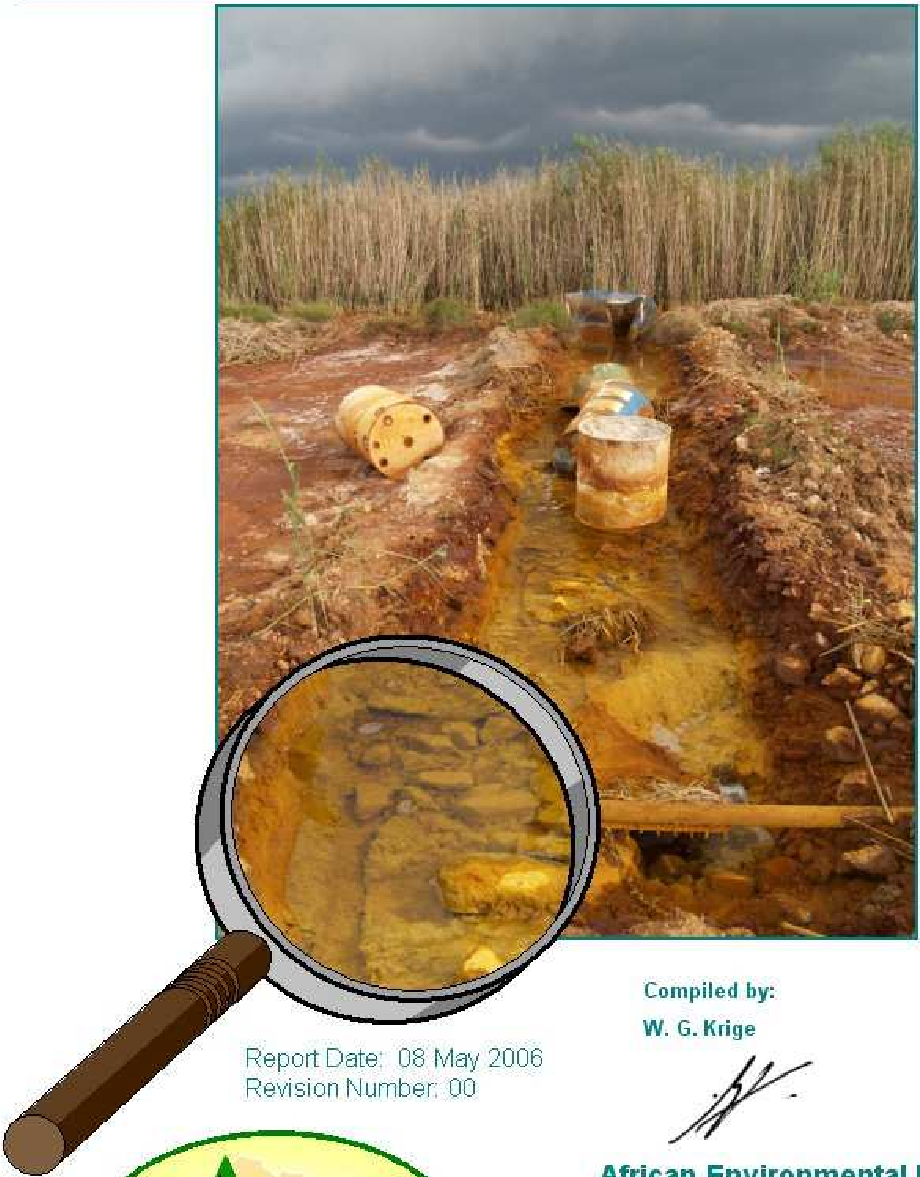
HYDROLOGICAL/CHEMICAL ASPECTS OF THE TWEELOPIE-/RIET-/BLAAUWBANKSPRUIT, WITH SPECIFIC REFERENCE TO THE IMPACT WATER, DECANTING FROM THE WESTERN BASIN MINE VOID, HAS ON THIS SYSTEM



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HYDROLOGICAL/CHEMICAL ASPECTS OF THE TWEELOPIE-/RIET-/BLAAUWBANKSPRUIT, WITH SPECIFIC REFERENCE TO THE IMPACT WATER, DECANTING FROM THE WESTERN BASIN MINE VOID, HAS ON THIS SYSTEM

Executive Summary

African Environmental Development was commissioned by Johan Fourie & Associates to conduct a study on behalf of Harmony Gold Mining Co. Ltd. Randfontein Operations on the impact of decanting mine void water on the surface water of the Tweelopie-/Riet-/Blaauwbankspruit and on the Zwartkrans Dolomitic Compartment. This study forms part of the EIA on the area as directed by the Department of Water Affairs and Forestry.

The report starts with providing the reader with a general overview of the surface water environment and provides a brief synopsis of the geology comprising the study area. It then proceeds to describe the gold mining history in the West Rand and discussed the association between the gold mining industry in the West Rand and the pollution of the Tweelopiespruit through the pumping of underground water for a period covering most part of a century.

A detailed section on the chemistry of the oxidation of pyrite to sulphate, the causative agent of acid mine drainage (AMD) follows and the mechanisms controlling the reactions are explained.

The following sections involve the measuring of flow and salt load into and out of the Zwartkrans Compartment. This section culminates in a water and salt balance of the compartment. The salt load of the Tweelopiespruit from the point where the mine water decants on surface up to its confluence with the Rietspruit is discussed in detail.

The impacts the mine void water will have on the dolomite of the Zwartkrans compartment is discussed and the chemical reactions that could occur are explained. These consequences include toxicity, ground stability and economic considerations.

The last sections of the report discusses the mitigation measures which will be required to improve the situation and to restore the downstream environment back to its original state.

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1. Introduction and Background

During the month of August 2002, an event took place that would have a far-reaching impact on the Cradle of Humankind World Heritage Site (Cradle) and the dolomitic aquifer underlying it, the Zwartkrans Compartment. This event was, of course, the first decanting of water from the flooded gold mines of Krugersdorp and Randfontein, collectively referred to as the Western Basin Mine Void. The water, decanting from a disused mine shaft, flowed through the Krugersdorp Game Reserve and entered the dolomitic aquifers of the Cradle. Although predicted by specialists as early as 1996, the magnitude of the event still caught many people, mining houses and authorities by surprise.

Photo 1 – The first water to decant from the flooded mine void occurred from a borehole sunk into a dolomitic inlier which, in turn, was linked to the flooded mine workings. This borehole was alongside the Tweelopiespruit. (Photo taken by G Krige on the 28th August 2002).

The decanting of polluted mine water was the final stage in a sequence of events which took approximately 115 years to complete. The process started back in 1887. Approximately a year after the discovery of gold on the Witwatersrand, the gold-bearing reefs of the Western Basin were discovered and have been mined ever since. During this mining process, water was pumped from the mine workings into the streams feeding the dolomitic aquifers of the Cradle, via the Tweelopiespruit, to enable deeper mining to take place. This pumping continued until around 1998, when a final decision was made to stop the last pumping operations at Harmony's Central Ventilation Shaft and allow the mine void, created during the previous 110 years, to flood.

For the next 4 years the mine void gradually flooded, mines' ownership changed and the predictions of 1996 were all but forgotten, until 2002, that is, when the water in the mine void finally reached the surface and started to decant into the Tweelopiespruit, upstream from the Krugersdorp Game Reserve, less than a month earlier than what was predicted in 1996.

Initially the water decanting from a dolomitic borehole was of a relatively good quality. However, some two weeks after the initial decant started from a borehole, the increased water pressure opened a previously unknown Black Reef incline shaft and the volume decanting from the mine void increased progressively while the quality of the decanting water decreased.

At first the mine water flowed freely down the Tweelopiespruit and caused all the aquatic life in the Krugersdorp Game Reserve to die, while accusations were also made of many animal deaths in the game reserve as a result of drinking water from the stream. Shortly after leaving the northern boundary of the game reserve, the Tweelopiespruit crosses a geological fault and within a few hundred meters, all the surface flow in the stream is lost into the dolomitic aquifer of the Zwartkrans Compartment.

Harmony GM Co Ltd. Randfontein Operations (hereafter referred to as "Harmony"), the company on who's land the shaft is located from which the mine water is decanting, erected an HDPE-lined dam to intercept the mine water and to pump it, initially to Robinson Lake, and later, via a treatment plant, to the Cooke Attenuation Dam in the Wonderfonteinspruit.

This study forms part of the Environmental Impact Assessment (EIA) as instructed by a Directive from the Dept of Water Affairs and Forestry (DWAF) and is intended to describe the current state of the water entering and leaving the Zwartkrans dolomitic compartment while also discussing the potential impact the mine water has had and may in future have on the water quality and quantity of the Zwartkrans dolomitic compartment.

1.1 Description of the Surface Water Catchment

The Tweelopiespruit forms part of the catchment of the Blaauwbankspruit, which, in turn, is a tributary of the Crocodile River upstream from the

Hartbeespoort Dam. This system forms part of quaternary catchment A21D. This catchment has a surface area of 371.584 Km^2, a mean annual precipitation of 713.73 mm with a reported mean annual run-off into surface streams of 56.3 mm (Midgley, *et. al. 1994*). Ref. ***Figure 1*** for location.

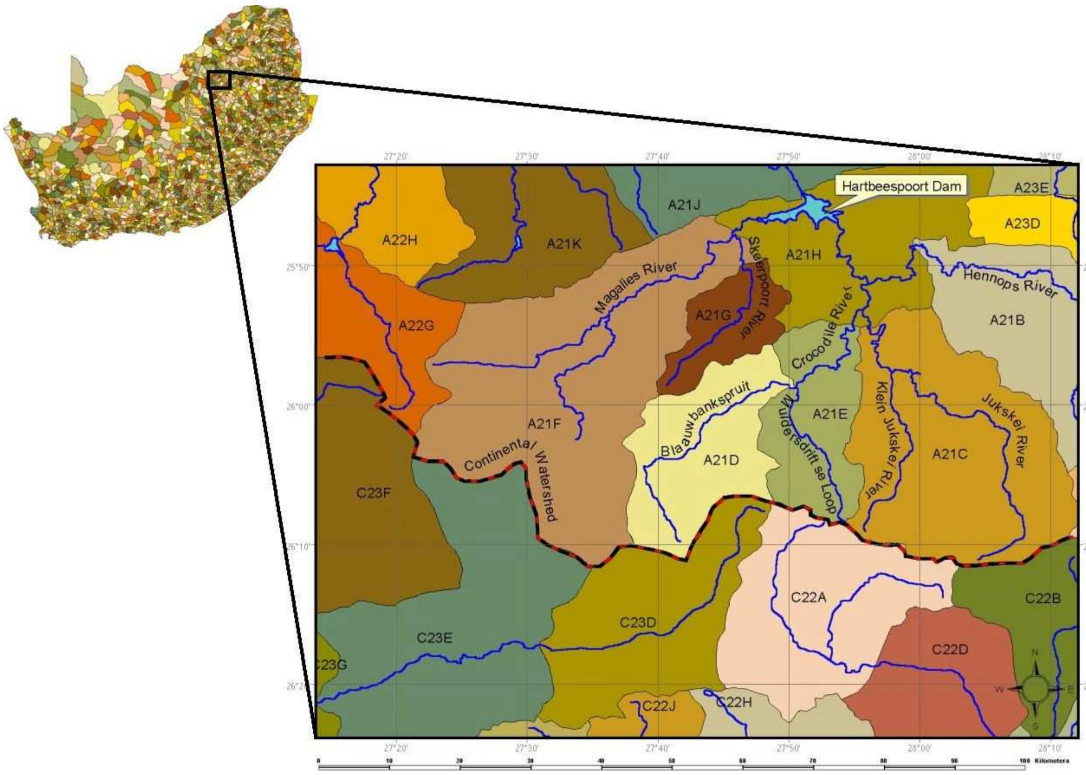

Figure 1 – The location of the Blaauwbankspruit in quaternary catchment A21D.

From the south, the Blaauwbankspruit has two major tributaries, the Rietspruit and an unnamed stream originating in the Rant-en-Dal and Noordheuwel suburbs of Krugersdorp. This unnamed stream flows through the farm Honingklip 178 IQ before its confluence with the Blaauwbankspruit in the vicinity of the Kromdraai Cash Store on the farm Kromdraai 520 JQ. For the purposes of this report, we will be referring to this stream as the "*Honingklip Stream*".

The Rietspruit originates at Robinson Lake in Randfontein. It drains some of the storm water from the older part of the town as well as run-off water from the streets. After leaving the town, it receives some 8.16 Ml/day of treated sewage effluent. Immediately downstream from the sewage effluent discharge point, the stream flows off the rocks of the Witwatersrand Supergroup and onto dolomite of the Chuniespoort Group, Transvaal Supergroup. For some distance, the stream follows a fault line, part of the Rietfontein Wrench fault system, further enhancing the permeability of the streambed. Refer ***Figure 4*** for details relating to the location of the faults. From this point the water gradually disappears into the ground until there is no flow in the stream by the time it reaches Tarlton. It continues as a dry stream up to the confluence with the Blougatspruit. From here the sewage effluent discharged into this stream from the Percy Stewart Sewage Plant makes it a perennial stream. It, however, remains a losing stream (i.e., it loses water via streambed seepage to the underlying groundwater), as will be shown hereunder. The part of the Rietspruit between Tarlton and the confluence of the Blougatspruit only flows on surface under severe rainfall conditions. Such conditions are reported by local residents only to occur once every 3 to 5 years.

