

WITWATERSRAND MINE VOIDS – THEIR HYDROCHEMISTRY AND HYDRODYNAMIC CHARACTERISTICS.

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Abstract.

Gold mining on the Witwatersrand has started in the late 19th Century as sporadic open cast mining and ceased in the late 20th century leaving a complex network of haulages, tunnels and ultra-deep vertical shafts/sub-vertical shafts. At least three ore bodies (conglomeritic horizons) were mined down to a depth in excess of 3000m from surface. Three large mining basins resulted from the mining methodology applied, viz. the Western, Central and Eastern (Rand) Basins.

In the early days of mining on the Witwatersrand reefs, gold mine companies realized that dewatering of their mine workings is required to secure mining operations at deeper levels and decades of pumping and treatment of pumped mine water followed.

As the majority of deep gold mines on the Witwatersrand ceased operations since 1970, the deeper portions of the mine voids became flooded and lead to a new era in the mining history in the Witwatersrand.

Rewatering of the mine voids is a combination between excessive surface water ingress generated by surface runoff and to lesser degree recharge from an overlying fractured and weathered aquifer systems (where developed). The flow regime in the mine voids from a scattering of ingress/direct recharge points and single discharge points are complex and is driven by shallow (<100m) and probably deep (>1000m) manmade preferential pathways.

The high concentrations of iron sulphide minerals (pyrite (e.g. FeS₂) content, three percent (by weight), of the mined reefs/backfilled stopes and surrounding waste rock piles/tailings dams mobilized significant levels of sulphates (SO₄) and ferrous iron (Fe²⁺) producing an acidic mine void water (<3pH).

Monitoring of the rewatering mine void hydrological regime became necessary following the first acid mine water decant from a borehole in the West Rand Basin and the Department initiated a mine-void water table elevation trend and water quality monitoring program. Results from this monitoring program will be illustrated and discussed in this paper with some views on the future water quality and discharge scenarios.

1. INTRODUCTION.

Gold was discovered north of Mogale City (Krugersdorp), on the farm Kromdraai (520JQ) by S.W. Minnaar and was proclaimed as the first proclamation in the Witwatersrand Basin for gold mining in 1875 (Handley, 2004). The West Rand, Central Rand and East Rand Basins are roughly 86km long in the west-east direction. The Central Rand Basin forms the central part of the Witwatersrand Region and is approximate 45km from west to east (Figure 1). The ore bodies consists of conglomerate layers interbedded in mainly a sedimentary sandstone/shale sequence – 3000 to 2700Ma. The sandstone was subsequently altered to quartzite through rock diagenesis. Due to tectonic events (warped, tilted and fragmented due to faulting) the Witwatersrand Basin has been block-faulted into three separate basins with significantly different hydraulic characteristics. The Central Rand Reefs were explored by several prospectors since 1875, viz. the Confident Reef by Fred Struben in September 1884 and the Main Reef in March 1886 by Harrison and Walker. The first relatively deep exploration borehole was drilled in the Central

Rand Basin (CRB) in 1890 and several others followed of which the Turffontein East borehole (1901) intercepted the Main Reef at 1489m bGL (Viljoen and Reimold, 2002). Mining activities since the discovery of the so-called “Reef Model” concentrated along and adjacent to the strike length of the reefs resulted in an extended open cast void all over the Central rand from Roodepoort to Boksburg, with similar sporadic open pit excavations in the Western and the northern limb of the East Rand Basin.

Several gold bearing reefs occur in the Central Rand Basin (CRB) of which the Main and Kimberly Reefs were mined extensively down to ~3400mbGL (~1600mbSL).

