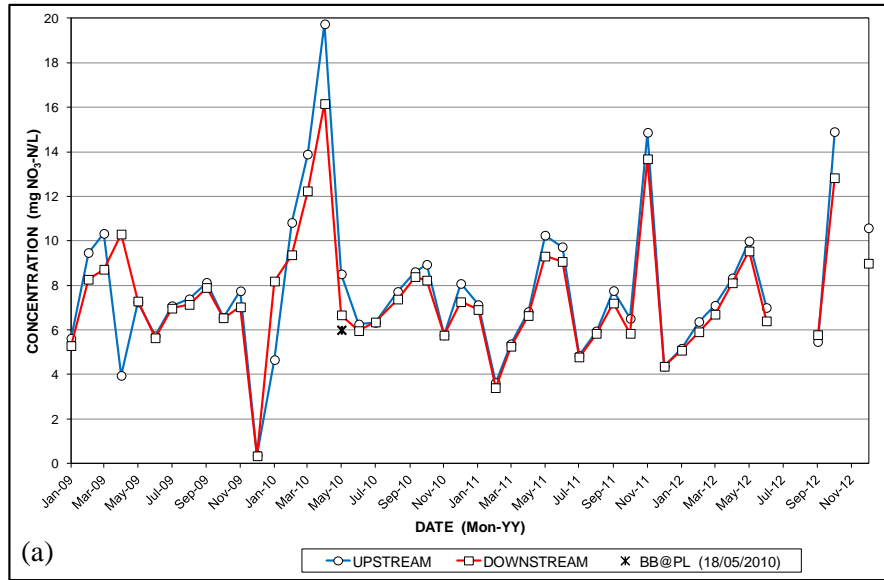


Figure 23 Recent temporal pattern of (a) NO₃-N, (b) PO₄-P, (c) COD and (d) faecal coliforms in Bloubank Spruit water at the Nedbank Olwazini Estate

4.3 Salt Load

4.3.1 Riet Spruit

The TDS and SO₄ loads lost to the karst aquifer between stations F11S12 and MRd are illustrated in **Figure 24** and **Figure 25**.

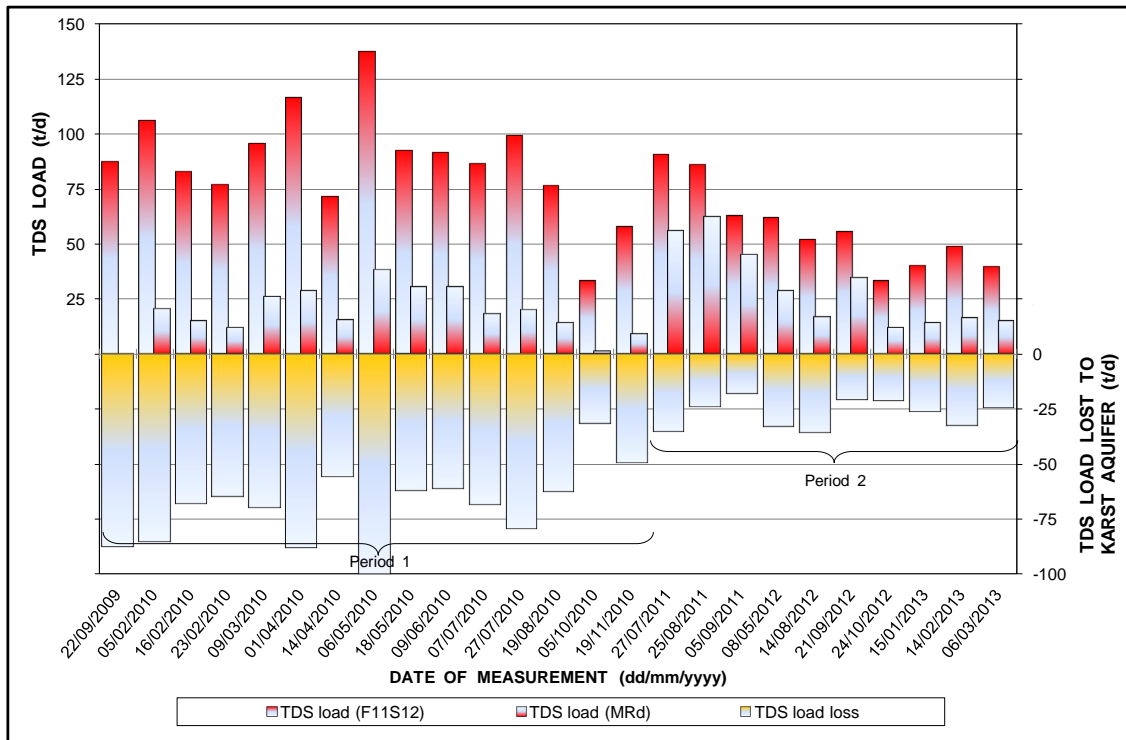


Figure 24 Bar graph of surface water TDS load loss to groundwater in the lower reach of the Riet Spruit

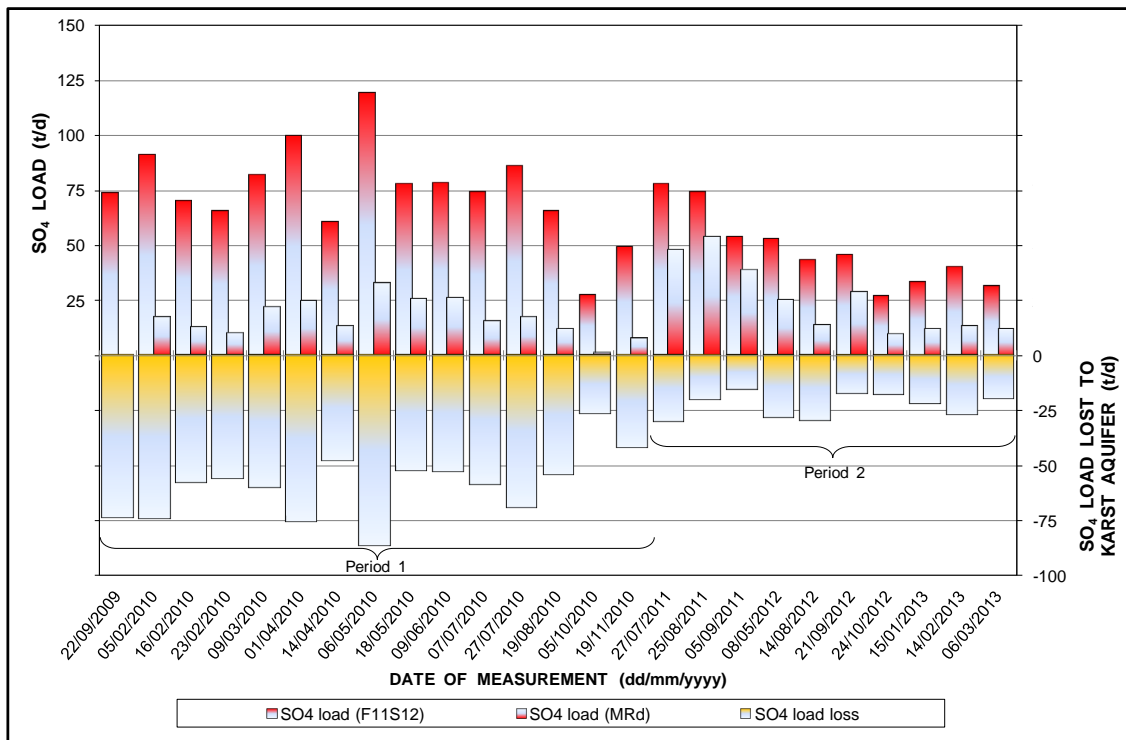


Figure 25 Bar graph of surface water SO₄ load loss to groundwater in the lower reach of the Riet Spruit

The concern previously expressed for the quality of the water entering the karst aquifer is echoed in the median TDS and SO₄ loads of ~56 and ~48 t/d, respectively, associated with this allogenic recharge. These values represent ~70% of the load in surface water entering the stream reach at station F11S12.

4.3.2 Bloubank Spruit

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 26**, and for sulphate (SO₄) in **Figure 27**. The ratio of SO₄ to TDS illustrated in **Figure 28** 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 26**) and upper reach of the Crocodile River (**Figure 29**) 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 26** 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 SO₄ load delivered by the Bloubank Spruit (**Figure 27**) mimics the TDS load pattern (**Figure 26**) in the most recent period of record. This is unsurprising under circumstances where SO₄ comprises ~62% of the major ion concentration in mine water.

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 SO₄:TDS ratio at station A2H049. This is illustrated in **Figure 28** for the long-term record, and in **Figure 31** for the period since the start of decant.

The closer inspection in **Figure 30** and **Figure 31** of the SO₄ 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 SO₄ (>150 mg/L) and SO₄:TDS (>30) values, indicates a rising trend in both instances. These trends indicate that SO₄ 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 28**.

A possible explanation for the 1986–2001 trend is the greater contribution of dolomitic groundwater, typically very low in SO₄, draining from the Zwartkrans and Krombank compartments following the breaking of the drought that characterised the early 1980s. The preceding (1979–1985) rising SO₄ trend (**Figure 28**) 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.

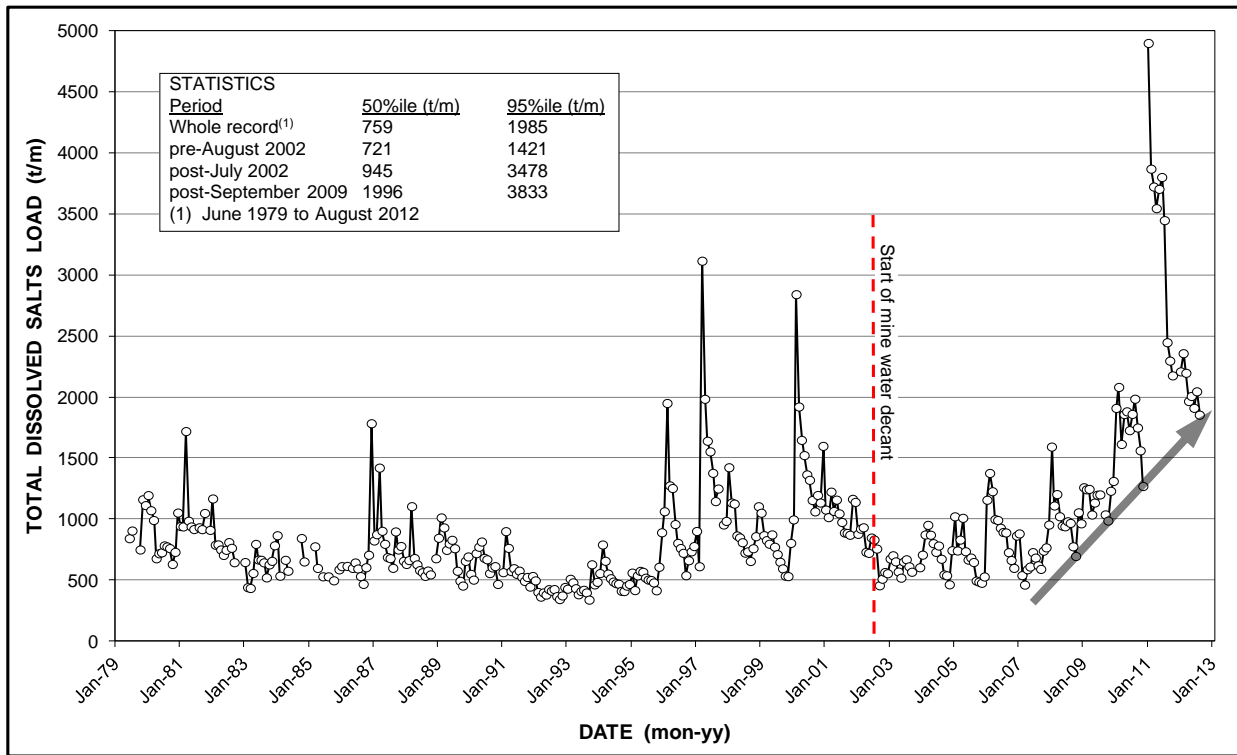


Figure 26 Long-term (June 1979 to August 2012) monthly TDS load pattern and trend in the Bloubank Spruit at DWA station A2H049