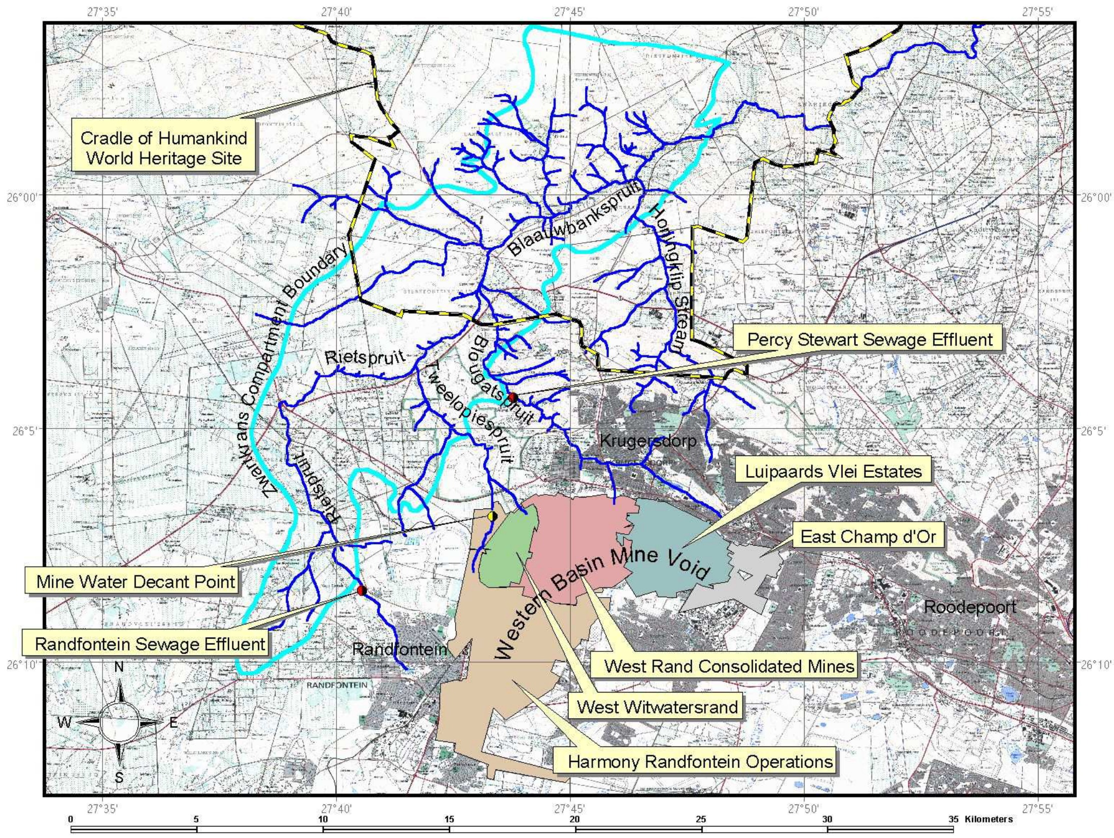

Figure 2 – The catchment of the Blaauwbankspruit showing all its tributaries as well as the three major point sources of pollution, the mine water decant point and the two sewage plants. The approximate extent of the Western Basin Mine Void is also shown.

For the purposes of this report, the most important tributary of the Rietspruit is the Tweelopiespruit. This seemingly insignificant stream originates approximately 4.5 Km to the south of the Krugersdorp Game reserve at Robinson Lake. The mine water originating from the flooded gold mines is currently decanting from an old Black Reef incline shaft some 900 m south of the Krugersdorp Game Reserve Boundary into the Tweelopiespruit.

The stream is located on a dolomitic inlier at the mine water decant point. This dolomite extends up to the first dam in the game reserve, originally called the “Dry Dam” as it hardly ever contained water, and is now referred to as the

"Hippo Pool" as, in spite of the poor quality of the water in the dam, two hippopotamuses have taken up residence in the dam since the mine water started to decant and filled the dam. The dam is located on the contact between the dolomite of the inlier and the Witwatersrand rocks located immediately below it. The stream traverses some 2.3 Km of Wits rocks, before flowing onto the main dolomite of the Zwartkrans groundwater compartment. The flow in the stream gradually increases in spite of it flowing over dolomite, as it is fed from a number of dolomitic springs along its course. The stream therefore remains a gaining stream, at least for a while.

However, between the last dam in the game reserve, the "Aviary Dam" (named because it is located near a large aviary in the game reserve) and the Krugersdorp Brick Works Dam (KBW Dam), located some 15 m from the N14 roadway, the stream crosses sections of the Rietfontein wrench fault system and loses a significant amount of its flow. In fact, some 500 m downstream from the bridge under the N14 Roadway (and approximately 300 m after its confluence with the Rietspruit), the remaining water in the stream disappears altogether. The stream therefore becomes a losing stream downstream from the northern boundary of the game reserve.

The next important tributary of the Rietspruit is the Blougatspruit. It originates in the industrial area, Factoria, in Krugersdorp. It receives surface run-off from Factoria and then flows through a rehabilitated landfill site where, some decades ago, the stream valley was simply filled in with domestic and garden waste. Since then, the landfill site has been covered with a layer of soil. A leachate dam is located downstream from the landfill site, but a significant amount of water underflows this leachate dam along the original streambed or overflows it during the rainy season. From this point, the stream is perennial, fed by springs from the surrounding quartzite and shale of the Witwatersrand Supergroup. The stream continues through the Vleiloerie Nature Reserve into the Eeufees Dam. From there the stream is canalised for the entire distance it flows through the town of Krugersdorp. Although the water leaving the Eeufees Dam is of a good quality, by the time the stream leaves the town of Krugersdorp, the water visibly resembles raw sewage and contains significant amounts of industrial effluent. From the end of the concrete canal, it flows through the quartzite hills past the industrial area of Delporton, up to a point immediately to the south of the contact between the Witwatersrand and Transvaal rocks where the dolomite of the Zwartkrans compartment begins. At this point the stream receives, on average, 19.3 Ml/day of sewage effluent from the Percy Stewart Sewage Treatment Works. Some 900 m after receiving the sewage effluent, the stream flows off the Wits rocks and onto dolomite. It remains on dolomite up to its confluence with the Rietspruit some 5.4 Km downstream of the sewage works. The stream receives small amount of seepage water for its entire length across the quartzite and shale of the Witwatersrand Supergroup and is therefore a gaining stream for its entire length up to the contact between the Wits and Transvaal Supergroups, it instantaneously becomes a losing stream after flowing onto the dolomite of the Chuniespoort Group, Transvaal Supergroup. The volumes lost will be discussed in ***Section 4***.

The last tributary of the Rietspruit is the *Honingklip Stream* draining parts of Rant-en-Dal, parts of the Krugersdorp Golf Course and surrounding areas and parts of Noordheuwel. It then flows through a more-or-less rural area, through Letamo Estates, also a rural residential area where there is a large dam in its watercourse, before it reaches its confluence with the Blaauwbankspruit on the dolomite of the Zwartkrans Compartment. In general, the water in this stream is of a good quality, the only significance of this stream, for the purposes of this report, being the volumetric contribution to the Zwartkrans compartment. It's quality could, however deteriorate, as a sewage plant on the premises of Letamo Estates serving the hotel and restaurant, "*Forum Homini*" now also discharges its effluent into this stream.

The entire study area with all the tributaries discussed in this section is shown in ***Figure 2***.

1.2 Geological and Groundwater Settings of the Blaauwbankspruit Catchment

Although Rison Groundwater Consulting will describe the geology of the area in detail in the Groundwater report, our report will not be complete without a brief description of the geology. This particular catchment is unique insofar as the interaction between surface- and groundwater is concerned. This is typical of karst landscapes and there are no clear dividing lines between surface- and groundwater as the same water flowing on surface disappears in places into the ground, only to reappear again further downstream as springs. For this purpose, a brief description of the geology and geohydrology is included in this report.

Figure 3 shows the general geological settings of the entire catchment, while ***Figure 4*** shows more detail of the Tweelopiespruit vicinity and the mine water decant point.

In ***Figure 3*** the Malmani Dolomite of the Chuniespoort Group is shown in light blue and also shows that the dolomite is divided into three groundwater compartments, the Steenkoppie, the Zwartkrans and the Cradle of Humankind North Compartments.

Figure 4 is a close-up of the area around the Tweelopiespruit and the Western Basin Mine Void. In this figure, the Western Basin Mine Void is also shown in relation to the mine water decant point in the upper reaches of the Tweelopiespruit.

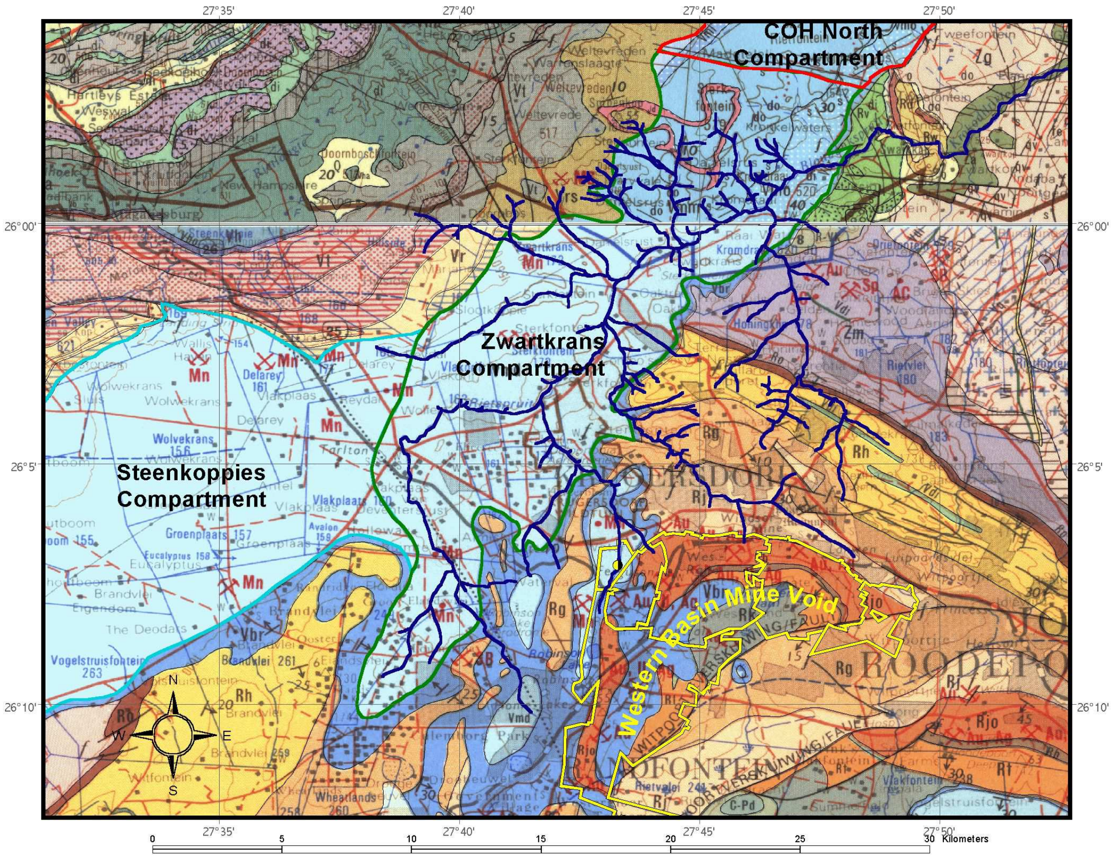

Figure 3 – The geology underlying the Blaauwbankspruit catchment. Also shown in this figure are the Western Basin Mine Void, the three dolomitic groundwater compartments and the extent of the surface river system.

In the vicinity of the mine water decant point, two different gold-bearing reef horizons were mined. The first was the main Witwatersrand series of reefs while the other was the Black Reef of the Chuniespoort Group, Transvaal Supergroup, overlying the Witwatersrand rocks. In most other areas, the Black Reef is a relatively thin band underlying the Malmani dolomite and is not known to contain significant values of gold. However, in this particular area, the Black Reef was deposited in deep paleo-valleys following a predominantly southeast-northwest direction, very similar to the current direction of flow of the Tweelopiespruit today. As the infilling material was mostly derived from the Witwatersrand reef outcrops and this erosion and deposition occurred during a period of the earth's history before free oxygen was available in the atmosphere, no oxidation of the eroding reef outcrops occurred and significant amounts of gold was deposited within the matrix of the Black Reef.

Gold mining activities linked the large mining void created to the east of the decant point with the smaller, overlying Black Reef mining operations through a series of tunnels linking the two reef horizons with each other. More recently, the Black Reef was mined using opencast mining methods. Most of the pits created by these mining operations still remain open today and act as direct ingress points for rainwater into the deeper mining voids.

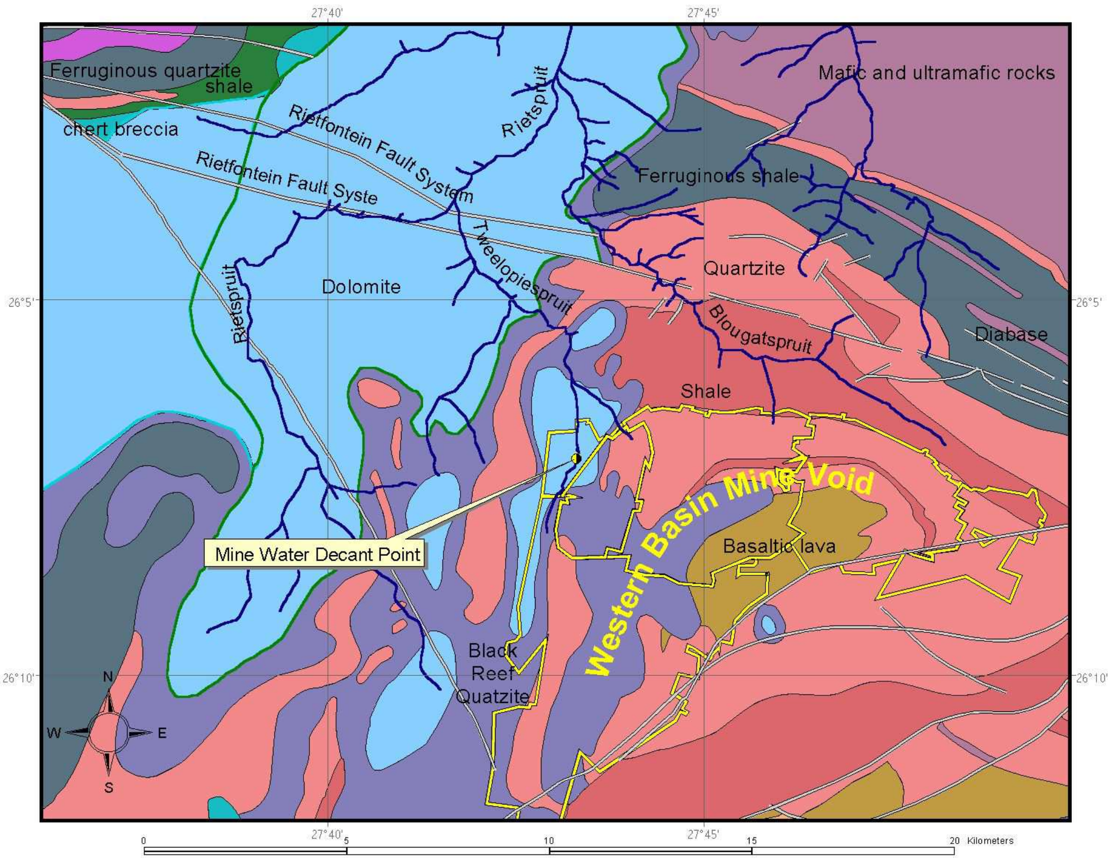

Figure 4 – A closer view of the geology in the vicinity of the Western Basin Mine Void and the Tweelopiespruit.