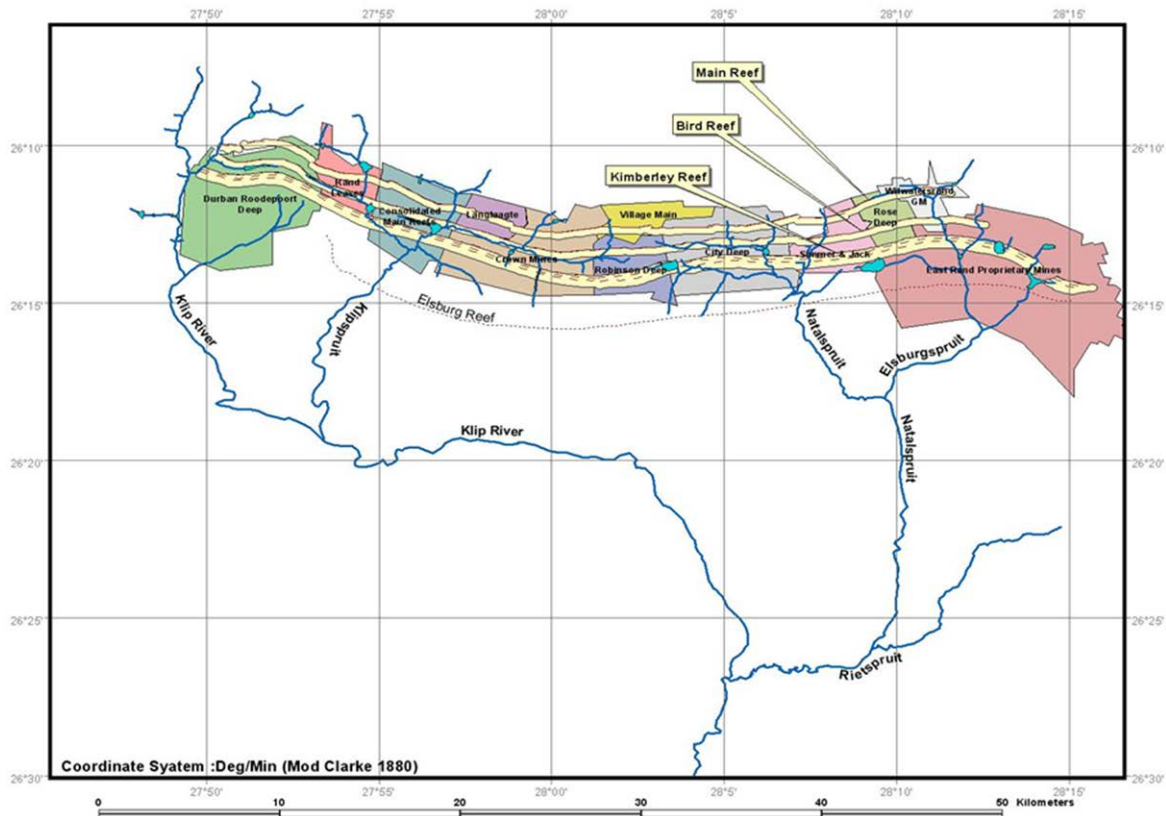


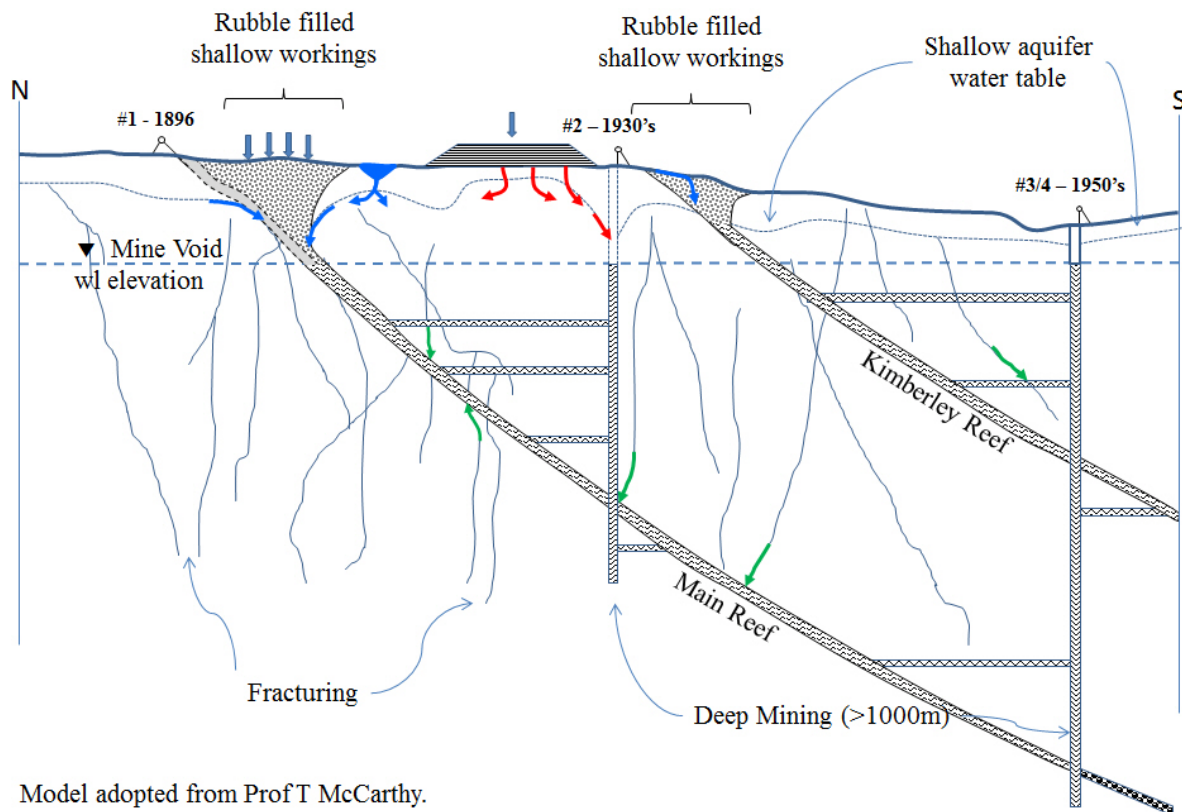
Figure 1. The Central Rand Basin showing the mine lease areas, drainage systems and the strike of the gold bearing reefs (Main, Bird and Kimberley Reefs). DWA, 2011.

The reefs were mined in specific “mine compartments” due to the management of airflow and excess water originating from upper level inflows through the first generation incline shafts (such as the Cason, Anglo Main and Crown Mines incline shafts) and fissures.

When gold mining reached its final underground working depths (3000m), several deep-level shafts existed south of the reef outcrop zones (Figure 2). The depths of these shafts, for its time (for example Crown Mine No. 5 Shaft, sunk in 1902 went down to 1560m in 1912). The Southwest Vertical Shaft and Sub-Vertical Shaft serviced mine workings at the lower end (eastern side) of the CRB; to approximately 1770mbSL.

Underground Mining operations in Witwatersrand Basin began to subside from the 1970's; underground operations in the West Rand Basin (WRB) ceased in 1998; although surface operations (mining of old sand dumps) are still ongoing today. Long-term rewatering of the underground mine workings proceeded the so-called “period of the new gold price era – 1971 to

1985' and since 1986 the gold mining industry moved into a decline, ranging from the number of mines, mining houses as well as production (Handley, 2004).



Model adopted from Prof T McCarthy.

Figure 2. Example of different stages of mining and shaft development and hypothetical subsurface flow regimes. Arrows indicate groundwater flow directions from surface (ingress) and deep fissure flow.

Deep mine dewatering by two remaining operational mines on the Central (E.R.P.M.) and Eastern (Grootvlei) Basins kept their mine void water-level elevations below operational levels, however, both operations cased in 2008 and 2011 respectively and flooding of the mine voids commenced at an average rate between $\sim 0.31\text{m/d}$ and $\sim 0.30\text{m/d}$.

Decanting of mine water was observed in the WRB in August 2002 from a borehole, followed by discharges from local inclines/shafts as the mine void became saturated and pressurized. The need for monitoring became a reality when the open pits in the WRB started to flood and acid mine water flowed down the Tweelopiesspruit into the Krugersdorp Game Reserve with serious environmental consequences. This event initiated a series of emergency processes lead by a Cabinet Committee to investigate management scenario's for the acid mine drainage problem in the Witwatersrand Region.

2. HYDROLOGICAL MONITORING

Monitoring of the mine water conditions (elevations and quality) requires a safe and accessible path down to the water table and deeper. Only three shafts were considered safe to perform these

operations, viz. Crown Mines No 14 Shaft (CRB), Spaarwater No 1 Shaft (ERB) and Sub-Nigel No 1 Shaft (ERB).

Monitoring of the WRB is straightforward due to the decanting status; thus representing the hydrogeological characteristics of a decanting Witwatersrand mine-void. Monitoring in the CRB and East Rand Basin (ERB) is complex. Firstly, the water level depths were deep (>450m) and secondly, access to the mine void water table elevation is only possible through a few open shafts. The Crown Mines No 14 Shaft (CM#14) serves the Gold Reef City underground museum at L5 (-215.36mbGL) and offers a unique opportunity for deep water elevation and quality observations. An incline shaft forms part of this mine workings, servicing the upper levels of the mine. The total depth of the CM#14 (the main shaft and two deeper sub-vertical shafts) goes down to 3293m; thus providing an excellent response to hydraulic responses and water quality in the CRB mine void.

Intermittent mine void water table monitoring were started to observe the rewatering of the WRB several years before the actual decant occurred in the Tweelopiesspruit. This decant initiated several monitoring programs by mining houses (Harmony – WRB, DRD Gold – CRB and Gold One – ERB). The WRB decant posed an immediate threat to the surface water resources downstream from the decant point which is only a 1.75km upstream from the “Hippo Pool” in the Krugersdorp Game Reserve. Observations by Mogale City environmental officials of a slow, but significant rewatering of the Hippo Pool, indicated that this mine void was reaching a decanting status several months before the first physical decanting mine water were observed at the Chinese Shaft (pers. comm. Messrs. G Krige and S du Toit, 2012) (Figure 3).