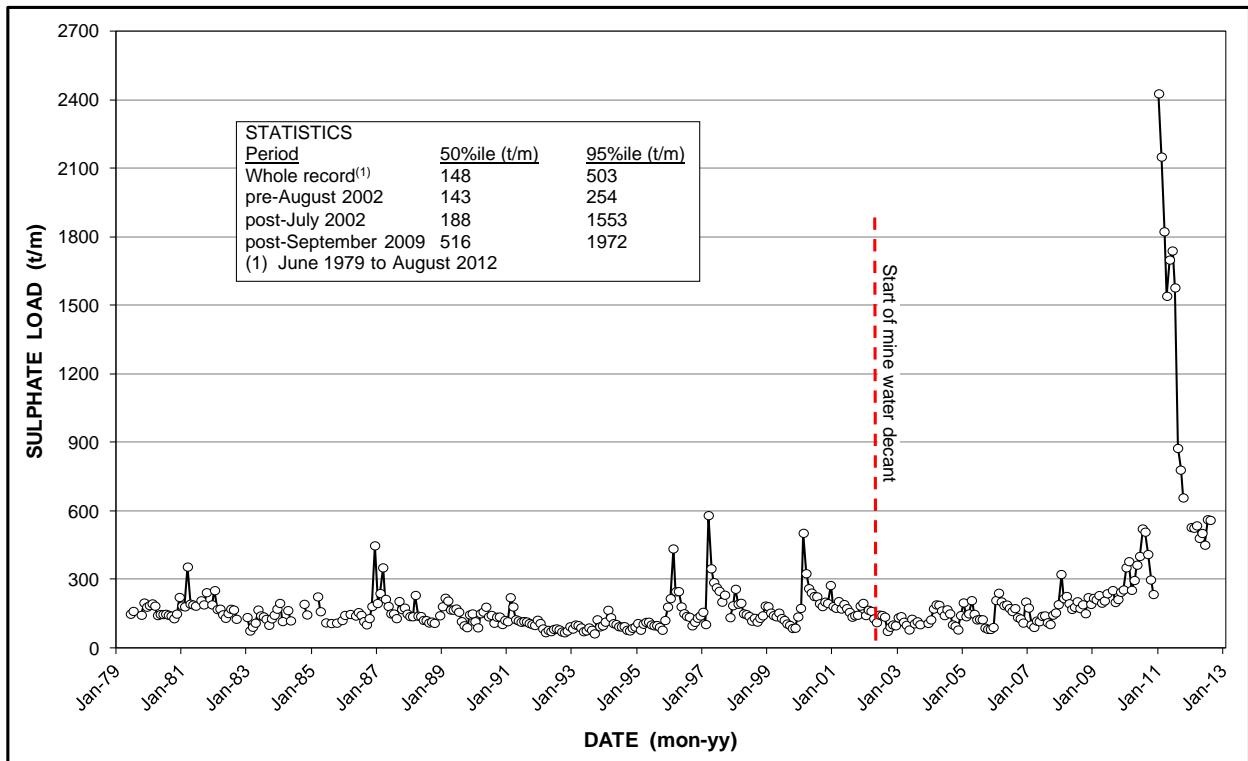


Figure 27 Long-term (June 1979 to August 2012) monthly SO₄ load pattern and trend in the Bloubank Spruit at DWA station A2H049

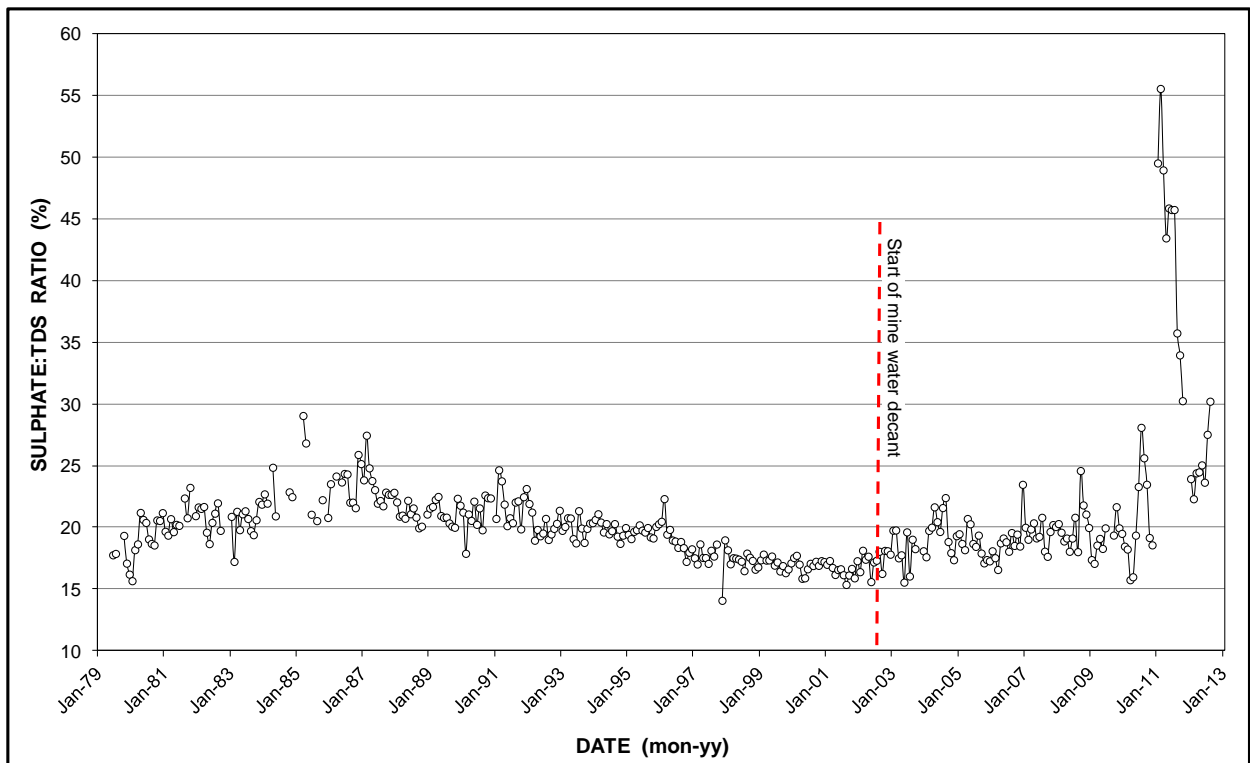


Figure 28 Long-term (June 1979 to August 2012) trend in the SO_4 :TDS ratio at station A2H049

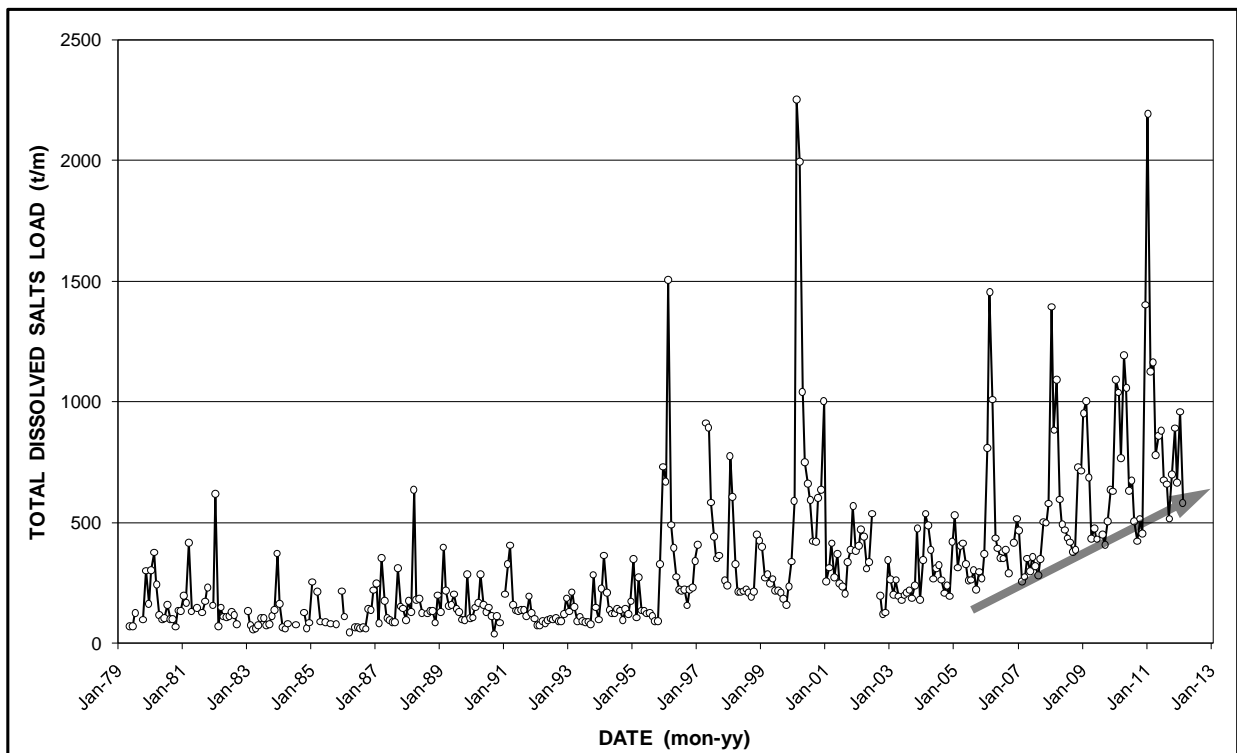


Figure 29 Long-term (May 1979 to August 2012) monthly TDS load pattern and trend in the upper reach of the Crocodile River at DWA station A2H050

