PROJECT TITLE

SURFACE WATER AND GROUNDWATER RESOURCES MONITORING, CRADLE OF HUMANKIND WORLD HERITAGE SITE, GAUTENG PROVINCE, SOUTH AFRICA

REPORT TITLE

WATER RESOURCES STATUS REPORT FOR THE PERIOD APRIL TO SEPTEMBER 2013

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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. The monitoring programme has been extended into the 2013–'14 financial year (April 2013 to March 2014), and the mid-term results for this period are presented in this water resources status report.

An assessment of impacts on the water resources environment of the COH WHS has again taken a holistic view with a specific focus on the area that is at greatest risk from a wastewater impact, yet maintaining a 'watching brief' on the remaining far larger extent of the property. The outcome of the monitoring programme as documented in this report continues to confirm the conceptual hydrophysical and hydrochemical model developed for the property in the situation assessment report.

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

- The Bloubank Spruit system did not experience exceptionally high discharge conditions in the most recent (2012–'13) wet season, indicating a return to more 'normal' flows compared to the abnormally high discharges of the preceding three summers.

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

- Synoptic discharge measurements at two stations in the lower reach of the Riet Spruit continue to confirm previous results regarding quantified losses of AMD-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, and also reflects the influence of the more recent improved AMD-impacted surface water quality.

- The impact of allogenic recharge from the losing reach of the Riet Spruit to the karst aquifer of the Zwartkrans Compartment continues to be 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 decline in the Main Lake water level since mid-2012 has continued at a rate of ~0.04 m/month, but is expected to 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 remains 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 hydrodynamic conditions that have precipitated an adjustment of the natural water resources environment which, in the case of groundwater, is immediately and most evident in potentiometric levels. 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 continues to suffer from a compromised groundwater quality. Sulphate levels of >1 000 mg SO_4/L will definitely impact on the potability of groundwater-based water supplies in the area effected. Although the commissioning of the immediate mine water control and management intervention measures in mid-2012 has ameliorated the quality of surface water in the Bloubank Spruit system, the impact on the groundwater environment in the effected portion of the Zwartkrans Compartment will take significantly longer to manifest an improvement.

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

~	approximately
>	greater than
<	less than
%	per cent (parts per hundred)
%ile	percentile
°C	degree(s) Centigrade
Δh	change in head
a_h	hydrological year
AMD	acid mine drainage
amsl	above mean sea level
bc	below collar
BRI	Black Reef Incline
bs	below surface
ca.	circa (about)
cfu	coliform forming units
COH WHS	Cradle of Humankind World Heritage Site
CoV	coefficient of variation
DL	detection limit
DWA	Department of Water Affairs (formerly DWAF; Department of Water Affairs and Forestry)
EC	electrical conductivity
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
RMW	raw mine water
RU/G1	Rand Uranium/Gold 1
SD	standard deviation
SDM	synoptic discharge measurement
TCTA	Trans-Caledon Tunnel Authority
TMW	treated (neutralised) mine water
t/d	ton(s) per day
TDS	total dissolved salts
U_T	total uranium
U_D	dissolved uranium
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 property (**Figure 1**). Amongst a number of techno-scientific reports, the project produced a situation assessment of the surface water and groundwater resource environments (Hobbs, 2011).

The pilot implementation of a water resources monitoring programme in the 2012–’13 financial year yielded a substantial amount of new data that facilitated an update of the water resources situation and status to reflect more recent patterns and trends (Hobbs, 2012; 2013). The extension of the monitoring programme into the 2013–’14 financial year provides for the situation assessment and status to be updated even further. This is given effect in this report, which covers the period April to September 2013, and represents the mid-term monitoring report that serves as the first of two deliverables for the current monitoring contract. The report concentrates on the status of the water resources rather than on an exhaustive update of the situation assessment. The latter is considered to be the focus of the second deliverable, a contract closing out report due in March 2014.

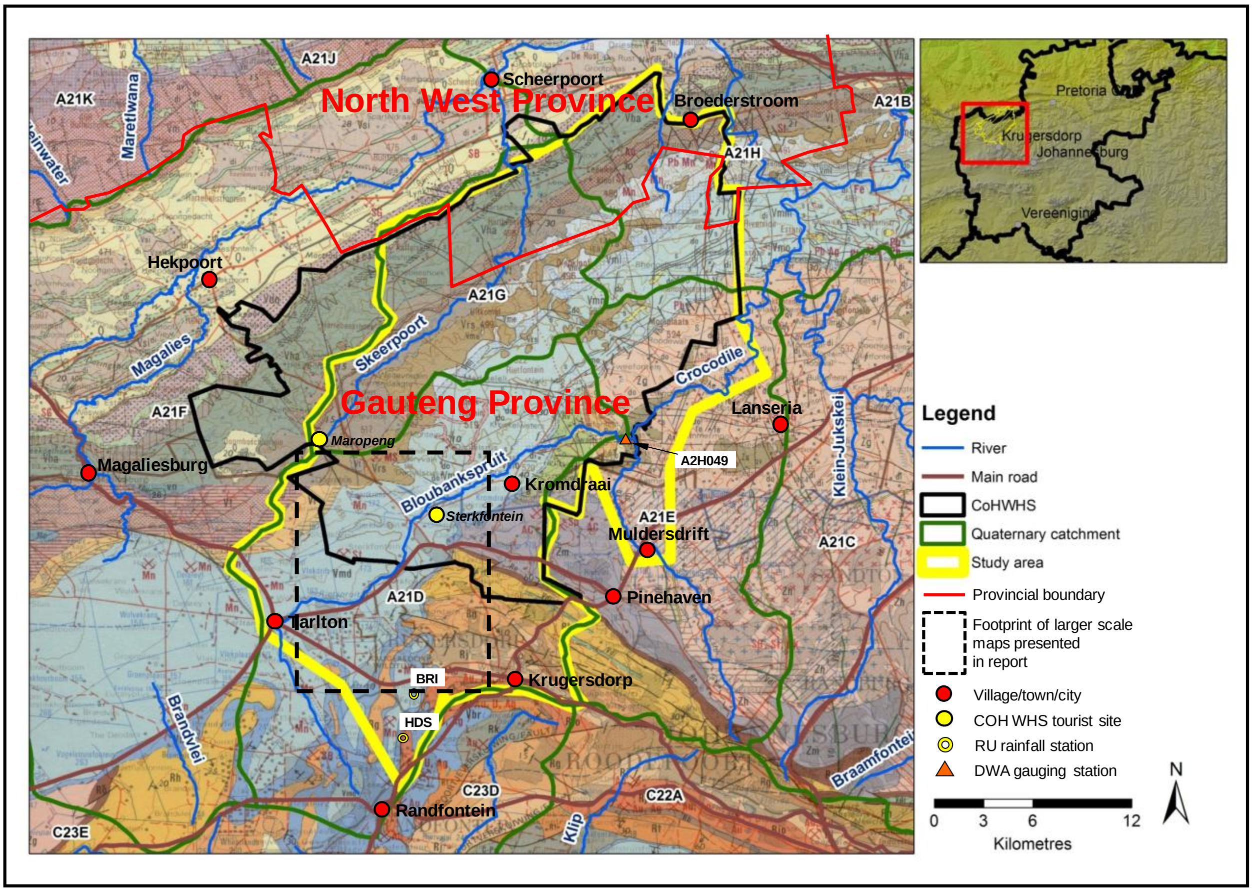

Figure 1 Definition of the study area in regard to the regional geology, surface water drainages, quaternary catchments and other geographic locations for orientation

2 TIMELINE OF KEY EVENTS

In keeping with the contextualisation of the material presented and discussed in these reports in terms of a timeline of key events since the inscription of the COH WHS as a World Heritage Site in 1999, an updated timeline is presented in **Figure 2**.

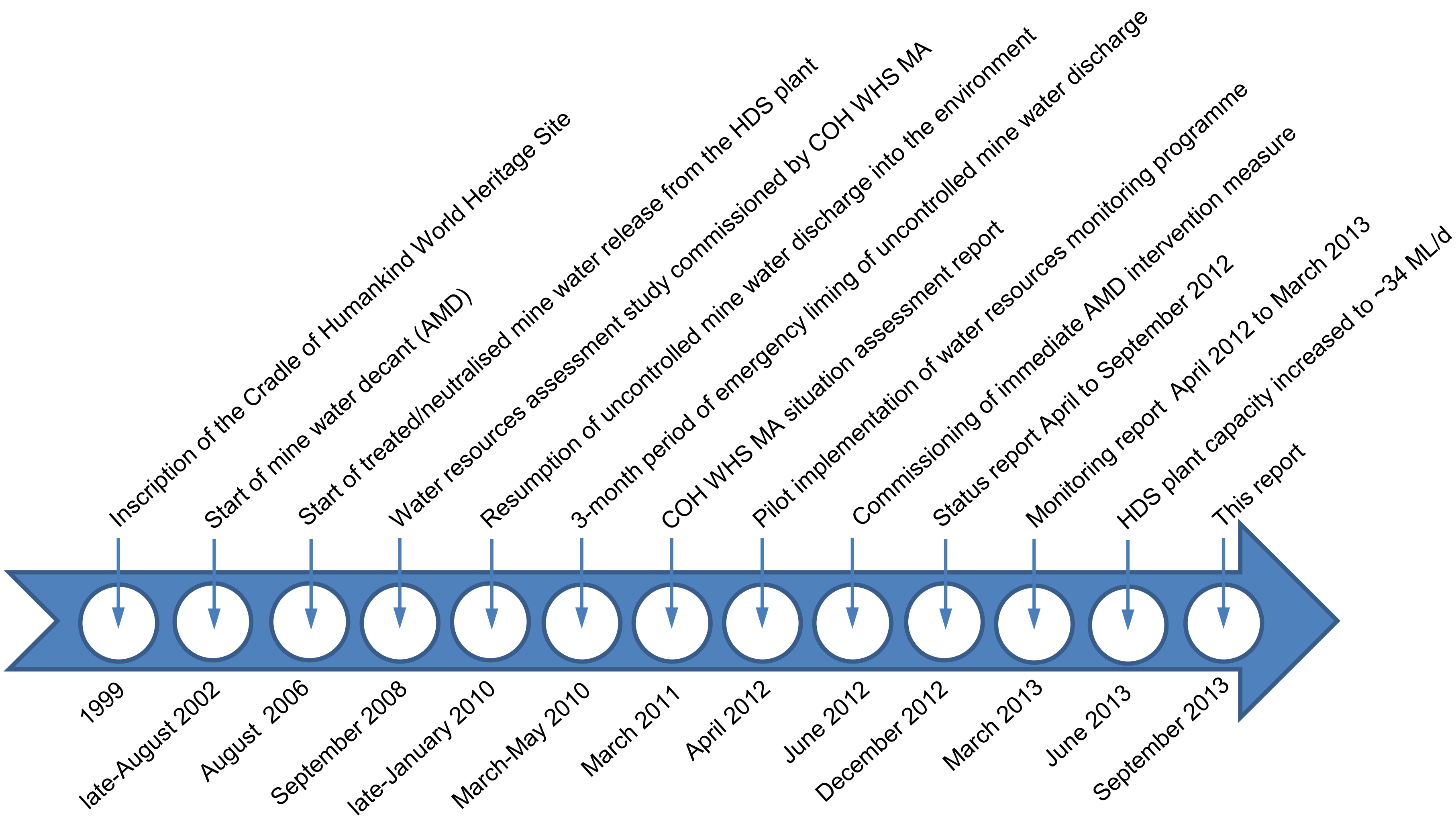

Figure 2 Timeline of events relevant to this report

The most important recent key event on the timeline (**Figure 2**) is the expansion of the mine water high density sludge (HDS) treatment facility to a capacity of ~34 ML/d. This is in accordance with the immediate and short-term intervention measures commissioned by the Department of Water Affairs (DWA) and implemented by its Implementing Agent, the Trans-Caledon Tunnel Authority (TCTA), to control and manage AMD in the Western Basin. This marks a further milestone that will again alter the dynamic of a mine water impact on the receiving water resources. The commissioning of the upgraded facility in June 2012 already manifested a positive impact on the surface water environment (Hobbs, 2013).

A second recent key event is the delivery of a water resources monitoring report for the period April 2012 to March 2013 (Hobbs, 2013) documenting an updated situation assessment and status update of monitoring data generated in the course of the pilot implementation of a surface water and groundwater resources monitoring programme for the COH WHS. This report is available in the public domain, and has been distributed widely amongst various authorities.

3 RAINFALL

The monthly precipitation record for the period October 2008 to September 2013 (**Figure 3**) of the Rand Uranium/Gold 1 (RU/G1) rainfall stations BRI and HDS (**Figure 1**), reveals the return to more normal summer rainfall seasons (**Figure 4**) with values <600 mm. It is also evident from **Figure 3** that April 2013 experienced exceptional rainfall with >125 mm being recorded at all three stations, and station HDS recording as much as 167 mm. The rainfall data also confirm the observation (Hobbs, 2011) that monthly precipitation at station BRI to the north of the continental divide is generally less than that measured at station HDS on the divide. The updated record suggests a difference of ~11% (**Figure 5**).

Also shown in **Figure 3** and **Figure 4** are the contemporary rainfall data recorded at the Sterkfontein Caves gauging station by the DWA. An analysis of the common monthly rainfall record (n = 34) 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 = 0.91) with the HDS record (**Figure 6**). This correlation indicates a ~13% lower monthly rainfall at Sterkfontein Caves than at the HDS station located ~13 km to the south on the continental divide. Although exhibiting a poorer correlation of R^2 = 0.85 (**Figure 6**), the difference with the BRI station is only ~6%.

In addition to the rainfall gauging stations listed above, the DWA has installed a further three totalling stations at the following locations:

- the HDS mine water treatment plant (in mid-March 2013) where Gold1 already maintains the HDS rainfall gauge;
- the monitoring borehole cluster A2N0576 and GP00303 on the farm Vlakplaas 160IQ at Tarlton (also in mid-March 2013); and
- the monitoring borehole GP00301 on Ptn 8/2 of the farm Sterkfontein 173IQ near the southern boundary of the COH WHS (in mid-April 2013).

The rainfall record for the three “new” stations is too short to warrant an evaluation of the data, the stations only being commissioned in mid-March and mid-April 2013 as indicated above.

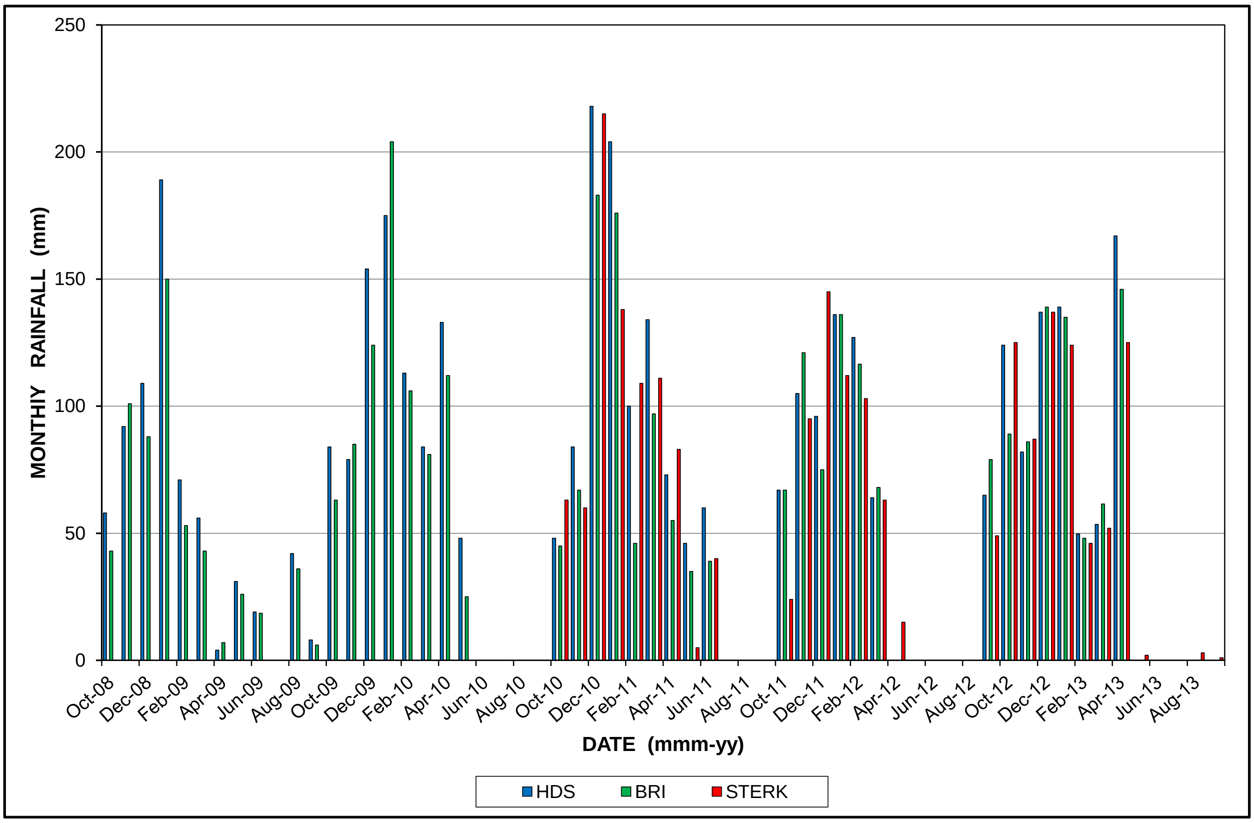

Figure 3 Monthly precipitation at the RU/G1 rainfall monitoring stations HDS and BRI in the period October 2008 to September 2013, also showing the available record for the Sterkfontein Caves station

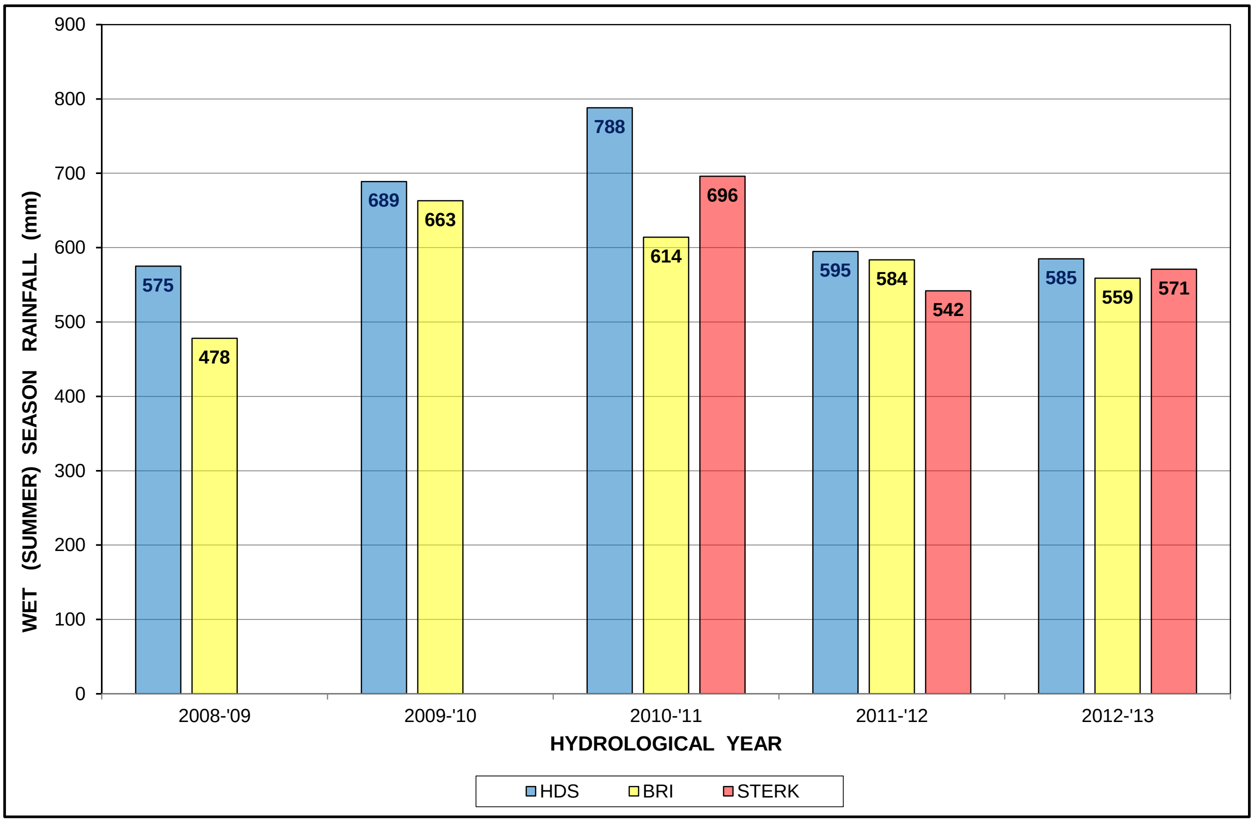

Figure 4 Comparison of total wet season (summer) rainfall at the RU/G1 rainfall monitoring stations HDS and BRI in the past five hydrological years, also showing the available record for the Sterkfontein Caves station

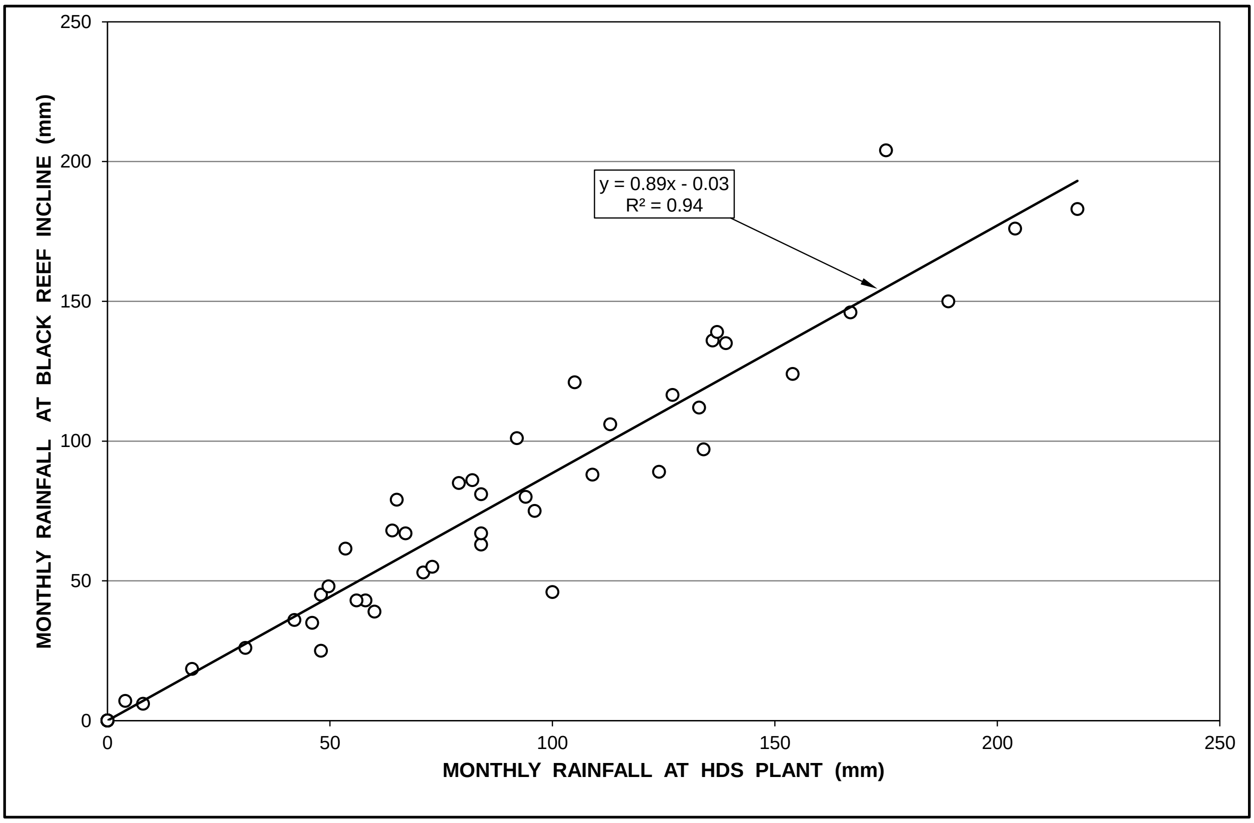

Figure 5 Correlation of monthly precipitation between the RU/G1 rainfall monitoring stations HDS and BRI in the period October 2008 to September 2013