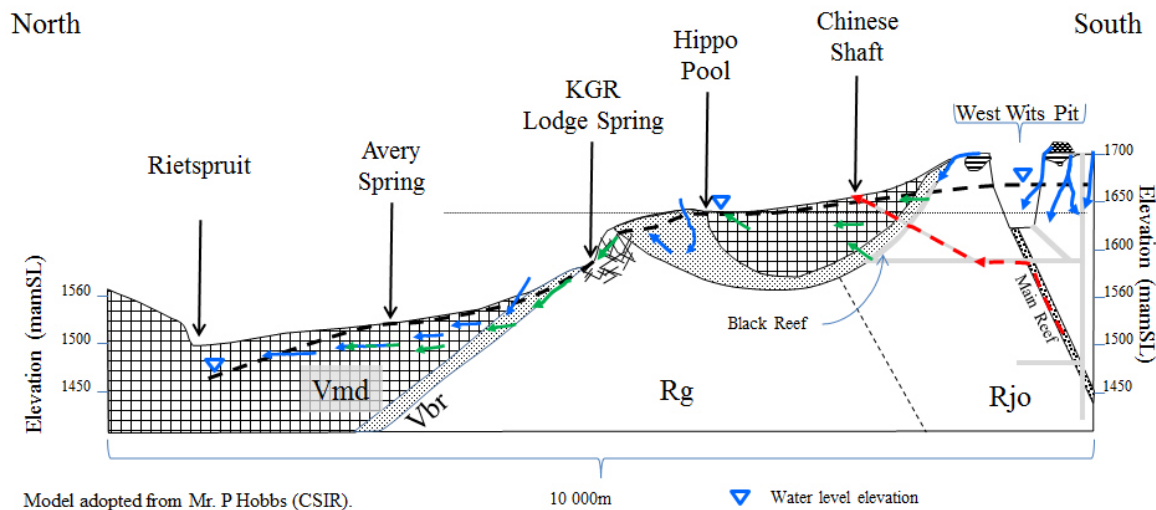


Figure 3. Diagram illustrating the hydrogeological conditions in the West Rand Basin; showing subsurface flow directions and hydraulic links between the Central Rand Group (Rjo) and Black Reef (Vbr).

Deep water level monitoring operations commenced in the CRB (DRD/Shango Solutions) in July 2009 and the Eastern Basin (Gold One) in May 2010. Sampling of water from the mine void, even at water table elevation was extremely difficult and several sampling units were lost. Deep camera logging by the Mine Rescue Services, however, provided some images of the mine shaft conditions above the water table and was valuable for planning purposes.

Deep water level monitoring and sampling were conducted the CRB and ERB using the department's borehole logging unit due to the depths (>450m) of the mine void water table

(2010-2011) and still record a reasonable accurate depth log ($\pm 10\text{cm}$). Mine-void water samples were obtained from several hundred metres below the current water table elevation and provided some insight of the actual mine-void water quality character.

The Department of Water Affairs initiated the Short Term Interventions (STI) program in February 2011 and planning/constructing of pump/treatment schemes for the Witwatersrand Basins became a crucial milestone to prevent decanting of the Central and Eastern Basins. The Directorate Hydrological Services, with support from the Council for Geosciences investigated the possibility to measure and sample deep mine void water from open mine shafts. These shafts were all 3rd and 4th generation shafts and although some of them were capped with port holes for monitoring, some were open and dangerous to monitor; special gantry's and equipment were required.

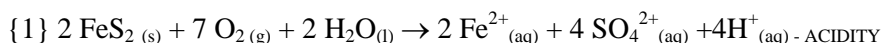
Water level depths in the WRB is already at surface since August 2002 and monitoring in the basin thus focused on the impact of acid main drainage on the environment (Tweelopiesspruit and downstream).

The department developed a monitoring program for deep mine void observations in the Crown Mines No 14 Shaft as this site contains a vertical shaft for deep water level/quality monitoring as well as shallow incline ingress; all at -215.36mbGL. The incline water monitoring provided an excellent example of the yield and hydrochemical character of shallow water ingress. In addition, this site shows how waste rock stock piling was performed underground, resulting in a significant underground rock-water surface interface; probably occurring throughout the Witwatersrand Region.

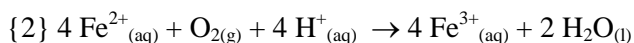
3. GENERATION OF ACID MINE WATER

The auriferous conglomeratic reefs in the Witwatersrand Basins are composed of quartz pebbles (~25mm diameter) with a quartzite matrix. Within the matrix are a wide range of heavy minerals (pyrite and pyrrhotite) in either crystalline or nodular form (Handley, 2004).

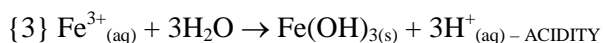
When the reef rock/waste rocks are exposed to oxygenated water and air during the mining processes underground and at surface (waste rock dumps and sand/tailings dams), the sulphide rich material is oxidized to sulphuric acid and iron. The oxidation chemistry of pyrite, the generation of ferrous ions (Fe^{2+}) and subsequently ferric ions (Fe^{3+}) is complex. Stumm and Morgan (1981, cited in Scott, 1995 and DWA, 2012) has simplified the reaction to the following reactions:



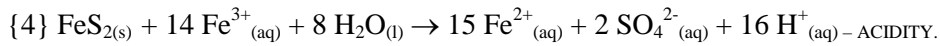
The oxidation process of pyrite (sulfide to sulfate) solubilizes the ferrous iron (Fe^{2+}) which is subsequently oxidized to ferric iron (Fe^{3+}). Although a slow process (Scott, 1995) the rate of oxidization is increased by microorganisms that derive energy from the oxidation reaction;



The ferric iron (Fe^{3+}) is then hydrolysed by water and forms ferrihydrate ($\text{Fe}(\text{OH})_3 (\text{s})$), an insoluble precipitate releasing more acidity to the environment (mine void, wetlands and stream);



The abundance of ferric irons (Fe^{3+}) produced by the latter process may enhance further oxidation of pyrite minerals which oxidizes into ferrous ions:



The net result of these chemical reactions is that H^+ is released which lowers the pH status of the mine void liquid and subsequently maintains the solubility and oxidation of sulphide and some of the oxide minerals in the ore body and underground workings. Scott (1995) notes that once acid generating reaction has started, oxygen (O_2) is only necessary for catalyzation by microorganisms to oxidize ferrous iron to ferric iron.

Mine void water quality observations in CM#14 Shaft since monitoring started in 2011 provided the authors with a baseline of the AMD characteristics in the deeper sections of the mine void (Figure 4).