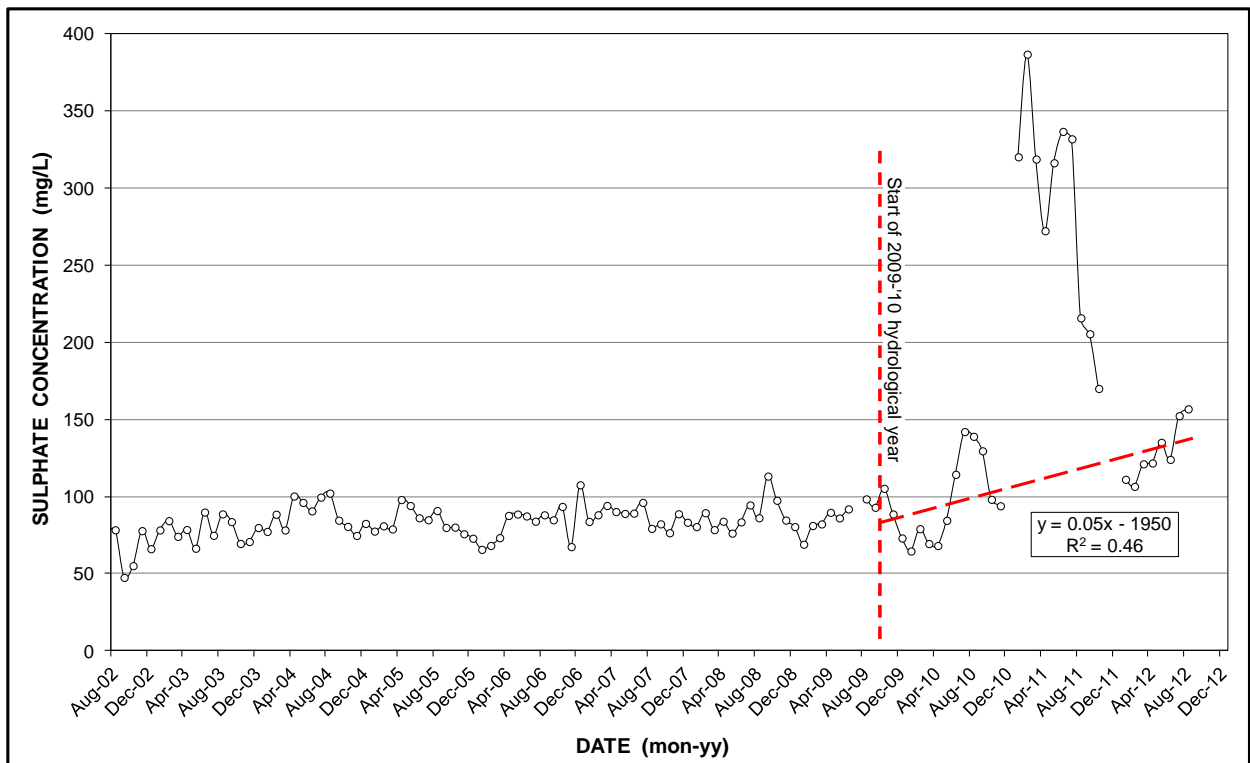


Figure 30 Pattern and trend in the SO₄ concentration at station A2H049 since the start of mine water decant in the Western Basin

The SO₄ concentration in the surface water passing station A2H049 (**Figure 30**) shows a return to the recent gradually rising trend since the start of the 2009–’10 hydrological year.

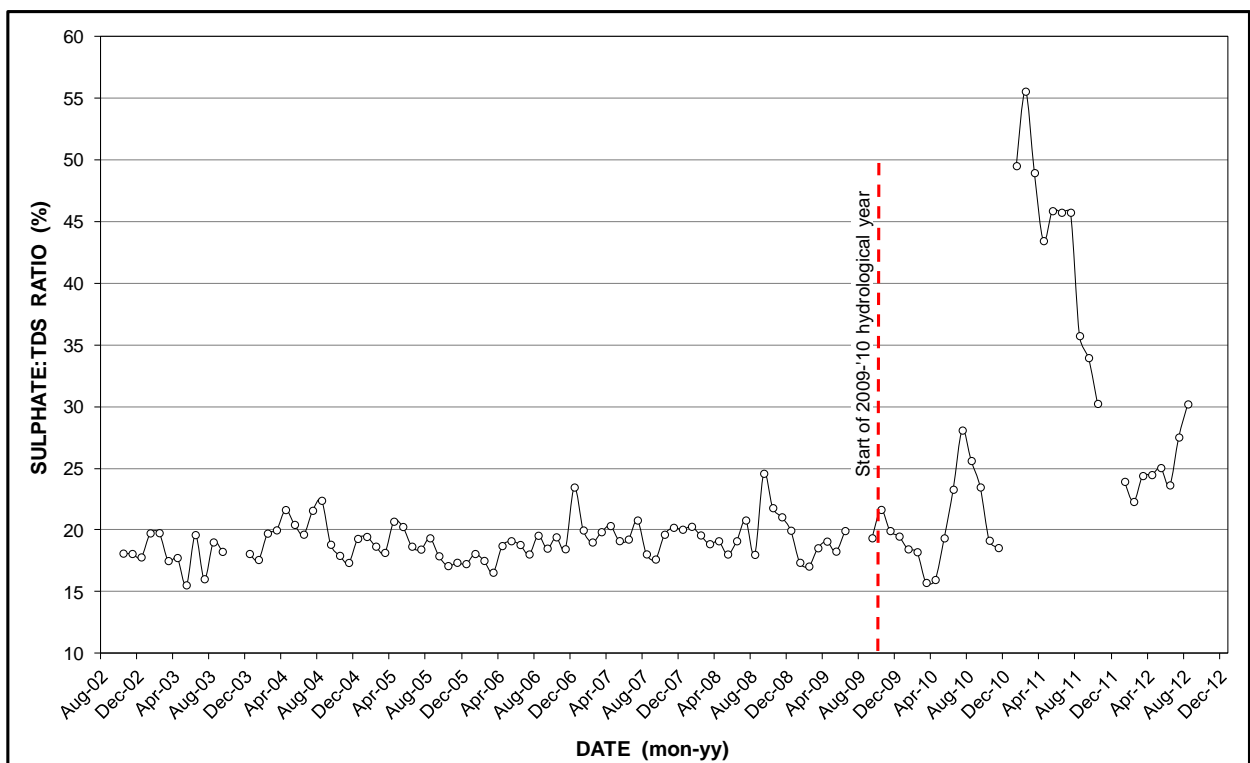


Figure 31 Pattern and trend in the SO₄:TDS ratio at station A2H049 since the start of mine water decant in the Western Basin

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. Even more recent values of 90 mS/m on 24 October 2012, 93 mS/m on 14 February 2013 and 91 mS/m on 6 March 2013 measured at this location (station BB@M in **Figure 8**) lend further corroboration of this observation.

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 SO₄ loads delivered by the Bloubank Spruit system is attempted in **Figure 32** and **Figure 33**. The cumulative TDS load (**Figure 32**) 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 SO₄ load (**Figure 33**), 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 SO₄) 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.

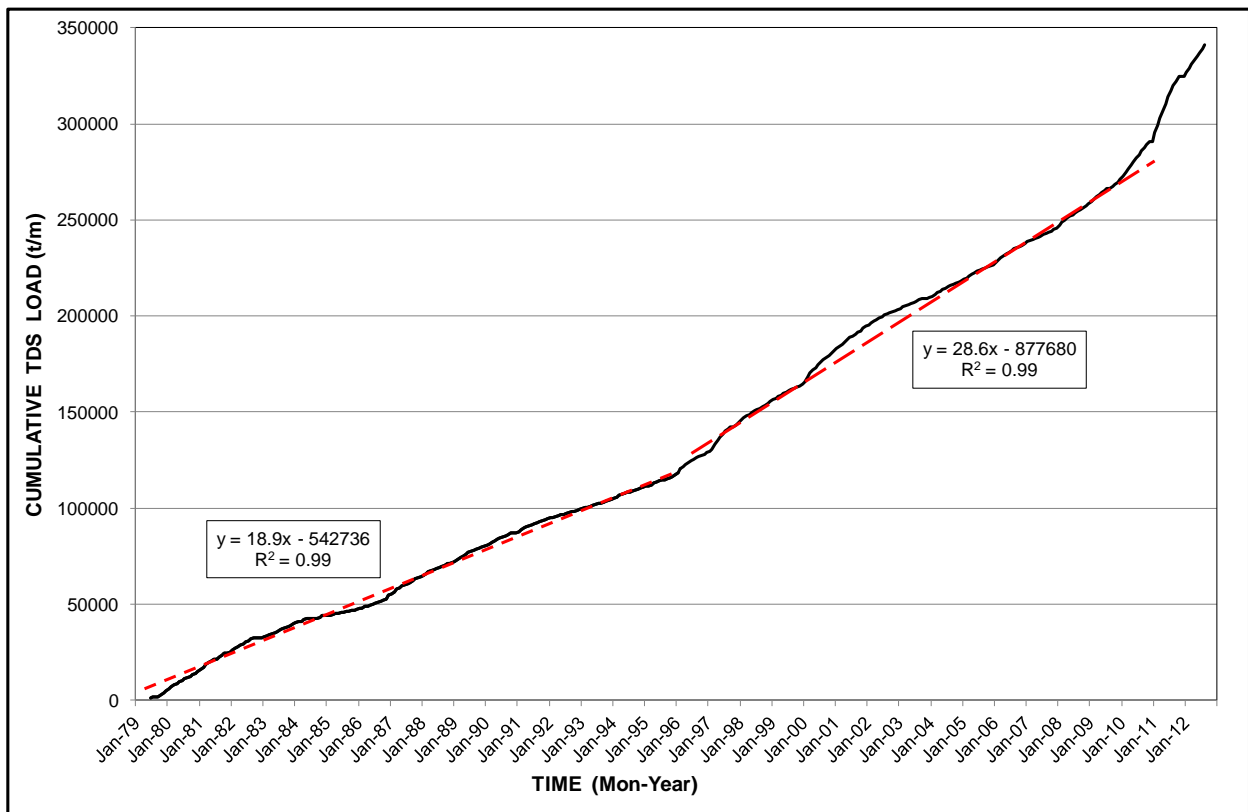


Figure 32 Pattern of cumulative monthly TDS load delivered by the Bloubank Spruit system in the long-term

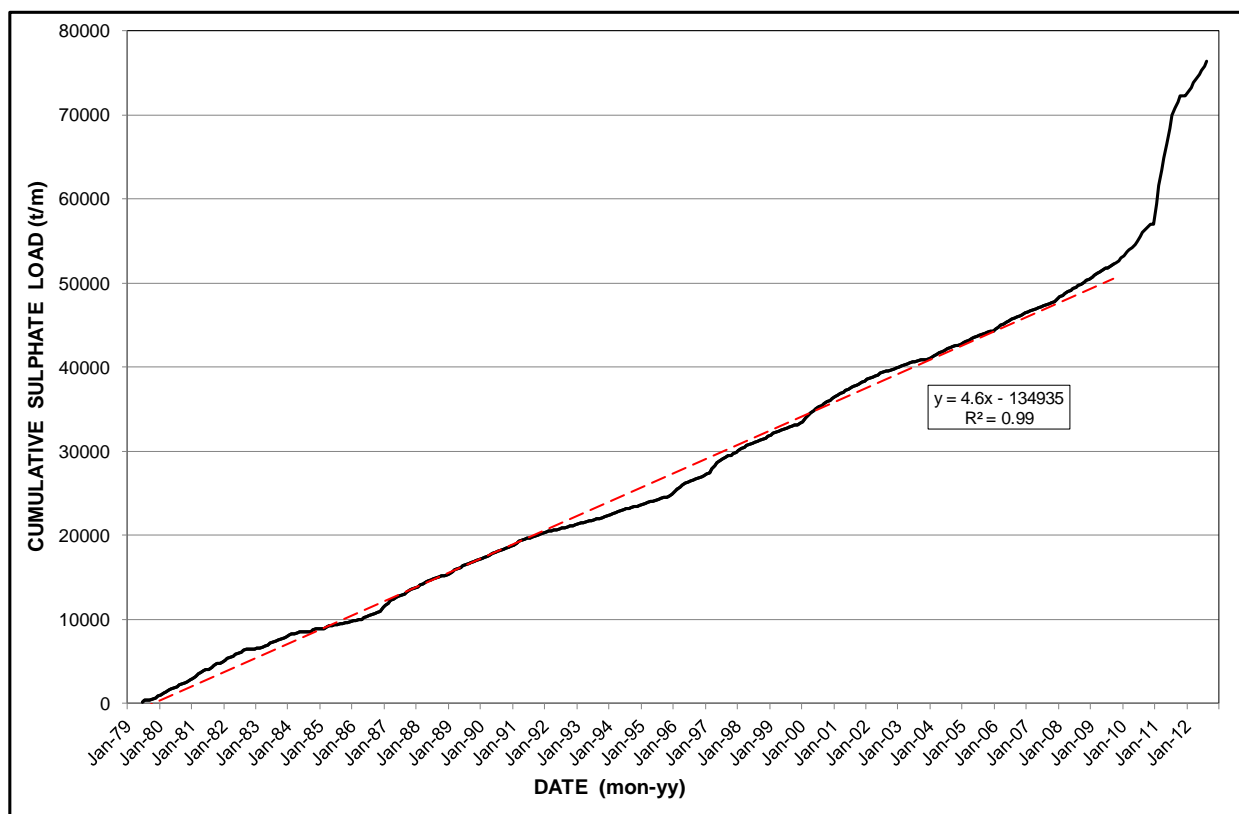


Figure 33 Pattern of cumulative monthly SO₄ load delivered by the Bloubank Spruit system in the long-term

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 6**. A graphical representation of the information is shown in **Figure 34**. 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 35**.