It should be noted that, although it is generally referred to as a point, the mine water decant point is actually an area of decanting. Most of the water flows from the Black Reef incline shaft (BRI) and an old ventilation shaft to the east of the BRI, but a significant volume also flows from boreholes downstream from the BRI and from the surrounding ground around the BRI. It is also suspected that an unknown quantity of water flows along the fracture zone comprising the subsurface part of the streambed of the Tweelopiespruit and actually never reaches the surface ("daylights") before it is discharged into the Zwartkrans dolomitic groundwater compartment.

Photo 2 shows the HDPE-lined dam constructed to intersect the water from the BRI.

Photo 2 – The dam constructed to intercept water decanting from the Black Reef incline shaft in the Tweelopiespruit. (Photo taken by G. Krige on 05/10/2004)

1.2.1 Stratigraphy and Lithology

The regional surface geology of the study area is discussed with reference to ***Figures 3*** and ***4***. The geology is described in chronological order from the oldest to the youngest formations.

Archaean Basement Granite

The geological basement in the study area consists of Archaean rocks, known as the Kaapvaal Craton. Most of the craton is composed of what is broadly referred to as granite. The granites are in fact a complex suite, not only are there true granites but there are granodiorites and quartz-diorites, as well as some more basic rocks. The Halfway House granite that outcrops in the northwest of the study area is representative of the Archaean Basement and consists of gneiss, granite and granodiorite.

A number of unmetamorphosed sequences were deposited on the Kaapvaal Craton and range in age from 3 000 to 1 750 million years (Truswell, 1977).

They have accumulated in basins and from oldest to youngest are the Pongola, Witwatersrand, Ventersdorp, Transvaal and Waterberg. With the exception of the Pongola and Waterberg all other basins are present in the study area.

Witwatersrand Supergroup

The Dominium Group, Witwatersrand Supergroup and Ventersdorp Supergroup constitute a volcano-sedimentary sequence that is well known for its fossil gold placers (*Tankard et. al. 1982*). Since gold-bearing conglomerates were discovered near Johannesburg in 1886 the mines in Gauteng, Northwest and Free State Provinces have produces more than 55% of all the gold ever mined in the world (*Pretorius, 1976*), 300 000 workers developed approximately 1 000 km of underground tunnels annually at an average depth of 1 650 m and mined 10^8 metric tons of ore to produce approximately 700 metric tons of gold annually.

The geology of the Witwatersrand Supergroup is well understood and documented as a result of extensive mining and exploratory drilling. The mines of the Western Basin Mine Void had their origin as a result of the gold-bearing conglomerates of the Witwatersrand Supergroup.

Ventersdorp Supergroup

The younger Ventersdorp Supergroup (2 300 million years old) overlies the Witwatersrand rocks. Although acid lavas and sedimentary intercalations occur, the Ventersdorp is composed largely of andesitic lavas and related pyroclastics. Prior to the deposition of the Klipriviersberg lava the Witwatersrand gold bearing reefs were partially eroded and again deposited in what is now known as the Ventersdorp Contact Reef (VCR).

Transvaal Supergroup

The entire area was peneplained in post-Ventersdorp time (*Lednor, 1986*) and it was on this surface that the Transvaal Supergroup was deposited, some 2 600 million years ago. The deposition commenced with the Kromdraai Member of the Black Reef at its base. The Black Reef has eroded the Witwatersrand outcrop areas and as a result contains zones (reef) in which gold is present. The occurrence of the gold is not as widespread as in the Witwatersrand and mainly restricted to non-persistent north-south trending channels. The Black Reef is overlain by a dark, siliceous quartzite with occasional grits or small pebble bands. The quartzite grades into black carbonaceous shale.

Overlying the Kromdraai Member is the dolomite of the Malmani Subgroup of the Chuniespoort Group. During the deposition of the Transvaal Supergroup the only living organisms on earth were anaerobic bacteria i.e. bacteria that lived in the absence of oxygen. Of particular importance were a group of bacteria that acquired the ability to photosynthesise. These are collectively known as the *cyanobacteria* or blue-green bacteria (also **incorrectly** referred to as blue-green algae) (*Pelczar, Reid & Chan 1977*). During the early periods of the Transvaal deposition, the atmosphere was completely devoid of free oxygen, making it impossible for air-breathing organisms to evolve. However, over many millions of years and as a result of the photosynthetic activities of the cyanobacteria, the Earth's atmosphere was eventually converted to an oxygen-rich atmosphere.

The cyanobacteria were indirectly responsible for the precipitation of the dolomite itself. Almost all other sedimentary rock types are formed as erosion products (particles), originating somewhere outside the water body in which it was finally deposited. Dolomite on the other hand was formed as a precipitation product of a chemical reaction that took place within the water body. As a result of the photosynthetic activities of the cyanobacteria, removing large quantities of dissolved CO_2 from the water in which they lived and consequently increasing the pH of the water, soluble calcium bicarbonate, $Ca(HCO_3)_2$, was converted to sparingly soluble calcium carbonate, $CaCO_3$. Subsequent to this, some of the calcium in the mineral was replaced with magnesium, producing the mineral, dolomite, $CaMg(CO_3)_2$. The dolomite also contains layers of chert. The dense, hard and fine-grained chert tends to stand out in relief and is mostly composed of silica material.

The remains of the cyanobacteria are abundant in the Cradle in the form of stromatolites. These are laminated structures that are considered to be similar to cyanobacterial mats still found today in places such as Shark Bay, Australia (*Truswell, 1977*). According to Truswell (*1977*) these structures form when the sticky upper surface of the cyanobacteria trap limy mud. This trapped material forms a distinct bedding plane. The cyanobacteria then grow through the mud and the process is repeated.

So, apart from the Cradle being the place in which Man evolved, geologically speaking, very recently, the Cradle can also be classified as a part of the place on Earth where life as we know it (aerobic) originated.

The dolomites that are 1 500 m thick in the study area are renowned for their huge water storage potential. Storage of as much as 8.5 x 10^6 m^3/km^2 and transmissivities as high as 29 000 m^2/day have been reported (*Vegter, 1984*) although fluctuating widely. Carbonate rocks are practically impermeable and therefore devoid of any effective primary porosity. During its geological history, however, the dolomite strata have been subjected to karstification and erosion. The potential for large-scale groundwater exploitation depends solely on the extent to which the dolomite has been leached by percolating rainfall and groundwater drainage and the degree to which it has been transformed

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into aquifers capable of yielding large quantities of water and sustaining high abstraction capacities. Previous studies (*Bredenkamp et. al., 1986*) indicated that significant aquifers have developed within the Cradle boundaries. The Sterkfontein Dolomite has been divided into different groundwater compartments by the later intrusion of diabase, syenite and dolerite dykes (***Figure 3***). The decanting of poor quality mine water will impact upon the Zwartkrans groundwater compartment. This compartment also contains the Sterkfontein caves. According to Jamieson *et. al.* (*2004*) the development of caves are largely controlled by the structural geology. Some of these geological features occur in definitive genetic relationships to existing surface watercourses and to known cave systems. WNW linear fracture zones accompanied by sinistral shear folding correlate with the distribution of bedding-parallel shear hosted gold mineralization, as well as of caves and sinkholes in the dolomites. The localities of some of the better-known caves in relation to the major faults are shown in ***Figure 5***.

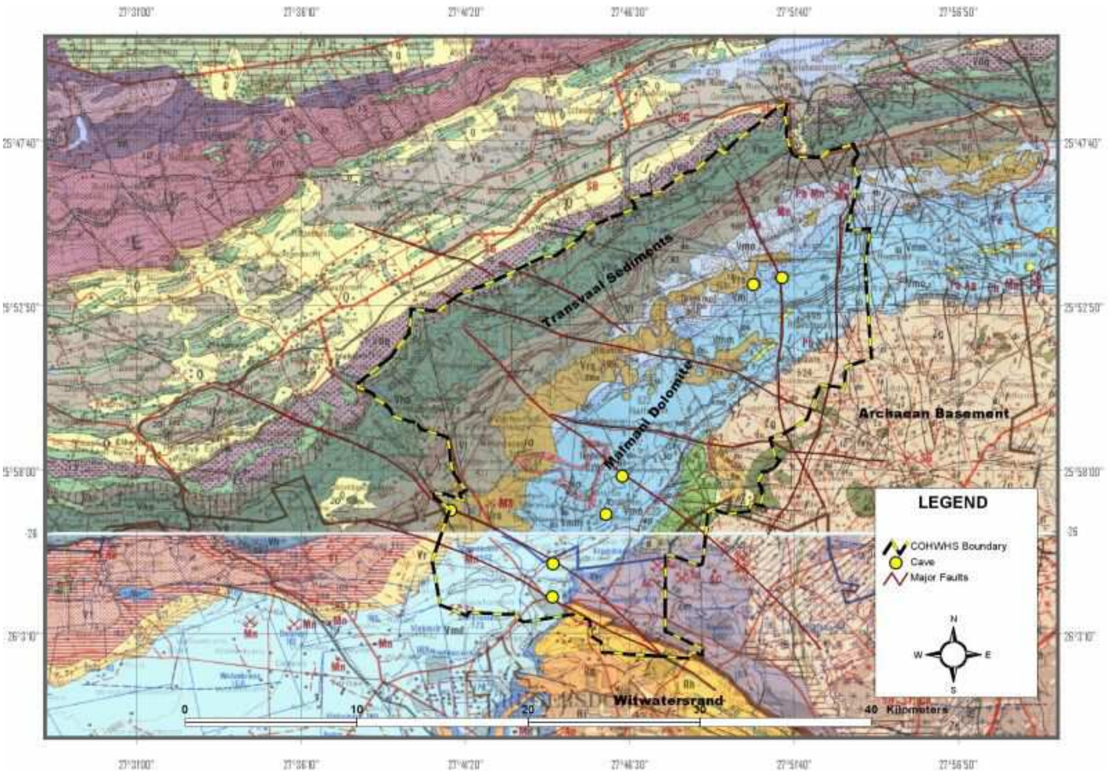

Figure 5 - Locality of some of the well-known caves in relation to the regional and structural geology.

The dolomites are partly overlain in the north by the Pretoria Group rocks. The Rooihoogte Formation forms the basal member of the Pretoria Group, consisting predominantly of shale and quartzite. These sediments were deposited at a time when the inland sea started to dry and these rocks represent beach and shallow water deposits.

Karoo Supergroup

The Karoo Supergroup was deposited approximately 345 million years ago. It commenced at the end of a glacial period during which most of South Africa was covered by a thick sheet of ice. This ice cap slowly moved towards the south, causing extensive erosion as a result of accumulated debris at the base. This debris was eventually deposited as Dwyka tillite. The latter is only partially preserved in small pockets in the study area. The subsequent sedimentary deposits of the Karoo Supergroup that consists of mudstone, shale and sandstone are also absent from the study area.

2. Gold Mining History with Specific Reference to Water Pollution of the Tweelopiespruit

Since a year after the discovery of gold on the Witwatersrand in 1886, the gold-bearing conglomerates of the Witwatersrand Supergroup have been mined on the West Rand in the Krugersdorp, Chamdor, Witpoortjie and Randfontein areas. The gold-bearing reefs outcrop along an east-west line following the railway line in the Krugersdorp area and curves progressively southwards around the axis of the West Rand Syncline towards the west until it runs almost entirely in a north-south direction in the Randfontein area. Initially the reef outcrops were mined from surface using primitive opencast methods, but as mines got progressively deeper, opencast mining methods were replaced with shafts, initially incline shafts, following the dip of the reef (approx. 60º) and later vertical shafts designed to intersect the reefs at pre-determined depths. In addition to the Witwatersrand reefs, Black Reef of the Transvaal Supergroup, overlying the Witwatersrand reefs and which are particularly deep in this area (deep valleys cut into the Witwatersrand Supergroup by ancient rivers that were subsequently filled in when the Transvaal Supergroup's Black Reef was being formed) in the area between Randfontein and Krugersdorp, was mined within the catchment of the Cradle, mostly by modern opencast mining methods.

As mines became deeper, increased problems were experienced with water ingress into the underground workings of the mines (*Scott, 1995*). This water was pumped from the mine workings into the Tweelopiespruit. At the peak of mining an average daily volume of 32 000 m^3 water was pumped into this stream. All this water eventually recharged into the Zwartkrans compartment. For many years this mine water discharge had been impacting on the Cradle. This fact became evident from the study by Bredenkamp, *et. al.* (*1986*) when it was found that the water in the sub-compartment of the Zwartkrans compartment immediately downstream from the Tweelopiespruit had sulphate concentrations in the region of 150 mg/l and above. High concentrations within this range are not normally expected to occur in dolomite.