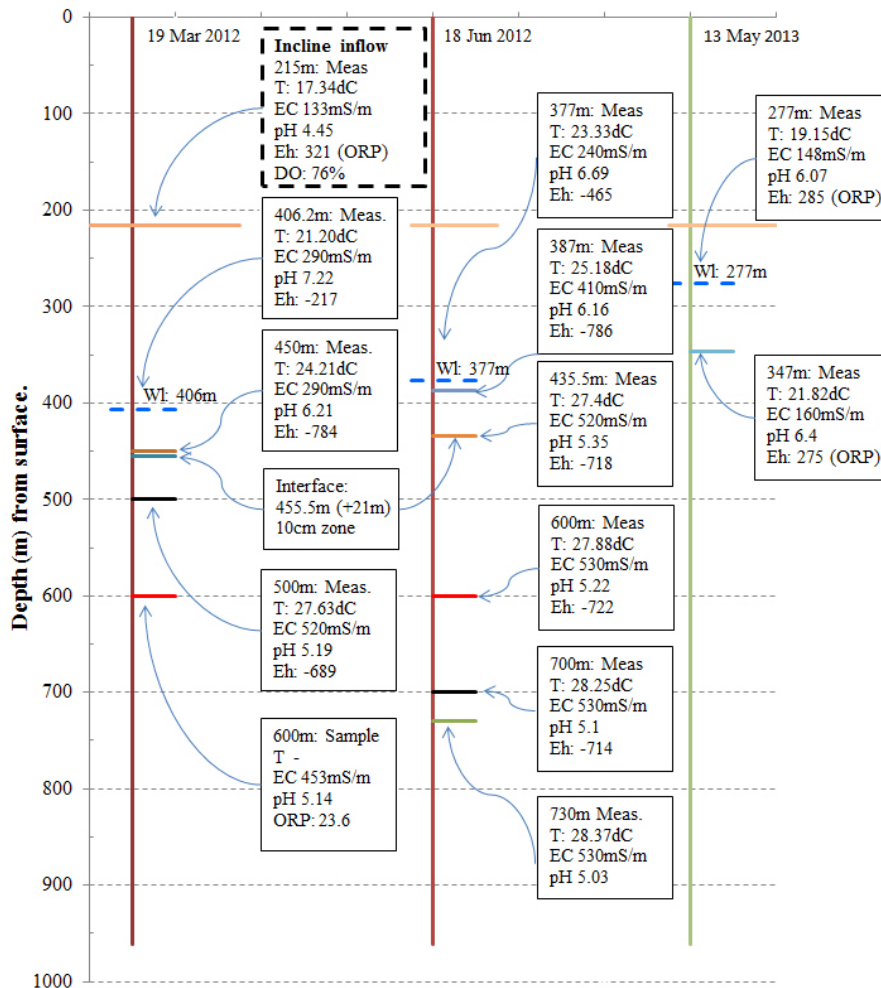


Figure 4. Observed water quality parameters at various depths in the Crown Mine No 14 Shaft.

Water quality measurements and hydrochemistry data close to the bottom of the shaft (961mbGL – 738mamSL) have the following hydrochemical signatures: pH ~5.0, Temp.: ~28.4°C, TDS: ~5600mg/l, Eh: ~700, SO_4 : ~3400mg/l, Ca: ~532mg/l, Mg: ~311mg/l, Fe: ~390mg/l and Mn: ~22mg/l. Eh values of the deeper mine void water indicates a reducing environment (viz. negative values, ~ -700).

The oxidation process in the Witwatersrand mine voids are significantly enhanced by the continuous ingress of oxygenated water from the surface. Many shafts in the region act as so-

called “recharge” shafts and feed shallow groundwater ingress to the deeper parts of the mine void. Most of the younger generation mine shafts are ultra-deep (viz. 2000m) and their links to the mine voids are deeper than 1000m. Profiling of the water quality in the shafts indicates a complex hydrochemistry; especially when the mine void is in a decanting stage such as the WRB. Due to the limitation of monitoring equipment, no information on the hydrochemistry character of the deeper (>1000m) sections mine void is available and therefore the status of AMD generation at these levels professes a significant surprise for us. Scott (1995) predicts that AMD generation is not oxygen dependent once the microbiological processes have started and depending on the availability of sulphides the AMD generation may still continue for millenniums.

The effect of chemical buffering by the mine shaft construction material (concrete/brick shafts barrel linings) is clearly observed in the water quality just below the water table, viz. almost neutral pH (6.07-7.22 with time) and positive Eh/ORP values (viz. oxidizing conditions).

4. MINE VOID HYDROCHEMISTRY.

The Witwatersrand mine voids are all in a different stage of rewatering and the WRB is currently fully flooded and decanting at several points. Profiling of the water quality in mine shafts indicates a complex mine void water evolution; especially in the case of flooded mine voids such as the WRB. A summary of the WRB hydrochemistry is presented in Table 1. It lists the long-term statistics (95 percentiles) of the decanting sites (17, 18 Winze and the Chinese Shaft (BRI or Black Reef Incline) (DWA, 2012).

Table 01. Mine water qualities in Western Basin

Parameter (25°C)	pH	EC	TDS	Ca	Mg	Na	Cl	SO ₄	Fe	Mn
Site	-	mS/m	↓	mg/l						
17 Winze (95%tile ¹)	3.45	442	4879	658		209		3253	895	85
18 Winze (95%tile ¹)	4.18	446	5487	713		66		3658	968	76
BRI (95%tile ¹)	4.62	435	5366	724		199		3577	923	94
CPS-Bh May'12 ²	4.3	164	1738	144	71	41	20	773	93	11
18 Winze – May'12 ³	4.4	425	4505	805	45	104	37	3230	446	44
Lion Camp – May'12 ⁴	2.9	353	3741	596	133	90	34	2250	59	54
N14-2LS May'12 ⁵	2.9	331	3506	549	117	87	32	2100	42	49
RU #8 Shaft - May'13	3.5	425	4505	778	45	108	218	2847	674	46
17 Winze – Jun'13	2.9	468	4960	686	48	104	41	2931	681	49
18 Winze – Jun'13	3.5	460	4876	773	35	105	41	3100	630	49
* EC→TDS conversion factor (~10.6; AMD FS LTS (DWA, 2012)). ¹ Period 2011-2012: AMD FS LTS (DWA, 2012), biased towards 95 percentiles; ² Sample from ~58m bGL in mine workings (tunnel) - ³ Flowing from leaks in shaft collar and syphon pipe – oxidized decanted mine void water. ⁴ N14 and Tweelopies Spruit crossing (bridge-crossing) – surface water. ⁵ Krugersdorp Game reserve – Lion Camp Tweelopiesspruit monitoring site – Surface water.										

In the WRB, several shafts (No's 8, 9 and 17 and 18 Winze), as well as the Central Power Station (CPS) borehole, were profiled. The CPS borehole, drilled as an emergency escape route for miners, intercepts a mine tunnel at 57mbGL. The mine void acidity (viz. pH) in the WRB varies significantly; in the mine void (CPS borehole at 58m) pH values varies from 3.95 (well bore) to 5.2 (tunnel) and is based on the oxidation status (availability of O₂). In flowing shafts (e.g. 18 Winze) the water quality parameters (pH, Spes. Cond. and temperature) are stable down to the bottom of the shafts (±75mbGL) , however, variations in the oxygen content varies from 9.1%

(top) and 17.1% (bottom) as illustrated in Figure 5. At the 18 Winze shaft the pH values dropped from 5.8 (1m below shaft collar) to 4.5 (decanting stream) over a distance of roughly 10m. This phenomenon was observed at other monitoring sites in the WRB as well; a response described by Hem (cited in Hobbs, 2011) and illustrated in the hydrolysis reaction {3} above. A summary of the hydrochemistry character of the mine void water and decanting mine void water is illustrated in Figure 5; further stating the complexity of a flooded, decanting mine void.