The comparison in **Figure 35** indicates two distinct groupings of hydrograph, namely Group A occupying an elevation of >1 530 m amsl, and Group B occupying an elevation <1 490 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 36** (Group A) and **Figure 37** (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 37**) 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 44**). 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.

Table 6 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

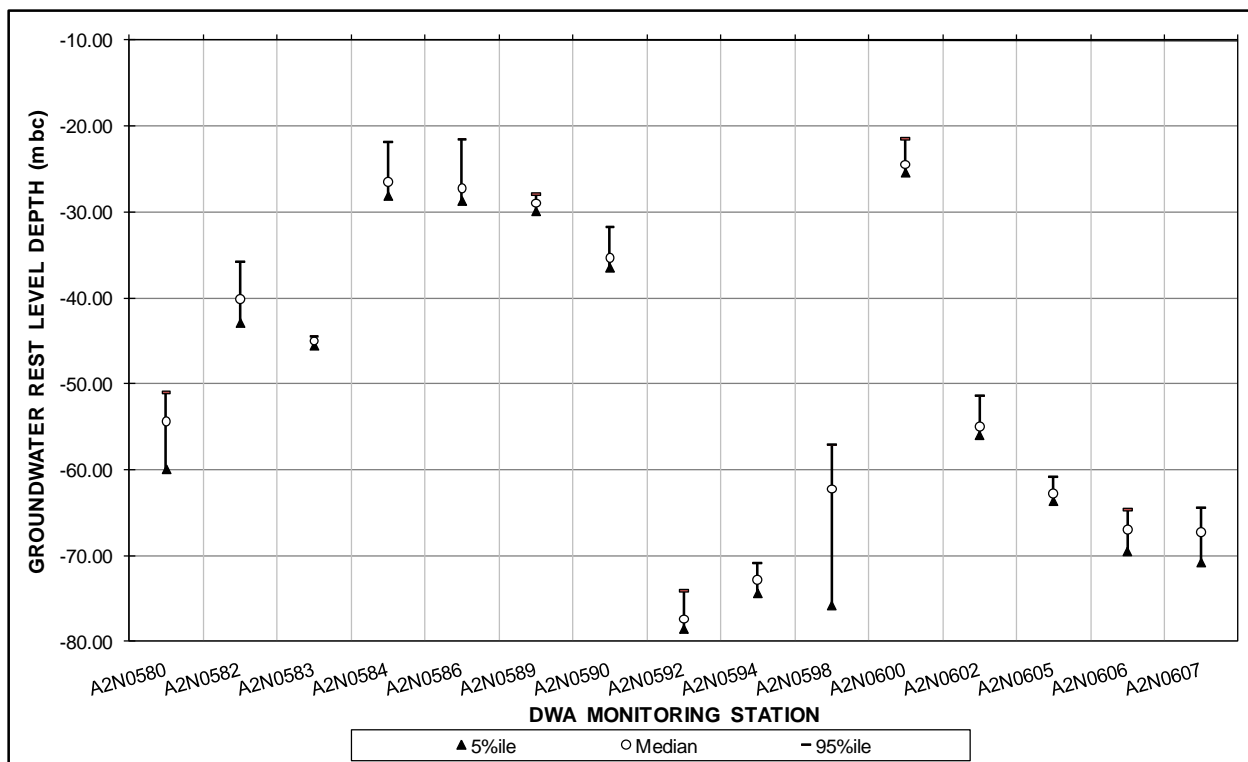


Figure 34 Graphic comparison of the statistical hydrographic response observed in DWA groundwater level monitoring stations in the period 1985 to 2012 (data from **Table 6**)

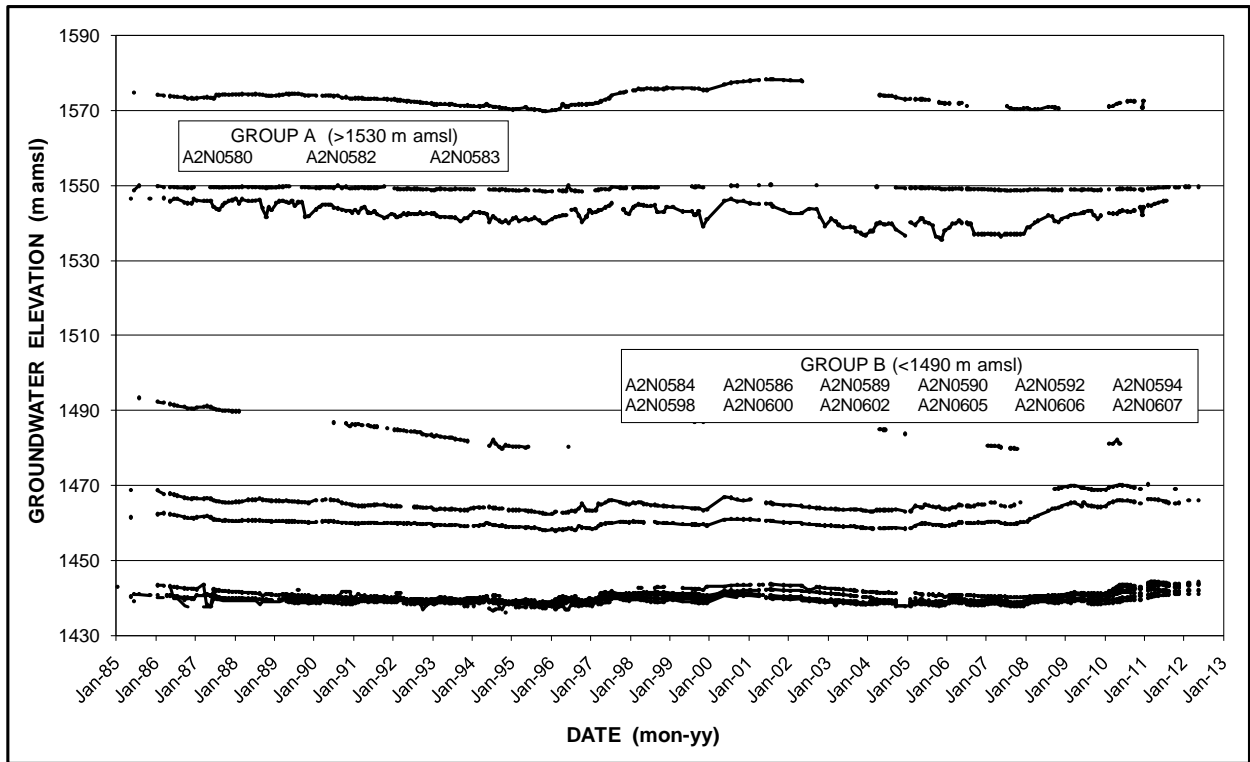


Figure 35 Long-term groundwater level response pattern in DWA monitoring boreholes

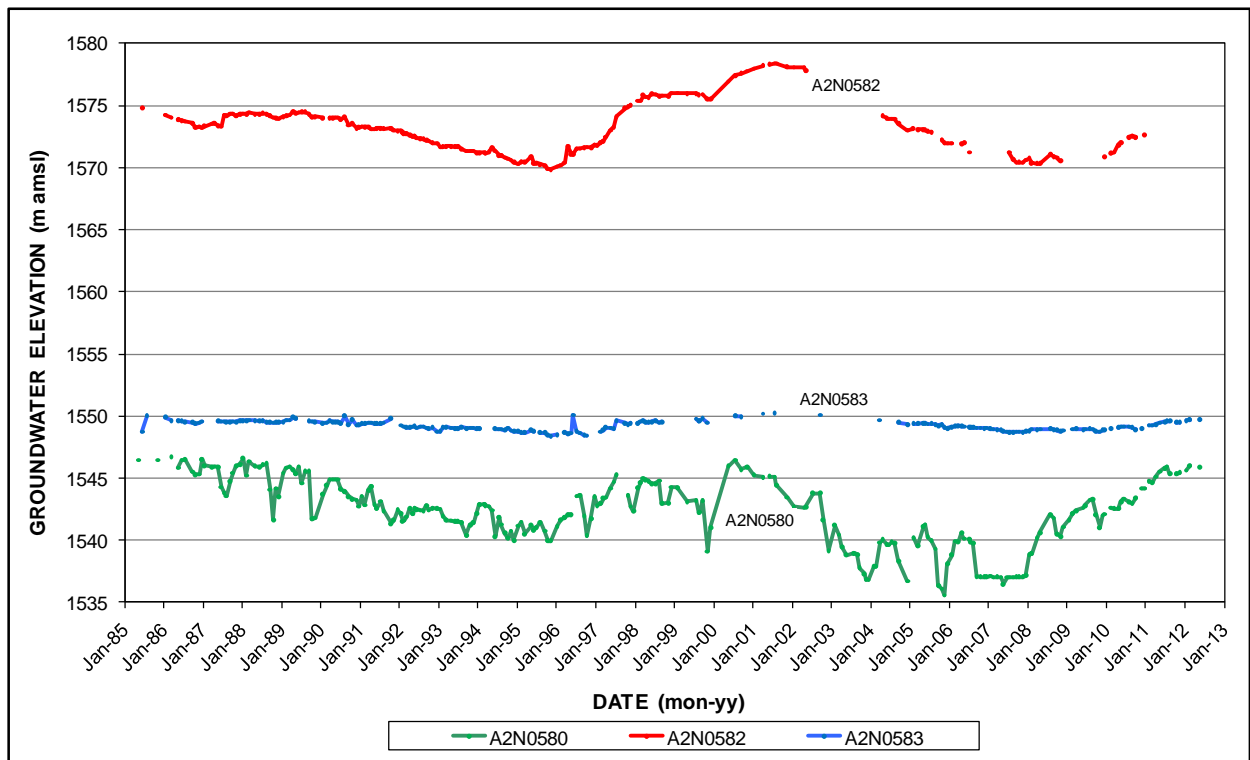


Figure 36 Long-term groundwater level response pattern in Group A boreholes from **Figure 35**