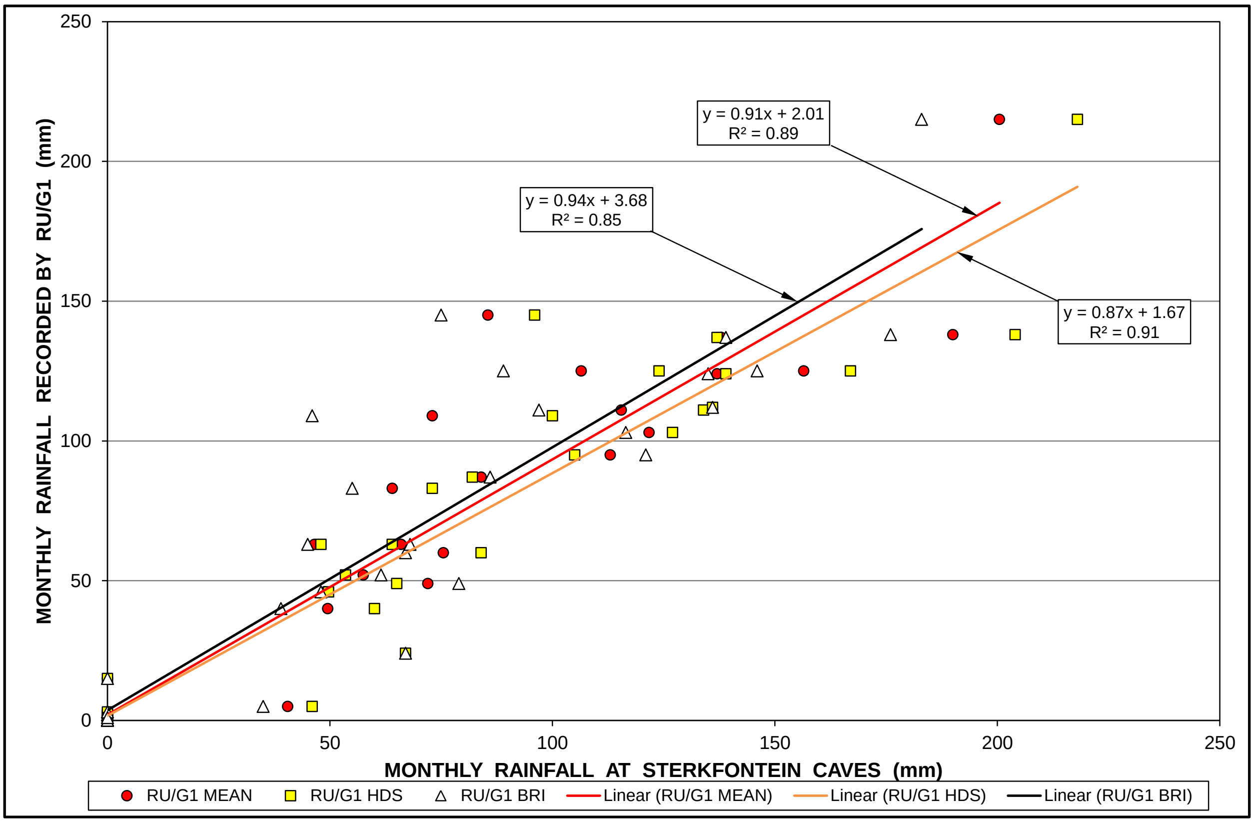

Figure 6 Correlation of monthly rainfall at Sterkfontein Caves with the RU/G1 record for stations HDS and BRI in the locus of decant

4 SURFACE WATER HYDROLOGY

4.1 Physical Hydrology

4.1.1 Mine Water Discharge

The pattern and trend of mine water discharge into the environment since the start of gauged monitoring is illustrated in **Figure 7**. The graph distinguishes between raw mine water (RMW) and treated/neutralised mine water (TMW), the aggregate of which represents the total mine water discharge. The period during which the RMW contribution to total mine water discharge regularly exceeded 10 ML/d is clearly evident in **Figure 7**. Under circumstances where the TMW contribution reflects a reasonably consistent discharge of 10–15 ML/d prior to mid-2012[1], it is clear that the RMW proportion in total mine water discharge consistently exceeded that of TMW in the period February 2010 to mid-2012. This is illustrated in **Figure 8**, which also shows the return to pre-2010 conditions in the latter part of the record, i.e. since mid-2012, clearly demonstrating the efficacy of the immediate AMD intervention in managing mine water discharge in the Western Basin. It is these circumstances that inform the impacts on surface water chemistry (quality) in the downstream receiving reaches of (in turn) the Tweelopie Spruit, the Riet Spruit and the Bloubank Spruit as described in **Section 4.2**.

4.1.2 Surface Water Fluxes

The significance of the interaction between surface water and groundwater in a karst environment has been stressed in previous monitoring reports (Hobbs, 2012; 2013). In-stream synoptic discharge measurements (SDMs) made on 28 occasions (**Table 1**) at stations F11S12 and MRd (**Figure 9**) quantify and elucidate the magnitude of surface water loss to the karst aquifer. The results of the SDMs are illustrated in **Figure 10**, and continue to indicate an absorptive capacity defined by a minimum ingress value of ~14 ML/d (~41 L/s/km). The observation (Hobbs, 2013) that the absorptive capacity of the karst aquifer underlying the losing ~3.9-km reach of the Riet Spruit reached a new equilibrium condition that continued into the 2011–'12 hydrological year, remains valid also for the 2012–'13 hydrological year as is reflected in the linear regression trendline for period 3 (**Figure 11**). Also evident in **Figure 10** is the recent increase in discharge measured at the upstream station F11S12, which exceeds 25 ML/d and approximates 30 ML/d (**Table 1**) for the first time since August 2011. This observation is in keeping with the increased capacity of the HDS plant to ~34 ML/d in June 2013 (**Figure 2**).

The surface water losses to the karst aquifer beg the question of how these inflows relate to discharge (outflow) from the Zwartkrans Compartment. The Zwartkrans Spring represents a point source of discharge that has been quantified at 136 L/s (11.7 ML/d) (Hobbs, 2013). In addition, groundwater resurgence in the stream channel upstream of the spring contributes as much as 215 L/s (18.6 ML/d) to the discharge of the Bloubank Spruit at this location (Hobbs, 2013). The total stream discharge of up to ~350 L/s (30.2 ML/d) below the Zwartkrans Spring therefore represents the groundwater discharge from the Zwartkrans Compartment dolomitic aquifer. This value is 12.9 ML/d greater than the median stream loss rate of 17.3 ML/d, and 12.1 ML/d greater than the mean loss rate of 18.1 ML/d (**Table 1**). These differences are readily contributed by streamflow losses in the Blougat Spruit that have been quantified at up to 7 ML/d (Hobbs, 2011), augmented with autogenic (natural) recharge at 17 ± 5% of MAP on the Zwartkrans Compartment that finds general application in the study area.

[1] The immediate AMD intervention measure in the Western Basin was commissioned in June 2012 (**Figure 2**).

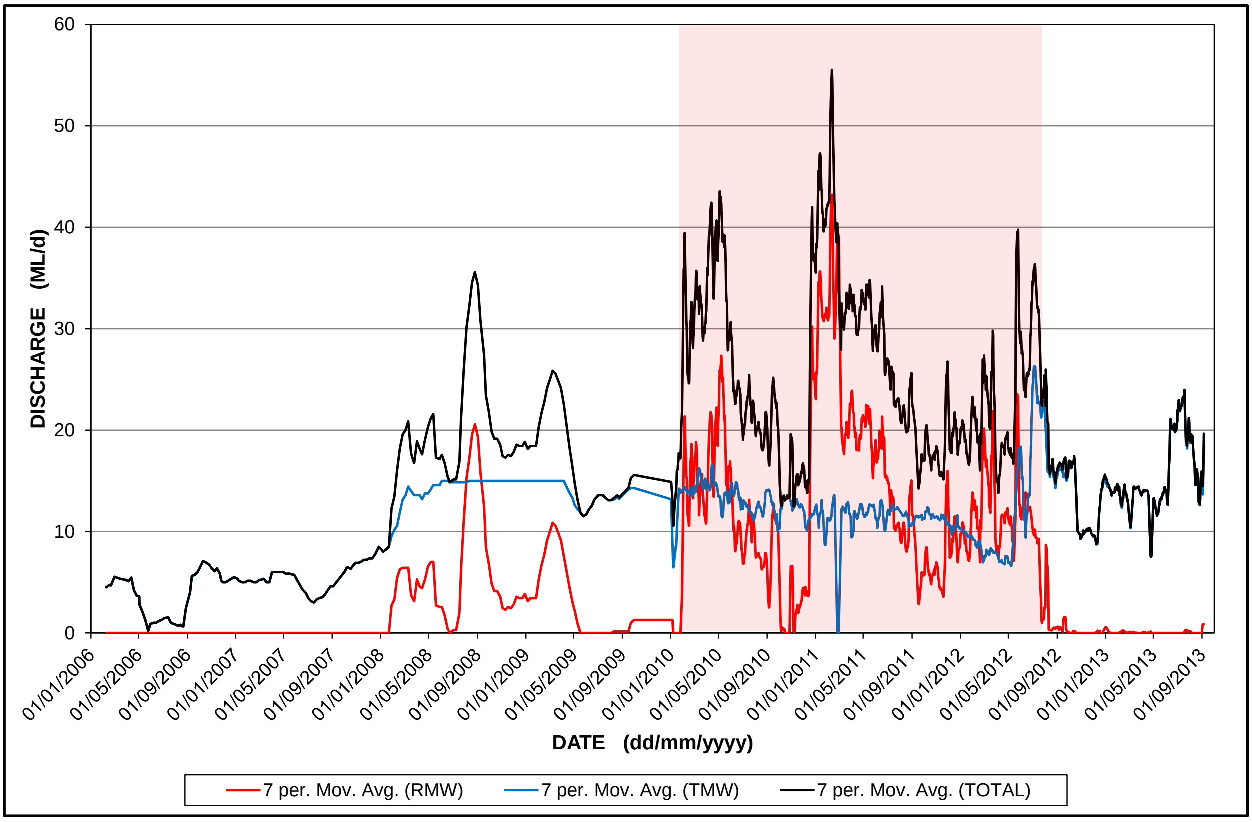

Figure 7 Pattern and trend of mine water discharge into the environment (RMW = raw mine water, TMW = treated/neutralised mine water)

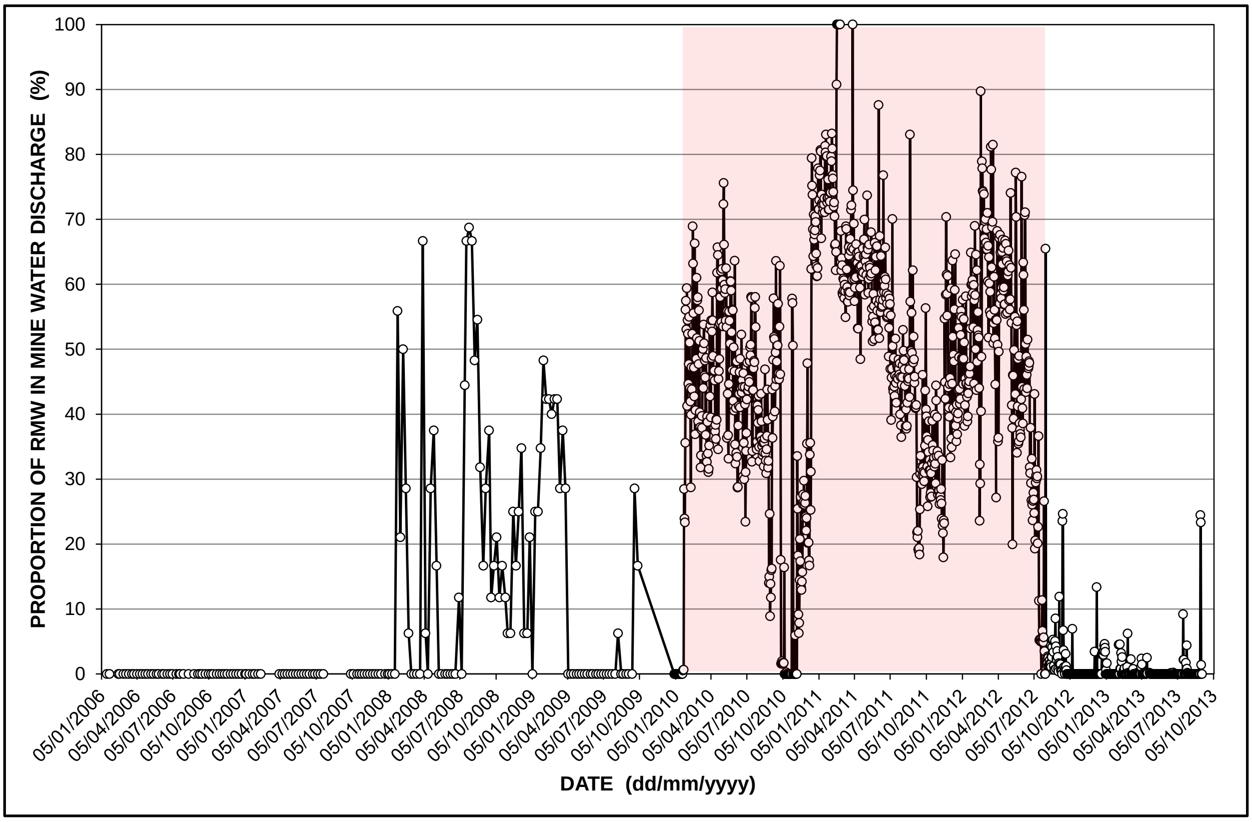

Figure 8 Pattern and trend of raw mine water (RMW) proportion in total mine water discharge into the environment

Table 1 Quantification of stream flow loss rate in the lower reach of 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
15/08/2103	30.1 ± 3.0	16.5 ± 0.8	13.6	40
15/10/2013	29.6 ± 3.0	14.1 ± 07	15.5	46
Count	28	28	28	28
Minimum	11.9	0.0	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	32.0	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

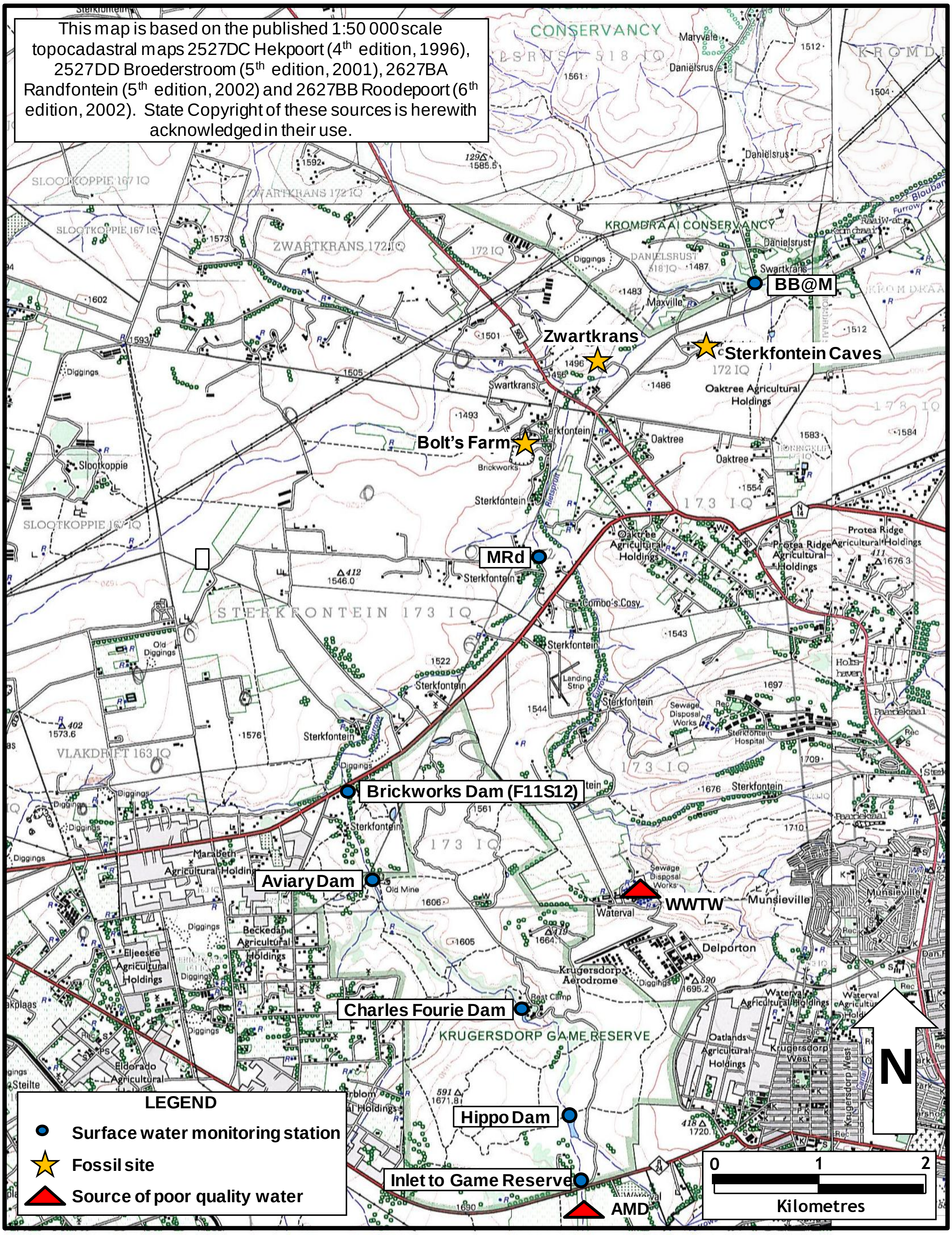

Figure 9 Locality map of surface water quantity and quality monitoring stations

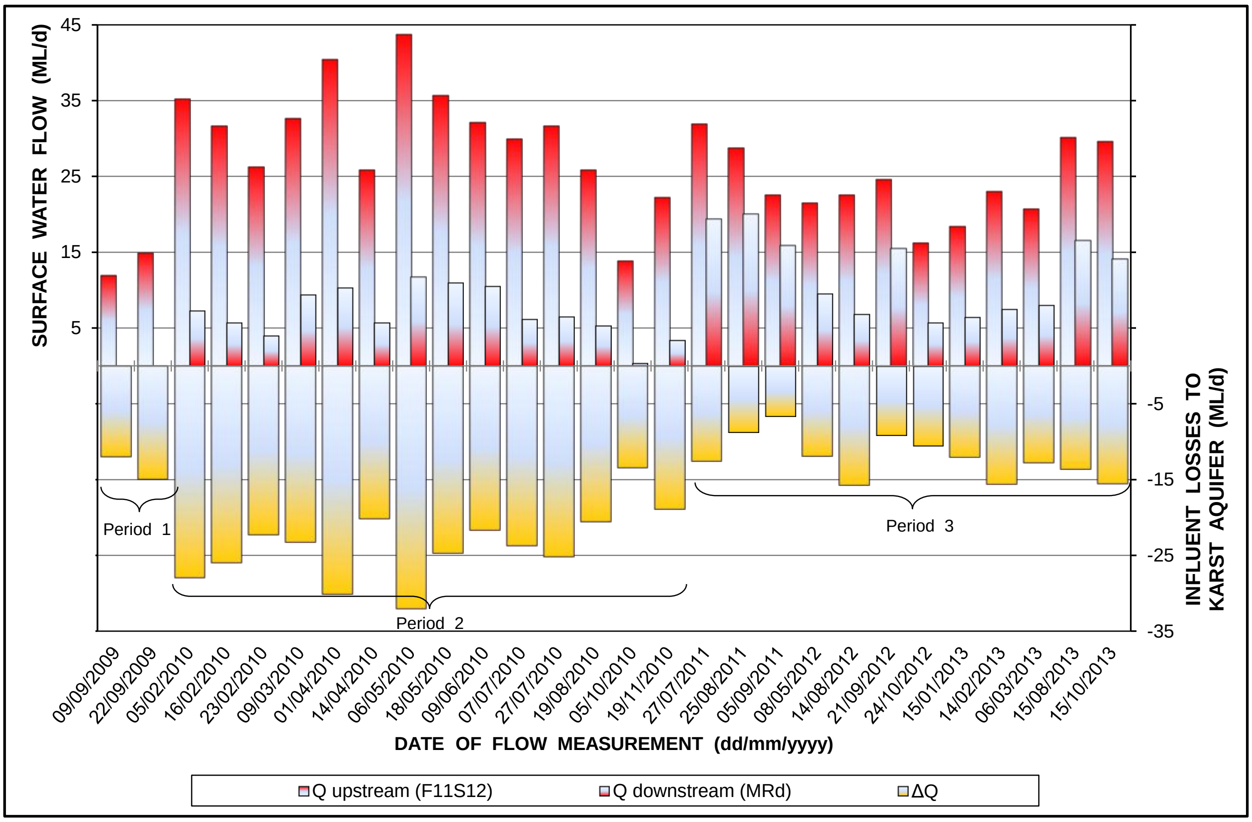

Figure 10 Graph of stream discharge and flow and losses to the karst aquifer in the lower Riet Spruit valley

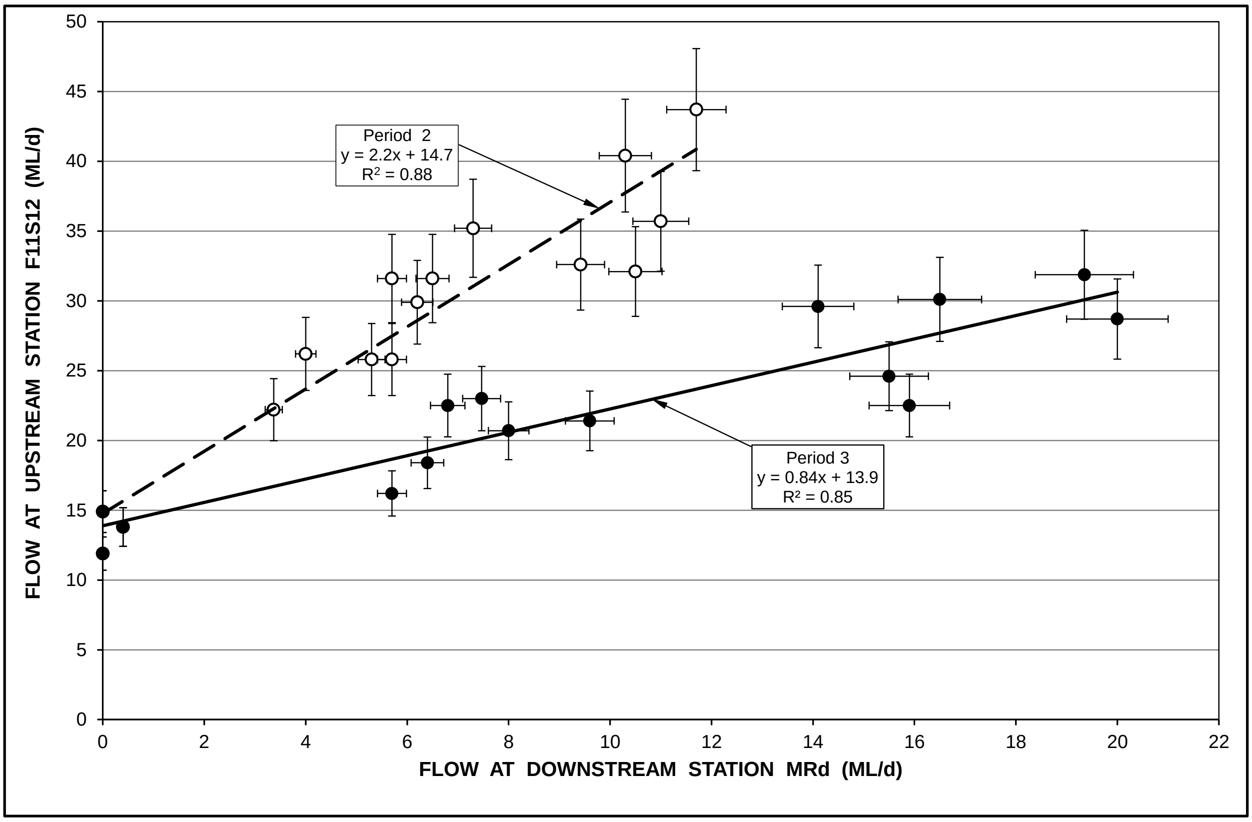

Figure 11 Correlation of stream flow at stations F11S12 and MRd in the Riet Spruit valley (respective regression lines explained in text and **Figure 10**), with error bars denoting ±10% at F11S12 (vertical) and ±5% at MRd (horizontal)

4.1.3 Catchment 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 2**.

Table 2 Statistical analysis of Bloubank Spruit monthly discharge data gauged at station A2H049 in the period October 1972 to September 2013

Variable	Month											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Count (n)	39	39	40	40	41	41	41	40	41	41	40	40
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	0.845	1.039	1.091	0.896	1.031	1.176	0.974	0.948	0.954	0.910	0.798
Mean	1.785	1.797	2.201	2.681	2.552	2.765	2.313	2.185	2.004	1.972	1.850	1.726
Median	1.536	1.680	1.872	2.375	1.946	2.432	1.920	1.799	1.696	1.637	1.555	1.386
95%ile	3.891	2.876	4.539	5.566	5.560	5.720	4.625	4.931	3.642	3.696	3.645	3.511
Maximum	4.211	4.577	5.900	12.079	10.619	9.358	6.081	5.373	5.166	4.754	4.055	4.342
SD	0.914	0.789	1.111	2.005	1.887	1.858	1.245	1.173	0.943	0.894	0.821	0.857
CoV (%)	51.2	43.9	50.5	74.8	73.9	67.2	53.8	53.7	47.0	45.3	44.4	49.6

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 12** indicates that the previous (to last) three hydrological years witnessed the 2nd, 3rd and 4th highest runoff (59.1, 50.0 and 44.9 Mm^3 after the 66.9 Mm^3 of the 1977–'78 hydrological year) in the historical record of this catchment. The significance of these circumstances is evident in their impact on the long-term median discharge of the Bloubank Spruit system, which reflects a median value of ~19.3 Mm^3/a for the period 1972–'73 to 2008–'09, and a 15% greater median value of ~22.7 Mm^3/a for the entire record. The 1972–'73 to 2008–'09 and the whole record median annual discharge values represent 11–12% of the net capacity (186.4 Mm^3) of Hartbeespoort Dam. 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. Due only in part to the exceptional rainfall of the 2009–'10 and 2010–'11 summers (**Section 3**), the contribution of mine water decant is discussed in **Sections 4.2, 4.3** and **5.2**. Nevertheless, the mine water impact might be reflected in the observation that the last six (6) years of hydrological record are only matched in contiguous duration by the seven (7) consecutive years 1975–'76 to 1981–'82 during which the whole record median discharge of ~22.7 Mm^3/a was consistently exceeded.