More than 100 years of mining created a combined mined-out void of 44 926 778 m^3 (*van Biljon & Krige, 2005*). This is now referred to as the Western Basin Mine Void and refers to the combined, interlinked mined-out void created by more than 100 years of gold mining in the region by a succession of several mining companies (***Figure 2***).

With reference to ***Figure 2***, the Western Basin Mine Void initially consisted of four major mines:

- Randfontein Estates Ltd (Now owned by Harmony Gold Mining Ltd).
- West Rand Consolidated Mines Ltd (Now owned by Durban Roodepoort Deep).
- Luipaards Vlei Estates Ltd (Now owned by Mogale Gold).
- East Champ D'Or GM Co Ltd (now owned by First Westgold).

As the gold reserves gradually became depleted, the underground mines started closing one by one and the focus shifted more to opencast mining. During this period, the West Wits pit was created by West Witwatersrand GM Co Ltd, now owned by Durban Roodepoort Deep. This pit is by far the largest opencast pit in this region and apart for its size, it is of importance for another reason. The pit was initially constructed to mine the Black Reef of the Transvaal Supergroup. However, during the mining of Black Reef, deeper Witwatersrand reefs were also intersected and mining breached the barrier between the two reef types. Any rainwater now falling into the West Wits pit or on any of the other Black Reef outcrops or pits would enter the Witwatersrand mine void via this breach.

During this time, pumping only occurred from Randfontein's Central Ventilation Shaft. This mine was now responsible for pumping the entire volume of water entering the underground workings of all its neighbouring mines. During 1998, a decision was made to stop the pumping operations altogether. Since then, the mine void has systematically been flooding and underground operations were restricted to retreat mining. Finally in September 2002 the poor quality water started to decant from a borehole and an old shaft into the headwaters of the Tweelopiespruit East in the Millsite vicinity (see ***Figure 2*** for locality).

3. Acid Mine Drainage

Apart from gold, a number of other metal-containing minerals are found along with gold in the gold-bearing Witwatersrand and Black reefs. Of particular importance is the mineral, iron pyrites, more commonly referred to as "pyrite", for its properties to produce acid mine drainage (AMD), also sometimes referred to as "acid rock drainage" (ARD). Pyrite, with a chemical formula of FeS_2 (iron disulphide) is a sulphur-containing mineral, which, in its un-oxidised form, superficially resembles the colour and sheen of gold and for this reason is often also referred to as "*fool's gold*".

As long as pyrite remains buried deep underground within the rocks of the Witwatersrand and Transvaal Supergroups, the sulphur remains in a stable, reduced state. However, when it is exposed to oxygen in the presence of water, a series of chemical reactions occur, which ultimately give rise to the production of acidic water. During this process a particular group of bacteria collectively referred to as the "sulphate oxidising bacteria" (SOB's) play a role in increasing the rate at which the chemical reactions take place.

There are four chemical reactions that represent the chemistry of pyrite weathering to form AMD:

Reaction 1: $\mathbf{2\ FeS_2 + 7\ O_2 + 2\ H_2O \rightarrow 2\ Fe^{2+} + 4\ SO_4^{2-} + 4\ H^+}$

Pyrite + Oxygen + Water → Ferrous Iron + Sulphate + Acidity

The first reaction in the weathering of pyrite includes the oxidation of pyrite by oxygen. Sulphur is oxidised to sulphate and ferrous iron is released. This reaction generates two moles of acidity for each mole of pyrite oxidised.

Reaction 2: $\mathbf{4\ Fe^{2+} + O_2 + 4\ H^+ \rightarrow 4\ Fe^{3+} + 2\ H_2O}$

Ferrous Iron + Oxygen + Acidity → Ferric Iron + Water

The second reaction involves the conversion of ferrous iron to ferric iron. The conversion of ferrous iron to ferric iron consumes one mole of acidity. Certain aerobic bacteria (the SOB's) increase the rate of oxidation from ferrous to ferric iron. This reaction rate is pH dependent with the reaction proceeding slowly under acidic conditions (pH 2-3) with no bacteria present and several orders of magnitude faster at pH values near 5 and in the presence of bacteria. This reaction is referred to as the "***rate determining step***" in the overall acid-generating sequence.

Reaction 3: $\mathbf{4\ Fe^{3+} + 12\ H_2O \rightarrow 4\ Fe(OH)_3 \downarrow + 12\ H^+}$

Ferric Iron + Water → Ferric Hydroxide + Acidity

The third reaction, which may occur, is the hydrolysis of iron. Hydrolysis is a reaction, which splits the water molecule. Three moles of acidity are generated as a by-product for every mole of ferric iron consumed. Many metals are capable of undergoing hydrolysis, not just iron. The formation of ferric hydroxide precipitate (solid) is pH dependent. Solids form if the pH is above about 3.5 but below pH 3.5 little or no solids will precipitate.

Reaction 4: $FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$

Pyrite + Ferric Iron + Water → Ferrous Iron + Sulphate + Acidity

The fourth reaction is the oxidation of additional pyrite by ferric iron. The ferric iron is generated by reactions 1 and 2. This is the ***cyclic and self-propagating*** part of the overall reaction and takes place very rapidly and continues until either ferric iron or pyrite is depleted. Note that in this reaction, iron is the oxidising agent, not oxygen. The reaction is therefore not reliant on the availability of oxygen.

All four of the above reactions can be summarised as follows:

Overall Reaction: $4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 \downarrow + 8\ H_2SO_4$

Pyrite + Oxygen + Water → Ferric Hydroxide + Sulphuric Acid

Overall, one mole of pyrite creates 2 moles of sulphuric acid. Note that only reactions 1 and 2 require the presence of oxygen. The only factor governing the rate at which reactions 3 and 4 will occur is the pH; a low pH slows the reactions down or brings it to a halt, while a higher pH increases the reaction rate.

During mining operations, ever-increasing underground rock surfaces containing pyrite are exposed to the effects of oxygen and water, setting the chemical reactions shown above in motion. Mining also introduced the SOB's that speed up the process. Lastly, in order to protect their pumps against the corrosive properties of the acidic mine water, mining engineers increase the pH of the mine water in the mine by adding lime to the water and in so doing play directly into the hands of the SOB's (refer Reactions 2 and 3). The resultant increased pH is, as a result of reactions 2 and 3, often short-lived. Researchers over many years and across almost all the continents have attempted to find a method of controlling SOB's in mines, to no avail. Apart from the cost, the problem is that during mining processes rock is fractured to several meters deep into the rock faces. There is no known disinfectant that can penetrate that deep into a fractured surface and the SOB's continued unhindered to produce sulphuric acid.

Once water becomes acidic, it will dissolve any other metal that may be present in its environment. AMD water therefore contains high concentrations of dissolved metals in addition to its acidic properties.

During the mining era, the water pumped from the underground workings was not of such a poor quality as the current decanting water. As water was pumped immediately after it entered the mine, there was often not sufficient contact time for it to acquire excessive amounts of contaminants. The water nevertheless, had elevated sulphate concentrations, but not nearly the concentrations that is found at present in the decanting water. However, after pumping operations ceased, the rising water in the old mining tunnels mobilised contaminants, mostly sulphates, which have been produced over long periods and which have been sitting there, in some areas for over 100 years, just waiting to be mobilised again.

The 15.5 Ml/day of water currently flowing from the decant point is of an extremely poor quality with sulphate concentrations in excess of 4 000 mg/l. The chemical quality will be discussed in detail in ***Section 5***.

4. Water Volumes

The objective of this section is to determine the overall in and outflows of the Zwartkrans dolomitic compartment. As can be imagined, this is a huge task given the time period within which the work had to be done and given the resources available, especially flow measuring resources as well as all the other unknown factors. Although the boundaries for the Zwartkrans compartment are demarcated, these boundaries are by no means cast in stone (no pun intended) and the actual boundaries may differ considerably from where we assume they are. Furthermore, it is a known fact that the compartment is divided into several sub-compartments through syenite, dolerite and diabase dykes (vertically) and sills (horizontally), while various additional layers (less permeable or highly permeable) may also exist that cut through the compartment. According to Jamison, (*2006*), there are layers of a type of shale, a metamorphic product of tectonic movement, which cut across the compartment and which may act as aquitards. Lastly, there are many known faults (and probably more unknown ones) transecting the compartment. It is a known fact that preferential pathways exist and that some dykes/sills are aquitards, while some leak or are breached by faults, etc.

In the light of the above, it would be an oversimplification to treat the Zwartkrans compartment as a single unit. However, in spite of the amount of research currently underway into attempting to understand the mechanism of groundwater movement through the Zwartkrans aquifer, no clear-cut answers are readily available to us, as yet. It could be years or decades before geohydrologists understand most of the mechanisms acting on the aquifer's water movement. We therefore attempted to model the aquifer as a single unit, in spite of the shortcomings of this method. After all, in spite of the existence of preferential pathways, aquitards, aquicludes and other mechanisms acting on groundwater movement through the aquifer, the simple principle of "*what goes in must eventually come out*" will still apply to the aquifer, in spite of the many unknowns along the way. We will use this simple engineering principle to determine the water balance over the compartment.

4.1 Flow measurements into the Zwartkrans Compartment

4.1.1 Streams and Rivers

There are no official gauging stations along any of the streams within the study area. The flow in the streams had to be gauged in the streams using whatever methods were available to us. During the end of the dry season of 2005 and the beginning of the rainy season of 2006, a number of points were identified as potential flow measuring points and these points were gauged.

As far as was possible, average dry weather flow was gauged, as most of the measurements were carried out just before the rainy season started. Due to difficulties experienced in measuring the flow, three points were gauged only after the rainy season started, but sufficient time was allowed for the streams to settle before the flows were measured. The flow measurements will be discussed hereunder.

The logic behind the dry-weather flow measurements was to exclude rainfall altogether from the balance. The resulting streams into the aquifer are therefore considered to be derived from either groundwater entering the streams or from human activities, such as sewage effluent. The input from rainwater was added afterwards using data from the Water Research Commission 1990 (Midgley, *et. al. 1994*). This method provided more control.

Figure 3 is a map of the entire aquifer, while ***Figures 6*** and ***7*** show the input streams measured during the study.

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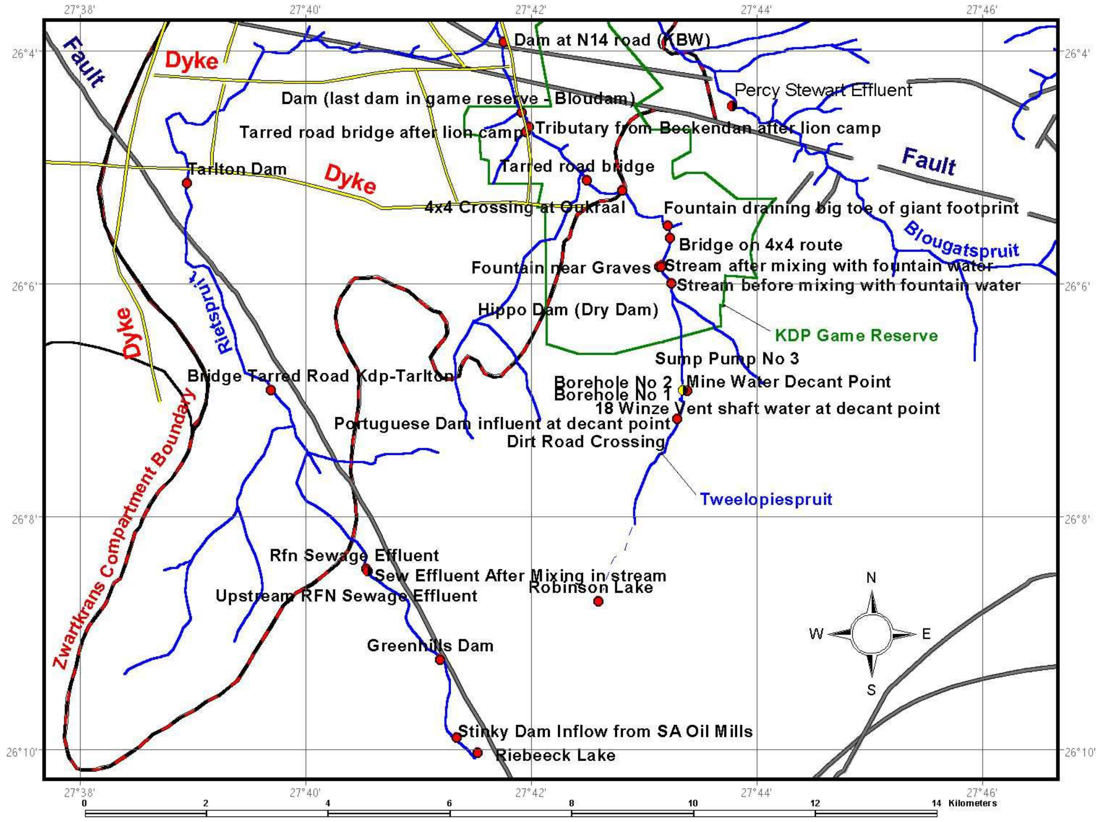


Figure 6 – Flow-measuring points in the streams entering the Zwartkrans Compartment -1