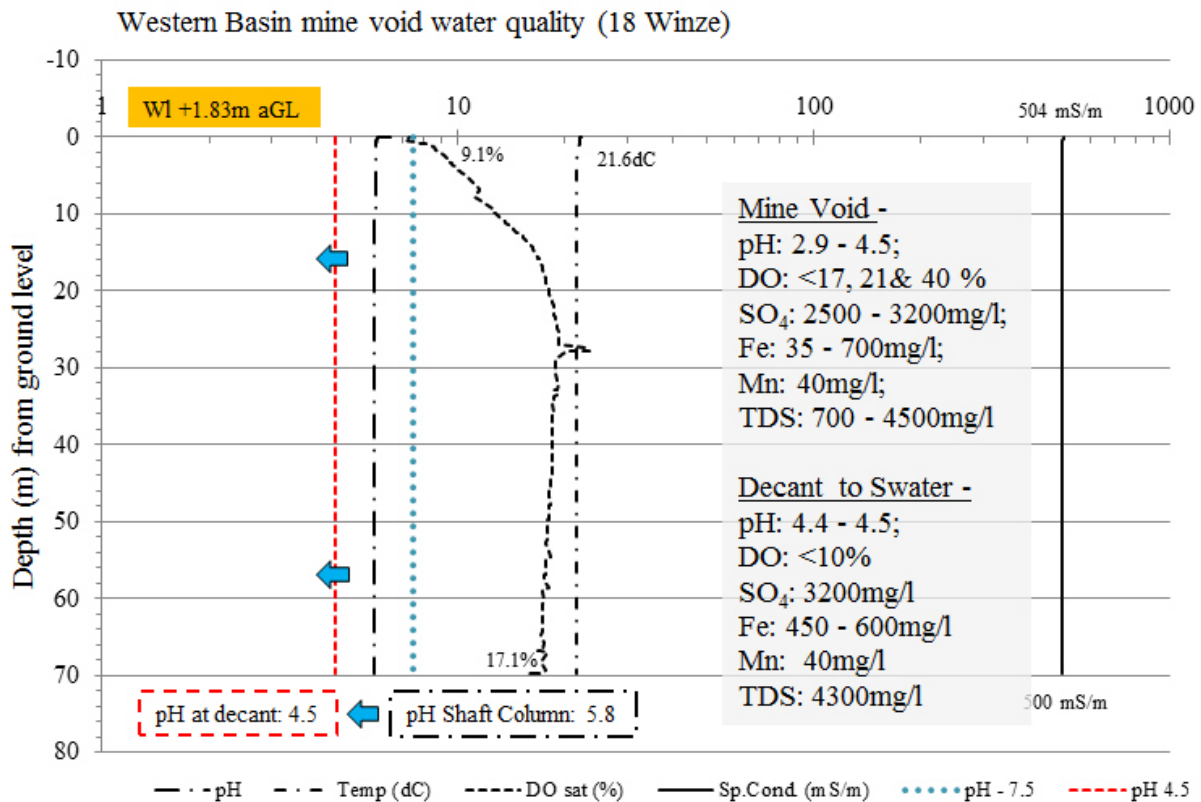


Figure 5. Profiling of 18 Winze Shaft from surface (2m above ground level) and pH values in Shaft column and a few metres from the decant point. Included is a summary of mine void and decanted water.

It is also evident that the generation of AMD (specifically its acidity signature) in flooded mine voids is probably an iterative process close to and at the decant points/surfaces (viz. intermittent availability of atmospheric derived oxygen in the vadose zone during recharge events).

Monitoring data from 18 Winze (May 2012) is similar in terms of the AMD indicators (pH, SO₄ and Fe). Further downstream (Tweelopiesspruit: N14 and Lion Camp monitoring sites) the character of the mine water is more acidic (due to hydrolysis, free ⁺H, Hobbs, 2011) coupled with a reduction/organic matter oxidation of SO₄ and decrease of Fe due to the precipitation of ferrihydrate (Fe(OH)_{3(s)}) (Hobbs, 2011). The decrease of the SO₄ concentration along the Tweelopiesspruit from the decant point (18 Winze – 3230mg/l SO₄ – May'12) down to the Rietspruit (N14-2LS – 2100mg/l SO₄ – May'12) could be the result of bacterial sulphate reduction process proposed by Hobbs (2011).

Monitoring results at 18 Wynze between 2012 (May) and 2013 (May and June) is presented in Table 1; showing noteworthy increased AMD signatures (acidity - pH: 4.4 to 3.5), Fe (446 to 630

mg/l) and TDS (4505 to 4876 mg/l); although the SO₄ concentration decreased slightly (3230 to 3100 mg/l).

The deep water quality measurements and hydrochemical analyses in the mine shafts were obtained with an Idronaut Ultra Deep water quality probe and an in-situ water sampling probe. These precise measurements and water sampling in the shafts allowed us to assess the water ingress in to the mine shafts, as well as the water flowing into the shaft column from the deeper mine void. Figure 4 illustrates the water quality characteristics of the ingress water flowing down the incline shaft (-215mbGL), coming from shallower (~75m) parts of the Kimberley mine workings in the Crown Mines Compartment. This ingress is acidic (pH=4.45), with a “fresh” specific conductance (<140mSm), but already reporting a SO₄ concentration of ~560mg/l. Figure 6 illustrates the situation as observed on the 19th of March 2012 during a water sampling exercise in the CM#14 at Gold Reef City.