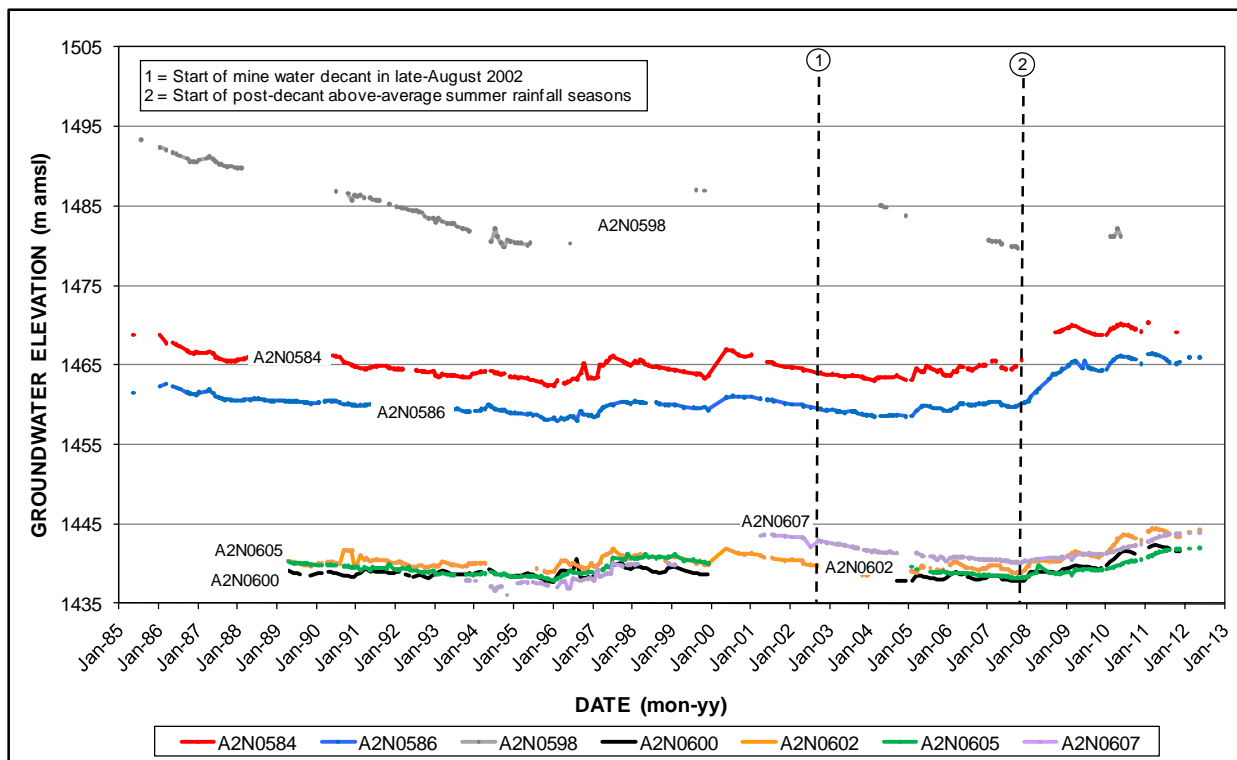


Figure 37 Long-term groundwater level response pattern in Group B boreholes from **Figure 35**

An inspection of the more recent potentiometric response in DWA monitoring boreholes located downstream of the LoD is presented in **Figure 38**. The boreholes are grouped into a southern, a central and a northern segment to distinguish between their location in the downstream receiving hydrogeologic environment. This distinction is particularly evident in the absolute groundwater level elevations that describe a decrease from south to north both within and between the respective segments.

The hydrographs indicate only very slight temporal variations that echo the decimetre scale of recent cave water level changes observed since mid-2010 (**section 5.1.2, Figure 39**). The long-term hydrographs presented in **Figure 37**, in particular those of stations A2N0583, A2N0584 and A2N0600, indicate that groundwater elevations in the last few years are the highest in the 25 to 30-year record of measurements. These hydrographs also indicate that periods of uninterrupted natural recession last from 5 to 10 years. The modification of the natural hydrologic and hydrogeologic balances brought about by the elevated and sustained mine water discharges (both treated/neutralised and/or raw mine water) will certainly alter the long-term natural groundwater level recession pattern and trend especially in the lower reaches of the Zwartkrans Compartment.

The mine water discharges have introduced a new set of drivers that have caused a resetting of the natural water resources environment that, in the case of groundwater, is immediately and most evident in the potentiometric data. The impact of these anthropogenic drivers on the chemistry of groundwater (which extends well beyond merely the quality aspect of this water) is discussed and evaluated in **section 5.2.3**. It is postulated, however, that their impact on the physical manifestation of groundwater change will result in higher baseflows in the Bloubank Spruit system in the future. The magnitude of this increase is anticipated to be in the order of 15–20% (2.9–3.9 Mm³/a).

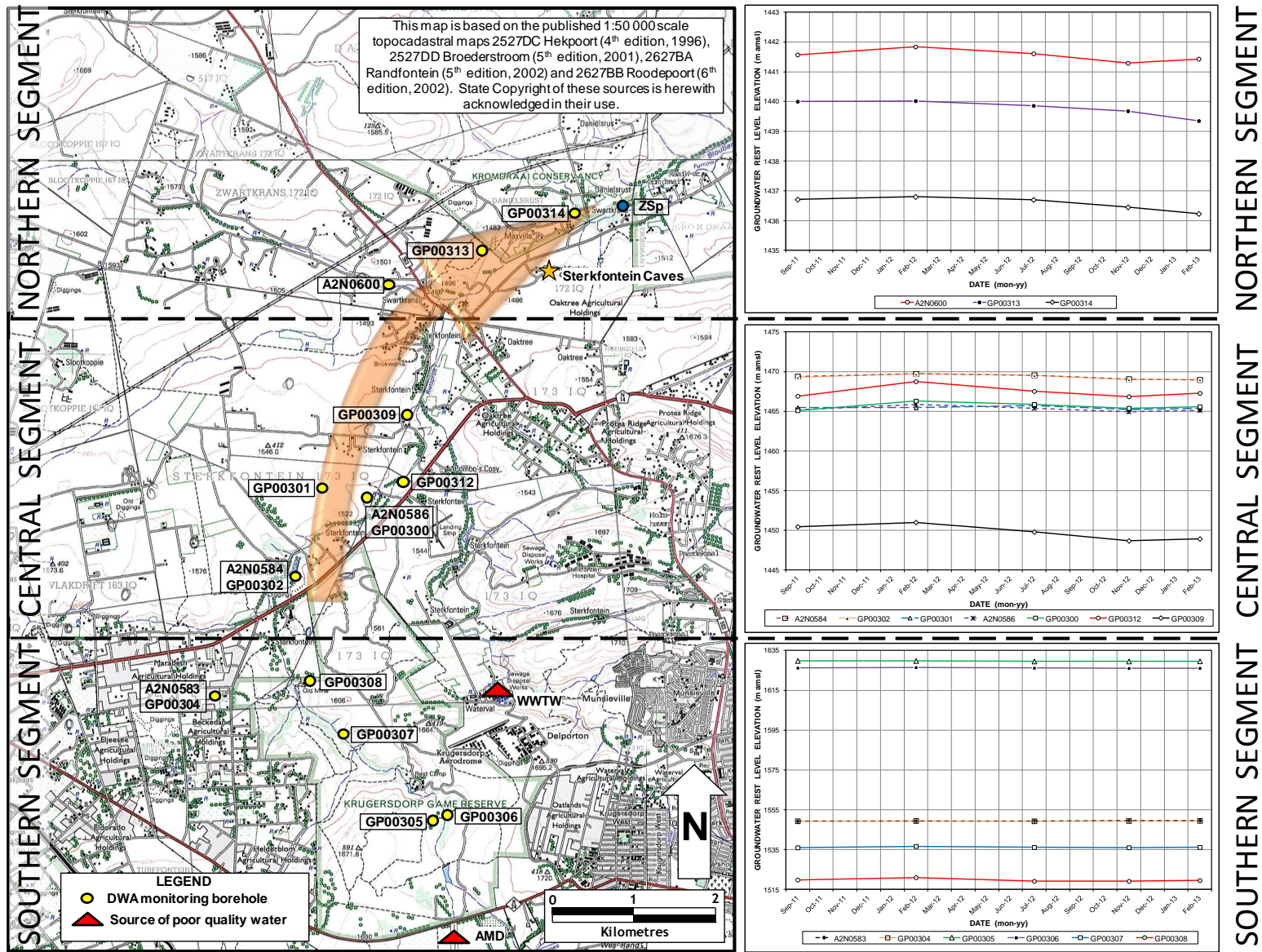


Figure 38

Distribution of DWA monitoring boreholes with groundwater hydrographs (right); arrow denotes principal direction of groundwater flow

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 39**), 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 39**, 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.

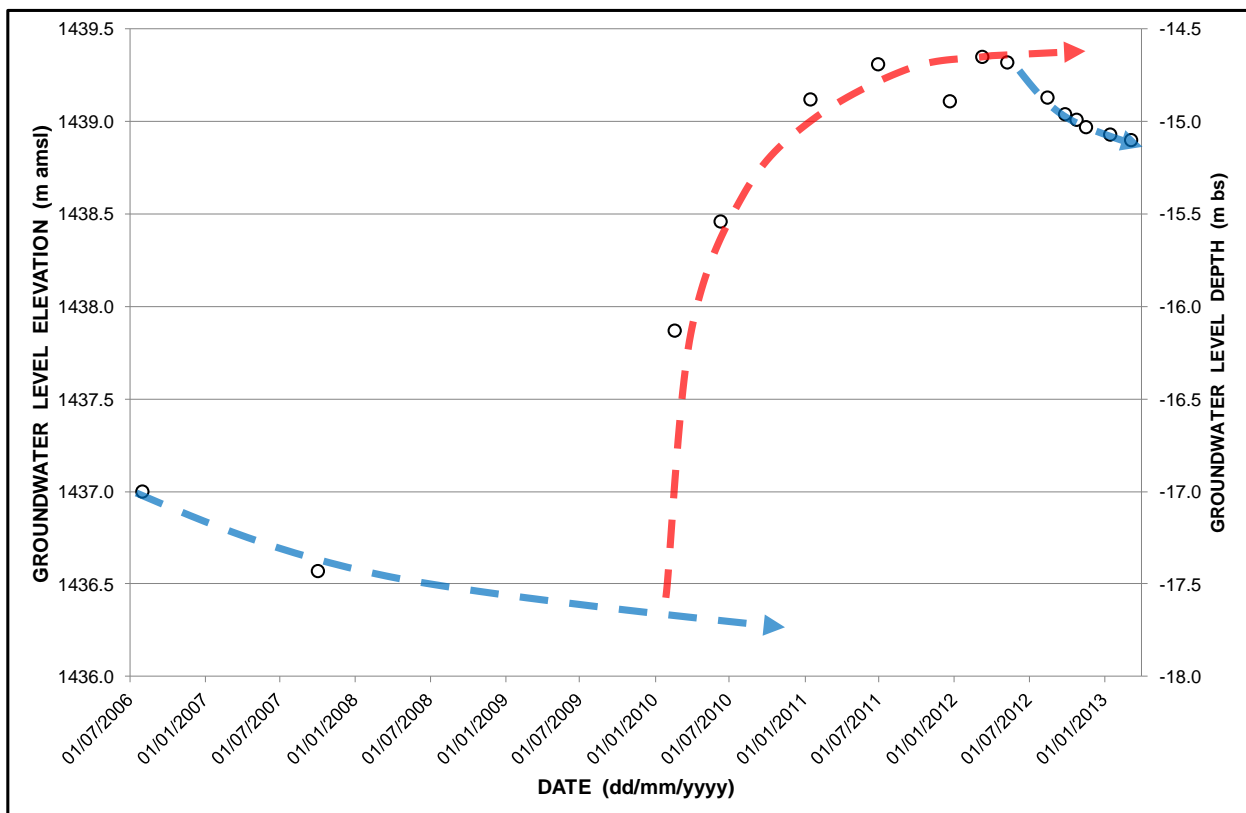


Figure 39 Recent groundwater level response pattern and trend in borehole SF1 that serves as a proxy for the Main Lake water level in Sterkfontein Caves

The ‘maximum’ elevation of ~1 439.3 m amsl (**Figure 39**) approaches the ~1 440 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 1 440 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 six most recent measurements in borehole SF1 (**Figure 39**) indicate a rate of decline of ~0.04 m/month in the period May 2012 to March 2013. This is similar to the rate of ~0.03 m/month observed for the early (pre-rise) part of the SF1 record shown in **Figure 39**.