The instantaneous monthly flow pattern at station A2H049 for the complete record is shown in **Figure 13**. This reveals a comparatively constant lowest value of 0.25 m^3/s, and distinct recession curves following peak discharge events. Station A2H049, however, is not only located a substantial distance (5–10 km) downstream of the 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 indicates that the instantaneous daily average flow of 18.6 m^3/s recorded on 16 December 2010 is the second highest[2] in the historical record of gauging at this station. This observation provides the context for the floods experienced in the Bloubank Spruit in mid-December 2010 as discussed by Hobbs and Mills (2011).

[2] After the maximum (highest) daily average flow of 34.3 m^3/s recorded on 28 January 1978.

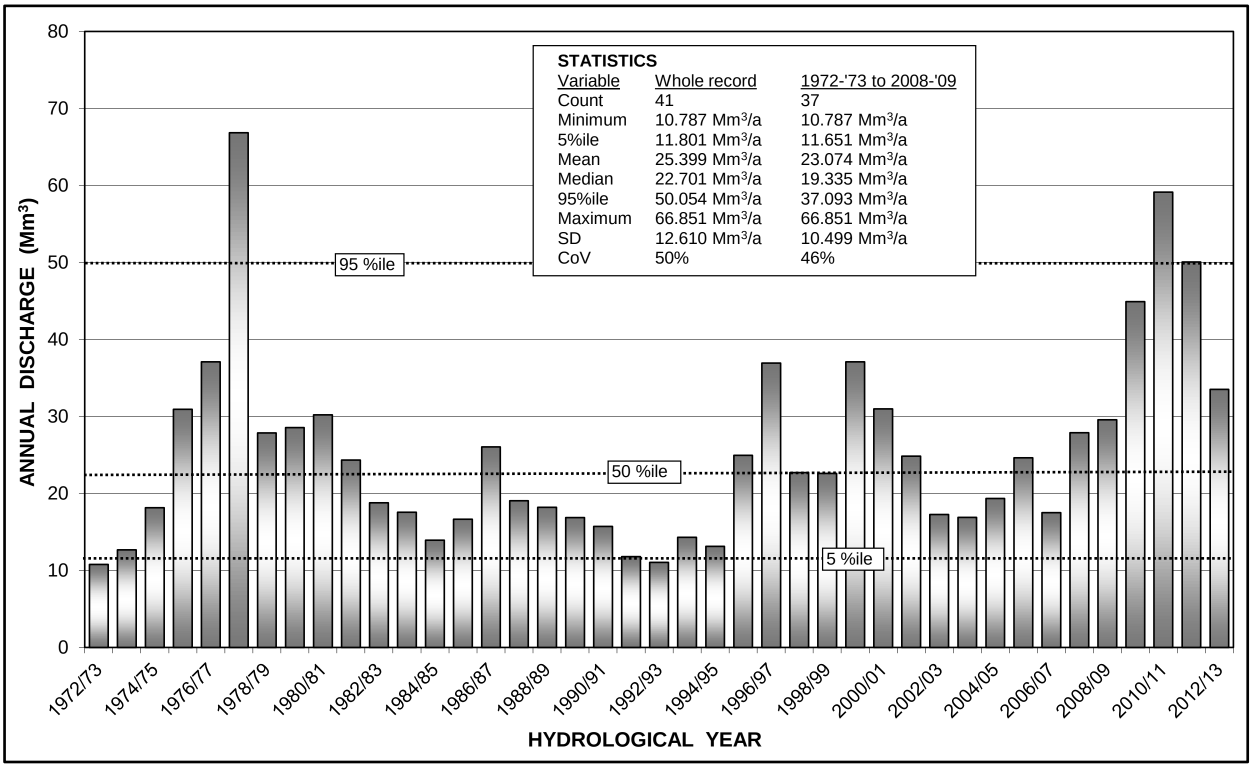

Figure 12 Graph of Bloubank Spruit annual (a_h) discharge gauged at station A2H049 in the period October 1972 to September 2013

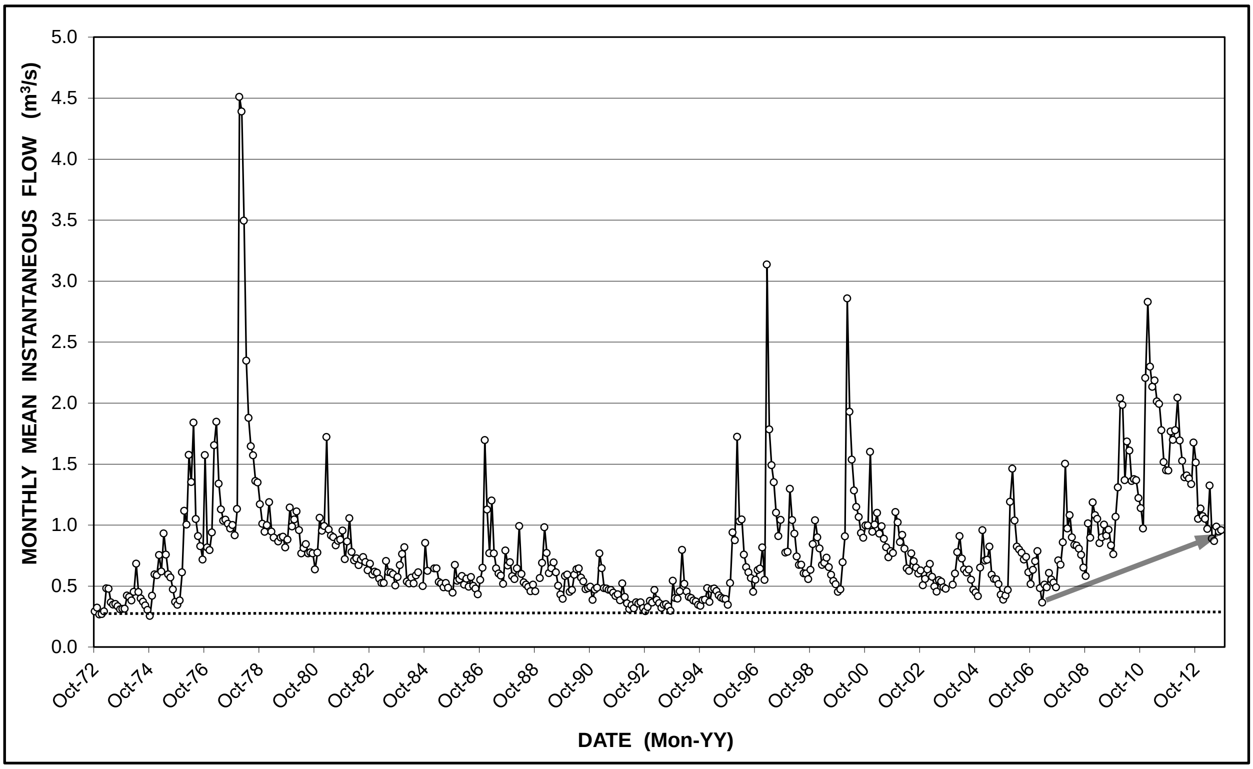

Figure 13 Long-term monthly hydrograph of the Bloubank Spruit at station A2H049 for the period October 1972 to September 2013

The significance of the Bloubank Spruit drainage in the catchment of the regionally important Hartbeespoort Dam is evident in **Table 3** and **Figure 14**. These show that the Bloubank Spruit contributes the third highest discharge (9%) to the dam after the Jukskei River (50%) and Hennops River (24%) in the long-term. However, the COH WHS property is also drained by the Skeerpoort River, which increases the long-term annual contribution of the property to 13% (34.7 Mm^3).

Table 3 Statistical analysis of the annual (a_h) discharge contributions associated with the main rivers draining the Hartbeespoort Dam catchment

Statistical Parameter	**Gauging Station and Drainage**					
	A2H013 Magalies R.	**A2H014 Hennops R.**	**A2H034 Skeerpoort R.**	**A2H044 Jukskei R.**	**A2H049 Bloubank Sp.**	**A2H050 Crocodile R.**
Minimum	0.799	11.422	4.858	66.027	11.051	2.592
5%ile	1.103	15.884	5.416	70.463	12.644	3.211
Mean	30.852	66.210	12.525	149.854	25.764	14.739
Median	19.642	58.679	11.154	124.587	23.520	11.361
95%ile	101.574	138.350	23.646	300.893	50.507	36.617
Maximum	127.094	168.195	34.745	326.546	66.851	43.098
SD	33.172	43.884	6.565	73.494	12.550	10.872
CoV (%)	108	66	52	49	49	74

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 analysis period spans the 40 full hydrological years 1973–'74 to 2012–'13 common to all six stations.
The Crocodile River data exclude the discharge generated downstream of station A2H050.

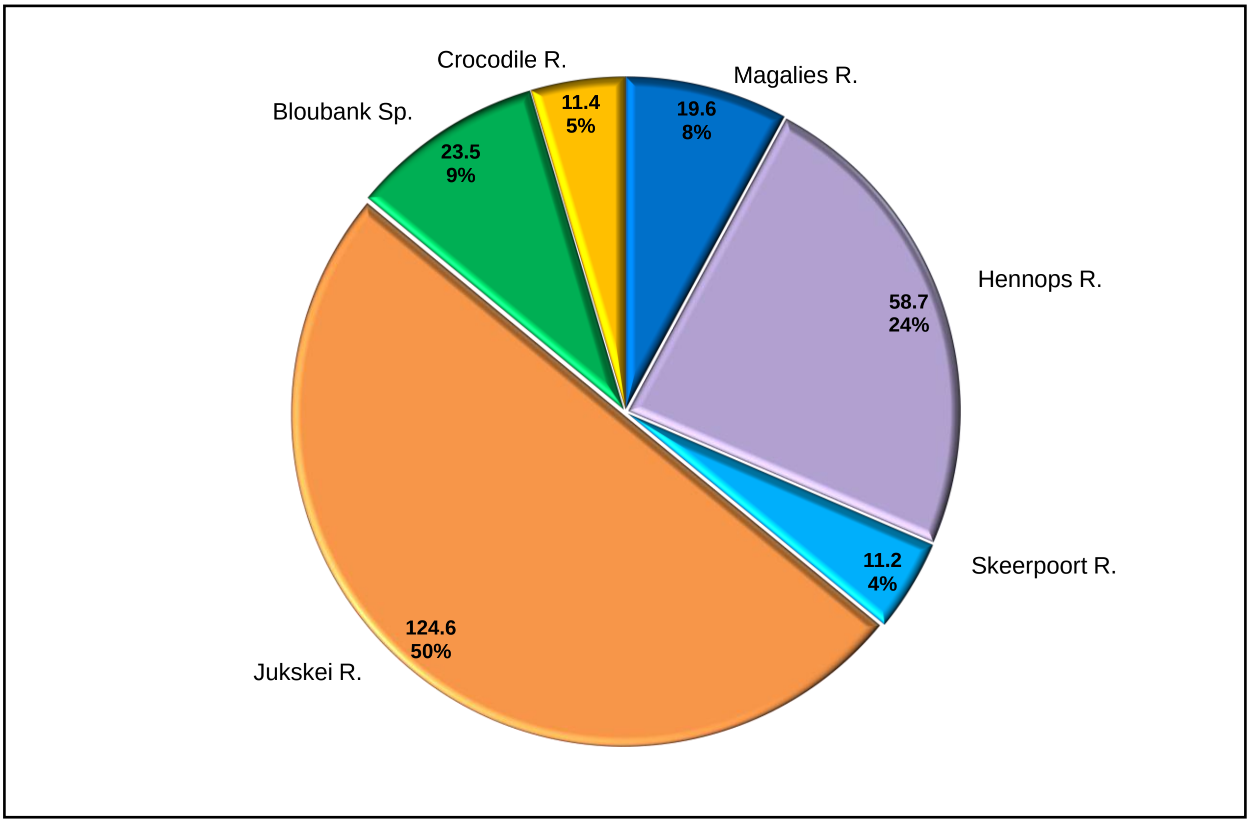

Figure 14 Comparison of median annual (a_h) discharge contributions as Mm^3 and % (out of a total of 248.9 Mm^3) of the main drainages in the Hartbeespoort Dam catchment (data from **Table 3**)

The lowest CoV values reported in **Table 3** are associated with those drainages that host sources of perennial discharge either in the form of an artificial contribution such as the Northern WWTW on the Jukskei River, or a natural contribution such as the karst springs of quaternary basins A21D (Bloubank Spruit system) and A21G (Skeerpoort River). These 'moderating' contributions are reflected in CoV values of ~49% (Jukskei River and Bloubank Spruit) and ~52% (Skeerpoort River). The poorest CoV value of 108% is associated with the Magalies River (quaternary basin A21F), and reflects the two-fold impact of excessive groundwater abstraction in the Steenkoppies Compartment on the discharge of Maloney's Eye (the source of the river), and agricultural use in the intensively developed valley. Proposed opencast gold mining in the Blaauwbank Spruit[3] valley upstream (west) of the town of Magaliesburg poses a further threat to the water resources of the Magalies River.

Further inspection of the discharge data for the different drainages in the period 1973–'74 to 2012–'13 indicates that the ~186 Mm^3 full supply capacity of Hartbeespoort Dam was exceeded in 27 of the 40 hydrological years on record (**Figure 15**). The years of 'deficit' (ΣQ <MAR) all precede the 1993–'94 hydrological year. The sustained period of 'below normal' runoff commencing in 1978–'79, terminated with >MAR conditions in the 1986–'87 hydrological year. The relative constancy of the springwater-driven Bloubank Spruit and Skeerpoort River in the 'below normal' runoff years is also evident. Equally evident is the sustained period of 'above normal' runoff commencing in 2005–'06, and including the two highest runoff years (2009–'10 and 2010–'11) in the 40-year record shown in **Figure 15**.

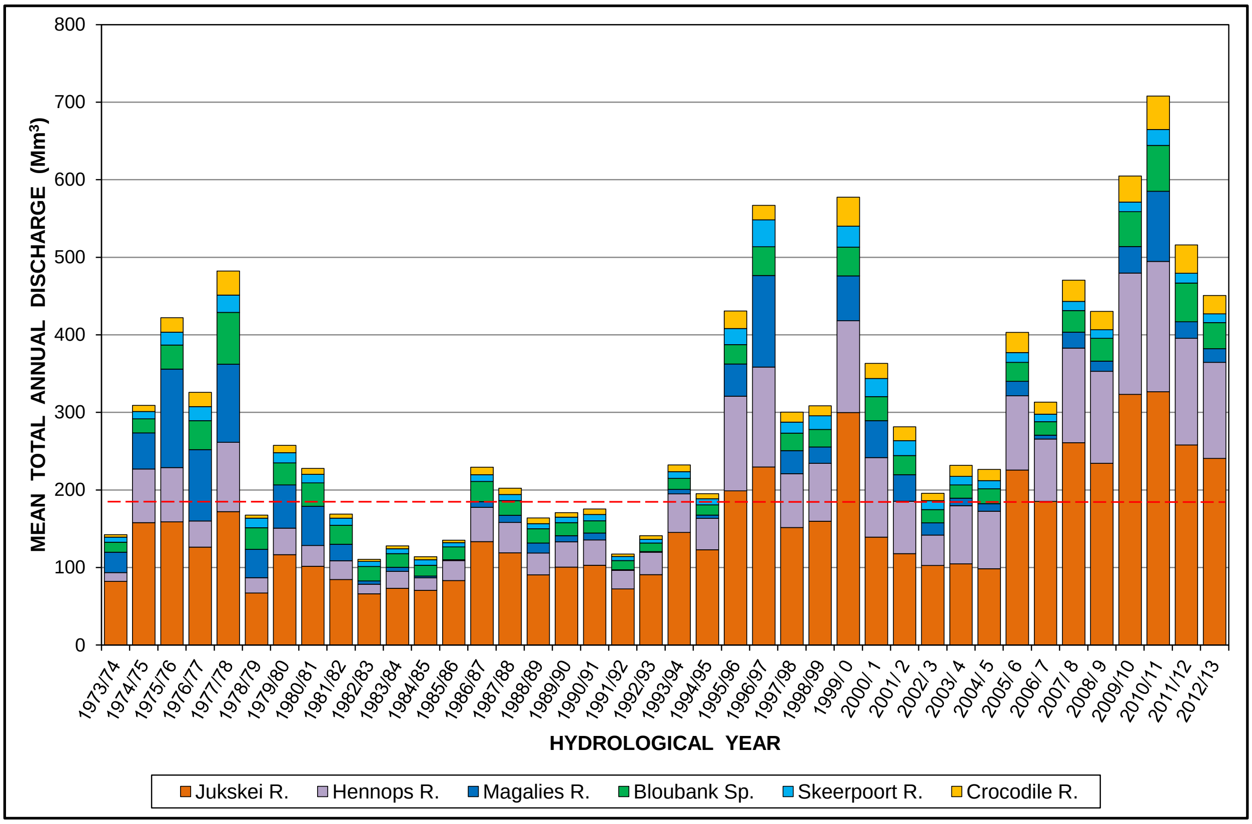

Figure 15 Pattern and trend of combined annual (a_h) discharge (ΣQ) by main drainages in the Hartbeespoort Dam catchment in the period of common record, compared to the ~186 Mm^3 full supply capacity of the dam (horizontal pecked line) that approximates the mean annual runoff to the dam

3 Not to be confused with the Bloubank Spruit of the COH WHS.

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 9** as (a) the inlet to the KGR, (b) the Hippo Dam, (c) the Charles Fourie Dam, (d) the Aviary Dam and (e) the Brickworks Dam (DWA station F11S12). The weekly monitoring of the variables pH, electrical conductivity (EC) and SO_4 dates back to May 2004. The results of this monitoring, excluding the inlet to the KGR location[4], the Charles Fourie Dam[5] and the Aviary Dam[6], are presented in **Figure 16** (pH), **Figure 17** (EC) and **Figure 18** (SO_4). The patterns revealed in these graphs indicate the variation and trend in the respective variable values that are manifested in surface water chemistry through the KGR over time. It is clear from **Figure 16**, and to a lesser extent from **Figure 17** and **Figure 18**, that the most severe and sustained impact of AMD on the receiving surface water environment of the Tweelopie Spruit that commenced in February 2010 (period B–C), has been mitigated by the commissioning in June 2012 of the immediate AMD management measures spanning the period C–. This is unequivocally shown in the somewhat shorter record of Fe (**Figure 19**), Mn (**Figure 20**) and U (**Figure 21**) values.

A scrutiny of the differences between the three periods of record defined by the divisions recognised in **Figure 16** to **Figure 21** returns the information presented in **Table 4** and illustrated in **Figure 22**. The graphs not only illustrate the differences, most notably the ‘poorer’ values in the B–C period of severest AMD impact, but also reveal other salient aspects such as (a) the generally greater variability in analyte concentrations at the upstream Hippo Dam station compared to the Brickworks Dam station, and (b) the typically lower analyte concentrations (including pH) at the downstream Brickworks Dam station compared to the Hippo Dam station.

The statistics for total uranium (U_T) in **Table 4** indicate the need for caution when considering U concentrations under circumstances where significant differences between the ‘normal’ A–B (September 2006 – January 2010) and C– periods (August 2012 – September 2013) and the ‘abnormal’ B–C period (February 2010 – July 2012) are evident. The mean and median values at both stations in the B–C period exceed the SANS (2011a) limit of 0.015 mg/L associated with a chronic health risk attributable to ingestion over an extended period. In contrast, the mean and median values for the other two periods meet the SANS (2011a) limit. A complication that is not considered, however, is the potential under-evaluation of U concentrations associated with a ‘biased’ sample collection regimen. For example, Winde et al. (2004) reports differences in U concentrations between daytime and night-time samples, the latter typically returning higher concentrations. Reasons put forward for this include preferential groundwater exfiltration and lower pH values at night when biological de-calcification and the associated U immobilisation is also at a minimum.

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[4] 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.

[5] The Charles Fourie Dam is excluded because its data is not mundane to the assessment presented in this report, and because most readers are not concerned with how much data is evaluated, but whether the data speaks to the specific agenda of the individual reader.

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

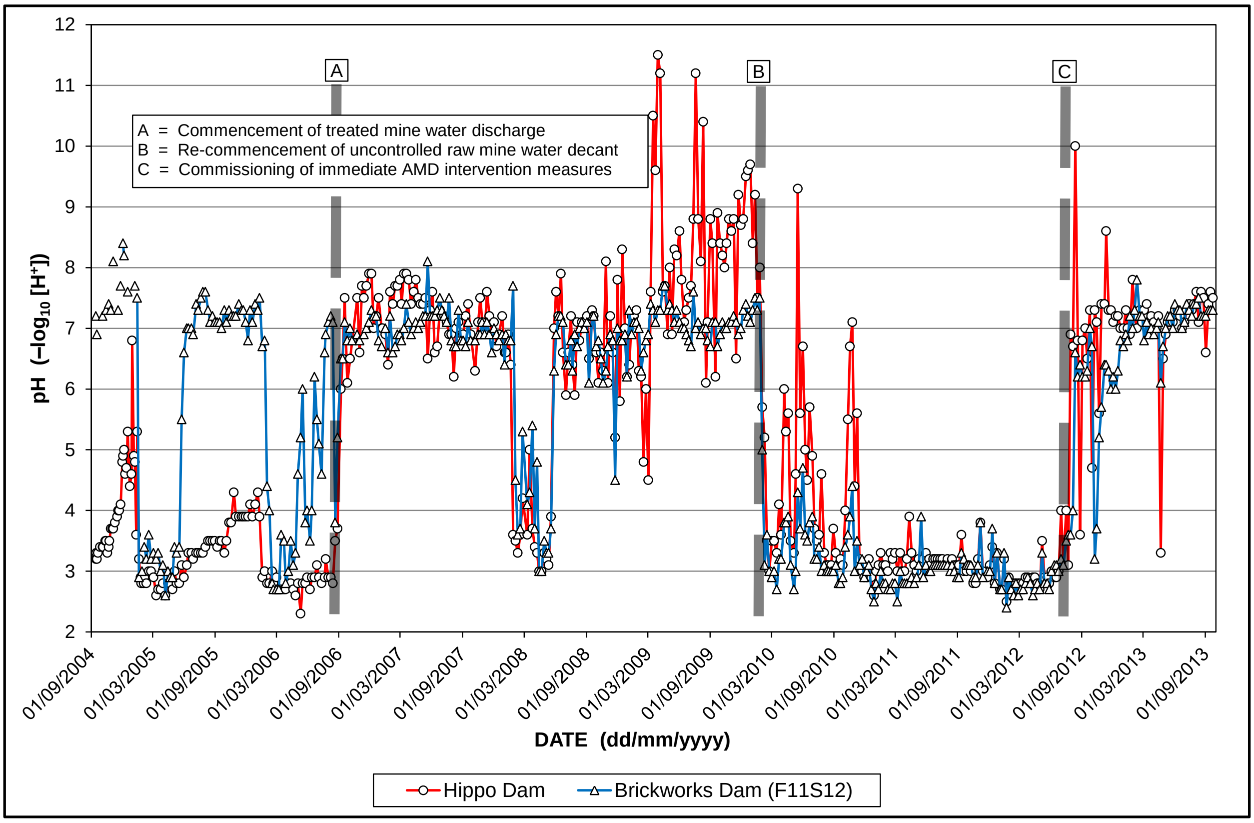

Figure 16 Pattern of pH values in the Tweelopie Spruit in the period September 2004 to September 2013