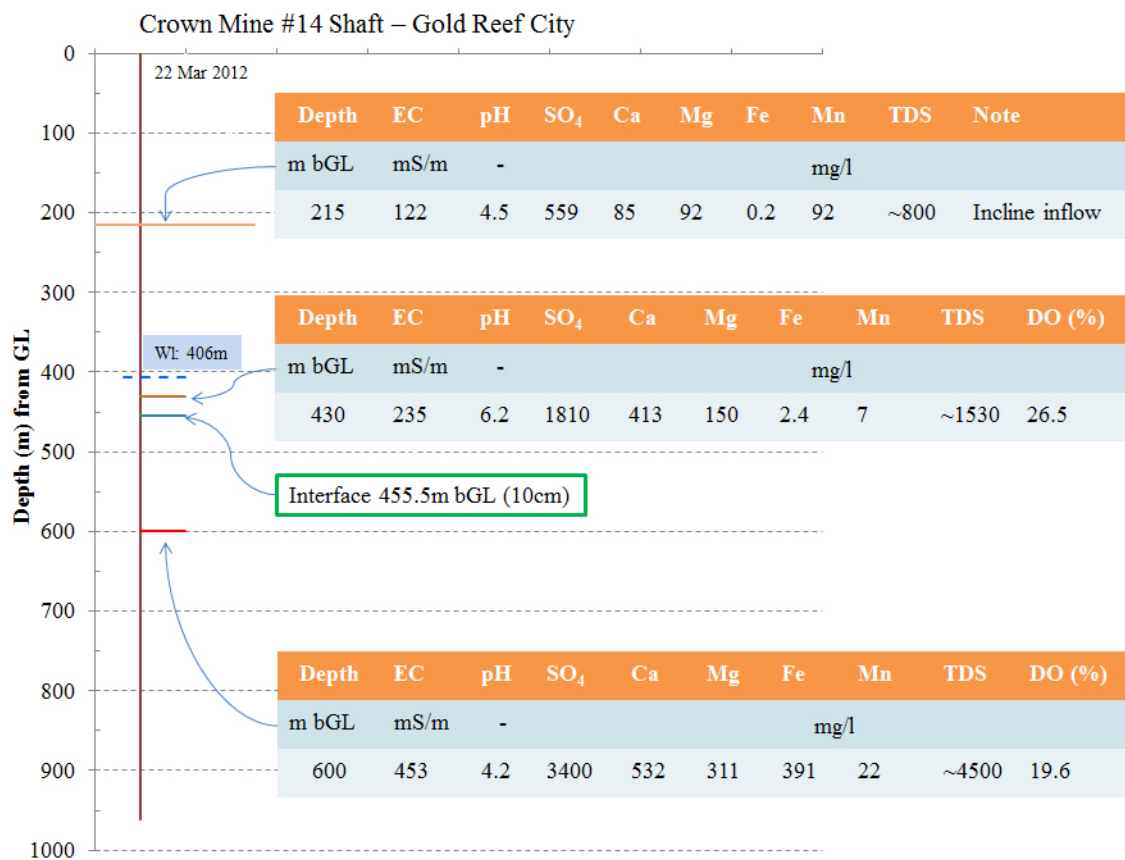


Figure 6. Illustrating the different water quality signatures of the ingress and upper and lower parts of the shaft water column in CM#14 Shaft, Crown Mines Compartment.

The vertical mine water quality variations in the CRB, illustrated in Figure 6, suggests at least a two layered mine void water body, viz. deep mine void water forced up in the shafts due to the regional mine void flow regime, based on a *U-tube effect* (Winde, 2004). The actual quality of the deep mine void water (viz. >2000m) is currently unknown, however, according to water quality data obtained for the planning of the Level 24 Pump Station in the E.R.P.M workings (Tyser, 1977) it was “acidic and contain a high proportion of solids”. He mentions: pH value: 3.2,

Fe₂: 1400mg/l and SO₄: 6400mg/l which is significantly higher than what is observed at any point/level currently monitored.

Ingress water, from shallow, unsaturated and ventilated mine workings (such as the Kimberley Reef workings at CM#14 Shaft) are channel into so-called “recharging shafts” mine shafts, linked with the deeper parts of the mine voids and thus adds recent water with high dissolved oxygen content (>50%) into the deeper parts of the mine voids. In addition, shallow polluted water from ingress points (cracks in old, shallow underground workings, old incline shafts and geological structures) and local shallow aquifer discharges into the mine void at numerous points along the strike of the reefs. One must bear in mind that these mine voids (WRB, CRB and ERB) are underlying a large urbanized region; which has significantly changed in terms of water input over the last 50 years and does not function as classic semi-arid water balanced catchments anymore.

5. HYDRODYNAMIC CHARACTERISTICS

The number of holings, inclined, vertical and sub-vertical shafts in the Witwatersrand, is probably exceeding a thousand. These are all potential entry points for surface water ingress into the underground mine workings and are spread over a vast area from the reef outcrop area, towards the south; thus the most recent generation of mine shafts are situated several kilometers south of the reef outcrops and their elevations are tens of metres lower than the mined reef outcrops. Many of these shafts are multi-shaft systems reaching down in excess of 3500m below ground level. The reef mining method followed in the Witwatersrand Region and the compartmentalization of mine workings according the surface lease areas, have resulted in a complex networking of incline shafts, mine tunnels/haulages. It has been noted that miners could at one stage of the underground developments, physically walk from the western side of the void, to the eastern side. Observations by miners of the rock wall temperatures in the deeper sections of the workings, was close to 50°C (Handley, 2004). These conditions support the deep mine void flow characteristics proposed by Winde (2004).

The monitoring program initiated by the department and mining companies provides a useful record of the Witwatersrand mine voids recharge progress. Water table monitoring in the WRB for example, predicted the actual decant date and almost match the day when the first decant was observed in a borehole at the Chinese Shaft (Figure 3).

The potential of acid rock drainage from the Witwatersrand mine voids became a 21st Century reality to the South Africans society observing the environmental impact caused by the WRB decant. The need for understanding the processes involved and the urgent requirement for AMD treatment necessitated a water level monitoring network. Estimations of the daily water table elevation rise for the CRB and ERB became the norm for predicting important dates set by various committees planning water treatment requirements and infrastructure development.

Since monitoring data for the CRB became available the daily mine void water table rise decreased from 0.46 to 0.32m/d (Table 2). One of the crucial decisions was to establish so-called *ecological critical levels* for the CRB and ERB and plan the treatment facilities accordingly.

Table 2. Daily mine void water table elevation rise in CRB

Hydrological Cycle ¹	Daily Rise (m)	Monthly Rise (m)
2009 - 2010	0.46	13.94
2010 – 2011	0.39	11.82
2011 – 2012	0.32	9.70
2012 - 2013	0.31	9.39
¹ October _n to September _{n+1}		

E.R.P.M. was the last working mine in the CRB and was forced to stop their pump and treatment activity in 2008. At that time the water table elevations along the strike of the CRB was at different levels; as indicated in Figure 7 below. A series of plugs prevented simultaneous flooding of the different mine compartments up to 2001 when pumping at DRD ceased. Due to the pump-treat program at E.R.P.M. the water table configuration indicated three sub-basins (Golder Associates Africa, 2008). They are:

- Western sub-Basin (DRD and Rand Leases);
- Central sub-Basin (Cons. Main Reef to Simmer and Jack, including Rose Deep); and
- Eastern sub-Basin (E.R.P.M. West and East).

Until 2008 this water level elevation configuration remained but due to connections at shallower levels of the mine void it became one interflowing system and elevation differences of a few centimetres between shaft water level elevations in DRD#6, CM#14, CD#4, SJ Catlin & Howard and SWV were observed which relates to incorrect shaft elevations instead. Over the period 2011 to 2012 all these shafts recorded a daily rise of 0.3m/d; thus indication a hydraulic linked system along the strike of the CRB (Figure 7).