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. The historical narrow focus on the spring discharge has returned flow values in the range 70 to 325 L/s, an untenable result that has prompted further investigation and clarification.

A set of SDMs carried out on 15 January 2013 differ from earlier attempts by the much tighter bracketing of the spring by the in-stream SDM positions. The upstream position was located ~20 m 'above' the spring, and the downstream position ~15 m 'below' the spring. Additional rigour was secured by having the irrigation water supply pumps installed at the spring switched off prior to the SDMs, a measure that was not implemented with any of the previous SDMs. The data presented in **Table 7** describe the results obtained.

Table 7 SDM and load-based calculation of the Zwartkrans Spring discharge on 15 January 2013

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	103	721 ⁽¹⁾ [=C _D]	~546 ⁽²⁾ [=Q _D]	47.2	393 713	34.0	
Upstream	105	735 ⁽¹⁾ [=C _U]	~410 ⁽²⁾ [=Q _U]	35.5	301 656	26.1	
Calculated difference in salt load						92 057	7.9
Zwartkrans Spring	95	665 ⁽¹⁾ [=C _S]	~136 ⁽³⁾ [=Q _S]	11.7	90 206	7.8	

(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 7** is interrogated on the basis of a mass balance calculation as follows:

$$Q_S = [(Q_D \cdot C_D) - (Q_U \cdot C_U)] / C_S = [393\,713 - 301\,656] / 665 = 138 \text{ L/s} \quad [\text{Table 7}]$$

The derived spring discharge value of 136 L/s (Q_S , **Table 7**) is very close to the mass balance calculated value of 138 L/s. These results are in reasonable agreement with those obtained from the 13 August 2010 SDMs, as well as the mass balance derived values associated with the 27 July and 13 August 2010 measurements, which gave a spring discharge of 72–128 L/s. These findings indicate that a discharge of ~135 L/s in mid-January 2013 may confidently be assigned to the Zwartkrans Spring.

Flow measurements carried out at station BB@M (**Figure 8**) and ~20 m upstream of Zwartkrans Spring on 15 January 2013 provide additional data that further elucidate the postulated resurgence of groundwater in the stream channel upstream of the spring. The data presented in **Table 8** describe the results obtained. The veracity of the flow measurements presented in **Table 8** is again interrogated on the basis of a mass balance calculation as follows:

$$Q_G = [(Q_D \cdot C_D) - (Q_U \cdot C_U)] / C_G = [301\,656 - 215\,600] / 665 = 129 \text{ L/s} \quad [\text{Table 8}]$$

Table 8 Calculation of groundwater resurgence in the Bloubank Spruit upstream of Zwartkrans Spring on 15 January 2013 using SDMs and salinity-based 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 ⁽¹⁾	105	735 ⁽³⁾ [=C _D]	~410 ⁽⁴⁾ [=Q _D]	35.5	301 656	26.1
Upstream ⁽²⁾	108	756 ⁽³⁾ [=C _U]	~285 ⁽⁴⁾ [=Q _U]	24.6	215 600	18.6
Calculated difference in salt load					86 056	7.4
Groundwater resurgence	95 ⁽⁵⁾	665 ⁽³⁾ [=C _G]	~125 ⁽⁶⁾ [=Q _G]	10.8	83 125	7.2

- (1) Located ~20 m upstream of the Zwartkrans Spring
- (2) Located at station BB@M
- (3) EC * 7.0 used as a proxy to derive a theoretical TDS value
- (4) Synoptic discharge measurement (SDM) value
- (5) Assumed similar to that of Zwartkrans Spring water (**Table 7**)
- (6) Derived value from the difference of the SDM values

The derived groundwater resurgence value of 125 L/s (Q_G , **Table 8**) is very close to the mass balance calculated value of 129 L/s. These results indicate a surface water gain of ~125 L/s over a stream length of ~460 m, which equates to ~270 L/s/km. Together with the spring discharge of ~135 L/s, the quantified groundwater discharge from the Zwartkrans Compartment amounts to ~260 L/s. This is in reasonable agreement with reported historical spring discharges (e.g. Bredenkamp et al., 1986), and approaches the highest of the supposed spring discharge values more recently obtained from SDM measurements. The SDMs reported in **Table 7** and **Table 8** do not, however, include groundwater resurgence contributed upstream of station BB@M. Potentiometric information and earlier SDMs indicate that a stream reach of ~1.6 km upstream of BB@M is potentially contributing surface flow via groundwater resurgence in the amount of ~90 L/s (~56 L/s/km). This implies a recent total groundwater discharge from the Zwartkrans Compartment of ~350 L/s, and supports the hypothesis by Hobbs (2011a) that the Zwartkrans Spring is not the only source of groundwater loss from the Zwartkrans Compartment. It does, however, deliver a reasonably constant ~135 L/s, which is augmented by up to ~215 L/s of groundwater resurgence in the stream channel upstream of the spring.

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 four 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 44** and **Figure 45**.

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 40** 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.

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 41**). 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 this ratio associated with the cave water chemistry returns the trend illustrated in **Figure 42**. The increasing trend from ~13% to ~18% approaches a value that characterises more recent surface water chemistry in the Bloubank Spruit.

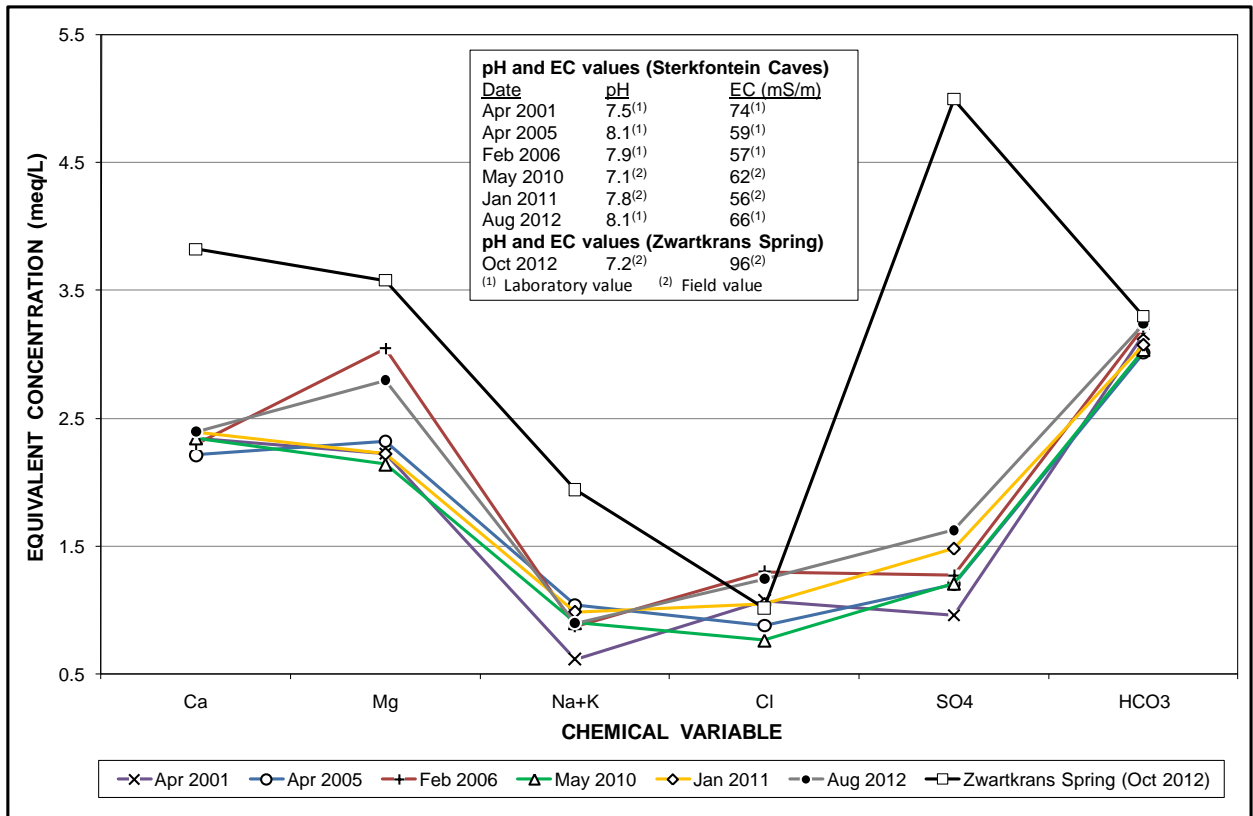


Figure 40 Graphical comparison of historical and recent Sterkfontein Caves groundwater chemistry

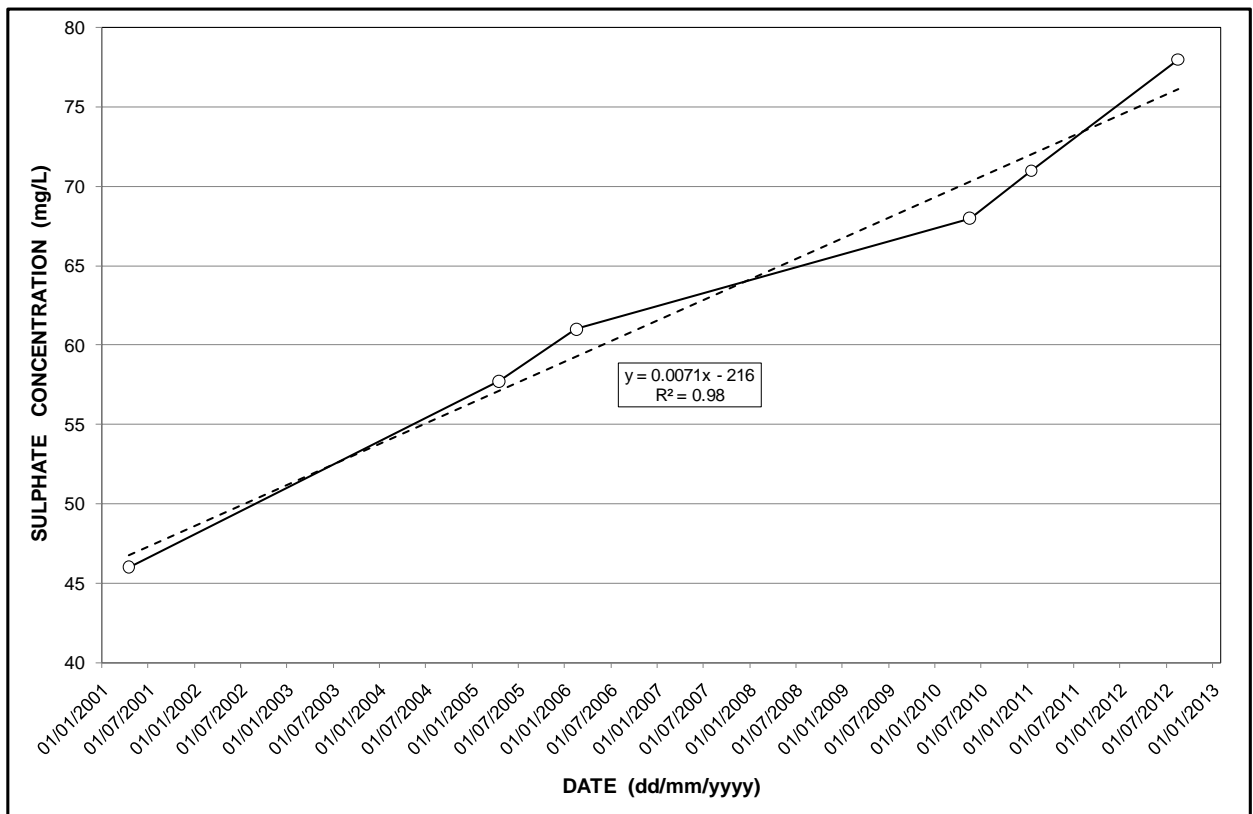


Figure 41 Pattern and trend of sulphate concentration in Sterkfontein Caves lake water