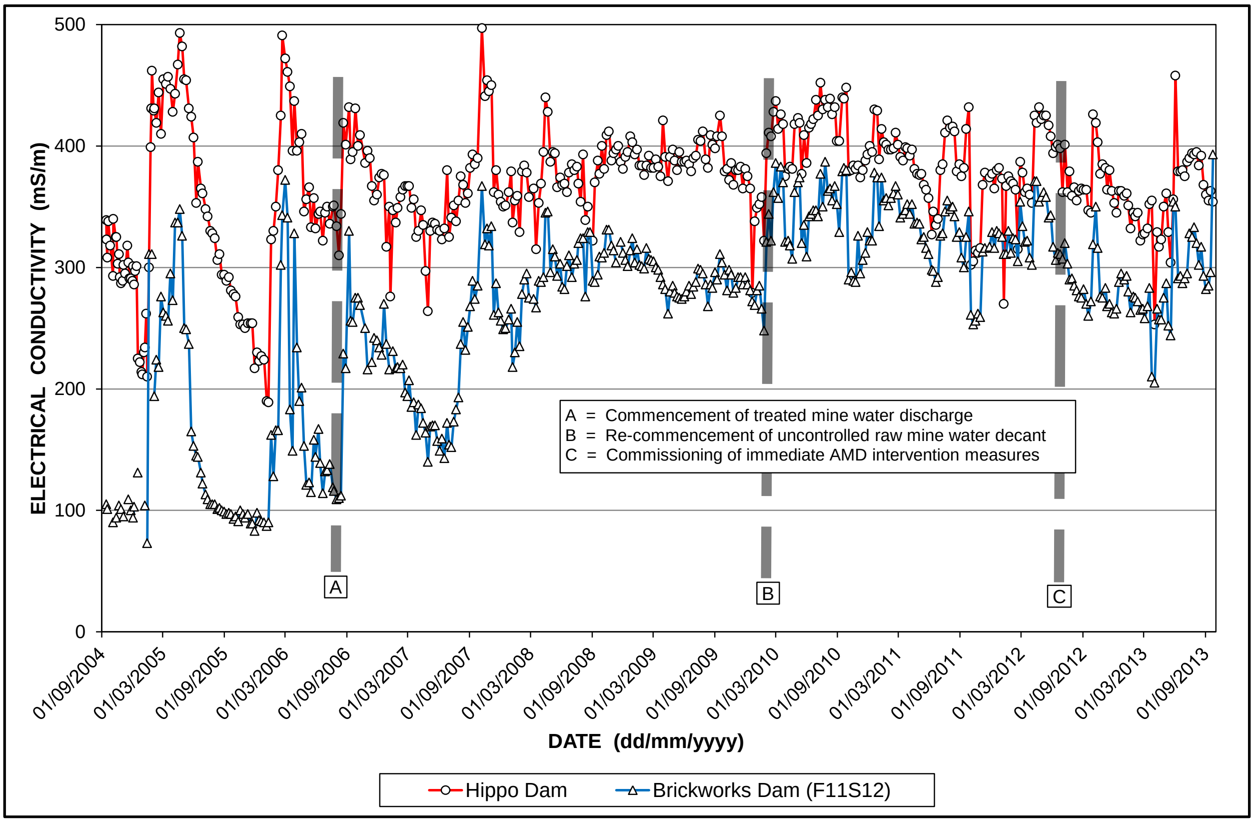

Figure 17 Pattern of electrical conductivity values in the Tweelopie Spruit in the period September 2004 to September 2013

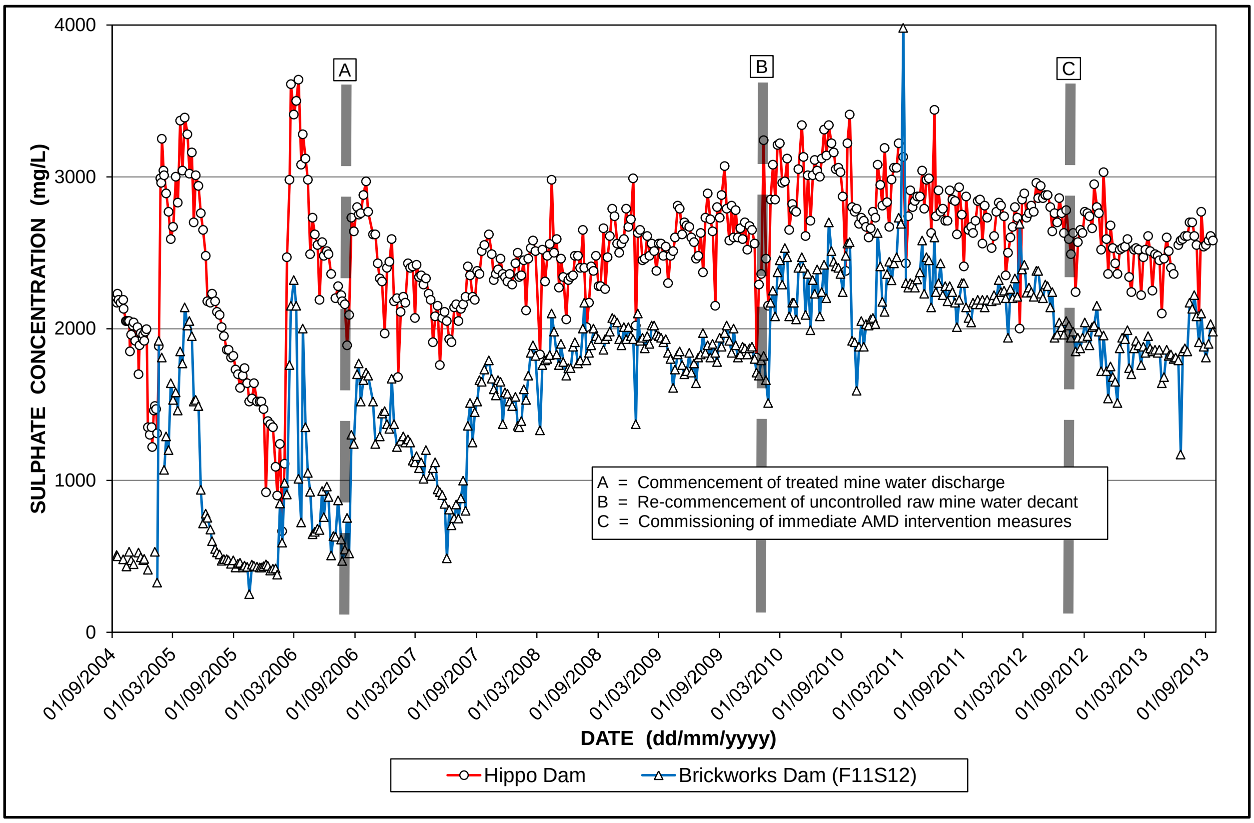

Figure 18 Pattern of SO_4 values in the Tweelopie Spruit in the period September 2004 to September 2013

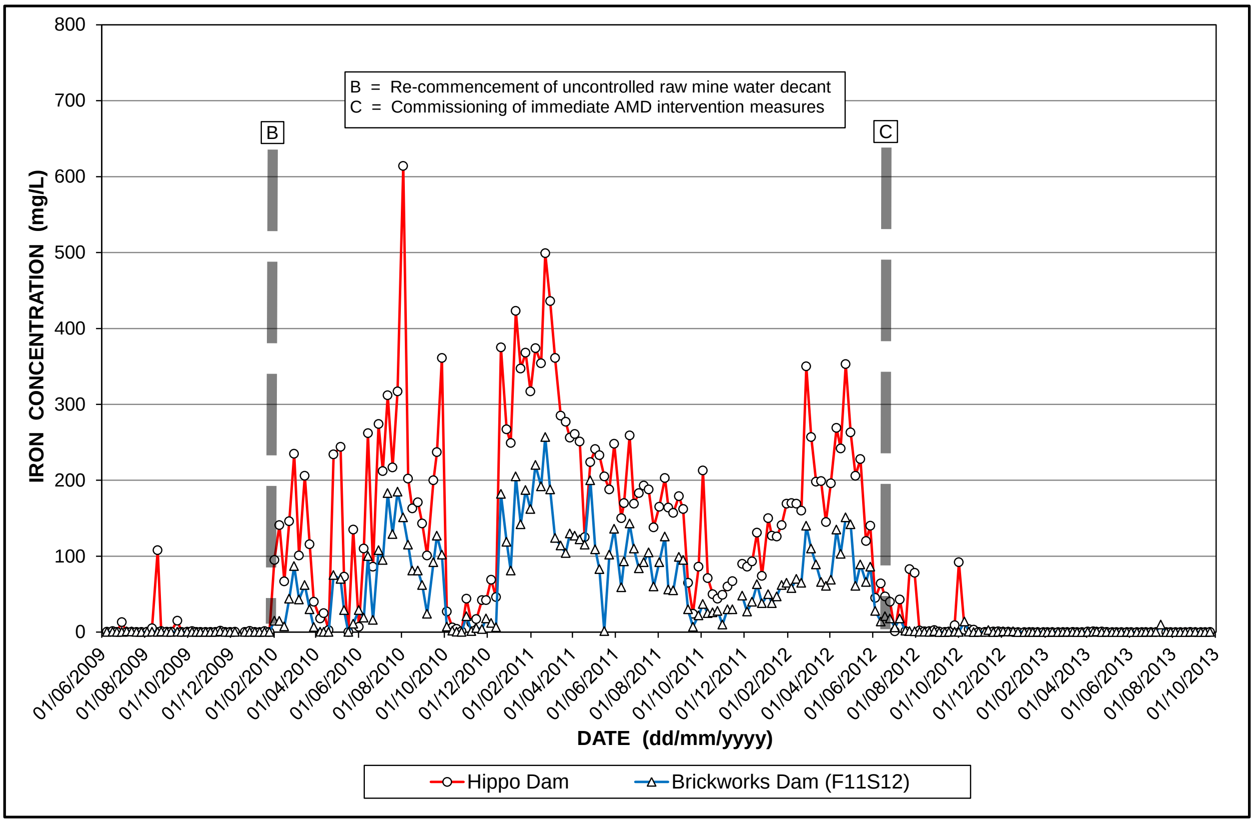

Figure 19 Pattern of Fe values in the Tweelopie Spruit in the period June 2009 to September 2013

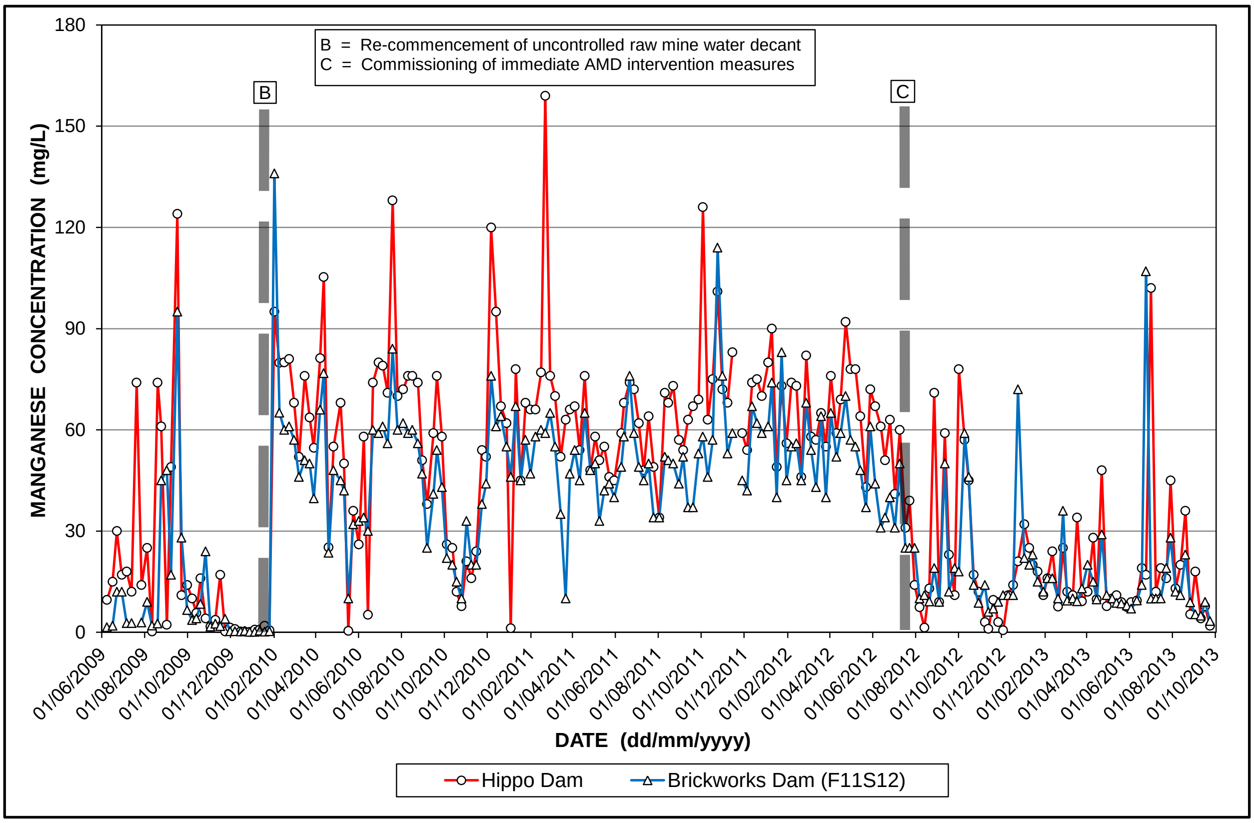

Figure 20 Pattern of Mn values in the Tweelopie Spruit in the period June 2009 to September 2013

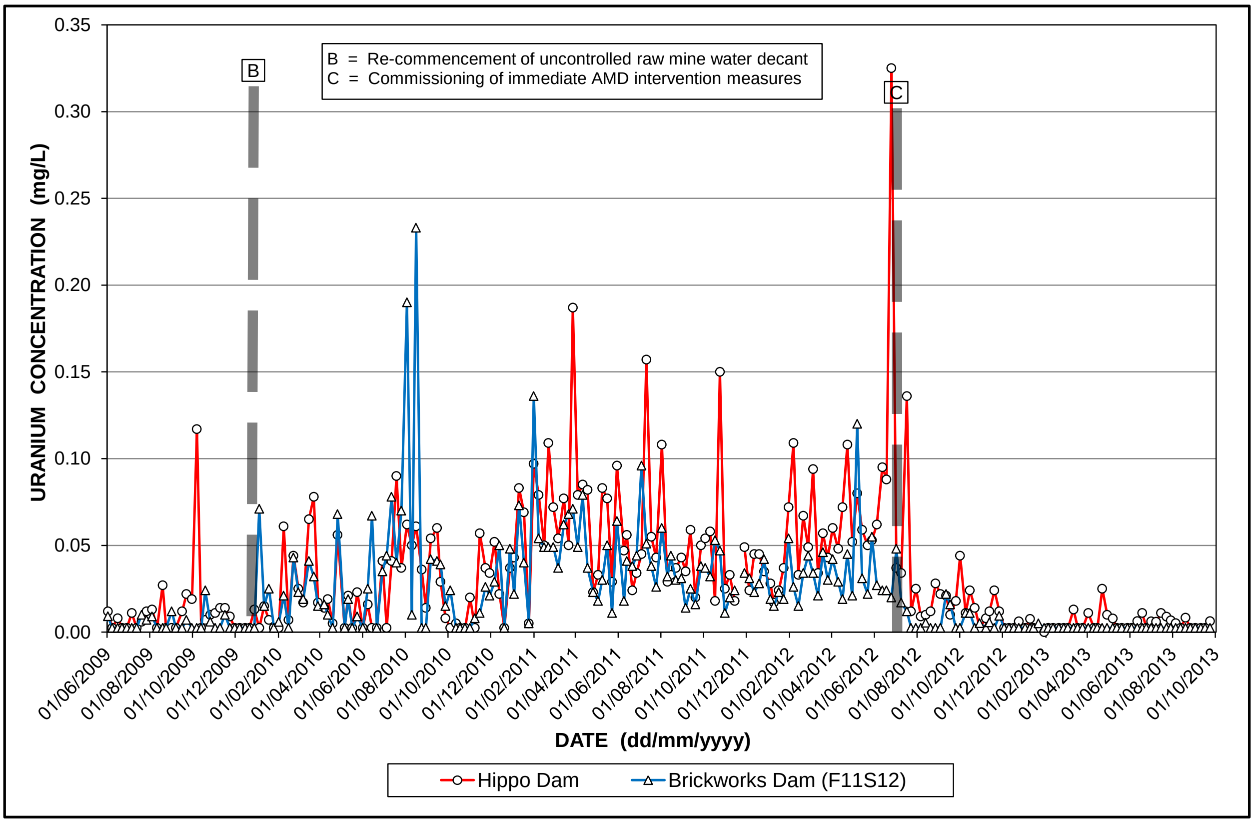

Figure 21 Pattern of U values in the Tweelopie Spruit in the period June 2009 to September 2013

Table 4 Summary statistics of periodic-related surface water chemistry changes in the Tweelopie Spruit associated with three distinct mine water discharge regimes

Variable	Statistical Parameter	Hippo Dam			Brickworks Dam (F11S12)		
		A—B(1)	**B—C(2)**	**C—(3)**	**A—B(1)**	**B—C(2)**	**C—(3)**
pH $(-\log_{10}[H^+])$	n	175	129	61	173	128	61
	5%ile	3.6	2.8	5.6	3.9	2.7	4.0
	Mean	—	—	—	—	—	—
	Median	7.2	3.2	7.2	6.9	3.0	7.0
	95%ile	9.3	5.7	7.6	7.4	3.9	7.4
	SD	1.5	1.0	0.9	0.9	0.4	1.0
	CoV	21.8	29.7	12.9	14.1	13.7	14.3
EC (mS/m)	n	174	129	61	172	128	61
	5%ile	324	320	322	167	288	252
	Mean	374	391	361	268	332	285
	Median	379	393	361	283	330	282
	95%ile	426	438	403	329	378	350
	SD	32	33	31	48	29	31
	CoV	8.5	8.4	8.5	18.0	8.7	11.0
SO_4 (mg/L)	n	175	128	60	171	128	61
	5%ile	2 017	2 511	2 239	893	1 947	1 640
	Mean	2445	2 846	2 544	1 636	2 264	1 867
	Median	2 460	2 815	2 550	1 760	2 240	1 870
	95%ile	2 810	3 220	2 772	2 015	2 593	2 130
	SD	259	226	177	349	245	168
	CoV	10.6	7.9	6.9	21.3	10.8	9.0
Fe (mg/L)	n	33	129	61	33	128	61
	5%ile	0.1	6.5	0.004	0.1	1.2	0.010
	Mean	4.7	168.4	3.376	0.3	72.9	0.613
	Median	0.4	163.0	0.040	0.2	64.0	0.100
	95%ile	13.8	365.2	4.000	0.8	186.3	1.200
	SD	18.8	116.2	15.270	0.3	57.7	2.183
	CoV	399.1	69.0	452.4	94.4	79.1	355.9
Mn (mg/L)	n	34	129	61	33	128	61
	5%ile	0.2	22.2	1.9	0.1	20.7	6.0
	Mean	18.1	62.7	20.0	10.3	50.3	17.6
	Median	9.8	65.0	13.0	2.7	50.0	11.0
	95%ile	74.0	95.0	59.0	46.2	76.0	50.0
	SD	27.6	23.5	19.7	19.4	17.6	17.3
	CoV	152.5	37.6	98.5	187.6	35.1	98.2
U_{TOTAL} (mg/L)	n	56	129	61	56	128	61
	5%ile	0.003(4)	0.00(4)3	0.00(4)3	0.003(4)	0.003(4)	0.003(4)
	Mean	0.013	0.049	0.009	0.008	0.035	0.004
	Median	0.010	0.043	0.006	0.003(4)	0.030	0.003(4)
	95%ile	0.030	0.109	0.025	0.026	0.076	0.011
	SD	0.018	0.042	0.008	0.011	0.032	0.003(4)
	CoV	135.0	84.6	97.8	147	90.5	95.1

(1) September 2006 – January 2010
(2) February 2010 – July 2012
(3) August 2012 – September 2013
(4) Value biased by the detection limit (DL) of 0.005 mg/L, analysed as 50% of DL (0.0025 mg/L) if <DL

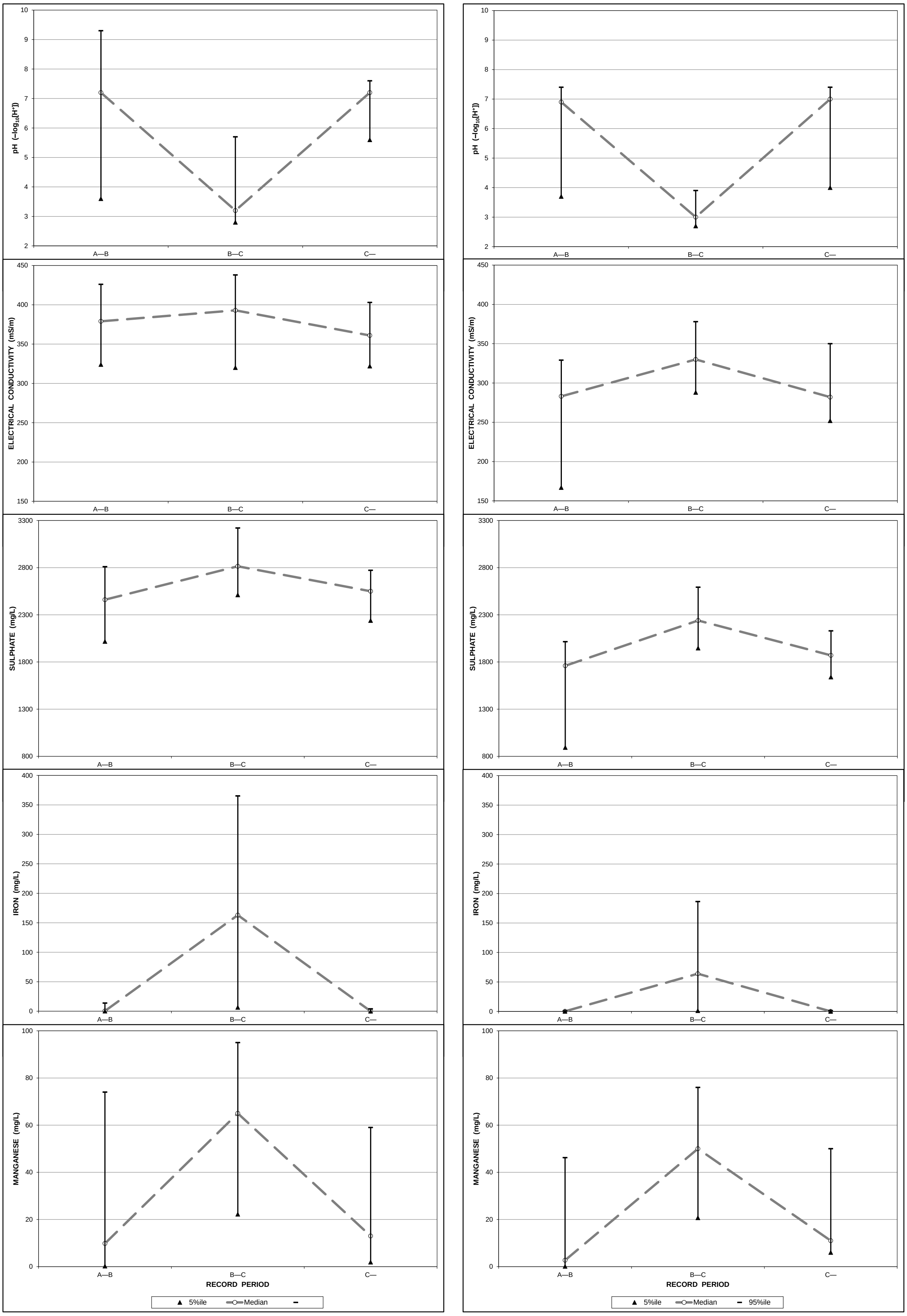

Figure 22 Period-related surface water chemistry changes in the Tweelopie Spruit for the variables (from top to bottom) pH, EC, SO_4, Fe and Mn at the Hippo Dam (left) and Brickworks Dam (right) (period and data definition from **Table 4**)

The measured salinity and pH values and derived[7] SO_4 values associated with each SDM reported for stations F11S12 and MRd in **Table 5** are graphed in **Figure 23** (EC and pH) and **Figure 24** (SO_4). It is this allogenic recharge that has manifested the mine water imprint on the karst groundwater of the Zwartkrans Compartment (**Section 5.2.2**). The positive influence of the immediate AMD management measures is evidenced in all of **Figure 16** to **Figure 24**. 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 5.2.2**).