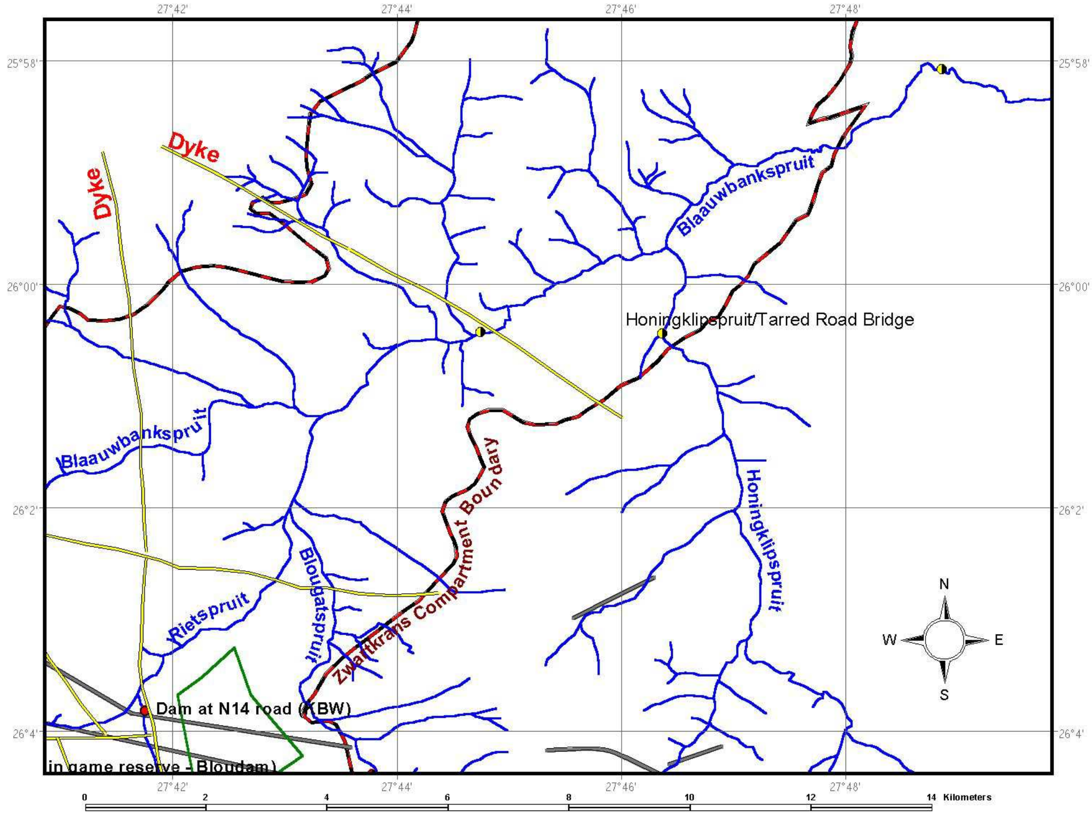


Figure 7 – Flow-measuring points in the streams entering the Zwartkrans Compartment - 2

The following flow rates were measured:

NAME	FLOW (l/s)	Flow (Ml/day)
Rietspruit		
Riebeeck Lake	No Outflow	
Stinky Dam Inflow from SA Oil Mills	4	0.35
Greenhills Dam	5	0.43
Upstream RFN Sewage Effluent	5	0.43
Rfn Sewage Effluent	116	10.02
Sew Effluent After Mixing in stream	121	10.45
Bridge Tarred Road Kdp-Tarlton	130	11.23
Tarlton Dam	No Outflow	
Tweelopiespruit		
Robinson Lake	No Outflow	
Dirt Road Crossing	Unable to measure	
Portuguese Dam influent at decant point	Unable to measure	
18 Winze Vent shaft water at decant point	Unable to measure	
Borehole No 1	Unable to measure	
Borehole No 2	Unable to measure	
Mine Water Decant Point	Unable to measure	
Sump Pump No 3	Unable to measure	
Hippo Dam (Dry Dam)	No Outflow	
Stream before mixing with fountain water	Unable to measure	
Fountain near Graves	Unable to measure	
Stream after mixing with fountain water	Unable to measure	
Bridge on 4x4 route	17	1.47
Fountain draining big toe of giant footprint	12	1.04
4x4 Crossing at Oukraal	29	2.51
Tarred road bridge	50	4.32
Tarred road bridge after lion camp	58	5.01
Tributary from Beckendan after lion camp	6	0.52
Dam (last dam in game reserve - Aviary Dam)	59	5.10
Dam at N14 road (KBW Dam)	9	0.78
Blougatspruit		
B/gat before P Stewart	27	2.36
P Stewart Sewage Effluent		19.30
Honingklipspruit		
Bridge at tarred road	11	0.95

Table 1 – Stream flow into the Zwartkrans Compartment

Where possible, the streams were measured by filling a container with a known volume and measuring the time it took to fill the container. This is by far the most accurate way of measuring flow.

Where this was not possible, flow was measured through a pipe, usually under a bridge. A floating object was placed in the entrance to the pipe and the time was measured for it to travel the distance of the pipe. We developed a spreadsheet named “PipeQ” to determine the flow rate. Apart from the pipe length and time required for the floating object to move from the one end of the pipe to the other, the only other measurements that are required is the pipe diameter and water depth. Although not quite as accurate as the above method, this method still produced acceptable results.

Where neither of the two methods could be used, a section of stream that had a reasonable rectangular profile, was chosen and the time it took for a floating object to travel a pre-determined distance was measured. The average width and depth of the stream was also measured and the flow rate was calculated using Mannings coefficients for open channel flow. This was the least accurate of the methods employed, but still produced acceptable results.


Photo 3 – Two methods of flow measurement. The first is at the KBW Dam where an uneven weir made flow measurement impossible. A temporary wall was built with bricks to channel the water to a spillway point where the flow was then measured by determining the time it took to fill a container of known capacity. The second photo shows a bridge in the Blaauwbankspruit (near the Zwartkrans Cave). Here the time it took for a floating object to cover the distance of each of the pipes were measured and the flow rate through the two pipes were then calculated using the spreadsheet, PipeQ.

4.1.2 Rainfall

Quaternary catchment A21D has an average rainfall of 713.73 mm with a mean annual run-off of 56.3 mm (Refer ***Section 1.1***). The volume contributed by rainfall was calculated using two different methods.

Firstly, it was found that all the water flowing down both the Tweelopiespruit and the Rietspruit upstream from Tarlton recharged into the Zwartkrans compartment. Under normal circumstances, the section of the Rietspruit from Tarlton up to its confluence with the Blougatspruit never has water in it. The same is true for the Tweelopiespruit. Shortly after its confluence with the Rietspruit downstream from the KBW Dam, the remaining water in the stream disappears into the ground. The catchment of the **losing section** of the Zwartkrans Compartment was subsequently digitised and the annual volume of water falling onto this catchment and running off into the surface streams was calculated. The entire volume was used as an input into the compartment. (*Catchment = 274 041 891* m^2*, Volume = 42.27 Ml/day*)

Secondly, 13% of the rainfall falling directly onto the aquifer (dolomite) was used and the volume was added to the input volumes into the aquifer (13% of 713.73 mm/a over a catchment of 153 980 000 m^2, Volume = 39.14Ml/day).

Using flow measurements shown in ***Table 1***, the streambed loss between the Percy Stewart sewage effluent discharge point and the bridge across the Blaauwbankspruit shown in ***Photo 3***, were used to calculate the streambed loss as follows:

Flow in stream upstream from Percy Stewart Sewage Plant originating from manmade origins: 2.4 Ml/day

Percy Stewart Sewage Effluent: 19.3 Ml/day
Total: **21.7 Ml/day**

Flow measured at the small bridge across the Blaauwbankspruit between the Sterkfontein and Zwartkrans Caves: **8.18 Ml/day**

Streambed loss after flowing over 5.86 Km of dolomite: **13.57 Ml/day**

This amounts to a streambed loss of **2.3 Ml/Km/day.**

Definition: Gaining and Losing Streams

The above section described sections of streams that either gain water from groundwater or lose water through streambed loss to groundwater. A **gaining stream** is therefore a stream where groundwater moves from the groundwater environment to the surface water in the stream. A **losing stream** is the opposite from a gaining stream, i.e. water moves from the surface stream into the groundwater environment. An example of a gaining stream is the section of the Tweelopiespruit from where it first encounters the dolomite of the Zwartkrans Compartment up to the Aviary Dam in the Krugersdorp Game Reserve. An example of a losing stream is the section of Rietspruit from Tarlton up to around Danielsrust area. To confuse matters somewhat, Parsons (*2004*) refers to gaining and losing streams as **effluent** and **influent streams** respectively. And effluent stream is a stream where groundwater leaves the groundwater environment to the surface water environment, while an influent stream is the opposite. To avoid confusion with terms such as sewage effluent, etc, we will refrain from using the terms, effluent and influent streams and only refer to the terms gaining and losing streams.

4.1.3 Other Input Volumes

Volumes obtained from Mogale City and Randfontein Local Municipalities were used to calculate the input volumes derived from sewage effluent.

It should be noted here that all inflows were recorded as input volumes into the aquifer, not just the volumes recharging into the aquifer. When the outflows, discussed in the next sub-section, are calculated, the outflow is subtracted from the inflow and the balance is calculated. It therefore does not matter if a certain percentage of water flows across the surface of the aquifer to the outlet.

4.2 Flow Measurements out of the Zwartkrans Compartment

4.2.1 Stream Flow Leaving the Zwartkrans Compartment

The flow in the Blaauwbankspruit was measured at a point immediately after the stream leaves the dolomite of the Zwartkrans Compartment. The selection of an appropriate site for the measurement of flow posed quite a problem as, in almost all cases where one could get access to the stream, the stream was either extremely overgrown with trees/reeds or the stream formed more than one channel in the area where the flow was to be measured. Furthermore, the stream flow had to be measured reasonably close to the point where the stream leaves the aquifer. This left us with only approximately a 3 Km section of stream in which to obtain a flow measuring point. The only reasonable site for measuring the outflow out of the compartment within this section of stream was at a dirt road crossing as shown in ***Photo 4***. This bridge was approximately 2.5 Km downstream from the point where the stream leaves the dolomite of the Zwartkrans Aquifer.

Although the flow could be measured accurately through the pipes, some water was bypassing the pipes by underflowing the pipes and flowing in the gaps in-between the pipes. From an engineering point of view, this is a sure way of losing the bridge during the next heavy downpour! From a flow-measuring point of view, this caused us some headaches. By dividing the underflow into smaller portions and measuring the time each smaller portion would take to fill a container with a known capacity we were able to estimate this bypass volume. This was not the ideal way of measuring the flow, but it was probably the only way available to us. Previously, we attempted to use an in-stream flow meter, but due to the variable stream cross-section profile and the amount of in-stream vegetation, this method was abandoned as it produced totally inaccurate readings.

Photo 4 – The bridge where the flow in the Blaauwbankspruit leaving the Zwartkrans compartment was measured. Although the flow through the pipes was measured accurately, some water bypassed the pipes and flowed under the pipes. This volume was estimated by attempting to canalise it in parts into containers with known volumes.

There is an irrigation canal leaving the Blaauwbankspruit at Danielsrust. This water is utilised by the local farmers for irrigation of crops and for watering of livestock. As far as we could determine, if all the water in the canal is not used up along the length of the canal the balance is returned back to the Blaauwbankspruit **after** it leaves the Zwartkrans Compartment (i.e. downstream from the bridge where we measured the final outflow of the Blaauwbankspruit). The entire flow in the stream was therefore used as an outflow out of the system.

4.2.2 Evapotranspiration

The evapotranspiration derived from vegetation along and within the streams were calculated as follows:

	Evapotranspiration		
	River length on dolomite where river actually flows on surface…		
	15.48	Km	
	4.07	Km	
	7.91	Km	
	27.46	**Km**	
	1.0984	Km2 (40m wide area of evaporation)	
			Evapotranspiration Summer = 0.65xA-pan
			Evapotranspiration Winter=0.9xA-pan
			Average: 0.775 x A-pan
			A=pan Evap JNB Intl = 2160 mm (ave/annum)
	1674	mm/a	Evapotranspiration = 0.775 x 2160 mm
Area:	1098400	m2	
Evaptransp	1838721600	l	
	1838.7216	Ml/annum	
	5.037593425	**Ml/day**	

4.2.3 Evaporation

The A-Pan evaporation in the study area is 2160 mm/a. The evaporation from the stream surfaces was calculated as follows:

	Evaporation:	
A=pan Evap JNB Intl = 2160 mm (ave/annum)		
River length on dolomite where river actually flows on surface…		
	15.48	Km
	4.07	Km
	7.91	Km
	27.46	**Km**
	0.4119	Km2 (15m wide area of evaporation)
Evaporation:	2160	mm/a
Area:	411900	m2
Evaporation:	889704000	l
	889.704	Ml/annum
	2.437545205	**Ml/day**

4.2.4 Domestic Use

Data obtainable from the Municipal Demarcation Board was used to calculate the number of people living on the Zwartkrans Compartment. The 2000 municipal election statistics was used. Unfortunately, the 2006 municipal election data is not yet available.

In short, what we did was to digitise the different wards that fell wholly or partially on the Zwartkrans compartment. We then digitised the portions falling on the compartment and multiplied the total population of the ward with the percentage of the area falling on the compartment. The results are shown hereunder:

Ward	Municipal Area (Km2)	Mun. Population	Area on Zwartkrans Dolomite (Km2)	Percentage of total population (%)	Population using water from aquifer	Estimated water use @ 300 l/person/day in Ml/day
Mogale 19	147	6692	64.0	43.5	2914	0.87
Mogale 12	40	6818	15.4	38.5	2625	0.79
Mogale 11	40	6343	5.9	14.8	936	0.28
Randfontein 1	298	6760	94.1	31.6	2135	0.64
Randfontein 3	28	8953	7.0	24.9	2225	0.67
GTDMA41	243	2291	69.5	28.7	656	0.20
			Total Population on dolomite:		11491	
			Total water use for domestic purposes (Ml/day):			3.45

4.2.5 Irrigation

There are almost no borehole pumps fitted with flow meters in the Zwartkrans compartment area. Direct readings are therefore out of the question. In any case, even if there were flow meters, these instruments are notoriously inaccurate.

Our first attempt to quantify the volumes of groundwater used for irrigation purposes entailed using a satellite image of the area and we simply digitised all the areas under irrigation falling on the Zwartkrans compartment. We then used a value (equivalent rainfall) of 25 mm/Ha/week and calculated the amount of water required from the aquifer for irrigation of the measured areas. This method provided a value of 109 Ml/day pumped from the aquifer.