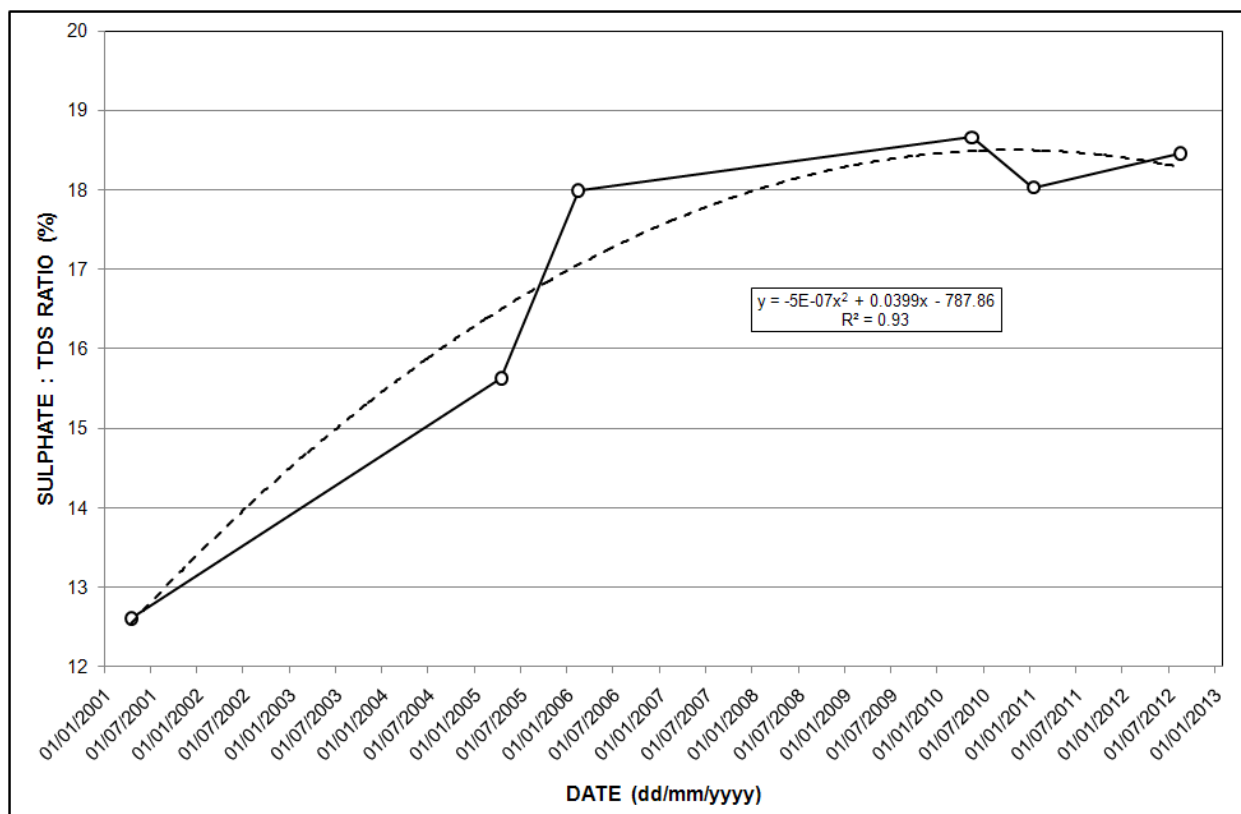


Figure 42 Trend of the SO₄:TDS ratio in cave water chemistry since 2001; trendline represents a 2nd order polynomial fit

The preceding evaluation 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 4.2.2**), the corollary transposes a muted mine water impact also on the cave water chemistry.

5.2.3 Mine Water Impact

A Piper diagram that characterises the groundwater chemistry in the Zwartkrans Compartment in October 2012 (**Figure 43**) clearly reflects the mine water impact at all but one of the monitoring stations. 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 44** and **Figure 45** with the aid of bar graphs for the chemical variables pH and electrical conductivity (EC) respectively.

The bar graphs in **Figure 44** 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 45** similarly reflect the general progressive increase in salinity from south to north within the central segment. In the northern segment, however, the spatial trend along the flow path 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 44**), this influence is least at the southern margin (stations A2N0584 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.

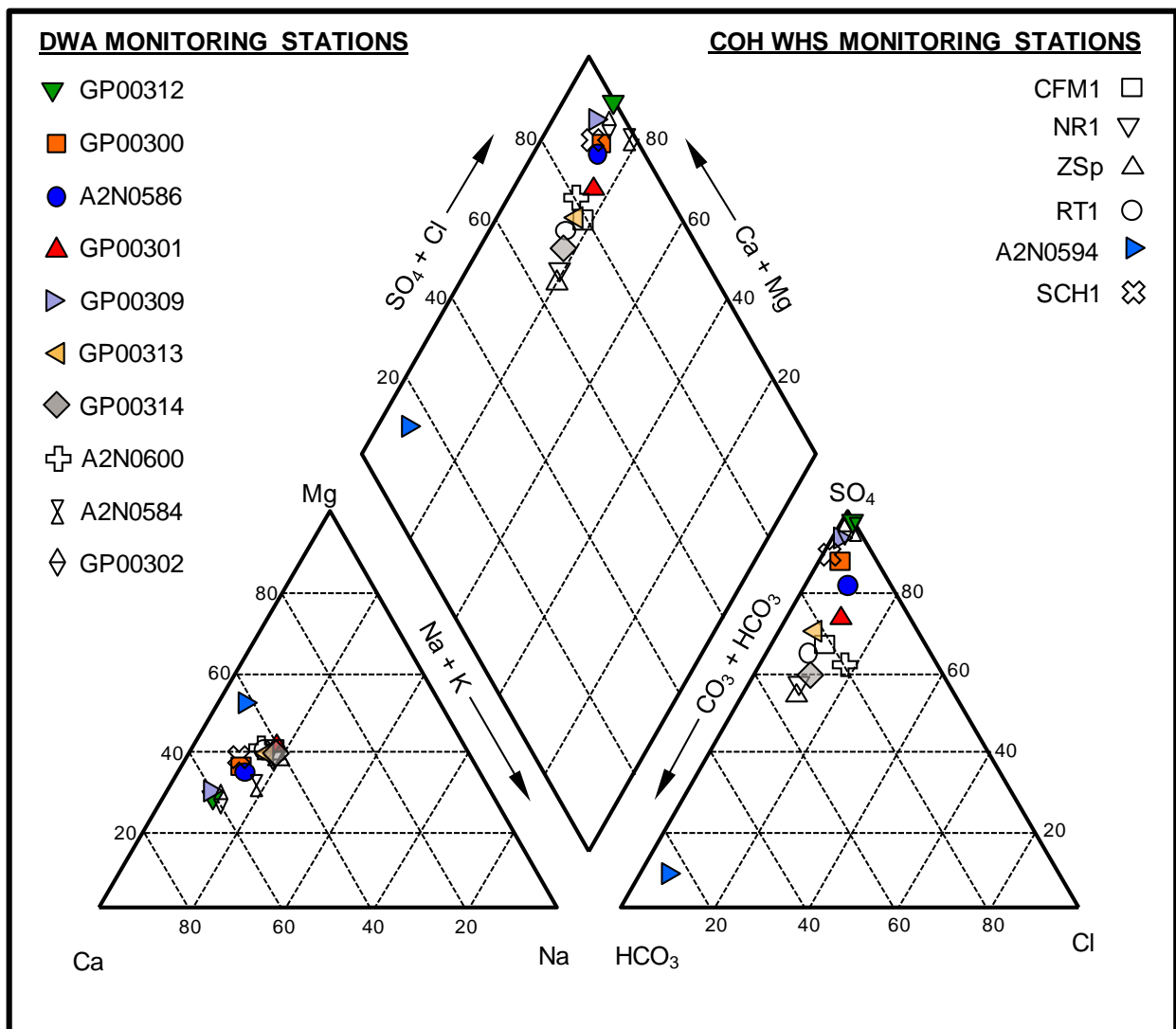


Figure 43 Characterisation of groundwater chemistry in the Zwartkrans Compartment in October 2012

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 46**, and 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 4**) in all three instances. It would also appear from **Figure 46**, however, that the sulphate levels have most recently started to decline. This might reflect the passage of the contamination peak through the karst aquifer at this locations.