Table 5 Record of electrical conductivity and pH measurements made at stations F11S12 and MRd on the occasion of flow gauging measurements (SDMs), also showing derived SO_4 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	2 094	2 479	6.7				
05/02/2010	389	2 588	2 997	3.9	358	2 361	2 759	4.1
16/02/2010	339	2 219	2 610	4.2	335	2 190	2 581	4.2
23/02/2010	379	2 512	2 918	4.1	383	2 541	2 948	3.9
09/03/2010	379	2 512	2 918	4.1	353	2 323	2 720	4.0
01/04/2010	374	2 475	2 878	3.6	358	2 361	2 759	3.4
14/04/2010	358	2 358	2 757	3.7	347	2 277	2 672	3.6
06/05/2010	408	2 726	3 142	3.2	420	2 814	3 234	3.3
18/05/2010	335	2 189	2 580	5.5	356	2 344	2 741	4.4
09/06/2010	370	2 447	2 849	4.4	373	2 469	2 872	4.5
07/07/2010	374	2 476	2 880	4.0	376	2 491	2 895	3.9
27/07/2010	407	2 718	3 134	3.7	395	2 630	3 042	4.1
19/08/2010	384	2 549	2 957	2.6	335	2 189	2 580	2.7
05/10/2010	307	1 983	2 364	3.0	383	2 542	2 949	2.5
19/10/2010	314	2 035	2 418	3.6	326	2 123	2 510	3.1
19/11/2010	338	2 211	2 603	2.8	333	2 175	2 564	2.8
18/12/2010	416	2 785	3 203	2.7	376	2 491	2 895	3.0
27/07/2011	369	2 439	2 841	2.7	373	2 469	2 872	2.9
25/08/2011	389	2 586	2 995	2.9	405	2 704	3 119	2.5
05/09/2011	362	2 388	2 787	2.6	367	2 424	2 826	2.6
08/05/2012	372	2 461	2 864	2.6	388	2 579	2 988	2.9
14/08/2012	299	1 925	2 302	6.3	309	1 998	2 379	4.2
21/09/2012	290	1 859	2 233	7.6	288	1 844	2 218	6.9
24/10/2012	264	1 667	2 033	4.3	270	1 712	2 079	3.8
15/01/2013	282	1 800	2 171	6.6	283	1 807	2 179	4.9
14/02/2013	274	1 741	2 110	7.0	277	1 763	2 133	6.4
06/03/2013	244	1 520	1 879	6.9	241	1 498	1 856	6.6
15/08/2013	219	1 337	1 686	7.1	219	1 337	1 686	6.6
15/10/2013	275	1 748	2 118	6.6	274	1 741	2 110	6.2
Count	28	28	28	28	28	28	28	28
Minimum	219	1 337	1 686	2.6	219	1 337	1 686	2.5
Mean	340	2 223	2 615	—	339	2 221	2 613	—
Median	360	2 373	2 772	4.0	355	2 333	2 730	3.9
Maximum	416	2 785	3 203	7.6	420	2 814	3 234	6.9
SD	54	395	414	1.6	51	377	395	1.3
CoV (%)	16	18	16	37	15	17	15	33

(1) $SO_4 = 7.35*EC - 273$ ($R^2 = 0.91$) to derive a theoretical representative SO_4 value
(2) EC * 7.7 to derive a theoretical representative TDS value

[7] The correlation between EC and SO_4 derived from the large RU/G1 data set for the Brickworks Dam (F11S12) monitoring station (see **Figure 17** and **Figure 18**) allows for the derivation of SO_4 values according to the relationship described in Note 1, **Table 5**; this relationship is also considered to hold true for station MRd.

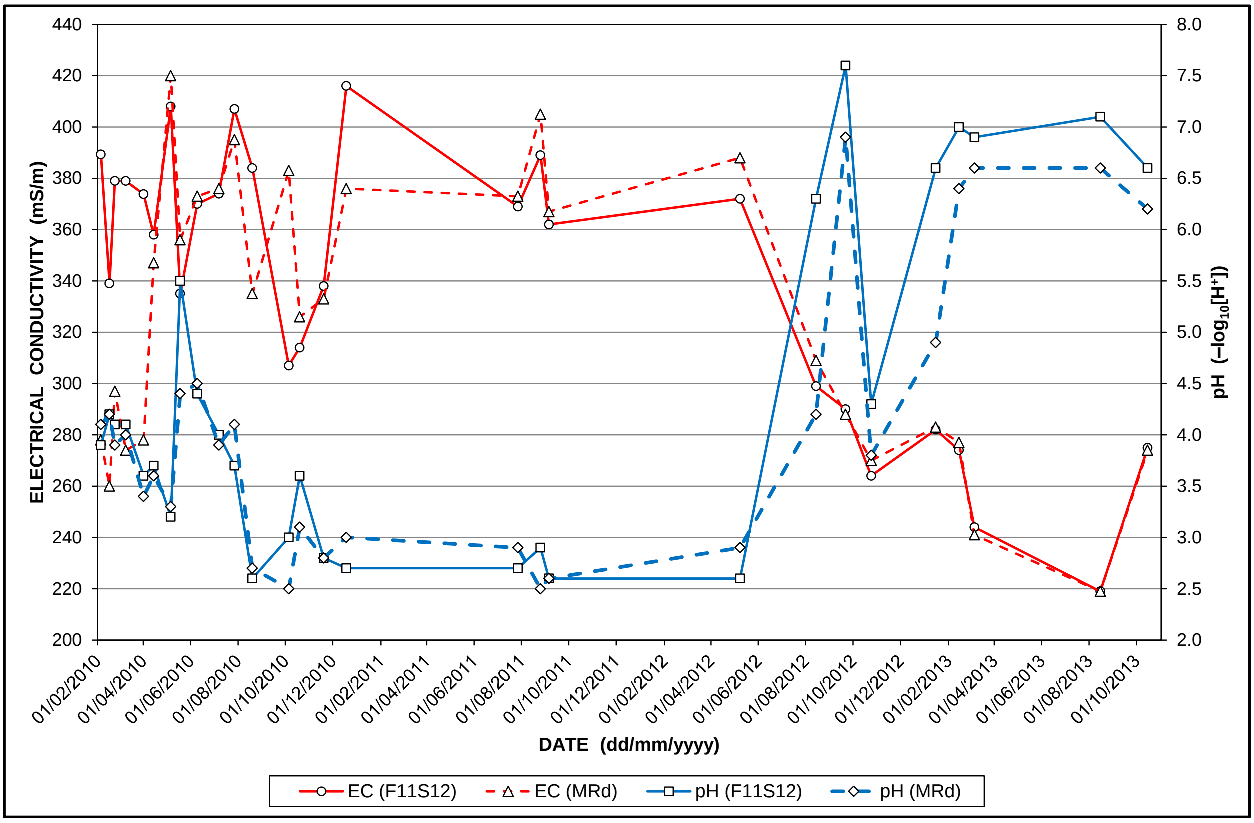

Figure 23 Pattern and trend of electrical conductivity and pH of surface water at stations F11S12 and MRd on occasion of the SDMs (data from **Table 5**)

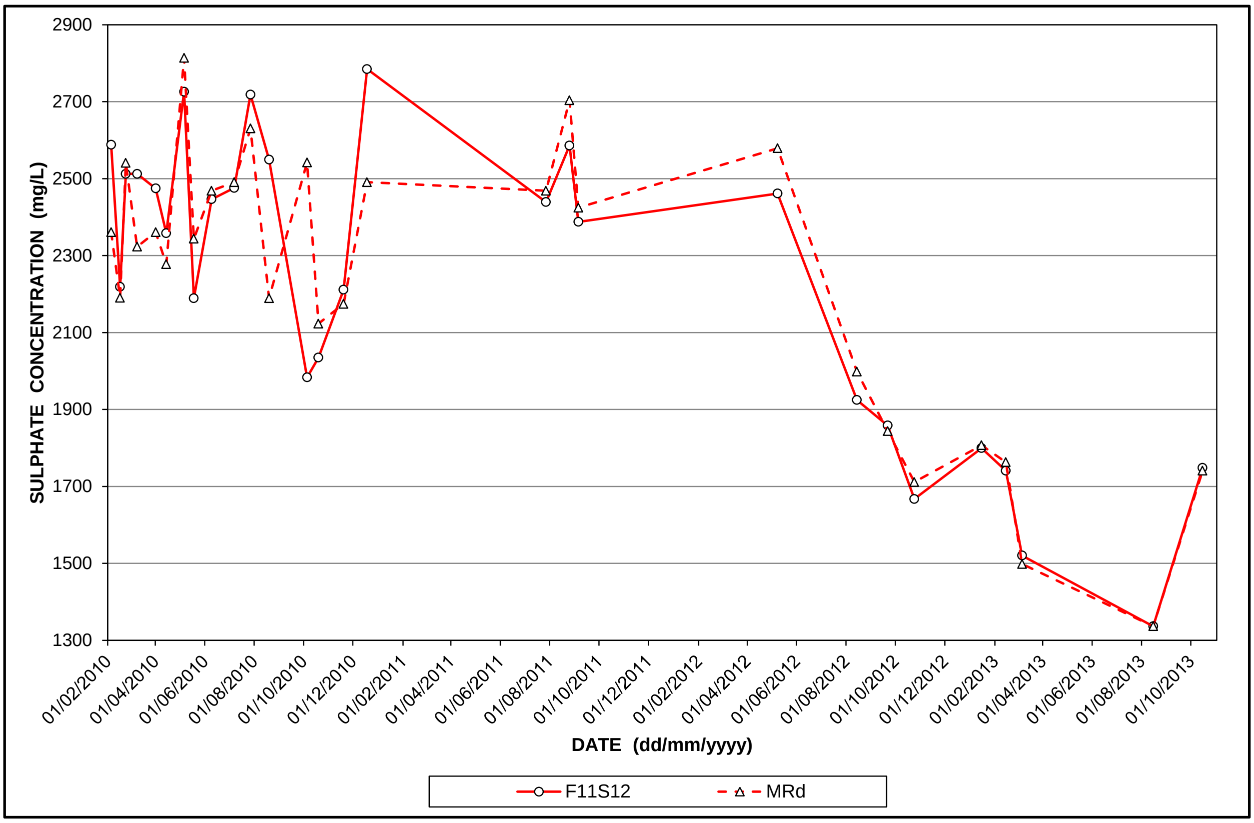

Figure 24 Pattern and trend of SO_4 in surface water at stations F11S12 and MRd on occasion of the SDMs (data from **Table 5)**

The association of mine water with the presence of other metals such as aluminium (Al), cadmium (Cd), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn) raises concern for the levels of these elements in the water discharged into the environment. The weekly surface water quality monitoring programme carried out by RU/G1 (and which forms the basis for the analysis presented in **Section 4.2.1**) has, since April 2005, included the analytes listed in **Table 6** for the periods indicated.

Table 6 List of metal analytes monitored in treated/neutralised mine water discharged into the environment from the locus of decant

Analyte	**Monitoring Period**				**SANS (2011a)[(1)]**
	05/2005 – 07/2009	**08/2009 – 09/2010**	**10/2010 – 11/2012**	**12/2012 – 09/2013**	
	Detection limit	Detection limit	Detection limit	Detection limit	
Fe (mg/L)	0.1	0.1	0.1	0.001	≤ 2
Al (mg/L)		1.0	1.0	0.001	≤ 0.3
Mn (mg/L)		0.1	0.1	0.1	≤ 0.5
U_T (µg/L)		5.0	5.0		≤ 15
Cr (mg/L)		0.001	0.001		≤ 0.05
V (mg/L)		0.001	0.001		≤ 0.2
Pb (mg/L)		0.001	0.001	0.001	≤ 0.01
Co (mg/L)		0.001	0.001		≤ 0.5
Ni (mg/L)		0.001	0.001	0.001	≤ 0.07
U_D (µg/L)			5.0	5.0	≤ 15
Cd (mg/L)				0.001	≤ 0.003
Cu (mg/L)				0.001	≤ 2
Zn (mg/L)				0.001	≤ 5

(1) Standard health-related limit for consumption of 2 L/d over 70 years by a 60 kg person
U_T denotes total uranium, and U_D denotes dissolved uranium
Shaded cells denote analyte monitoring
Blank cells denote exclusion / discontinuance of analyte monitoring

Interrogation of the data set represented in **Table 6** returns the statistical results presented in **Table 7**. The results reflect concern for the analytes Mn, Ni and Cd at the 50%ile and greater level.

Table 7 Statistical analysis of metal analyte concentrations in treated/neutralised mine water discharged into the environment from the locus of decant per distinctive monitoring period

Analyte	**Monitoring Period**											
	08/2009 – 09/2010				**10/2010 – 11/2012**				**12/2012 – 09/2013**			
	Σn	>DL	50%ile	95%ile	Σn	>DL	50%ile	95%ile	Σn	>DL	50%ile	95%ile
Fe[(1)]	307	283	0.8	**55.7**	113	108	1.0	**31.5**	43	43	0.03	1.5
Al	61	0	—	—	113	0	—	—	40	40	0.009	0.120
Mn	61	58	**8.65**	**66.35**	113	112	**11.00**	**60.90**	43	43	**13.00**	**55.30**
U_T	61	30	14.00	**73.25**	113	89	**16.00**	**700.20**				
Cr	61	9	0.001	0.019	113	18	0.001	**0.866**				
V	61	4	0.001	0.002	113	2	0.001	0.001				
Pb	61	16	0.002	**0.033**	113	22	0.005	**0.030**	41	3	0.002	0.002
Co	61	60	0.070	**2.005**	113	111	0.050	0.350				
Ni	61	56	**0.150**	**3.725**	113	113	**0.170**	**0.940**	41	41	**0.100**	**0.160**
U_D					113	51	9.9	35.0	43	21	7.0	13.0
Cd									41	2	**0.007**	**0.010**
Cu									41	31	0.002	0.009
Zn									41	41	0.019	0.100

(1) Values for period 08/2009 – 09/2010 calculated from 05/2005 as per **Table 6**
Analyte units (and symbols) as per **Table 6**
>DL denotes number of analyte values that exceed the detection limit as per **Table 6**
Bold text denotes value exceeds standard limit as described in **Table 6** (Note 1)
Shaded / blank cells as described in **Table 6**

A slightly different picture emerges when an interrogation of the data set represented in **Table 6** is carried out on the basis of the three (3) periods of distinctly different discharge chemistry recognised in **Figure 16** to **Figure 21** and **Table 4**. This is presented in **Table 8**, and despite the differences with **Table 6**, the results again reflect concern for the analytes Mn, Ni and Cd at the 50%ile and greater level.

Table 8 Statistical analysis of metal analyte concentrations in treated/neutralised mine water discharged into the environment from the locus of decant per distinctive discharge period

Analyte	**Discharge Period**											
	A—B(1)				**B—C(2)**				**C—(3)**			
	Σn	>DL	50%ile	95%ile	Σn	>DL	50%ile	95%ile	Σn	>DL	50%ile	95%ile
Fe	116	103	0.5	**77.4**	130	121	1.200	**29.0**	61	59	0.040	**7.8**
Al	26	0	—	—	130	0	—	—	58	40	0.009	0.120
Mn	26	24	**6.5**	**72.7**	130	128	**10.5**	**46.95**	61	61	**12.0**	**60.0**
U_T	26	13	12.0	**66.2**	130	90	**16.5**	**700**	18	16	**15.5**	**79.0**
Cr	26	3	0.010	0.024	130	19	0.001	**0.764**	18	5	0.001	0.003
V	26	2	0.002	0.002	130	4	0.001	0.001	18	0	—	—
Pb	26	6	0.002	**0.023**	130	27	0.005	**0.037**	59	7	0.002	0.003
Co	26	25	0.039	**2.900**	130	130	0.050	**1.063**	18	16	0.023	**0.523**
Ni	26	22	0.069	**7.995**	130	129	**0.180**	**1.820**	59	59	**0.100**	**0.400**
U_D					95	43	9.8	**22.9**	61	29	7.2	**28.8**
Cd									41	2	**0.007**	**0.010**
Cu									41	31	0.002	0.009
Zn									41	41	0.019	0.100

(1) September 2006 – January 2010
(2) February 2010 – July 2012
(3) August 2012 – September 2013
Analyte units (and symbols) as per **Table 6**
>DL denotes number of analyte values that exceed the detection limit as per **Table 6**
Bold text denotes value exceeds standard limit as described in **Table 6** (Note 1)

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 9**. The median and mean electrical balance values afford the analytical results a high degree of confidence. The 95%ile EB value of 9.5% suggests the increasing inaccuracy of analyses at higher SO_4 concentrations. None of the analytes recorded in **Table 9** exceed the respective SANS (2011a) health-related limit where specified[8].

The distinct Ca·Mg–HCO_3 composition of the water as per the whole record data set (**Figure 25a**) 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 25**, top left) and the pre-decant period (**Figure 25**, top right). The decant period, however, reflects small but notable increases in the median Na and Cl concentrations (**Figure 25**, bottom left) compared to the pre-decant and whole period values. These are considered to reflect the municipal wastewater influence on surface water quality. A more distinct AMD influence is evident in the greater variability associated with the SO_4 concentration (and to a lesser extent also the Ca and Mg concentrations) in the decant period compared to the pre-decant period. This variability increases significantly in the period of greatest impact, i.e. February 2010 to July 2012 (**Figure 25**, bottom right), together with a change to a Ca–HCO_3·SO_4 water composition. The record (**Figure 33**) also reflects a subsequent (August 2012 to present) return to more "normal" conditions.

8 The electrical balance limit (exceeded at the 95%ile level) is not a SANS (2011a) metric.

Table 9 Statistical analysis of Bloubank Spruit water chemistry data associated with station A2H049 for the period May 1979 to September 2013

Analyte	Statistical Parameter							SANS (2011a)(1)
	n	5%ile	Mean	Median	95%ile	SD	CoV (%)	
pH ($-\log_{10}$[H+])	965	7.4	—	8.2	8.5	0.3	4	5.0–9.7
EC (mS/m)	1 069	51.1	60.1	60.5	69.2	7.2	12	<170
TDS (mg/L)	1 070	355.5	436.5	443.9	492.2	55.2	13	<1 200
Ca (mg/L)	887	42.9	53.6	53.6	61.8	8.1	15	n.s.
Mg (mg/L)	885	25.1	32.3	32.5	37.8	4.6	14	n.s.
Na (mg/L)	882	10.0	22.0	21.9	33.7	7.1	32	<200
K (mg/L)	891	0.7	1.9	1.8	3.5	0.9	47	n.s.
Cl (mg/L)	891	20.0	31.8	32.1	40.8	5.9	19	<300
SO_4 (mg/L)	888	65.1	89.4	83.6	129.8	34.3	38	<500
HCO_3 (mg/L)	883	147.7	191.6	197.3	219.3	25.1	13	n.s.
NO_3+NO_2 (mg N/L)	922	3.00	4.55	4.36	6.41	1.74	38	<11
PO_4 (mg P/L)	961	0.005	0.093	0.054	0.316	0.106	113	n.s.
Si (mg/L)	961	5.09	5.98	5.98	6.82	0.81	14	n.s.
Fe (mg/L)	111	0.004	0.029	0.014	0.119	0.047	164	<2
Mn (mg/L)	111	0.001	0.118	0.003	0.146	0.657	557	<0.5
Al (mg/L)	106	0.003	0.046	0.011	0.091	0.206	452	<0.3
EB (%)	839	–1.2	3.6	3.6	**9.5**	3.9	107	±5
TDS:EC	1 068	6.7	7.3	7.2	8.1	0.5	7	n.s.
SO_4:TDS (%)	888	16	20	19	26	7	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

The surface water quality monitoring carried out at the Nedbank Olwazini Estate (NOE) complex (station NOE in **Figure 26**) 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 record represents almost exclusively[9] the water which drains the karst portion of the catchment.

The pH values and nutrient (NO_3-N, PO_4-P and COD) and bacterial concentrations in Bloubank Spruit water at the upstream end of the NOE property in the period January 2009 to July 2013 (4.5 years) are given in **Table 10**. The temporal pattern of the nutrient and bacterial variables is illustrated in **Figure 27**. The concern previously expressed by Hobbs (2013) for the faecal coliform count as far downstream as the NOE property remains valid. The association of higher faecal coliform concentrations with rainfall is again evident in **Figure 27**, and supports the observation (Hobbs, 2013) that significant bacteriological impacts on surface water quality are driven by rainfall. **Figure 27** shows that the highest faecal coliform count (5 876 cfu/100 mL) in the available NOE data set occurred in February 2013. It remains to be established whether this pattern correlates to municipal wastewater effluent from the Percy Stewart WWTW, or to general runoff from the urban areas (including Munsieville) served by this facility.

9 The ephemeral discharge of the Honingklip Spruit tributary is not considered.

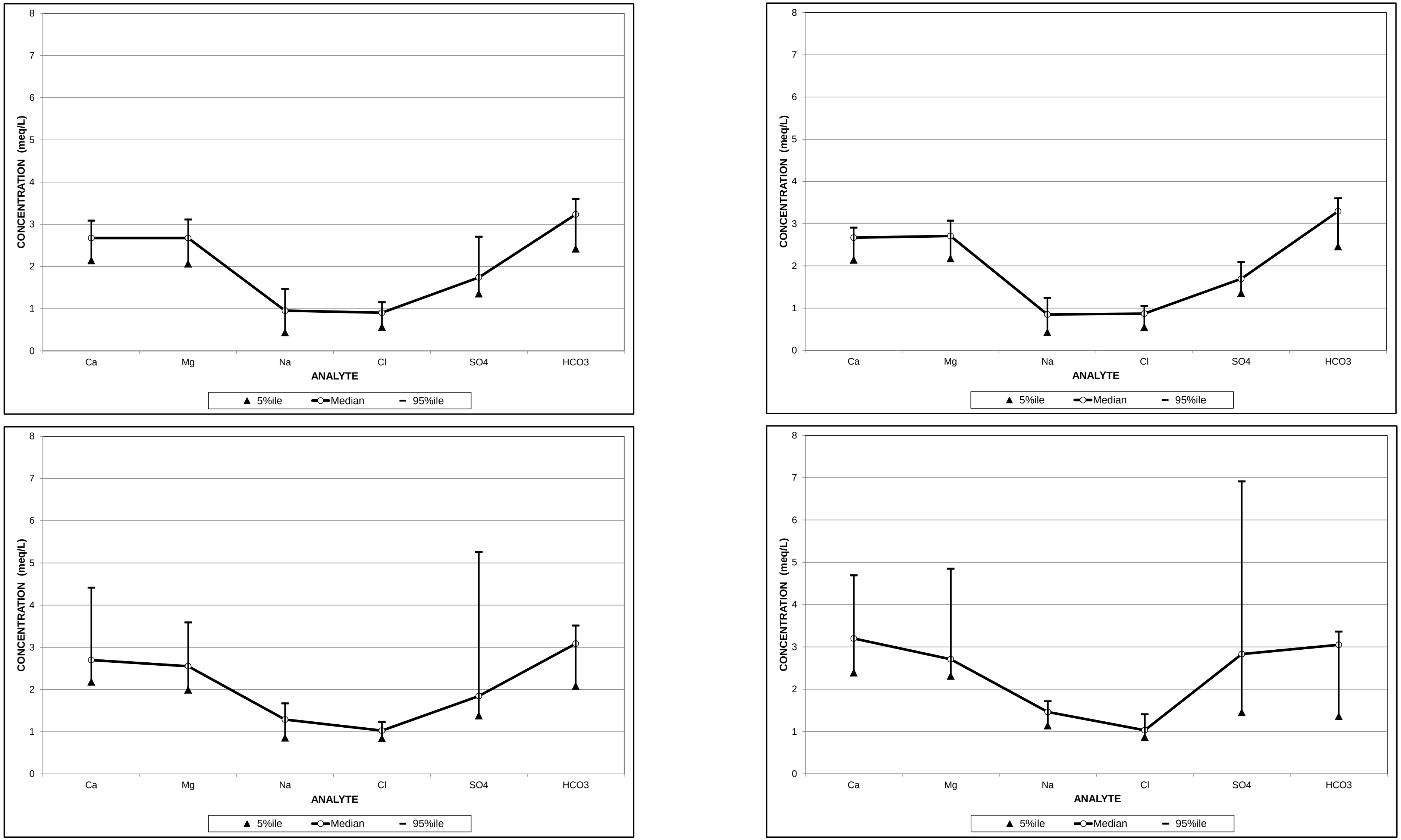

Figure 25 Variability of Bloubank Spruit water major ion chemistry recorded at DWA station A2H049 for the period May 1979 to August 2012 (top left), the period May 1979 to September 2002 (top right), the period October 2002 to August 2012 (bottom left) and the period February 2010 to July 2012 (bottom right)

The mean and median faecal coliform values of 681 and 310 cfu/100 mL respectively (**Table 10**), 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 26**). The lower NOE values fit the decreasing pattern associated with 'distance from source' previously reported by Hobbs (2011). Nevertheless, the results indicate a severe non-conformance of faecal coliforms (and therefore almost certainly also of *E. coli*) in regard to potable, animal and recreational use at the NOE property in the Bloubank Spruit system. This situation undoubtedly worsens progressively with distance upstream.

Table 10 Analysis of Bloubank Spruit water nutrient and bacterial content at the NOE property for the period January 2009 to July 2013

Analyte	**Statistical Parameter**								**SANS (2011a)(1)**	**TWQR(2) TWQR(3)**
	n	**1%ile**	**5%ile**	**Mean**	**Median**	**95%ile**	**SD**	**CoV (%)**		
$pH^{(4)}$ ($-\log_{10}[H^+]$)	51	—	7.5	—	8.1	8.6	0.3	4	5.0–9.7	—
NO_3 (mg N/L)	48	—	4.1	8.1	7.3	**14.9**	3.6	44	<11	—
O-PO_4 (mg P/L)	51	—	0.1	0.4	0.3	0.8	0.2	67	n.s.	—
COD (mg/L)	41	—	9	59	49	174	51.3	87	n.s.	—
Faecal coliforms (cfu/100 mL)	51	**38**	**54**	**681**	**310**	**2 590**	1 138	167	≤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

4.3 Salt Load

4.3.1 Riet Spruit

The combination of quantified stream flow losses (**Table 1**) and associated sulphate concentrations (**Table 5**) between stations F11S12 and MRd, allows for the derivation of the SO_4 loads lost to the karst aquifer as illustrated in **Figure 28**. The concern previously expressed for the quality of the water entering the karst aquifer is echoed in the median SO_4 load of ~48 t/d associated with this allogenic recharge. This value represents ~72% of the SO_4 load in surface water entering the stream reach at station F11S12, and ~86% of the TDS load in surface water passing 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 29**, and for sulphate (SO_4) in **Figure 30**. The ratio of SO_4 to TDS illustrated in **Figure 31** 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 29**) indicates an increasing TDS load (as indicated by the visually inserted arrows) since 2007. The long-term monthly trend in the SO_4 load delivered by the Bloubank Spruit (**Figure 30**) mimics the TDS load pattern (**Figure 29**) in the most recent period of record. This is unsurprising under circumstances where SO_4 comprises ~62% of the major ion concentration in mine water.