To verify our calculations, we purchased data from Schoeman & Associates, the civil engineering consultants currently in the process of collating this data for the Department of Water Affairs and Forestry. They calculated the data in much the same way we did in our original exercise, but also took the rainfall into account, which we didn’t, i.e. if it rained on a particular day, the amount of water required for irrigation was less. The exact formulae used in their calculations are, however, not known. Their data is therefore also coupled to surface areas under irrigation.

Although their data covered a period of a number of years, most of the data was interpolated using data from a few years where actual data was available. We therefore decided to only use the most recent available (actual) data, i.e.

for the rainy season of 2004/2005. This provided us with a value of 30.8 Ml/day abstracted from the aquifer. This value was significantly less than the value we obtained by digitising the areas under irrigation from the satellite photograph.

We then studied the actual areas used by Schoeman & Associates and found that some areas we used in our calculations were not represented in their data. As an example, areas under greenhouses/tunnels that do not show up on aerial photographs as irrigation areas were often not included. Furthermore, we also found that in certain smallholding areas (Beckendan, Eljeesee, Marabeth, Helderblom, Vlakdrift, Oaktree and Eldorado), there are many small areas under irrigation. Due to the small nature of the irrigation activities, they do not show up on satellite images as green zones. However, if all these small areas are added together, they make up a considerable surface area and could account for the difference in the data from Schoeman and our data.

Photo 5 – Examples of areas under irrigation that is not captured by Schoeman & Associates. From top left to bottom right: 1) LVG Nursery in Oaktree. 2) Makiti wedding venue and conference centre on the banks of the Blaauwbankspruit uses borehole water to maintain their lush lawns. 3) A rose farm on the farm, Sterkfontein is located at and pumps from one of the DWAF boreholes, 4) Part of Vlakdrift shows that all the smallholdings use groundwater for irrigation, at least on part of the smallholding.

Photo 5 shows some examples of these areas under irrigation that were not included in the Schoeman data.

We added the missing areas and calculated the new, adjusted volume irrigated from borehole water to be 70.3 Ml/day, using the Schoeman data as the basis for calculation.

We used the data obtained from Schoeman & Associates for the irrigation from river water, as is, i.e. we did not apply any corrections to their data, as was the case with the irrigation from groundwater data.

4.3 Final Water Balance

All the data described in ***Section 4.2*** was used to develop a water balance for the Zwartkrans compartment. As described right at the beginning of ***Section 4***, this is a first attempt to balance the in- and outflows of the Zwartkrans Compartment. Our work should be seen as a template, form which to work and on which to improve. As results form the various studies currently underway within the Zwartkrans Compartment and the Cradle of Humankind World Heritage Site becomes available, our water balance can be adjusted to incorporate the new data. Nevertheless, the balance as presented in ***Table 2*** is currently the best available as there is simply nothing available with which to compare it.

The water balance for the Zwartkrans Compartment is presented in ***Table 2***.

Zwartkrans Compartment Water Balance			
Item	**Site**	**Water into compartment (Ml/day)**	**Water leaving compartment (Ml/day)**
Tweelopiespruit East	Aviary Dam in Kdp Game Reserve	5.10	
Tweelopiespruit West (or Rietspruit)	Water upstream from Randfontein STW	0.43	
	Rfn Sewage Treatment Works Effluent	8.16	
Blougatspruit	Upstream from Sewage Plant	2.36	
	Percy Stewart Sewage Effluent	19.30	
Blaauwbank tributary (Honingklip Stream)	Measured at tarred road bridge	0.95	
Blaauwbankspruit	Canal leaving stream at Danielsrust		14.86
Blaauwbankspruit	River flow leaving compartment		3.14
Irrigation from boreholes	2654 Ha under irrigation using borehole water		70.30
Irrigation from rivers	458 Ha under irrigation using river water		8.93
Domestic Use	11491 people living on dolomite using 250 l/person/day groundwater		3.45
Evapotranspiration	1.1Km2 @ Evapotranspiration of 0.775 x A-pan evaporation		5.04
Evaporation	0.41 Km2 @ A- pan Evaporation of 1260 mm/a		2.44
Recharge from streambed loss derived from rainfall over catchment	100% of MAR of 56.3 mm over catchment of 274041891 m2, i.e. catchment of losing section of stream	42.27	
Recharge from rainfall directly onto dolomite	13% of 713.73 mm/year over a catchment of 153 980 000 m2	39.14	
		Total into compartment (Ml/day)	**Total leaving compartment (Ml/day)**
		117.71	**108.15**

Table 2 – The water balance of the Zwartkrans Dolomitic Compartment.

The in- and outflows of the Zwartkrans Compartment do not balance exactly, but, given the circumstances, come pretty close to balancing. There are a number of factors that we did not take into account when developing the water balance. As an example, the flow from the Zwartkrans, Danielsrust and Plovers eyes were ignored. The logic around this is that the water at each of these eyes decants from one sub compartment within the greater Zwartkrans Compartment to another section of the compartment. It is therefore classified as an internal flow and does not play a role in the overall water balance. Refer ***Figure 8***.

The missing outflow could probably be accounted for as water leaking to adjacent groundwater aquifers, either towards the Steenkoppie Compartment to the west of the Zwartkrans Compartment or to the COH North Compartment to its northeast (more probable).

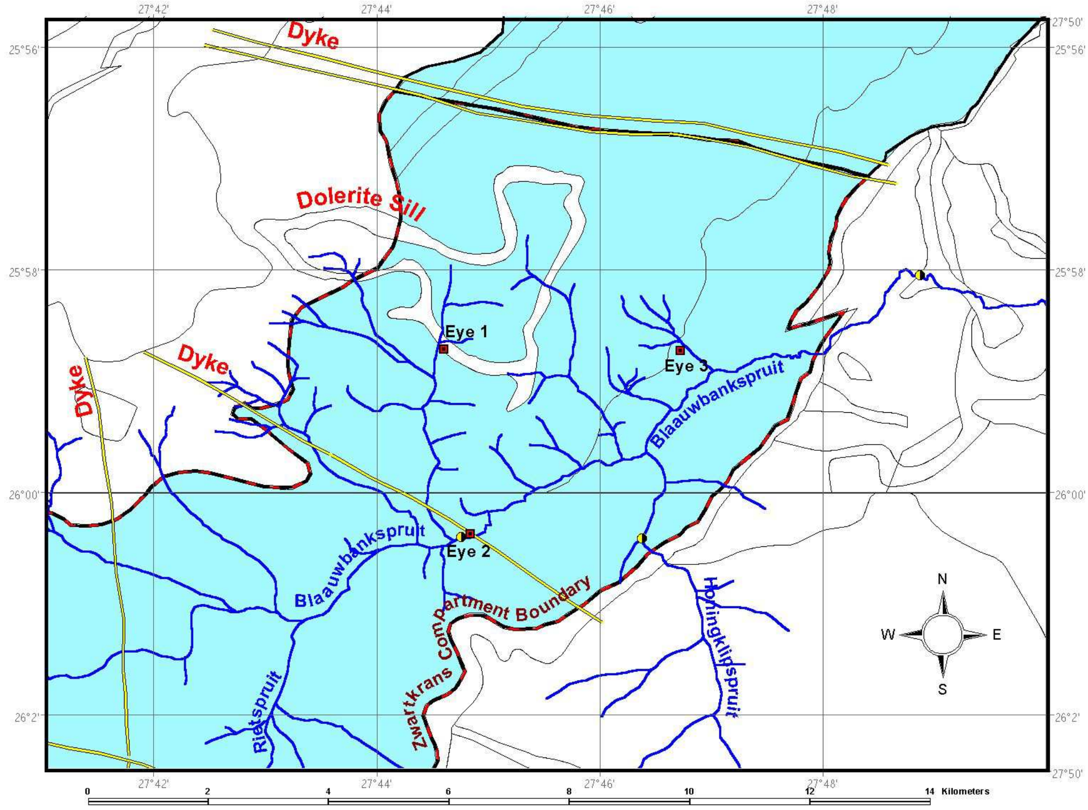


Figure 8 – A section of the Zwartkrans Compartment showing three of the eyes. Although the origin of Eye 3 is not known, it can be clearly seen that Eye 2 decants from one sub-compartment to another across a dyke, while Eye 1 drains the section of dolomite overlying a horizontal dolerite sill. All three eyes are located within the greater Zwartkrans Compartment and represents internal flow. Subsequently, they do not form part of the overall water balance.

5. Water Quality and Salt Balance

5.1 Salt Balance

Water qualities were measured at various points in the Zwartkrans aquifer as well as in its catchment. For the purposes of this study, we will use only the total dissolved solids in mg/l as a guide to the amount of salts entering and leaving the compartment.

The salt balance is presented in ***Table 3***.

Zwartkrans Compartment Water and Salt Balance							
Item	**Site**	**Water into compartment (Ml/day)**	**Water leaving compartment (Ml/day)**	**TDS into Compartment (mg/l)**	**TDS out of Compartment (mg/l)**	**TDS into Compartment (Kg/day)**	**TDS out of Compartment (Kg/day)**
Tweelopiespruit East	Aviary Dam in Kdp Game Reserve	5.10		589.78		3 008	
Tweelopiespruit West	Water upstream from Randfontein STW	0.43		151.60		65	
(or Rietspruit)	Rfn Sewage Treatment Works Effluent	8.16		613.65		5 007	
Blougatspruit	Upstream from Sewage Plant	2.36		267.88		632	
	Percy Stewart Sewage Effluent	19.30		504.00		9 727	
Blaauwbank tributary (Honingklip Stream)	Measured at tarred road bridge	0.95		230.60		219	
Blaauwbankspruit	Canal leaving stream at Danielsrust		14.86		417.59		6 205
Blaauwbankspruit	River flow leaving compartment		3.14		408.39		1 282
Irrigation from boreholes	2654 Ha under irrigation using borehole water		70.30		431.00		30 299
Irrigation from rivers	458 Ha under irrigation using river water		8.93		417.59		3 727
Domestic Use	11491 people living on dolomite using 250 l/person/day groundwater		3.45		431.00		1 486
Evapotranspiration	1.1Km2 @ Evapotranspiration of 0.775 x A-pan evaporation		5.04		0.00		0
Evaporation	0.41 Km2 @ A- pan Evaporation of 1260 mm/a		2.44		0.00		0
Recharge from streambed loss derived from rainfall over catchment	100% of MAR of 56.3 mm over catchment of 274041891 m2, i.e. catchment of losing section of stream	42.27		20.00		845	
Recharge from rainfall directly onto dolomite	13% of 713.73 mm/year over a catchment of 153 980 000 m2	39.14		20.00		783	
		Total into compartment (Ml/day)	**Total leaving compartment (Ml/day)**			**Total into compartment (Kg/day)**	**Total leaving compartment (Kg/day)**
		117.71	**108.15**			**20 287**	**43 000**

Table 3 – The Water and Salt Balance of the Zwartkrans Compartment.

It should be noted that this water and salt balance is based on data collected at the end of the dry season of 2005. The amount of water, originating from the mine void, entering the Zwartkrans compartment at this time, was limited to the volume of water flowing in the Tweelopiespruit at the bridge on the 4x4 route in the Krugersdorp Game Reserve (1.47 Ml/day and containing a TDS load of 1 098.65 mg/l). Until the mines are able to pump the total volume of water during the rainy season, this will not be the case in summer as significantly more water will enter the Zwartkrans compartment form this source.

Although the water volumes into and out of the compartment balance rather well, it appears at first glances that the salts do not balance at all. There are more salts leaving the compartment than there are salts entering the compartment.

It should, however, be kept in mind that the bulk of the water entering the compartment is rainwater. For convenience, we took the dissolved solids for rainwater as 20 mg/l, although this may not be quite true (it could be significantly more). Among other things, this rainwater contains dissolved CO_2 and will dissolve some dolomite rock in the process of percolating through the dolomite matrix from surface down to the groundwater table (refer to ***Section 6*** hereunder for a full discussion on the processes associated with the dissolution of carbonate rock). For the purposes of this section, however, it will suffice to say that CO_2 will dissolve dolomite rock and form a void space in the rock. The rock, dissolved in this process, then becomes part of the total dissolved solids in the groundwater.

The void space resulting from this process can be calculated as follows:

- Dolomite has a specific gravity (SG) of 2.84 Kg/dm^3, i.e. 2.84Kg/litre (refer ***Section 6***).
- The difference between the mass of solids entering and leaving the compartment is 22 713 Kg/day.
- 22 713 Kg occupies a volume of 7 997 litres.
- The surface area of the Zwartkrans Compartment is 153.98 Km^2.
- It can thus be calculated that each square kilometre would lose 52 litres of rock per day as a result of the dissolution process primarily driven by the dissolved carbon dioxide in the water.

This may sound alarming, but over an area of 1 Km^2 and roughly 60 m of dolomite between the surface and the groundwater, this amount becomes negligibly small (1 Km^2 = 1 000 000 m^2. Multiply this by 60 m depth and 1 Km^2 surface area represents 60 000 000 m^3 of dolomite rock).

The loss of 52 l/day over the 60 Million m^3 equates to a solids loss of 0.000 87 ml/m^3/day. This is really a very small volume but, over the surface area of the Zwartkrans Compartment, accounts for the difference between the solids into and out of the aquifer.

The dissolution of dolomite rock does not necessarily occur evenly throughout the rock matrix, but rather in areas of preferential flow such as through fractures, fissures, faults or existing caves. In these areas, the rate of dissolution of rock would occur at a rate several orders of magnitude faster than in solid, unbroken rock where there would be practically no dissolution at all. This is the process that is responsible for normal cave formation that goes on all the time in areas underlain by carbonate rock.

5.2 Salt Load of the Tweelopiespruit

Table 4 represents the flow and TDS data collected during 2005 shortly before the rainy season started. It therefore represents the flow in the streams unaffected by rainwater, in other words, water derived solely from groundwater sources or from human activities. If the data were collected during the rainy season, it would be very difficult to differentiate between the volume and salt load attributable to ground- or rainwater.