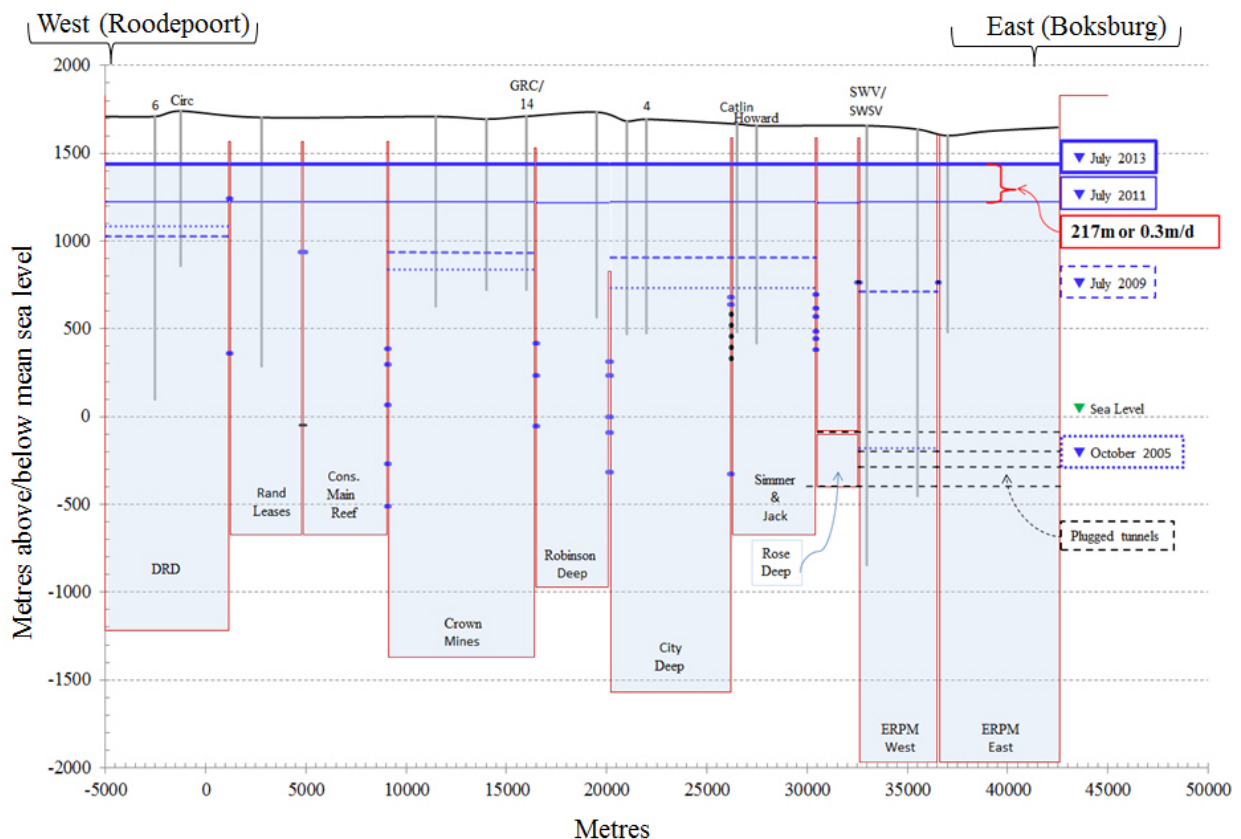


Figure 7. Illustrating the chronological rewatering of the Central Rand Basin since mine dewatering ceased in 2001.

Connectivity between the different mine compartments are illustrated (blue links) representing open tunnels/haulages where water flow from one compartment to adjacent ones; thus indication an effective deep (>1600mbGL) and shallow (<500mbGL) flow pattern.

The rate of rewatering in the CRB is closely monitored showing that the water table elevation will breach the Gold Reef City museum (-215.36mbGL) towards the end of 2013. The daily rise trend

calculated from physical measurements (solid dots) is shown in Figure 8 and illustrates the two important dates influencing the status of the CRB water table based on a linear trend line (open dots) with a gradient of 0.3055 (or ~0.31m/d).

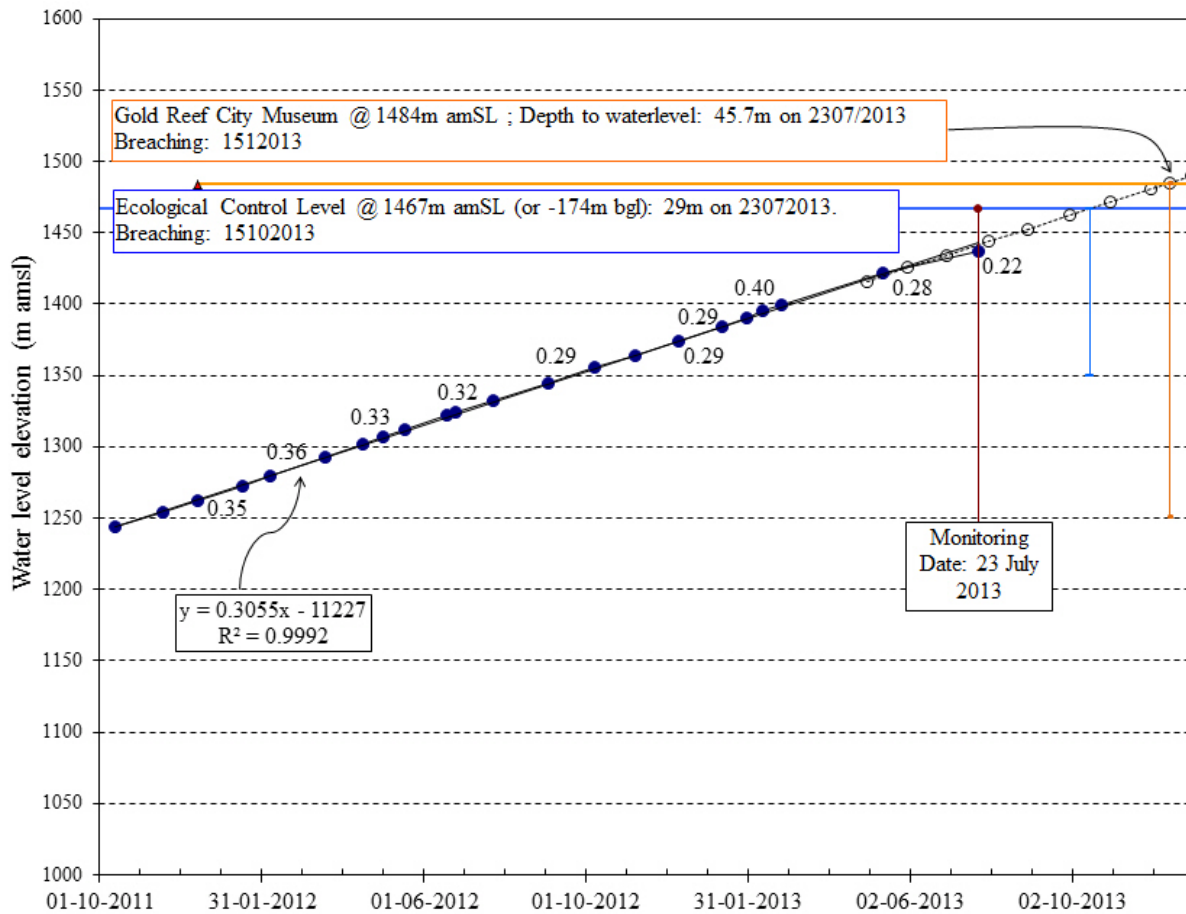


Figure 8. Water table trend (rising) in Crown Mine No 14 Shaft showing daily water table rise values since October 2011.