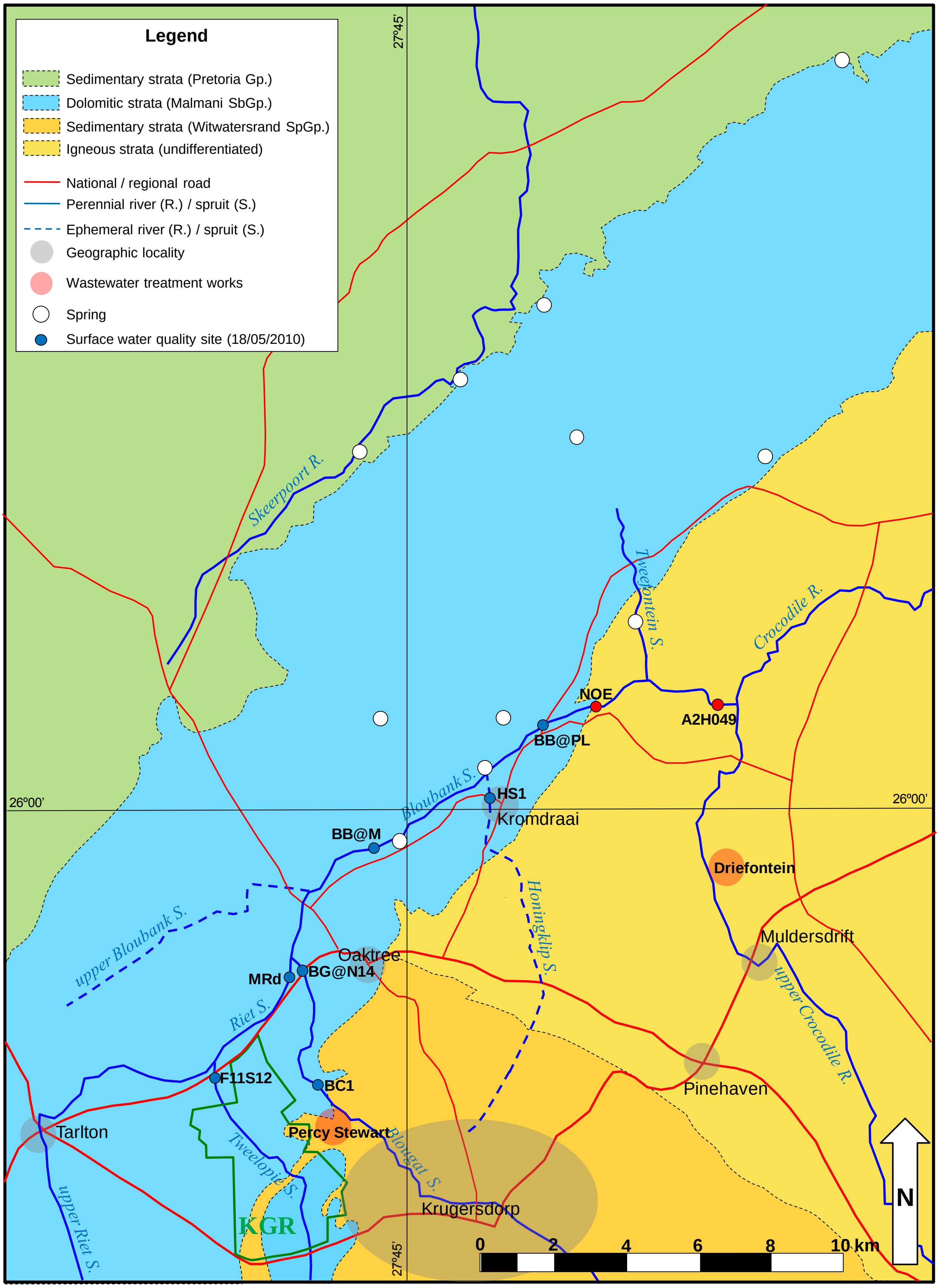

Figure 26 Surface water quality sampling sites in the study area

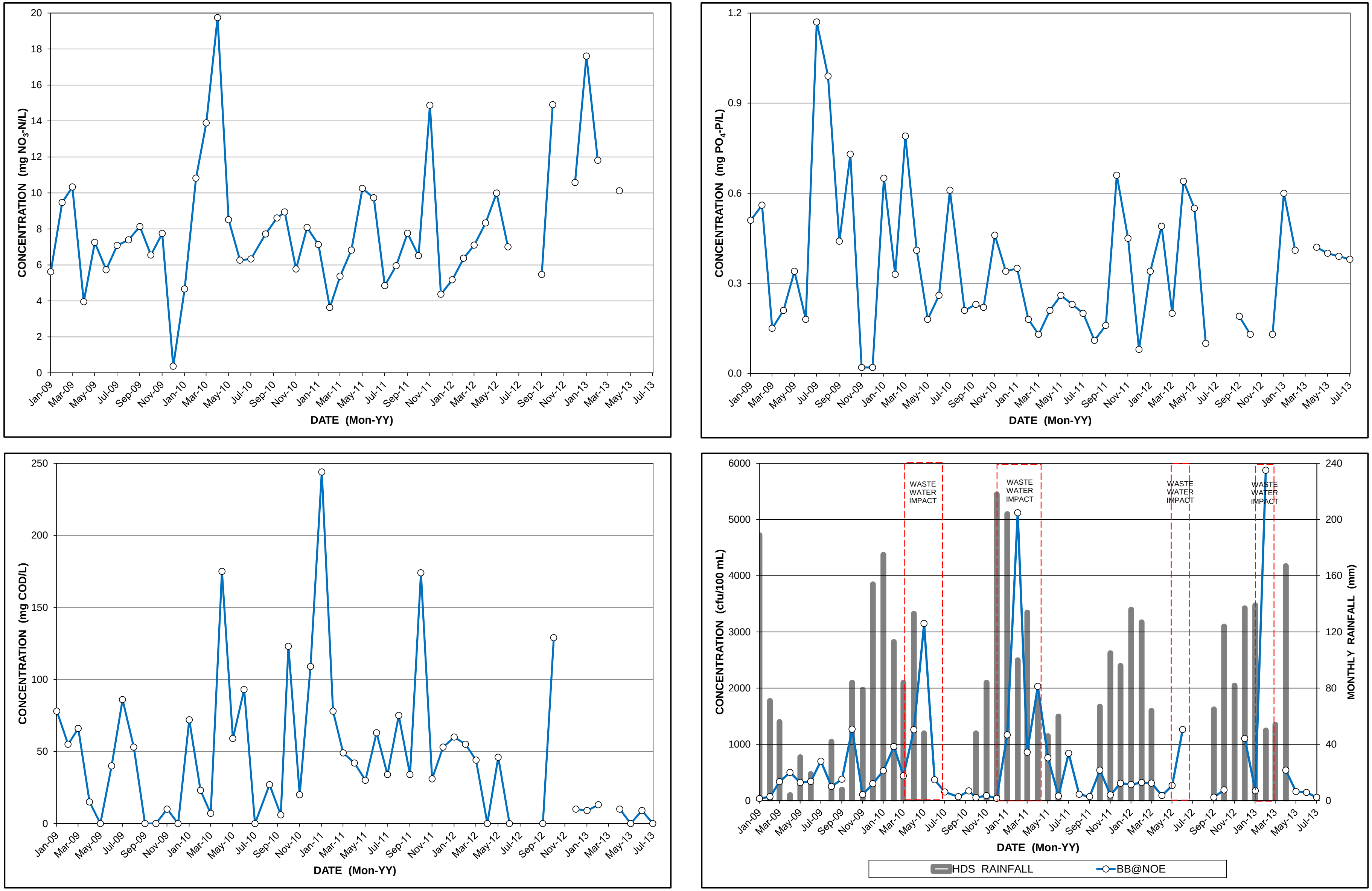

Figure 27 Temporal pattern of NO_3-N (top left), PO_4-P (top right), COD (bottom left) and faecal coliforms (bottom right) in Bloubank Spruit water at the NOE property

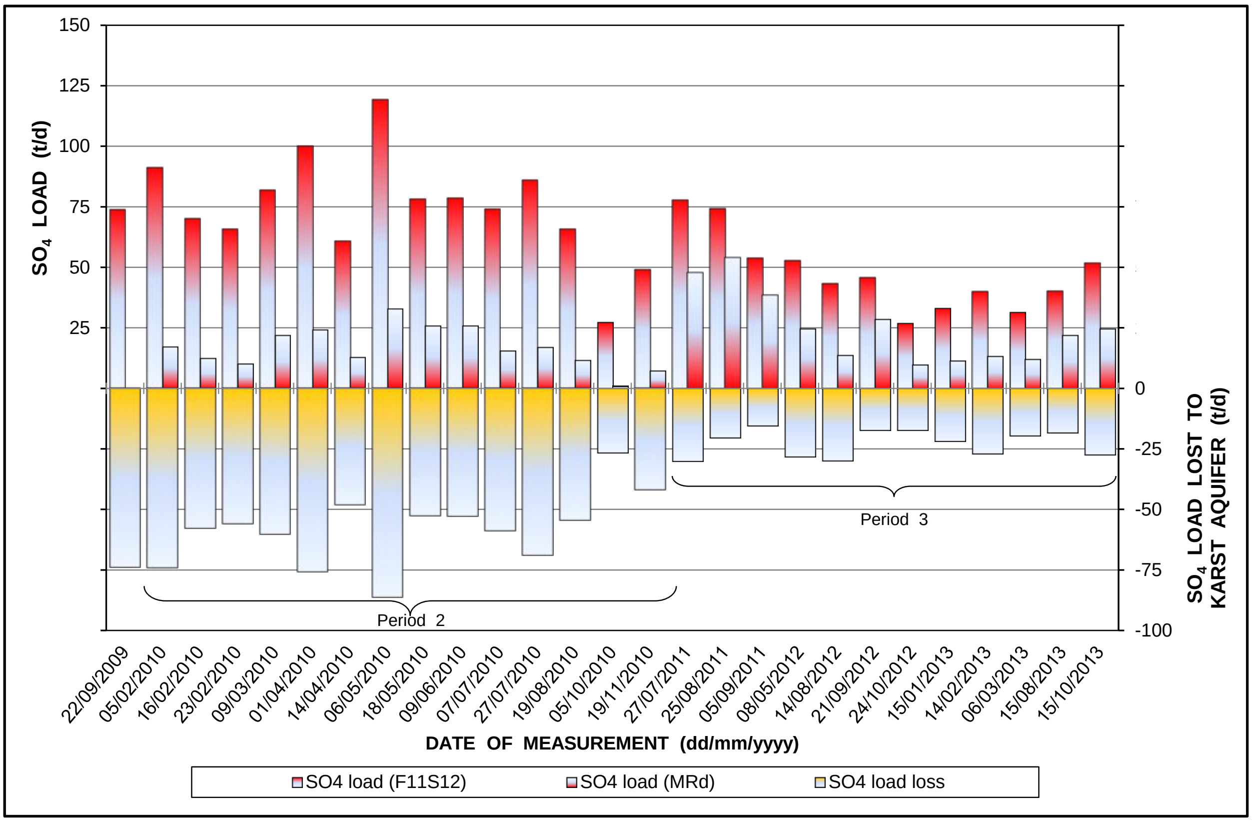

Figure 28 Graph of surface water SO_4 load lost to groundwater in the lower reach of the Riet Spruit

The SO_4**:**TDS ratio at station A2H049 is illustrated in **Figure 31** for the long-term record, and in **Figure 32** for the period since the start of decant. Together with the presentation in **Figure 33** of the SO_4 data recorded at station A2H049, these graphs reveal 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. This is evident in the increasing proportion of SO_4 to TDS 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 31**. A possible explanation for the 1986–2001 trend is the greater contribution of dolomitic groundwater, typically very low in SO_4, draining from the Zwartkrans and Krombank compartments following the breaking of the drought that characterised the early 1980s. The preceding rising SO_4 trend in the period 1979–1986 (**Figure 31**) 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.

Following the “peak” associated with the large and uncontrolled raw mine water discharges experienced in 2010, the SO_4 concentration in the surface water passing station A2H049 (**Figure 33**) shows a return to the rising trend evident since the start of the 2009–’10 hydrological year. The suggestion of another “peak” developing with the two most recent values (**Figure 33**) triggers a watching brief on the quality of Bloubank Spruit system discharge for the remainder of the monitoring period.

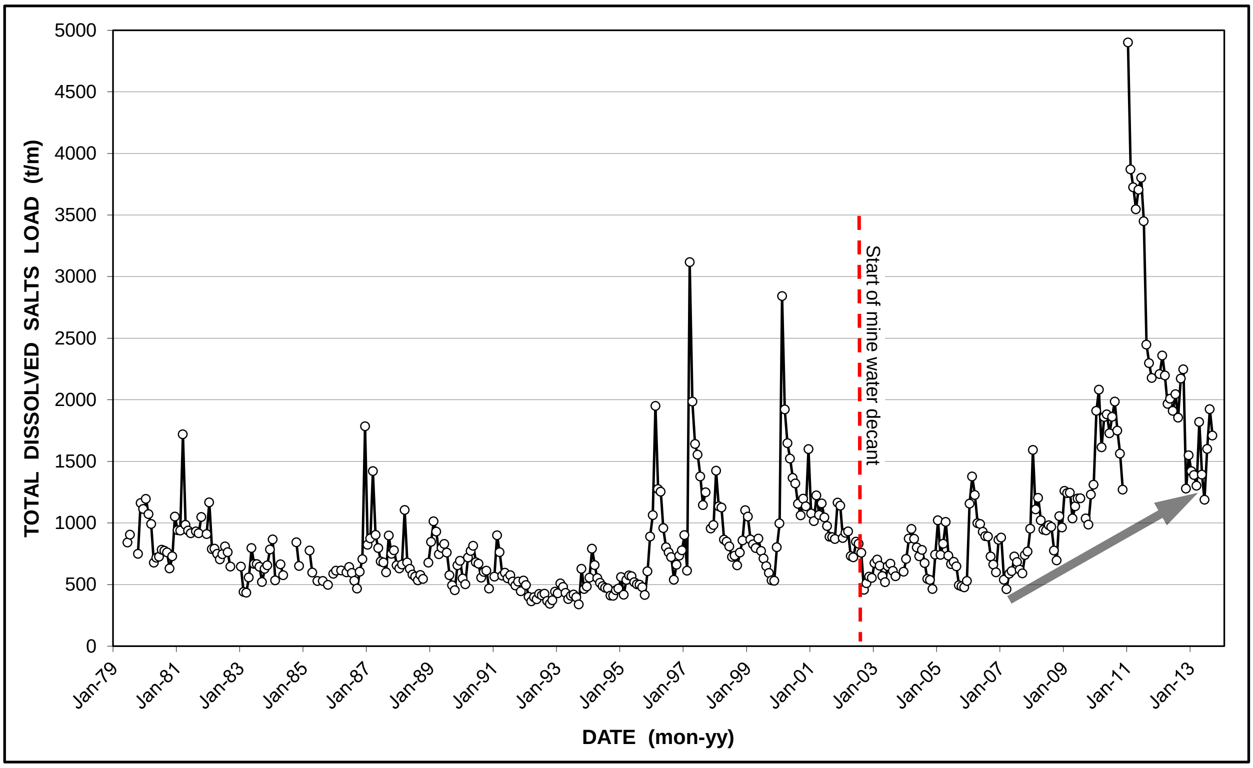

Figure 29 Long-term (June 1979 to September 2013) monthly TDS load pattern and trend in the Bloubank Spruit at DWA station A2H049

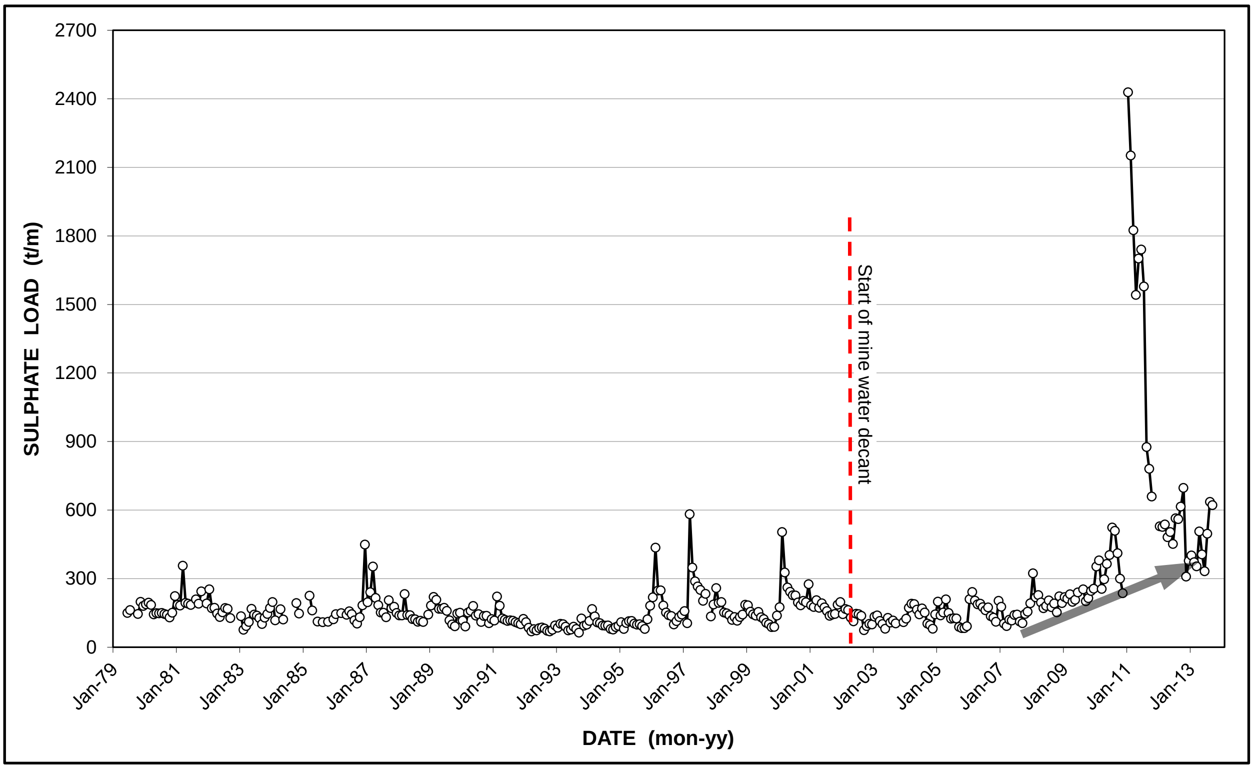

Figure 30 Long-term (June 1979 to September 2013) monthly SO_4 load pattern and trend in the Bloubank Spruit at DWA station A2H049

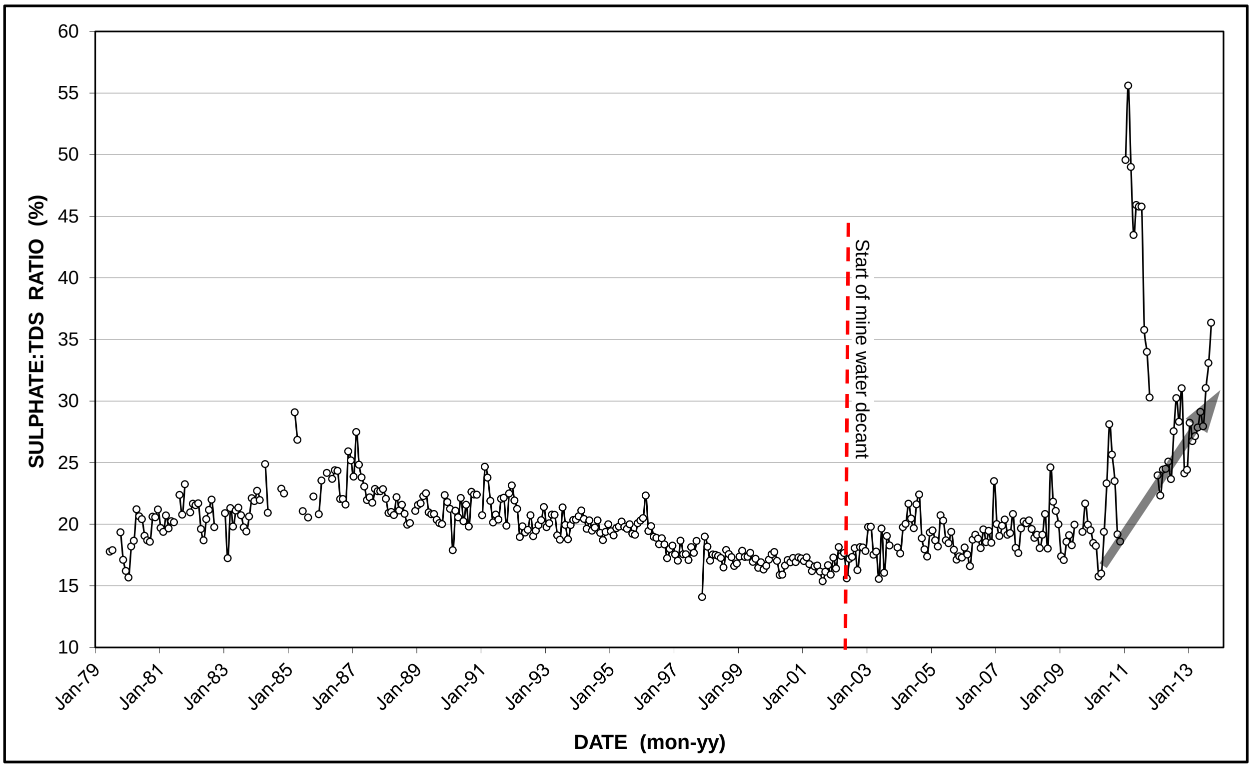

Figure 31 Long-term (June 1979 to September 2013) trend in the SO_4**:**TDS ratio at station A2H049

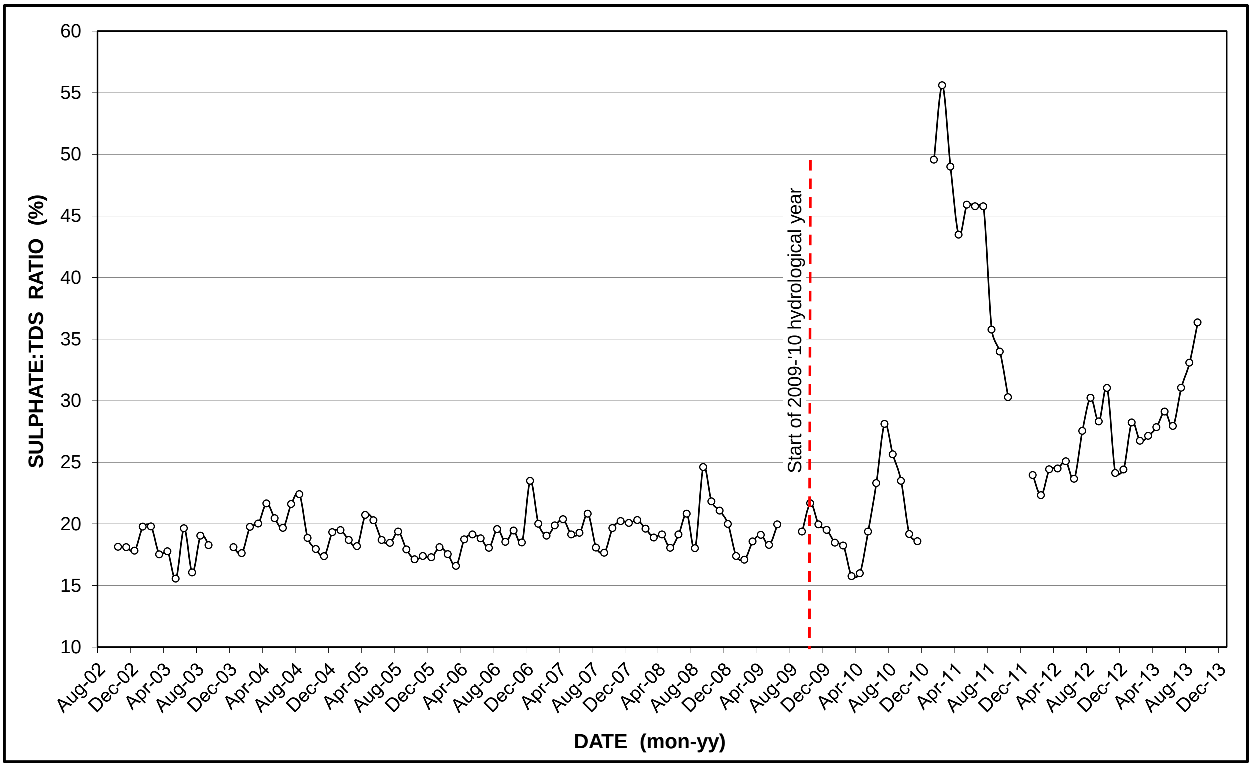

Figure 32 Pattern and trend in the SO_4**:**TDS ratio at station A2H049 since the start of mine water decant in the Western Basin