NAME	FLOW (l/s)	Flow (Ml/day)	Temperature (Deg. C)	Electrical Conductivity (mS/m)	TDS (mg/l)	pH
Rietspruit						
Riebeeck Lake	No Outflow		23.40	15.40	100.30	6.85
Stinky Dam Inflow from SA Oil Mills	4	0.35	20.70	40.80	281.27	7.02
Greenhills Dam	5	0.43	24.80	29.60	187.41	7.03
Upstream RFN Sewage Effluent	5	0.43	22.40	22.80	151.60	7.11
Rfn Sewage Effluent	116	10.02	23.70	94.80	613.65	7.65
Sew Effluent After Mixing in stream	121	10.45	22.50	92.30	612.42	7.63
Bridge Tarred Road Kdp-Tarlton	130	11.23	21.50	87.30	591.58	7.41
Tarlton Dam	No Outflow		25.60	50.50	314.73	8.94
Tweelopiespruit						
Robinson Lake	No Outflow		24.90	400.0	2527.53	2.25
Dirt Road Crossing	Unable to measure		23.30	400.0	2610.48	2.78
Portuguese Dam influent at decant point	Unable to measure		22.50	400.0	2654.03	2.90
18 Winze Vent shaft water at decant point	Unable to measure		24.70	400.0	2537.61	4.25
Borehole No 1	Unable to measure		22.70	400.0	2643.01	3.29
Borehole No 2	Unable to measure		22.40	301.0	2001.33	4.65
Mine Water Decant Point	Unable to measure		23.20	400.0	2615.84	3.61
Sump Pump No 3	Unable to measure		22.90	291.0	1914.83	3.63
Hippo Dam (Dry Dam)	No Outflow		25.00	241.0	1519.82	3.68
Stream before mixing with fountain water	Unable to measure		25.10	210.0	1321.70	4.60
Fountain near Graves	Unable to measure		21.20	58.0	395.56	5.91
Stream after mixing with fountain water	Unable to measure		24.60	174.1	1106.70	5.54
Bridge on 4x4 route	17	1.47	23.20	168.0	1098.65	5.70
Fountain draining big toe of giant footprint	12	1.04	21.00	94.2	645.21	5.62
4x4 Crossing at Oukraal	29	2.51	24.30	91.9	587.70	6.34
Tarred road bridge	50	4.32	24.20	98.7	632.46	6.06
Tarred road bridge after lion camp	58	5.01	21.00	100.5	688.36	6.83
Tributary from Beckendan after lion camp	6	0.52	21.00	22.2	152.05	7.48
Dam (last dam in game reserve - Aviary Dam)	59	5.10	23.10	90.0	589.78	7.14
Dam at N14 road (KBW Dam)	9	0.78	23.20	91.1	595.76	7.12
Blougatspruit						
B/gat before P Stewart	27	2.36	21.70	39.7	267.88	7.02
P Stewart Sewage Effluent		19.30	23	104.3	504.00	8.06
Honingklipspruit						
Bridge at tarred road	11	0.95	18.7	32	230.60	7.1
Blaauwbankspruit						
Canal leaving Blaauwbankspruit @ Danielsrust	172	14.86	19.5	59	417.59	7.6
Bridge where stream leaves Zwartkrans	36	3.14	19.5	57.7	408.39	7.78

Table 4 – The streams representing the in- and outflow of the Zwartkrans compartment at the end of the dry season of 2005.

The instrument we used for the measurement of the Electrical Conductivity (EC) had a maximum range of 400 mS/m. All the conductivity readings presented in ***Table 4*** as 400 mS/m should actually read, >400 mS/m. These are 1) Robinson Lake, 2) Dirt road crossing upstream from the Portuguese Dam, 3) Portuguese Dam influent, 4) 18 Winze ventilation shaft, 5) Borehole No 1 and 6) Mine water decant point (BRI).

This data was used to present the flow rate and salt load of the Tweelopiespruit as shown in ***Figure 9***. As stated above, this data represents the dry-weather flow in the stream.

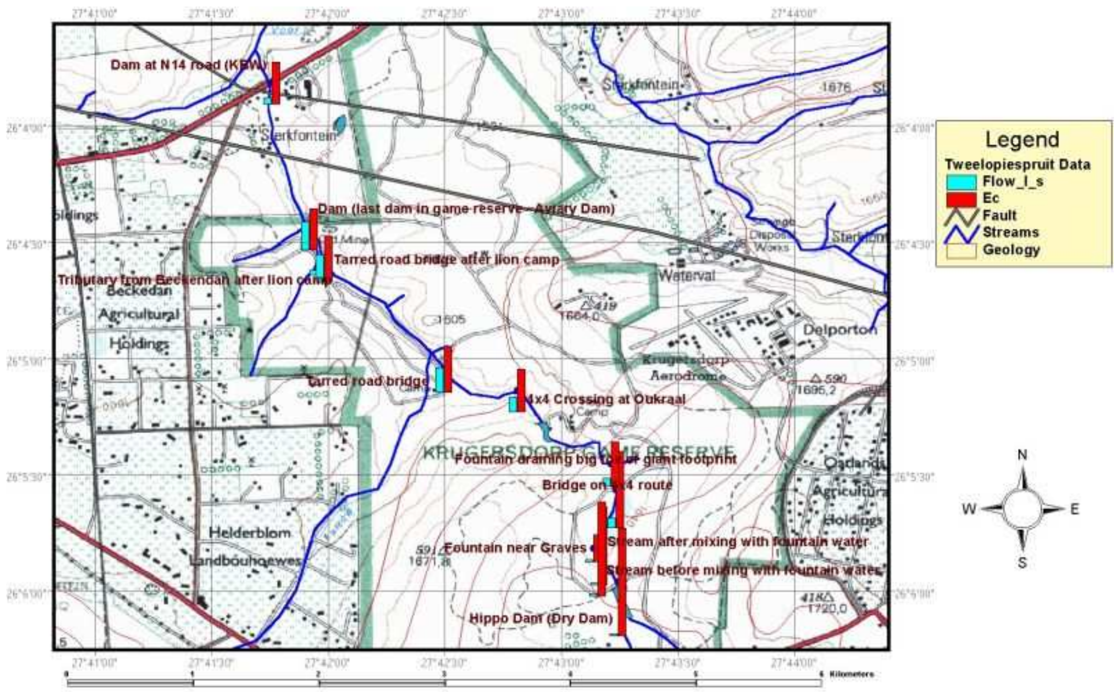


Figure 9 – The relationship between the flow rate (in l/s) of the water in the Tweelopiespruit and the Electrical Conductivity (EC in mS/m) thereof.

It can be seen from ***Figure 9*** and ***Table 4*** that the flow rate in the Tweelopiespruit is initially low in the upper reaches of the stream, while the EC is very high. As the stream progresses through the Krugersdorp Game Reserve, more and more water from relatively clean sources is added to the steam and the EC becomes a bit less. This is due to the gaining part of the stream and the significant volumes of dolomitic water that enters the stream. However, the fact that the EC is still in the low 90's when the water reaches the KBW Dam, shows that in spite of the relatively small flow from the mine void decant point, the impact of this water is significant.

Under normal circumstances, a stream originating at the continental watershed should contain very clean water. This was probably the case with the Tweelopiespruit before mining activities started in the area. A continuous stream of uncontaminated water would decant from the dolomitic inlier represented by the "sole" of the "giant footprint" (refer ***Figure 4***). This stream would become progressively larger up to the point where the water recharges into the Zwartkrans compartment in the vicinity of the Rietfontein fault. This is not the case with the Tweelopiespruit presently, as it receives highly contaminated water decanting from the Western Basin Mine Void.

6. Chemical Reactions between the Decanting Mine Void Water and the Dolomite of the Zwartkrans Groundwater Compartment

It is a known fact that the carbonate rock, dolomite, is dissolved in the presence of acidic water. In fact, the formation of caves and sinkholes in the dolomite is driven by the dissolution of carbon dioxide (CO_2) into rainwater forming the weak acid, carbonic acid (H_2CO_3), demonstrated in the equation:

$$H_2O + CO_2 \rightleftharpoons H_2CO_3.$$

A solution of carbon dioxide in water, in equilibrium with the atmosphere (*0.033% CO_2*), has a pH of 5.6. Rain water is normally not quite saturated with CO_2, and has a pH of around 6 in the absence of atmospheric pollutants (if industrial pollutants, such as sulphur dioxide, is present in rainwater it can lower the pH drastically). The acidity of rain water has important geological consequences for carbonate rocks such as dolomite. An equilibrium is established between the calcium carbonate of the rock and calcium bicarbonate in solution:

$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$$

This reaction can erode underground caverns around fault lines through which water infiltrates. As the calcium-rich water evaporates, the calcium carbonate precipitates as speleothems (e.g. stalactites and stalagmites) in deeper areas below the area where the initial dissolution occurred. This reaction, in essence, is the process responsible for forming caves and aquifer voids in the dolomite of the Zwartkrans Compartment.

Carbonic acid is a weak acid and, as demonstrated above, reaches an equilibrium with the carbonate in the dolomite rock. In contrast to carbonic acid, sulphuric acid (H_2SO_4) is a strong acid and never reaches an equilibrium with the carbonate rock until the reaction has been completed altogether. The reaction between sulphuric acid and the carbonate in the dolomite is demonstrated in the following equation:

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$$

The product, calcium sulphate ($CaSO_4$), remains in solution under normal temperatures found in the dolomitic aquifers and is responsible for "*permanent hardness*" in the groundwater and cannot be removed by boiling the water, in contrast to "*temporary hardness*" due to calcium and magnesium bicarbonates, which can be removed by boiling.

In ***Section 3*** it was demonstrated that, through the complex oxidation process of pyrite in the Witwatersrand rocks in the mine void, the product, sulphuric acid, is produced. To recap, the overall chemical reaction is shown below:

$$4\ FeS_2 + 15\ O_2 + 14\ H_2O \rightarrow 4\ Fe(OH)_3 \downarrow + 8\ H_2SO_4$$

Overall, 4 moles of pyrite creates 8 moles of sulphuric acid, or put differently, two moles of sulphuric acid is created from one mole of pyrite. There is ample sulphuric acid available in the mine water to dissolve the carbonate dolomitic rock. The question is exactly how much will be dissolved and what will occur in the dolomite.

6.1 Analytical Work

To answer this question, the analytical laboratory, *DD Science*, was commissioned to perform some tests on the dolomite and the mine water. Samples were collected at the decant point from one of the pumped boreholes downstream from the BRI. The reason why samples were not collected from the BRI or the ventilation shaft was that this water had already been exposed to oxygen and Reaction 2 (***Section 3***) had already occurred, either in full or partially. The water from the latter two sources was visibly orange indicating that at least some ferric hydroxide had already been formed (Reaction 3, ***Section 3***). Reaction 3 represents the hydrolyses of the water molecule (splitting of the water molecule and incorporating part of it in the ferric hydroxide molecule). The product, ferric hydroxide, therefore derives part of its mass from the water molecule. If this reaction were allowed to occur during analytical work, the additional mass derived from the water molecule would interfere with the results when weighing the products derived from a dolomite-sulphuric acid reaction. For this reason, the samples were collected from the borehole and not from the other sources. The sample containers were filled to capacity and capped without any air bubbles remaining in the containers before they were delivered to the laboratory.

A sample of crushed dolomite of the Oaktree Formation, Malmani Subgroup, Chuniespoort Group, Transvaal Supergroup, was also collected from the Sterkfontein Quarry and delivered to the laboratory for analyses.

The original idea was to allow a surplus mass of crushed dolomite to be dissolved by a known volume of mine water. After the reactions had been completed, the remaining solids would be dried and weighed and the mass difference calculated. This experiment was conducted, but, even after the air in the containers was replaced with nitrogen gas, some oxygen remained and some ferric hydroxide formed, interfering with the end results and rendering the results inconclusive.

The next step was to perform an acid-base titration using the mine void water. This experiment was based on the same procedure used in acid-base accounting procedures to determine the neutralisation potential of geological materials.

The results are shown in the next section (***Section 6.2***).

6.2 Discussion of Analytical Results

The results fro the analytical work were interpreted as follows:

- The mine void water was titrated against sodium hydroxide (NaOH) and the results were expressed as hydrochloric acid (HCl).
- The mine void water was titrated from a pH of 2.7 to a pH of 5.2. The reason for the low endpoint pH was to prevent the iron form interfering with the results.
- The normality of the western basin mine void water was determined to be 0.018N.
- The chemical reaction, $2\ HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O$, was used to determine the mass of dolomite involved in a reaction between the mine void water and the acid.
- The molecular mass of HCl is 36.45 atomic mass units (amu), i.e. 2HCl would be 72.9 amu.
- The molecular mass of $CaCO_3$ is 100 amu.
- From the chemical reaction above it can be seen that 2 moles HCl will neutralise 1 mole of $CaCO_3$, therefore 1 mole HCl will neutralise 0.5 moles of $CaCO_3$.
- From the above it is calculated that 36.45 g HCl would neutralise 50 g $CaCO_3$ and therefore that 0.018 moles HCl, i.e. 0.6561 g HCl, would neutralise 0.018 moles $CaCO_3$, i.e. 0.9000 g $CaCO_3$.
- At an equivalent concentration of 0.018 moles/litre HCl, one litre of mine void water would neutralise (dissolve) 0.9 g $CaCO_3$. Therefore, one Ml of mine water would dissolve 900 Kg $CaCO_3$.

The laboratory also determined the specific gravity (SG) of dolomite. It was found that dolomite had an SG of 2.84 Kg/dm^3, i.e. 2.84Kg/litre.

Therefore, 900 Kg $CaCO_3$ would occupy a space of 316.9 litres. One mega-litre of mine void water would therefore create a void in the dolomite of 316.9 litres (0.3169 m^3).

It should be noted that this void would not necessarily resemble a single cavern, but would rather be spread over some area in the form of a series of small solution voids. The reason for this is that dolomite is not pure calcium or magnesium carbonate, but a mixture of carbonates with some insoluble material, mainly silica, incorporated into the rock structure. The carbonate fraction of the dolomite would be dissolved leaving behind the insoluble material. This insoluble material is commonly referred to as WAD. Furthermore, the chemical reactions do not occur instantaneously, therefore some sulphuric acid would be available some distance downstream from the point where the water enters the dolomite.