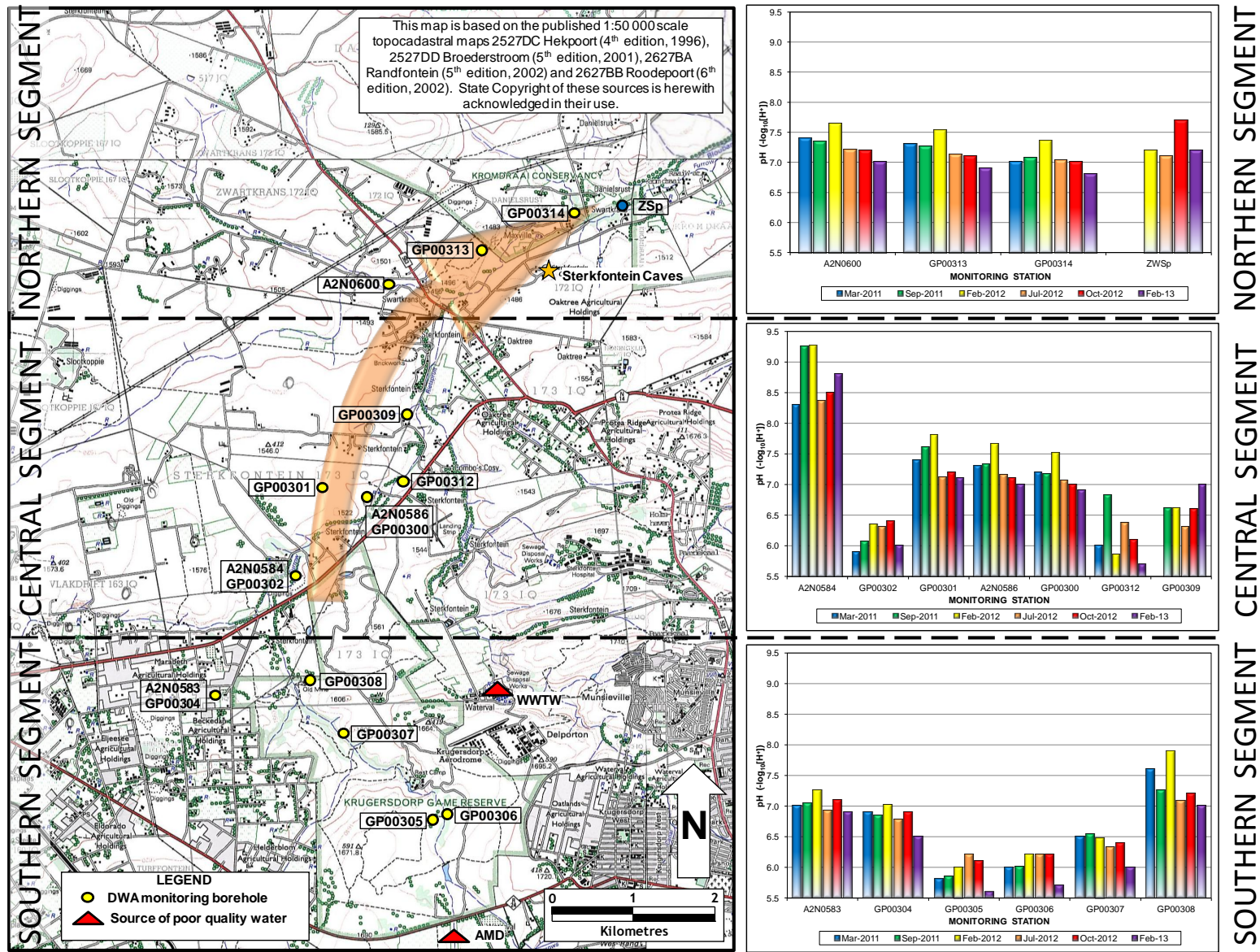


Figure 44 Distribution of DWA monitoring boreholes with pH pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

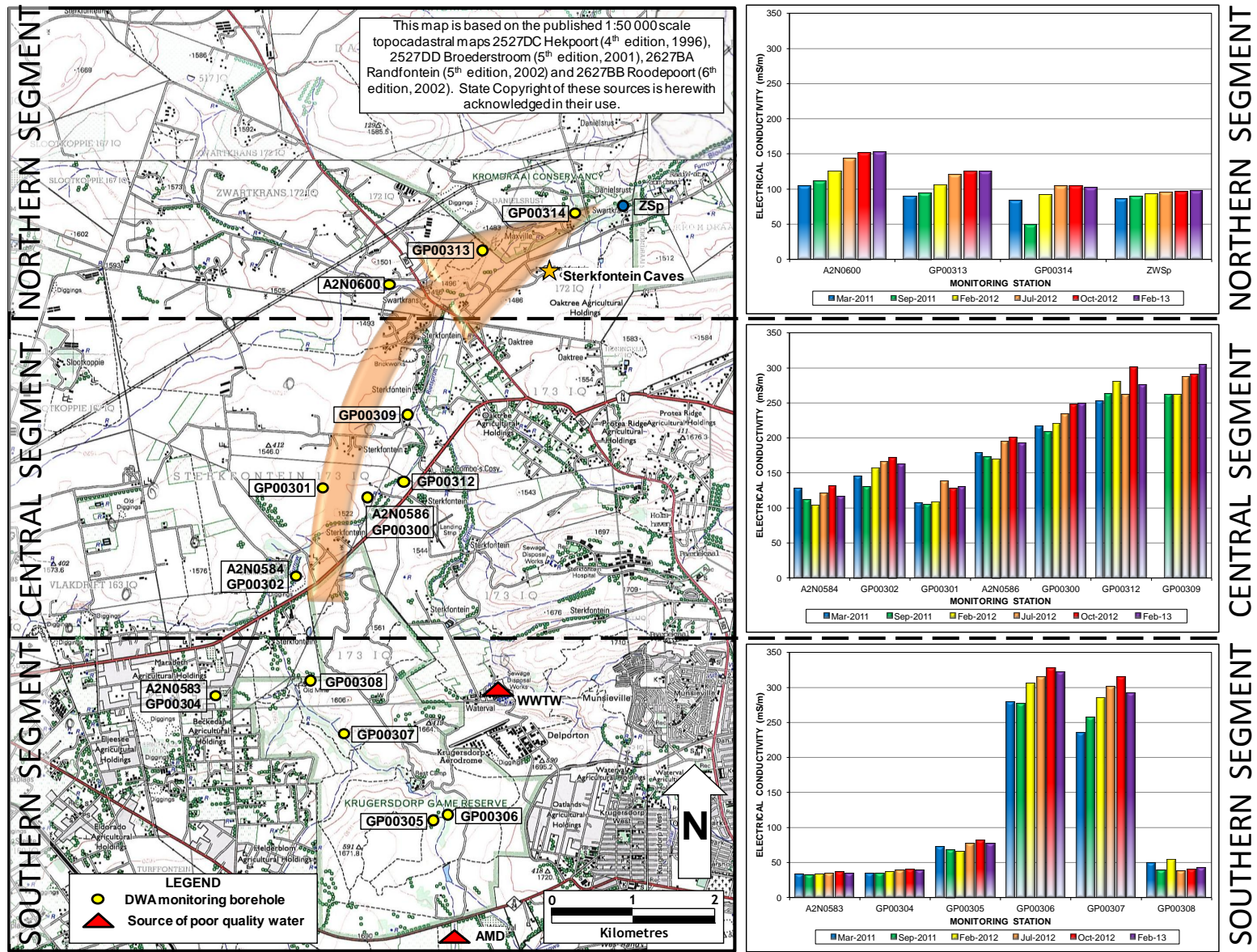


Figure 45 Distribution of DWA monitoring boreholes with EC pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

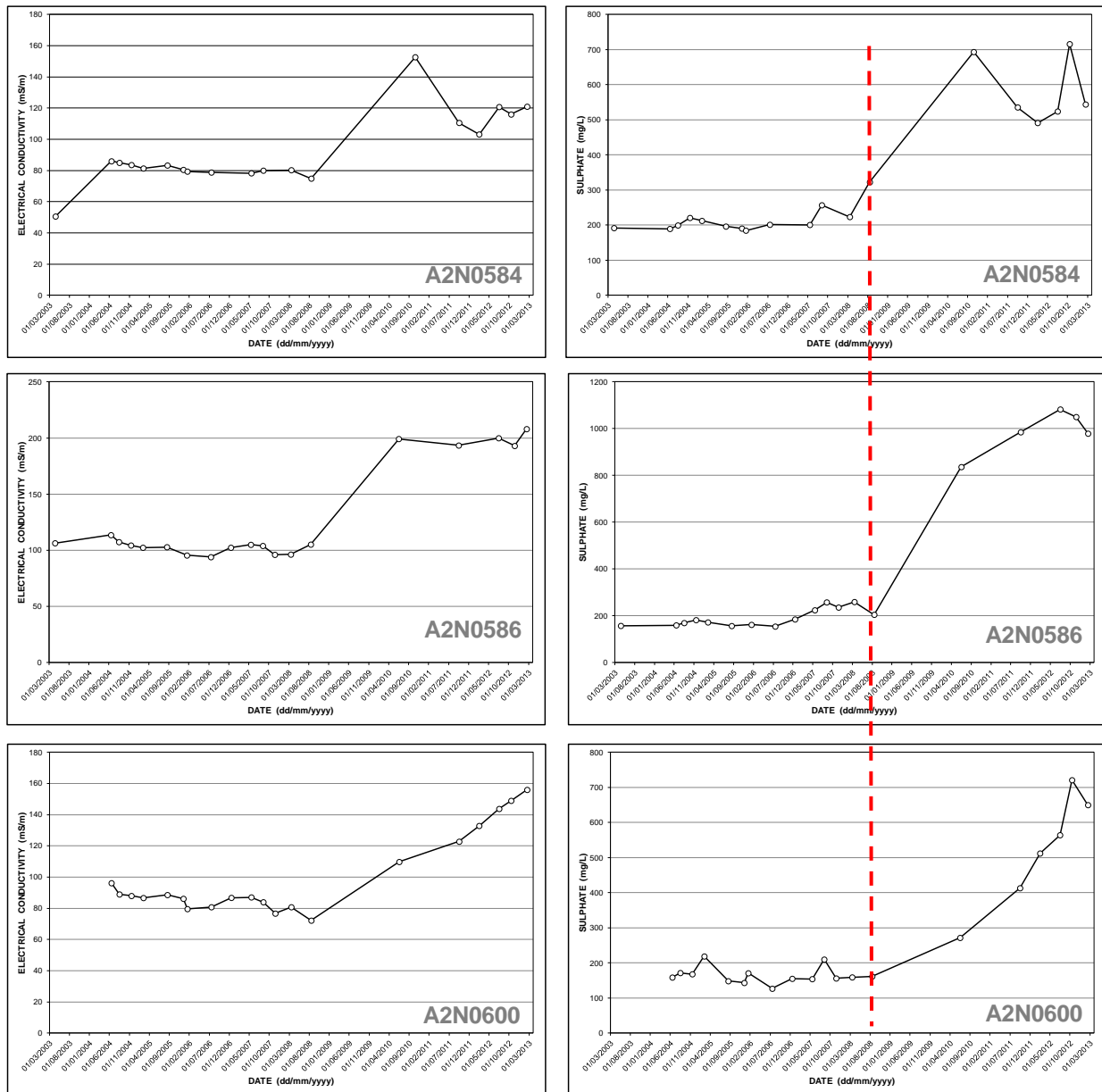


Figure 46 Long-term pattern and trend of electrical conductivity (left) and sulphate (right) in karst groundwater from DWA monitoring stations A2N0584, A2N0586 and A2N0600; note common time scales and postulated commencement of rise in concentrations (vertical pecked line)

The distribution of SO_4 concentrations associated with the stations represented in **Figure 43** is shown in **Figure 47**, and provides an indication of the footprint of this impact. The distribution pattern evident in the central diamond field of **Figure 43** 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 47**. Also evident in **Figure 43** is the position of the A2N0594 sample that characterises nearly pristine karst groundwater. **Figure 47** shows that this station is located in the upper reaches of the Zwartkrans Compartment within the flow path that describes autogenic recharge.

6 AUTOMATED 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.

At the request of the CSIR, the DWA has also installed 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.

An additional three rainfall monitoring stations have been installed in the study area to augment the existing rainfall monitoring network. Apart from the totalling rain gauge established at Sterkfontein Caves, similar gauges have been established in proximity to monitoring station GP00301, at Tarlton and at the HDS mine water treatment plant.

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 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 Mm³ respectively), after the 66.9 Mm³ 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 0.04 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.
- The municipal wastewater effluent discharged from the Percy Stewart Wastewater Treatment Works continues to manifest an unacceptable bacteriological quality in the downstream receiving reaches of the Bloubank Spruit system. This situation is indefensible given the attention that is directed at AMD as a source of impact on the receiving water resources environment of the COH WHS.
- The mine water discharges have introduced a new set of drivers that have caused a resetting of the natural water resources environment that, in the case of groundwater, is immediately and most evident in the groundwater level (potentiometric) data. It is postulated that this impact will result in higher baseflows (by 10–15%) in the Bloubank Spruit system in the future.

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 ~1 300 mg SO₄/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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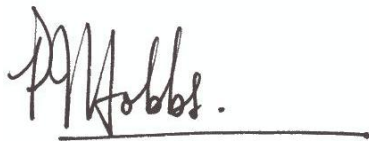
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A handwritten signature in black ink that reads "PJ Hobbs." The signature is written in a cursive style and is positioned above a solid horizontal line.

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