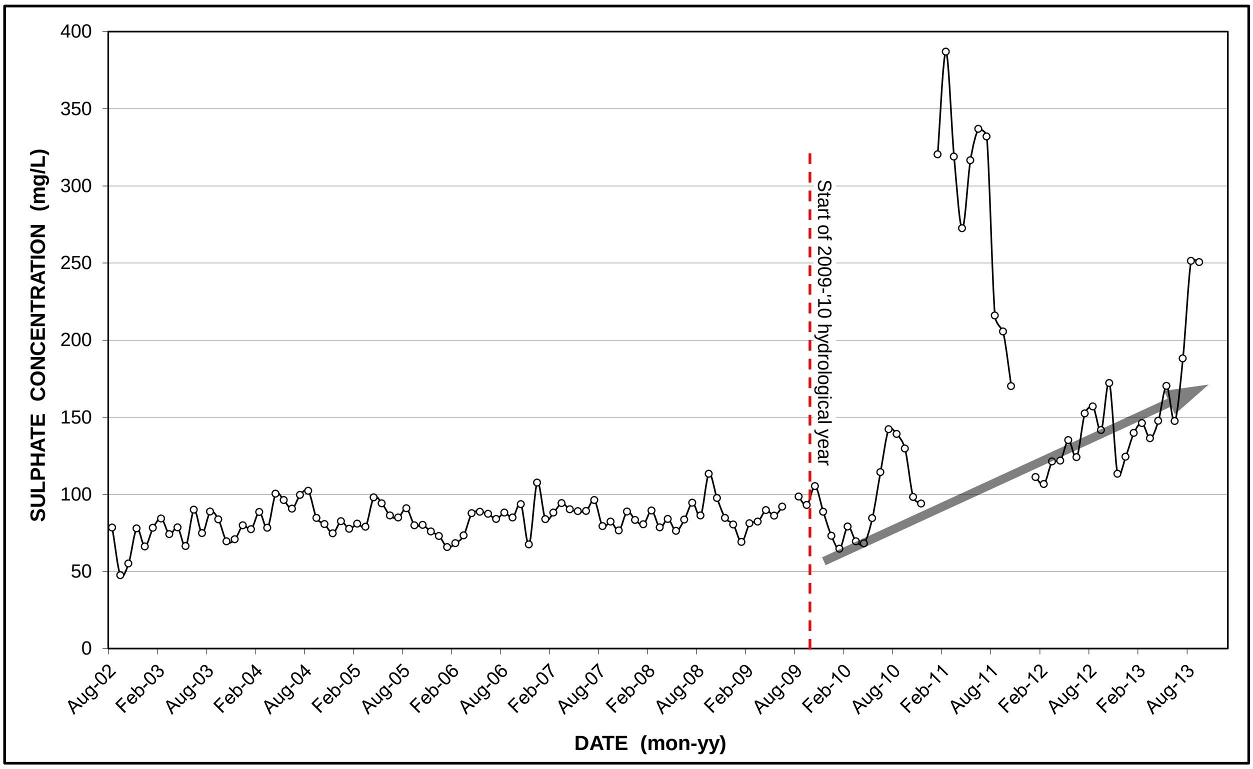

Figure 33 Pattern and trend in the SO_4 concentration at station A2H049 since the start of mine water decant in the Western Basin

5 GROUNDWATER HYDROLOGY

5.1 Physical Hydrogeology

5.1.1 Groundwater Levels

The behaviour of groundwater levels (the hydrostatic or potentiometric response) associated with the karst aquifer is reflected in the long-term water level records for DWA monitoring boreholes in the study area. An assessment of these data returns the statistics presented in **Table 11**. A graphical representation of the information is shown in **Figure 34**. An analysis of the %ile Δh data yields a 25%ile value of 3.8 m, a median value of 4.8 m, and a 75%ile value of 6.7 m.

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 circumstances behind the unprecedented rise in the groundwater level observed in stations A2N0584 and A2N0586 (amongst others) since late-2007 (**Figure 37**) is discussed by Hobbs (2013). The most recent record reflects a decline in groundwater levels since mid-2012, which coincides with the significant reduction in mine water discharge from the locus of decant as shown in **Figure 7**.

Table 11 Salient statistics for long-term DWA groundwater level monitoring data

Station	Groundwater Rest Level (m bc)							Record
	n	5%ile	Mean	Median	95%ile	Max Δh[(2)]	%ile Δh[(3)]	Period[(1)]
A2N0580	266	51.01	54.64	54.40	59.96	11.13	8.95	05/1985–11/2013
A2N0582	210	35.77	40.11	40.15	42.91	8.53	7.14	05/1985–12/2010
A2N0583	225	44.40	44.97	44.92	45.55	1.84	1.15	05/1985–11/2013
A2N0584	235	21.81	26.06	26.51	28.11	7.93	6.29	05/1985–05/2012
A2N0586	280	21.63	26.39	27.18	28.67	8.49	7.04	05/1985–11/2013
A2N0589	169	27.92	28.89	28.97	29.90	3.85	1.98	05/1985–06/2010
A2N0590	179	31.72	34.77	35.25	36.46	5.53	4.75	05/1985–11/2013
A2N0592	269	74.06	77.03	77.38	78.54	5.75	4.48	06/1985–11/2013
A2N0594	183	70.86	72.79	72.80	74.41	4.91	3.55	01/1985–09/2008
A2N0598	89	53.53	58.76	58.84	63.32	12.17	9.79	07/1985–05/2010
A2N0600	199	21.44	24.04	24.41	25.39	4.58	3.96	04/1989–11/2013
A2N0602	224	51.41	54.43	54.87	55.95	5.88	4.54	06/1987–11/2013
A2N0605	200	60.33	62.52	62.75	63.65	4.09	3.33	04/1989–02/2013
A2N0606	65	64.75	67.08	67.09	69.52	5.11	4.77	08/1989–11/2013
A2N0607	160	64.26	67.15	67.12	70.71	7.82	6.45	10/1993–11/2013

(1) From month of first measurement to month of most recent available measurement as at November 2013 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

An inspection of the more recent potentiometric response in DWA monitoring boreholes located downstream of the locus of decant 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. The long-term hydrographs presented in **Figure 37**, in particular those of stations A2N0584, A2N0586 and A2N0600, indicate that groundwater elevations in the recent past were the highest in the 25 to 30-year record of measurements, but have commenced a gradual decline. 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 northern segment).

The mine water discharges have introduced a new set of conditions that have precipitated an adjustment of the natural water resources environment which, in the case of groundwater, is immediately and most evident in potentiometric levels. 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 5.2.2**. 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. There is currently no reason to alter the anticipated magnitude of this increase from the range of 15–20% (2.9–3.9 Mm^3/a) put forward by Hobbs (2013). This will raise the long-term baseflow of the Bloubank Spruit system from its current ~22.7 Mm^3/a to between 25.6 and 26.6 Mm^3/a.

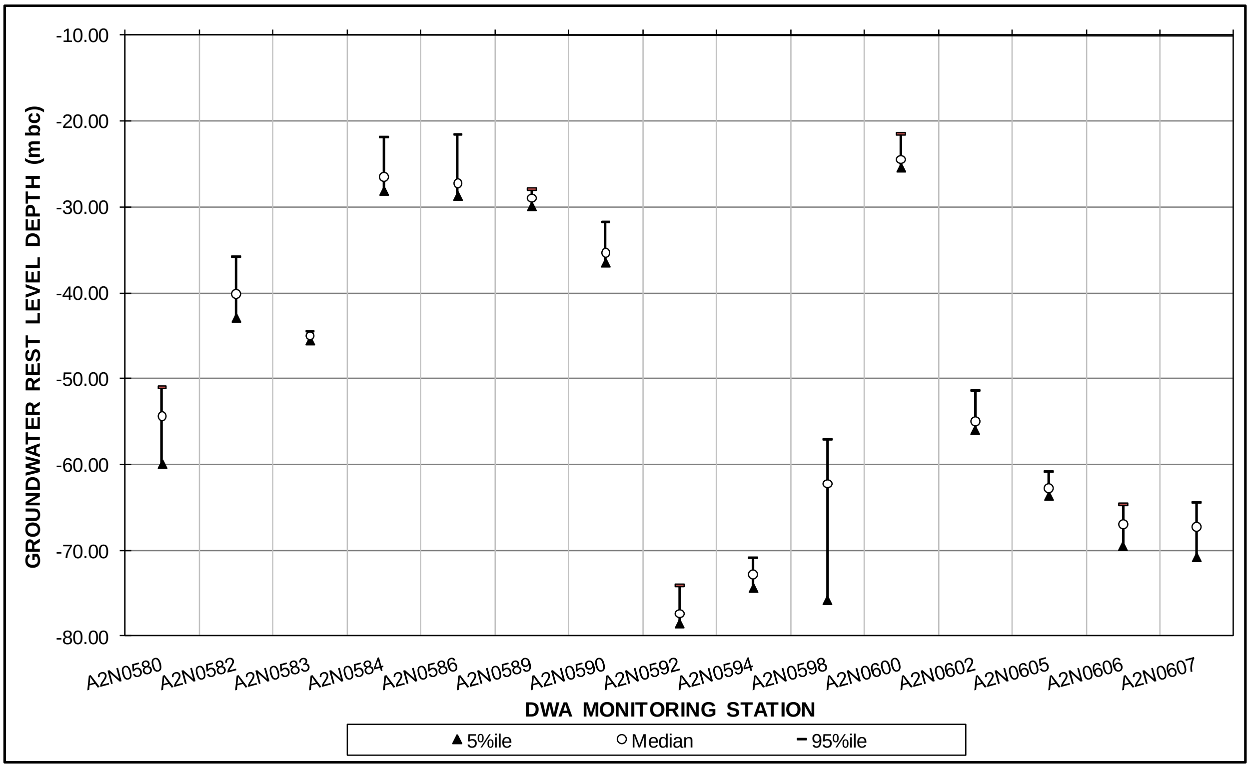

Figure 34 Graphic comparison of the statistical hydrographic response observed in DWA groundwater level monitoring stations in the period 1985 to 2013 (data from **Table 11**)

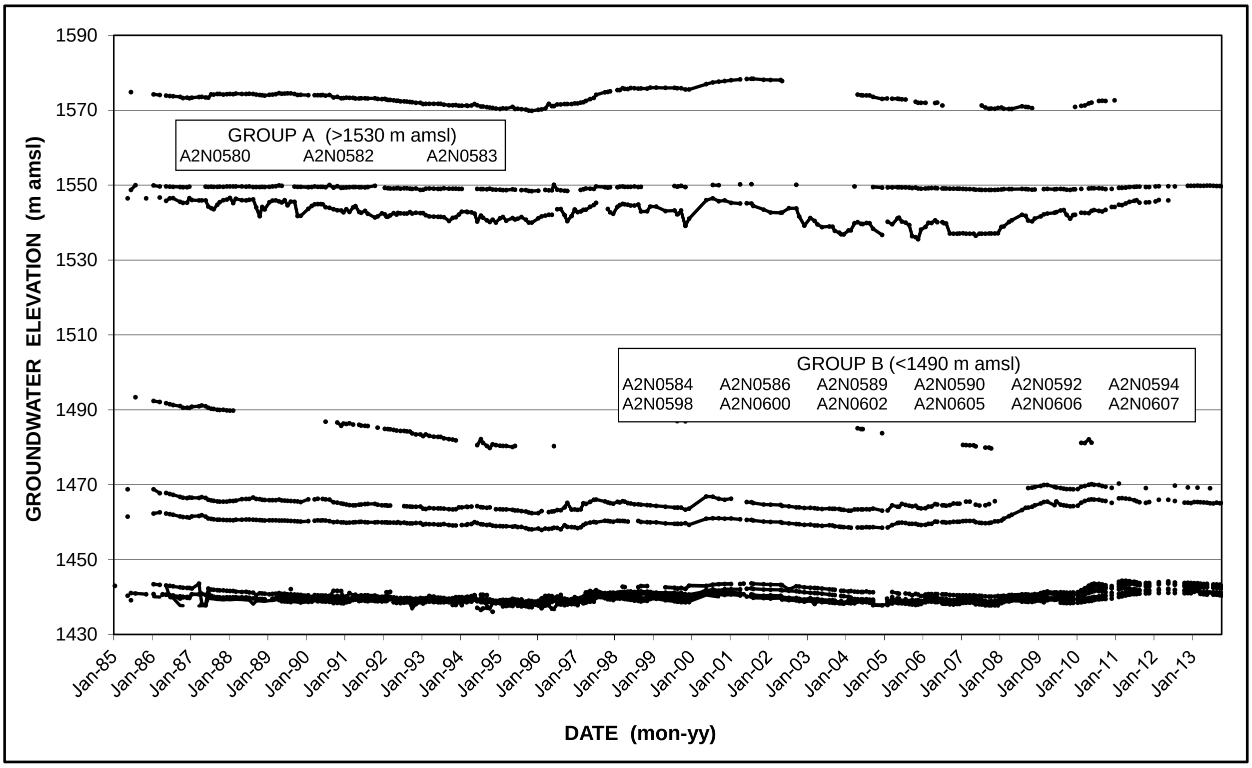

Figure 35 Long-term groundwater level response pattern in DWA monitoring boreholes

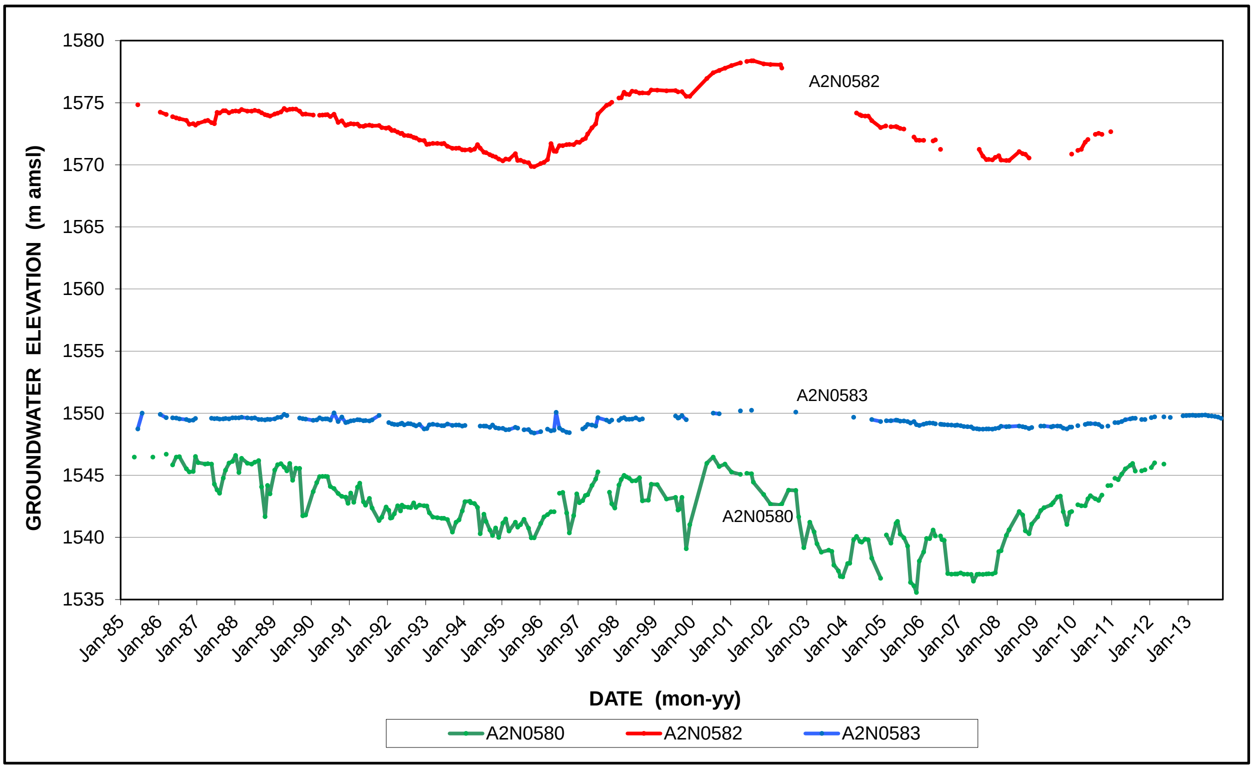

Figure 36 Long-term groundwater level response pattern in Group A boreholes from **Figure 35**

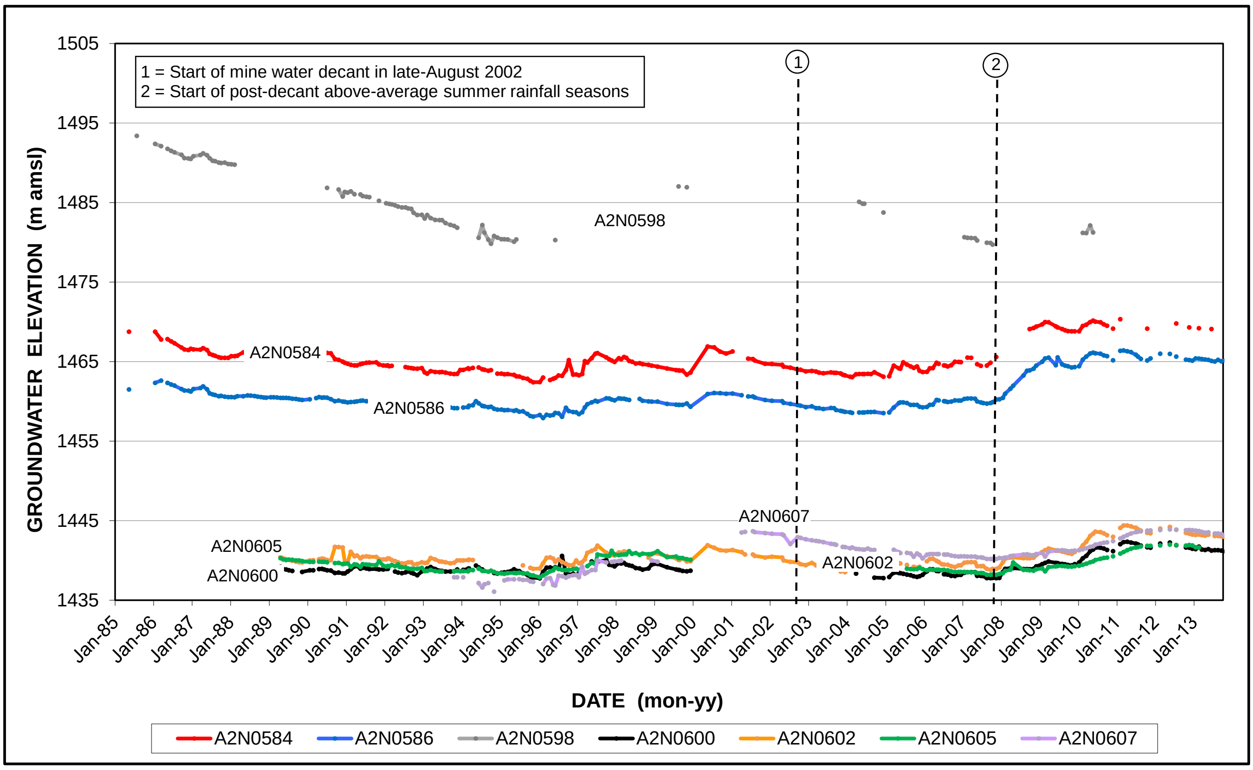

Figure 37 Long-term groundwater level response pattern in Group B boreholes from **Figure 35**

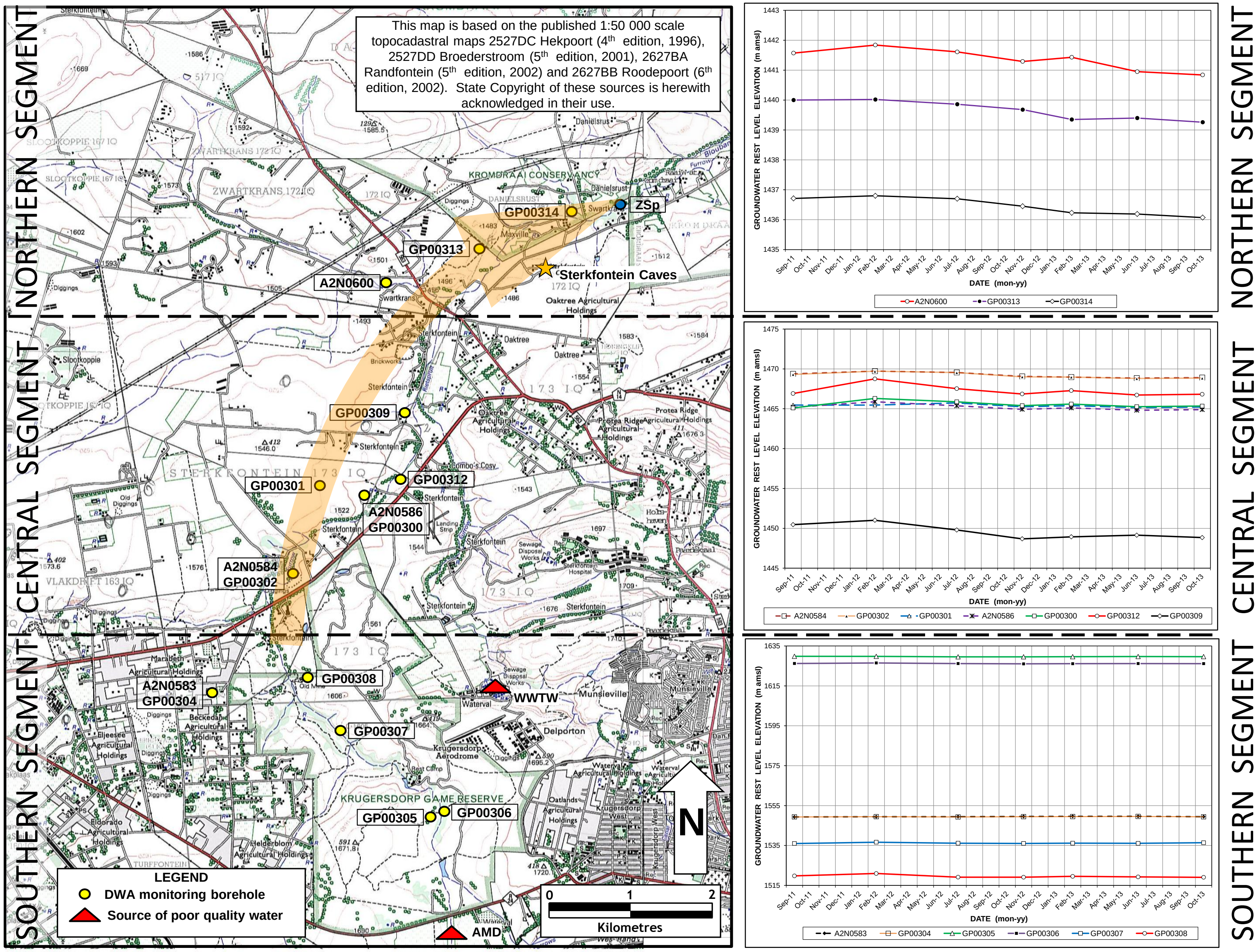

Figure 38 Distribution of DWA monitoring boreholes with groundwater hydrographs (right); arrow denotes principal direction of groundwater flow

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. Such an impact has been the recent substantial rise in the cave water level (**Figure 39**), which caused Maropeng āAfrika (the entity responsible for managing the tourist component of the site) to reroute the tourist path through the caves to successively higher elevations. This hydrostatic response is common to the Zwartkrans Compartment (**Section 5.1.1**), which confirms the hydraulic linkages of the Sterkfontein Cave system with the karst groundwater system of this compartment. More recent measurements, however, reflect the consistent decline in the Main Lake water level. The eleven (11) most recent measurements (**Figure 39**) indicate a rate of decline of ~0.04 m/month in the period May 2012 to October 2013. This is similar to the rate of ~0.03 m/month observed for the early (pre-rise) part of the record shown in **Figure 39**.