Water table monitoring in the ERB indicates several different water table elevations which are probably due to the geometry of the mine void which according to Scott (1995) consists of at least three different basins, viz. East Rand Basin, Brakpan Basin and the Sallies Basin. Long-term water level monitoring by DWA started in the southeastern part of the ERB at the Sub-Nigel workings in early 2010 with a long-term daily rise of 0.30m. Water level depths obtained from precise water level measurements in 9 shafts in the ERB do not indicate a plane elevation as observed in the WRB and the CRB. The reason for this phenomenon is unclear, although partial blockage of some shafts might be the reason for these differences.

6. CONCLUSIONS.

A hydrological monitoring program to observe the mine void water hydrochemistry and flow dynamics of the Witwatersrand Region has been established and maintained by the private sector

(mining houses) and the Department of Water Affairs. The results illustrate that the mine void water characteristics are complex and differ largely from basin to basin. The current (2013) water table elevations of the three Witwatersrand Basins are not on the same elevation level; thus indicating three different mine voids with different water table elevations (illustrated in Figure 9).

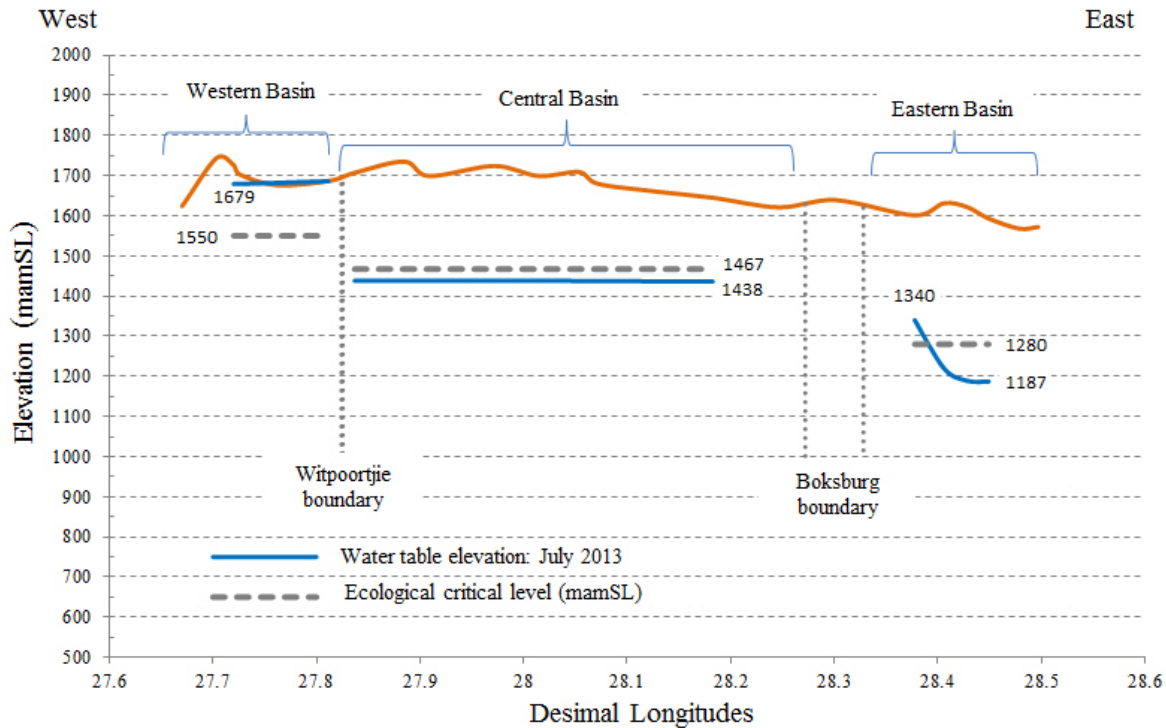


Figure 9. West to east section across the Witwatersrand mined basins illustrating the current (2013) water table elevations and ecological critical levels (metre above mean sea level).

The shallow water ingress into the mine voids is an ongoing phenomenon and drives the daily water table rise regardless of annual rainfall recharge. No specific water table rebound due to seasonal recharge could be observed in the monitoring period from 2010 to 2013. Observations in the Gold Reef City museum during the wet season (Jan – Mar) showed a slightly wetter mine void, although no increase in the incline discharge was noted.

The surface elevations of the Witwatersrand Basins varies significantly; the elevation difference along the reef-strikes of the Central Rand Basin varies almost 100m from west to east and creates the head difference for mine void decant/discharge at the lowest point (Boksburg Area). Currently the water table elevation in the Central Rand Basin (1437.5mamSL) is 176.5m below this elevation.

The decanting status of the West Rand Basin provides unique information of the mine void water quality regime which varies considerable between the underground parts of the mine void (CPS borehole) and at the shafts where the mine water is decanting (viz. 17 & 18 Winze and the Chinese Shaft). The third stage {3} of AMD generation is driven by atmospheric oxygen supplies at the decant site and further down the surface flow paths. Generation of acidity ($H^+_{(aq)}$) and the abundance of sulphate ($SO_4^{2+}_{(aq)}$) completes the $H_2SO_{4(aq)}$ character of the decant. It has been noted that the long-term water quality of the West Rand Basin is still deteriorating in terms of pH, Fe^{2+} and SO_4^{2+} concentrations.

In partially filled mine voids, such as the Central and Eastern Basins, there seems to be a significant difference between the shallow ingressing water (shallow underground workings such as observed in the Kimberley Reef developments in the Crown Mine compartment) and the deeper mine void water forced into the shallower sections of open mine shafts, viz. CM#14 and South West Vertical Shaft. Although the shallow ingress water is not mineralized yet, it already has an acid rock drainage character. In some cases elevated uranium levels were noted. Historical water quality data, however, indicated that the deep mine void water quality is highly contaminated with Fe^{2+} and SO_4^{2-} levels much higher than what is observed with the deep water observations in the mine shafts.

To conclude, the current knowledge of the Witwatersrand Regions mine void water characteristics is limited to what can be observed in the available shafts. These shafts, especially those situated on the lower elevations in each basin are so-called 4th generations shafts and are typically extremely deep and linked with at least two sub-vertical shafts in the same mine compartment. Due to the mine void geometry and elevations of ingress areas, these shafts may initiate U-tube flow systems and draw their discharges from the deeper levels of the mine void. The water quality, therefore, might be of a much poorer hydrochemical character than what is currently observed.

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