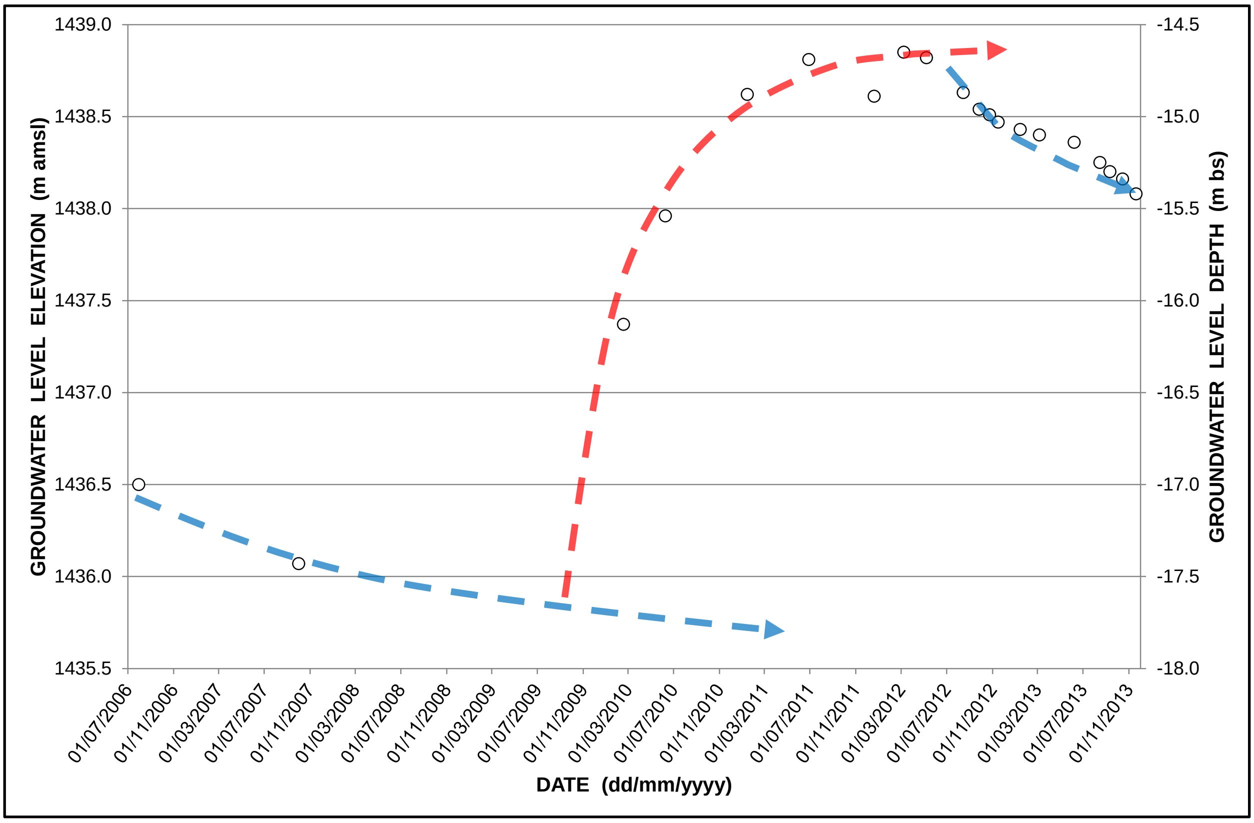

Figure 39 Groundwater level response pattern and trend in borehole SF1 that serves as a proxy for the Main Lake water level in Sterkfontein Caves

As previously observed by Hobbs (2013), 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 comparatively slow rate of decline, together with 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), support the hypothesis (Hobbs, 2013) that the Main Lake will maintain a high water level into the future. The driver of these circumstances will be the associated allogenic groundwater recharge in the Zwartkrans Compartment.

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 40** and **Figure 41**. 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).

5.2.2 Mine Water Impact

The groundwater chemistry data generated by the monitoring programme in the Zwartkrans Compartment provides an indication of the extent and magnitude of the mine water impact on the karst aquifer in this portion of the COH WHS. This is illustrated in **Figure 40** and **Figure 41** with the aid of bar graphs for the chemical variables pH and electrical conductivity (EC) respectively.

The bar graphs in **Figure 40** 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 41** 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 40**), 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.

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 42**, 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 analyte of concern is SO_4, which exceeds the SANS (2011a) standard health-related limit of 500 mg/L (**Table 9**) in all three instances. It would also appear from **Figure 42**, however, that the sulphate levels have most recently started to decrease. This might reflect the passage of the contamination peak through the karst aquifer at this location.

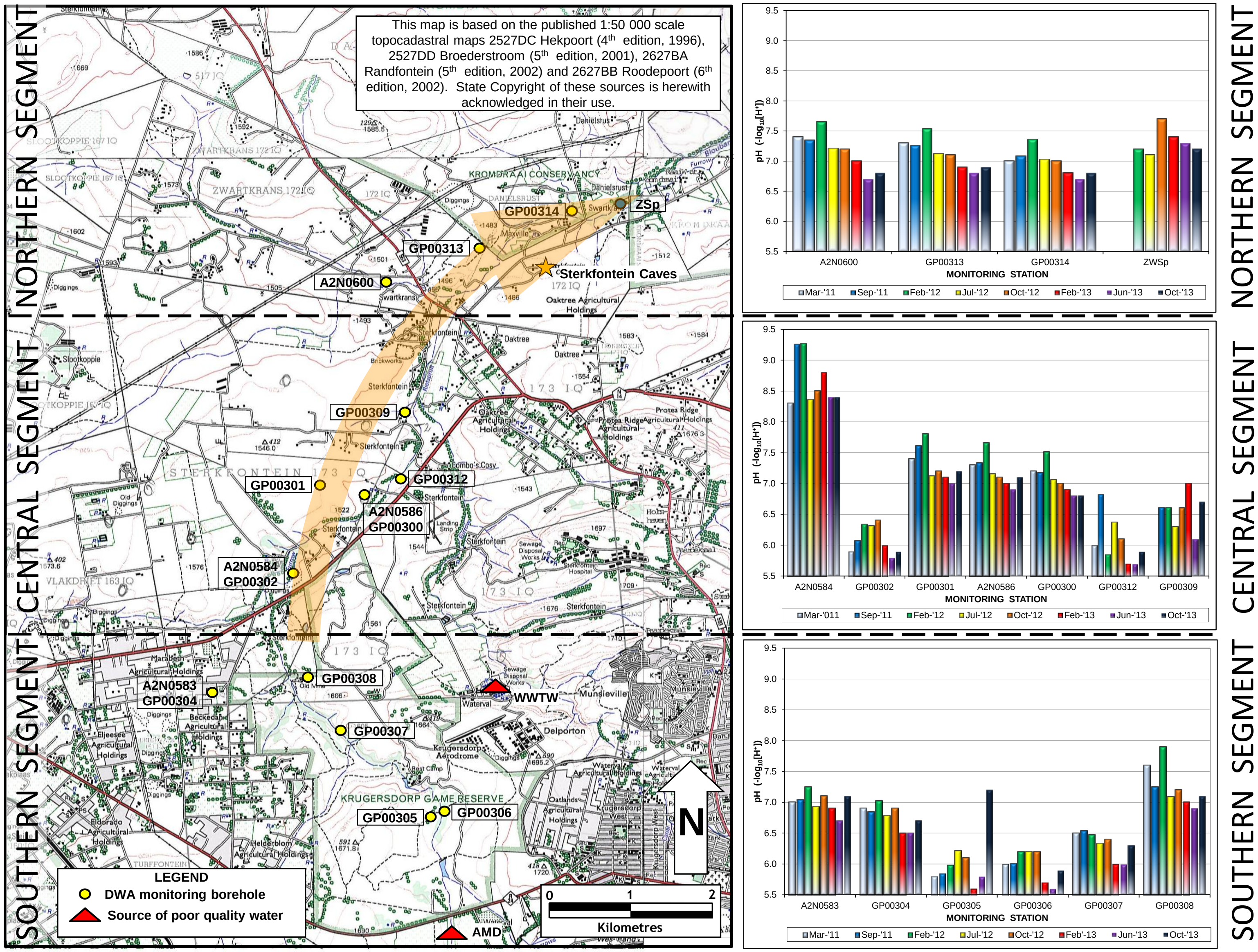

Figure 40 Distribution of DWA monitoring boreholes with pH pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

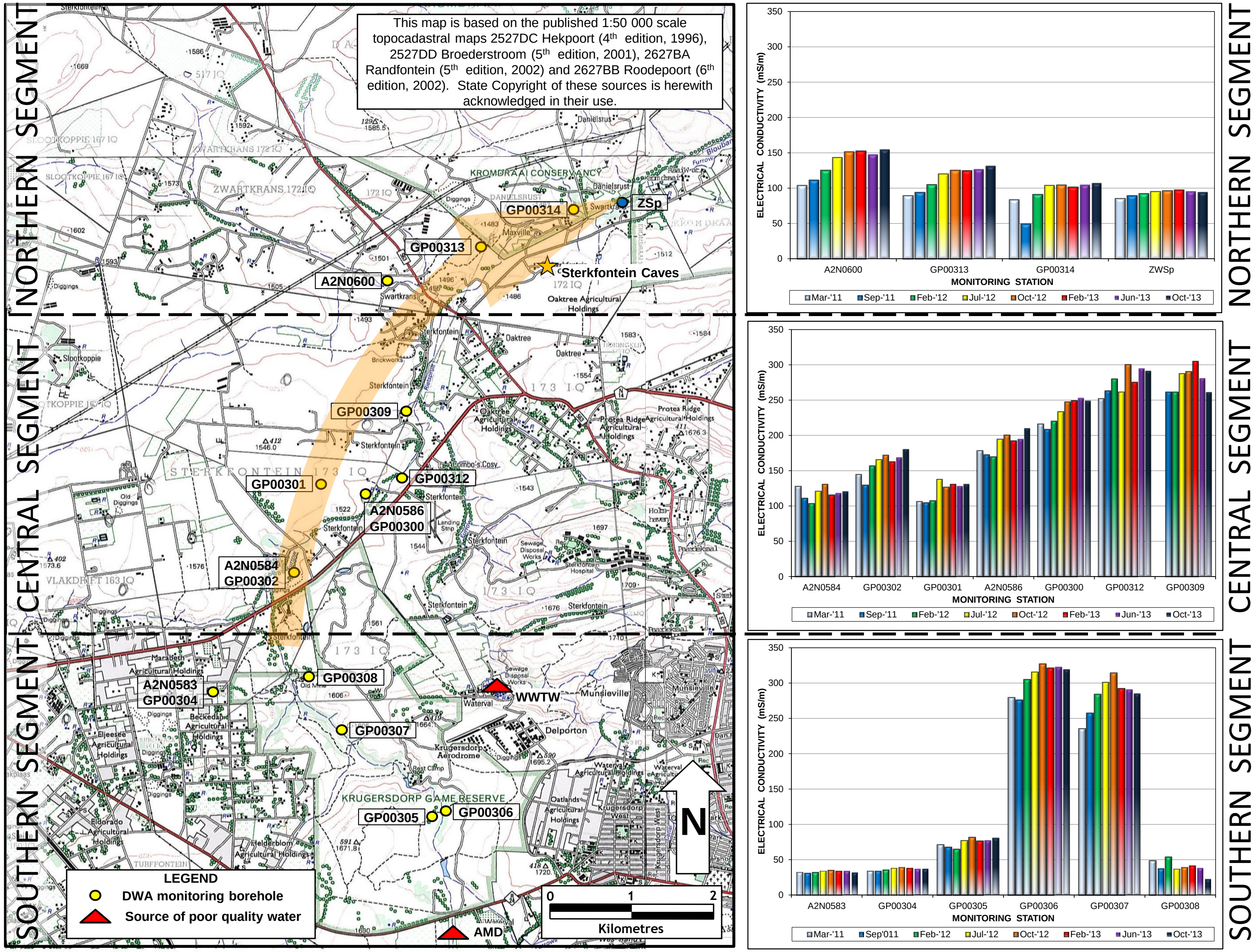

Figure 41 Distribution of DWA monitoring boreholes with EC pattern and trend as bar graphs; arrow denotes principal direction of groundwater flow

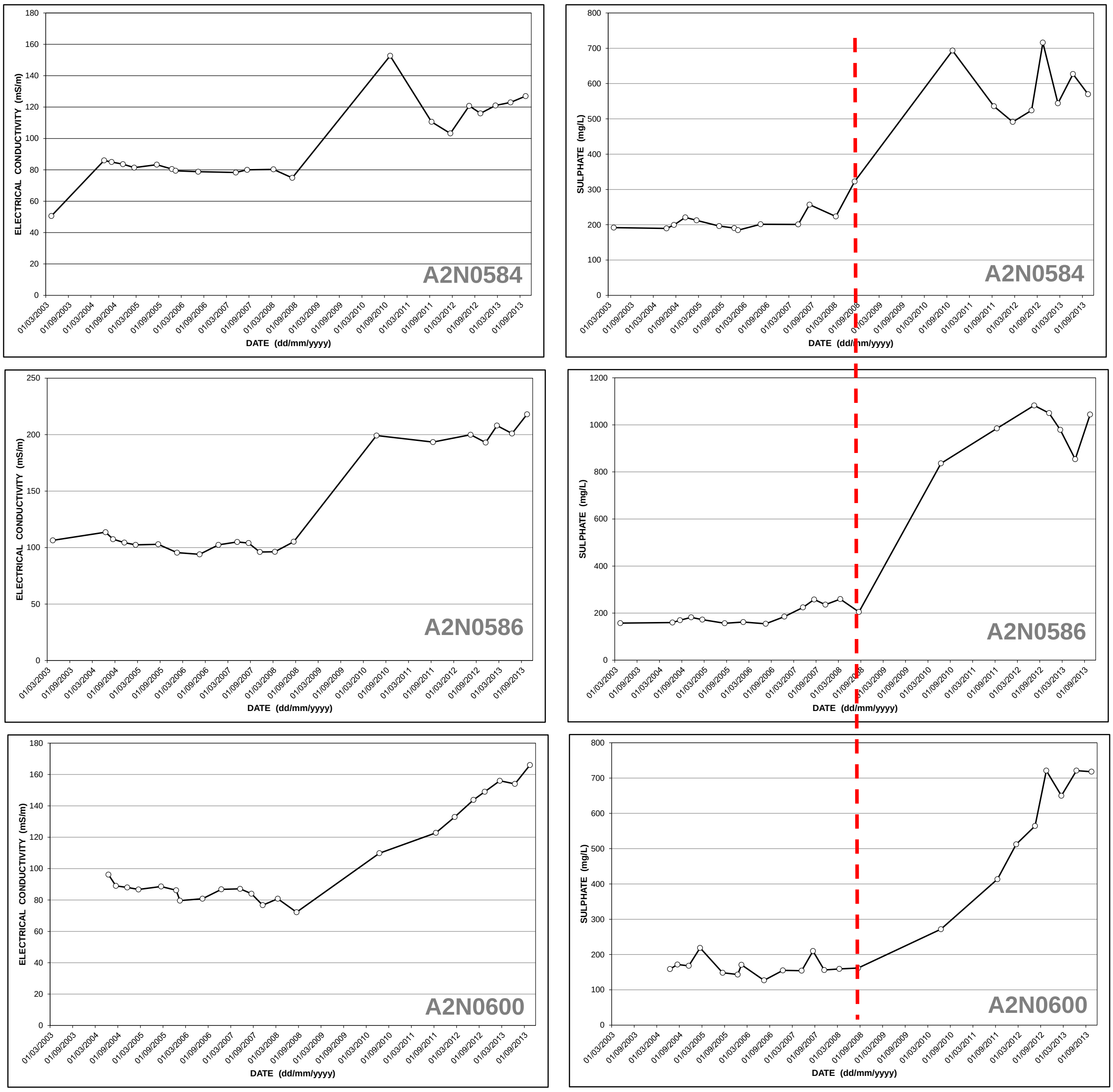

Figure 42 Long-term pattern and trend of electrical conductivity (left) and sulphate (right) in karst groundwater from DWA monitoring stations A2N0584, A2N0586 and A2N0600; note common time scales and postulated commencement of rise in concentrations (vertical pecked line)

The distribution of SO_4 concentrations associated with the monitoring stations is shown in **Figure 43**, and provides an indication of the footprint of this impact. The distribution pattern reflects a varying impact along a vector from upstream to downstream as illustrated by the flow path that describes the route followed by allogenic recharge of mine water impacted surface flow.

6 AUTOMATED MONITORING

The DWA has equipped a number of the monitoring boreholes with water level and field chemistry (salinity and temperature) sensors for the near real-time remote monitoring of these variables. The sensors have been calibrated and programmed, and transmit the captured data wirelessly to the DWA Head Office in Pretoria.

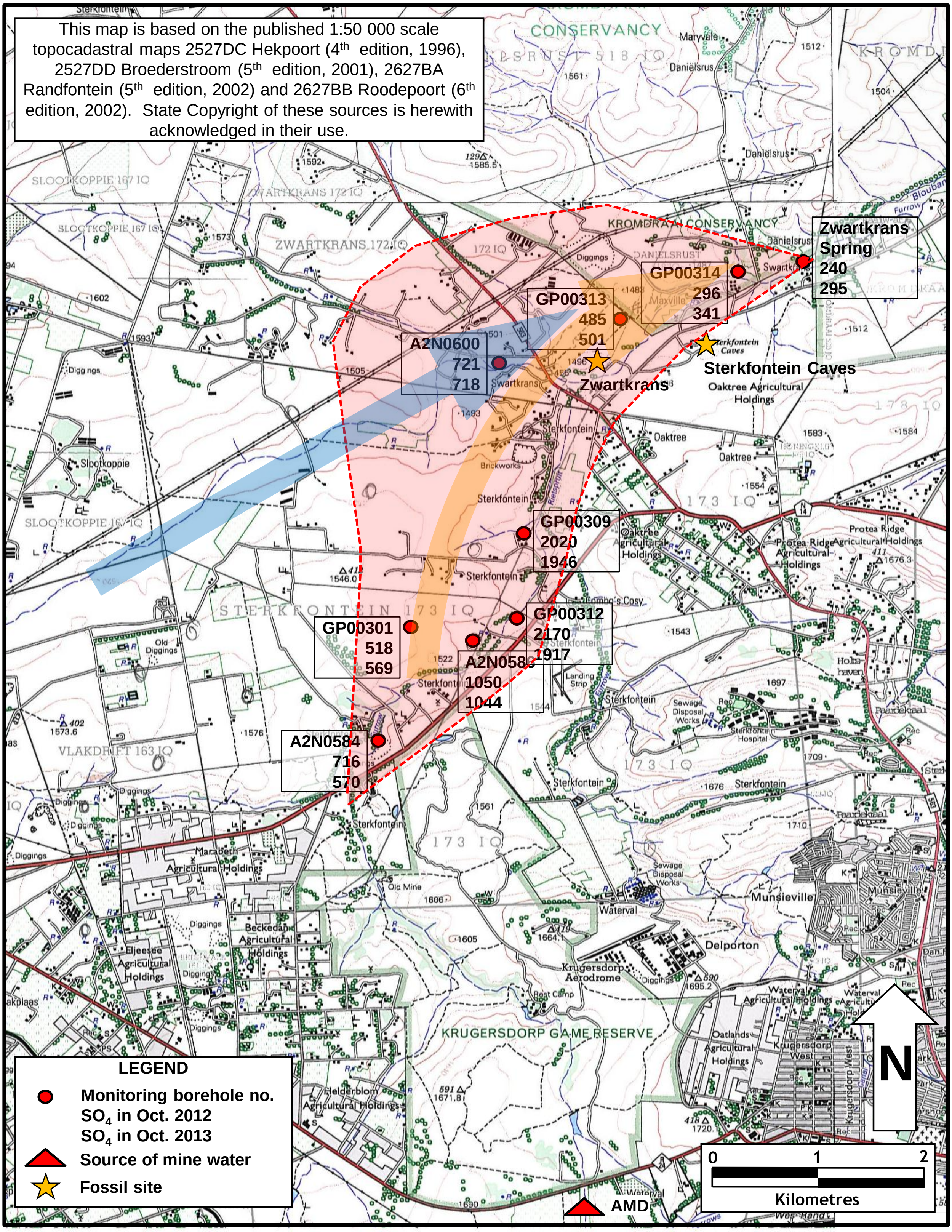

Figure 43 Distribution of SO_4 concentrations in groundwater of the Zwartkrans Compartment in October 2012 and October 2013, also showing the principal vectors of allogenic recharge (brown arrow), autogenic recharge (blue arrow) and the postulated footprint (shaded area) of a mine water impact on the karst aquifer

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 tracks the transit of the mass solute associated with the migration of mine water impacted karst groundwater exiting the Zwartkrans Compartment. After experiencing an extended period of data loss due to instrument programming problems, the sensor has returned the record illustrated in **Figure 44**. The chemograph indicates the gradually increasing salinity of the springwater. The rate of rise amounts to ~0.5 mS/m per month over the 4-month period of monitoring.

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 (**Section 3**).

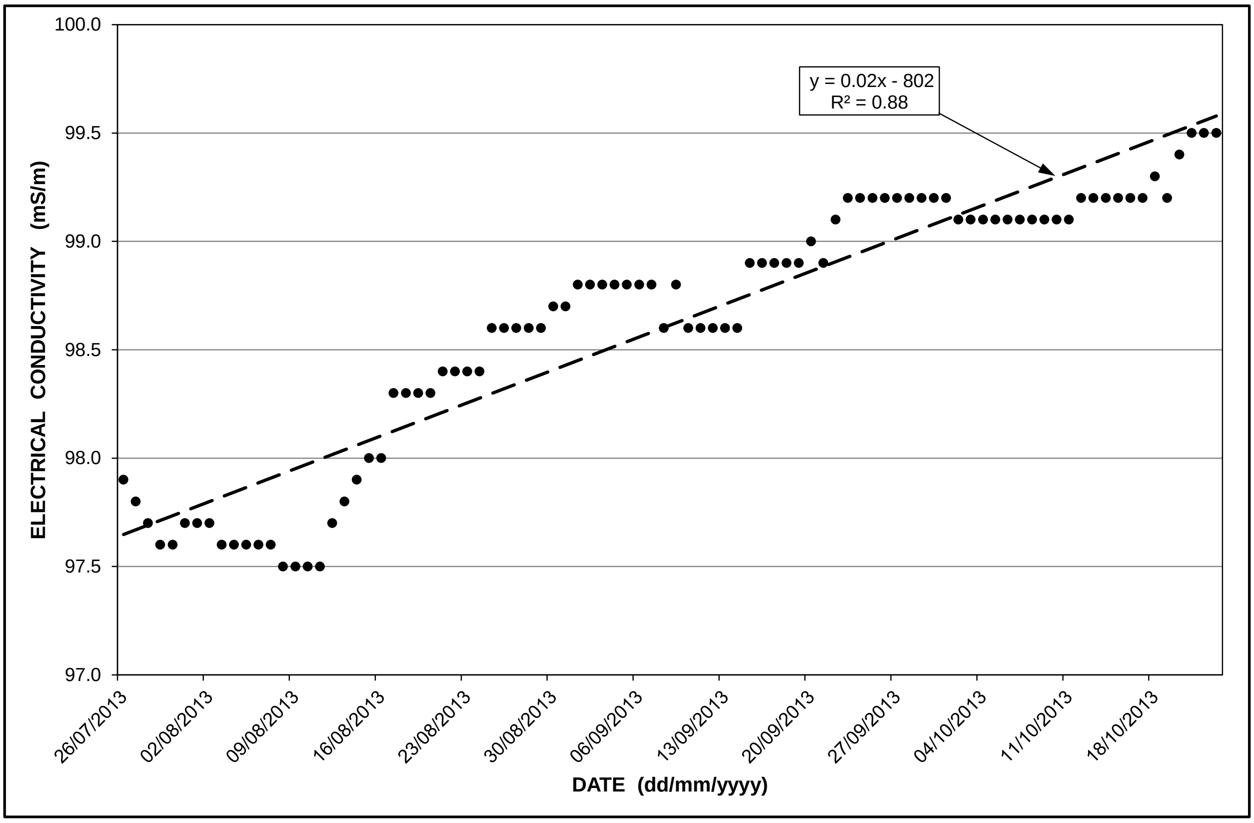

Figure 44 Chemograph of recent salinity of Zwartkrans Spring karst groundwater

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 extended monitoring programme 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, municipal and mine wastewater discharge, autogenic and allogenic recharge of the karst groundwater system, and groundwater discharge.

- The Bloubank Spruit system did not experience exceptionally high discharge conditions in the most recent (2012–'13) wet season, indicating a return to more 'normal' flows compared to the abnormally high discharges of the preceding three summers.

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

- Synoptic discharge measurements at two stations in the lower reach of the Riet Spruit continue to confirm previous results regarding quantified losses of AMD-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, and also reflects the influence of the more recent improved AMD-impacted surface water quality.

- The impact of allogenic recharge from the losing reach of the Riet Spruit to the karst aquifer of the Zwartkrans Compartment continues to be 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. There is tenuous evidence to suggest that the groundwater quality further upstream is starting to reflect a slight improvement, which will continue for as long as the immediate mine water (AMD) control and management intervention measures are maintained.

- The decline in the Main Lake water level since mid-2012 has continued at a rate of ~0.04 m/month, but is expected to 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 remains 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 hydrodynamic conditions that have precipitated an adjustment of the natural water resources environment which, in the case of groundwater, is immediately and most evident in potentiometric levels. 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 continues to suffer from a compromised groundwater quality. Sulphate levels of >1 000 mg SO_4/L will definitely impact on the potability of groundwater-based water supplies in the area effected. Although the commissioning of the immediate mine water control and management intervention measures in mid-2012 has ameliorated the quality of surface water in the Bloubank Spruit system, the impact on the groundwater environment in the effected portion of the Zwartkrans Compartment will take significantly longer to manifest an improvement.

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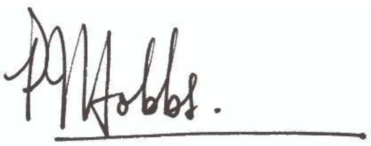

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