However, due to the relatively fast reaction time between the strong acid and the carbonate rock as well as the relative slow rate of groundwater movement through an aquifer, the void formation would not be spread over the entire aquifer but would probably rather occur in close proximity of the area where the mine water first comes into contact with the dolomite. The surface stream, the Tweelopiespruit, first comes into contact with dolomite in the Krugersdorp Game Reserve approximately halfway through the reserve, but it appears as if not too much streambed loss occurs within the section of the stream passing through the game reserve. In fact, this part of the stream is classified as a gaining stream. Most of the streambed losses occur between the game reserve's northern boundary and the N14 road where the stream transects the Rietfontein Wrench Fault (refer ***Figure 4*** for detail). This is also the area most likely to be impacted upon by the accelerated void formation in the dolomite. After the last dam in the Tweelopiespruit, the KBW Dam, right alongside the N14 road, the stream flows for a distance of approximately 300 m before the remaining water disappears into the ground. It is believed that the bulk of the void formation would occur in an area around the point where the stream crosses the fault lines as well as along the portion of the stream on dolomite up to the point where all the water disappears from the surface stream. ***Figure 10*** shows the most likely area for possible accelerated void formation. It should be kept in mind that the shape of this area is based on several assumptions. It is assumed that the water in the aquifer is reasonably stationary and that the conditions in the aquifer are mostly anaerobic. Should anaerobic conditions not prevail, ferric hydroxide formation would occur which could lead to a blinding effect on the dolomite exposed to the water. In this case, the area could become considerably larger over time than shown in this figure. Similarly, should there be accelerated flows along preferential lines such as along the fault lines, the area being impacted could potentially look a lot different to the area shown in ***Figure 10***.

The shape could also resemble the shape of the sulphate pollution plume in ***Figure 11***, but it is unlikely that the sulphuric acid would be transported that far without reacting in full with the dolomite.

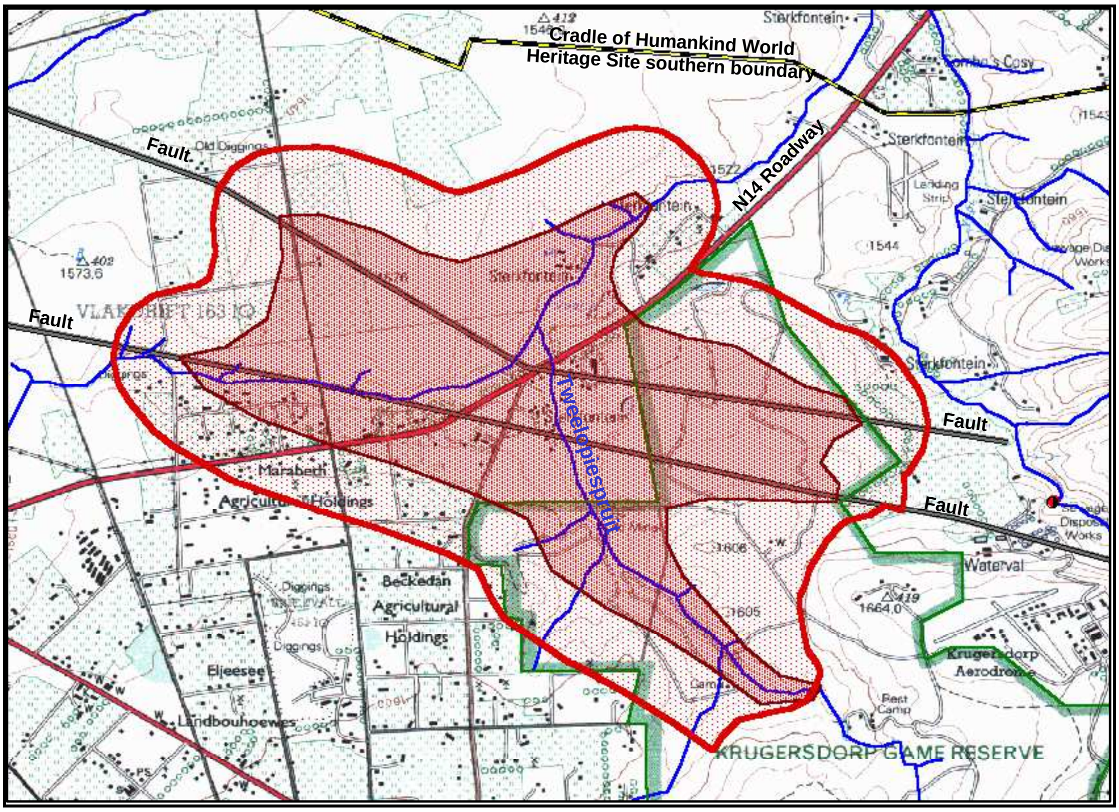


Figure 10 – The area that will most likely be subjected to accelerated void formation as a result of the acidic mine water flowing in the Tweelopiespruit.

It is likely that accelerated void formation would initially occur along the inner shape in ***Figure 10***. Vertically, most of the chemical reactions will occur at or near the water table. As the dolomite within this region becomes depleted, the impacted area will gradually increase in size towards the outer shape in ***Figure 10*** and gradually creep towards the north and northeast and possibly also towards the west along the fault lines, depending on the difference in transmissivity between the faults and the surrounding aquifers. It is assumed that zones of high transmissivity exist along the fault lines. Of course, if the mine water stops flowing, the accelerated process will be halted and void formation will continue at a natural rate.

It has been shown earlier on in this section that each 1 Ml of mine void water would create a void volume of 0.3169 m^3. The mine void filled up and started to decant in August 2002. Water emerges from the mine at an average rate of 15.5 Ml/day (refer ***Section 7.1.1***). Since around February 2005, Harmony has been pumping a significant amount of the water via a treatment plant to the Wonderfonteinspruit. Before this date for a period of approximately two and a half years (30 months or 912 days), untreated or partially treated water flowed through the Krugersdorp Game Reserve and into the Zwartkrans compartment. In the light of the above calculations, it is potentially possible that a void of 4 480 m^3 had already formed by the time that the water was intercepted and pumped to the other stream.

Although all the water is supposed to be intercepted, an unquantified volume still flows sub-surface along the upper parts of the Tweelopiespruit, keeping the Hippo Dam full as well as keeping the fountains downstream from the dam flowing constantly. Furthermore, during the first months of 2006, the recharge from rainfall into the mine void proved too much for the pumping installation and treatment plant and large volumes of untreated water escaped downstream.

In addition to the sulphuric acid in the mine void water, the reaction shown earlier in this section shows that for each mole of $CaCO_3$ that is consumed by sulphuric acid, one mole of CO_2 is formed. As was shown right at the beginning of this section, CO_2 dissolves in water to form a weak acid, carbonic acid, H_2CO_3. Although this acid's actions on the carbonate rock occurs at a much slower rate than those of sulphuric acid, the carbonic acid will nevertheless also create some void space. The forming of this void space would probably only occur after the sulphuric acid in the mine void water had been exhausted completely. This implies that the actions of the carbonic acid would manifest mostly outside and downstream from the area shown in ***Figure 10***.

The void space that could potentially be formed by the reaction between carbonic acid and carbonate rock is not as simple to determine, as is the case with a strong acid such as sulphuric acid. The reason for this is that carbonic acid reaches equilibrium with the bicarbonate it forms when it reacts with the carbonate rock. To refresh, we repeat the equation here:

$$CaCO_3 + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$$

However, over time and distance the groundwater flows, most of the carbonic acid would eventually be consumed as the equilibrium is constantly pushed towards the right of the equation, as bicarbonate is removed or diluted by other water entering the aquifer from unpolluted sources. The above equation shows that one mole of $CaCO_3$ is dissolved by one mole of carbonic acid while the equation, $CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$, implies that one mole of sulphuric acid would produce one mole of CO_2. The equation right at the beginning of this section shows that one mole of CO_2 forms one mole of H_2CO_3. Therefore, for each mole of $CaCO_3$ consumed by sulphuric acid, one mole of CO_2 is formed which, in turn, could potentially (but not necessarily) consume 1 mole of $CaCO_3$.

Using the same calculations as was used with the experiment above, it can be shown that the CO_2 produced by the mine water reacting with the carbonate rock could also potentially consume a further 900 Kg (or 316.9 litres) of carbonate rock for each megalitre discharged into the dolomitic aquifer.

This void would probably not occur at the point where the mine water comes into contact with the dolomite, but would rather be spread across the entire area in which the groundwater flows. Potentially, however, the water that decanted from the mines, for the period before it was treated and pumped to the Wonderfonteinspruit, could have created a void of 8 960 m^3. The first half of this void space would have formed as a result of the actions of H_2SO_4 at and around the points where the mine void water enters the dolomite as shown in ***Figure 10***, while the second half formed by the actions of CO_2 with the dolomite would be spread diffusely over a much larger area.

To put this volume into perspective, it can be compared to the larger of the two commercial caves in the Cradle of Humankind, the Wondercave. The Wondercave has an approximate void space of 240 000 m^3. The void created by the mine void water is merely 8 960 m^3, or 3.7 % of the Wondercave's volume. The Wondercave was, however, formed over a period of millions of years, while the void resulting from the mine water was formed in only 2½ years. In contrast to the Wondercave, the void space created by the mine water is probably not located in one spot, but spread over a larger area as a series of micro voids, progressively concentrating around the area shown in ***Figure 10***.

Photo 6 – A section of the Wondercave. Probably only 30% of the void is visible in this photo. The 36-meter lift shaft structure is visible in the centre of the picture. The approximate total void volume of the Wondercave is 240 000 m^3.

6.3 Other Implications Relating to the Mine Void Water on Downstream Users

The potential forming of voids and the ground stability aspects associated with voids in dolomite is not the only potential negative impact on the Zwartkrans Compartment downstream from the decanting mine void water.

6.3.1 Toxicity of Mine Void Water

Together with the accelerated void formation and the resultant formation of subsidences/sinkholes, the most significant impact the contaminated mine void water would have on the groundwater in the Zwartkrans Compartment is the poisoning of the aquifer by sulphate, metals and radioactive elements. If the mine water is allowed to continue to decant into the Zwartkrans compartment, all the water in the aquifer would become poisoned and unfit to be used in any manner. In addition and over longer periods of time, water leaving the aquifer could eventually also become contaminated and increase the contaminant load in the Blaauwbankspruit/Crocodile River system.

Several deaths, claimed to have been directly related to the drinking of mine void water from the Tweelopiespruit (*J. Mostert, Pers. Comm. 2004*), have occurred among the animal population in the Krugersdorp Game Reserve. It is almost impossible to prevent game from drinking from the only river flowing through the entire length of the game reserve. For some reason, it appears as if the hippos that have take up residence in the *Hippo Pool* are more tolerant to the contaminated water than most of the other animals.

As is shown in ***Section 4***, in addition to the acidity in the mine water, a number of other elements/determinands are also present in the decanting water, mostly metals. The groundwater in the Zwartkrans compartment, for many people the only drinking water source available, is being contaminated with these metals. When the water in the mine void becomes acidic as demonstrated in ***Section 3***, it allows metals associated with Witwatersrand rocks to dissolve into the mine void water. Many of these metals are present in toxic concentrations in the mine water. In addition, radioactive metals also occur in the mine void water.

Although no human deaths have occurred so far as a result of drinking of mine void contaminated water, there is no reason to believe that the water would not also affect people in the same way the animals in the Krugersdorp Game Reserve are affected.

The following determinands in the mine void water exceeded the Maximum Allowable Limits (Class II) of the SABS 241 Drinking Water Standard, in many cases by several orders of magnitude:

PH, EC, TDS, SO_4, Fe, Mg, Ca, Mn, Al, Pb, Co and Ni.

The analyses results (obtained from *ERWAT* and *DD Science*) did unfortunately not cover the entire metals spectrum. We can therefore only report on the determinands covered by their analyses. It can, however, be assumed with a reasonable amount of certainty that most of the other metals would also be present in elevated concentrations. The mine void water is toxic and could lead to severe health effects or death in humans, should it be used for drinking purposes in its undiluted form.

In most cases, metals will precipitate out of solution if the pH is adjusted upwards, i.e. the water is made more alkaline. Different metals will precipitate at different pH values. In general, the concentration of most of the metals is reduced significantly within a relatively short time span after the mine water comes into contact with the dolomite in the Zwartkrans Compartment. This is as a result of the neutralisation of the sulphuric and carbonic acids in the mine water by the carbonate rock (refer ***Sections 6.1*** and ***6.2***), adjusting the pH upwards.

It should be noted that the metals have not simply disappeared but that they have merely changed to a different oxidation state, which changed them from a soluble form to a solid form. They are still there, in the area where the precipitation had occurred in the first place. The process could be reversed and the contaminants mobilised, should the water become acidic.

Furthermore, the sulphate in the mine void water has also undergone a change from being an acid to being a salt, after coming into contact with the dolomite rock. Both these forms are soluble and the sulphate will therefore remain in the water, albeit in a different format.

High concentrations of sulphate exert predominantly acute health effects (diarrhoea). These are temporary and reversible since sulphate is rapidly excreted in the urine. Individuals exposed to elevated sulphate concentrations in their drinking water for long periods, usually become adapted and cease to experience these effects. Sulphate concentrations of 600 mg/l and more cause diarrhoea in most individuals and adaptation may not occur.

The tendency of sulphate to induce diarrhoea in people depends to some extent on the associated cation. Magnesium will induce diarrhoea, whereas sodium will not. Unfortunately magnesium occurs in near-saturated quantities in dolomite, as it forms part of the dolomite mineral, $CaMg(CO_3)_2$. In concentrations over 200 mg/l, it will produce a brackish taste to water.

Sulphate imparts a salty or bitter taste to water. The taste threshold for sulphate falls in the range of 200 - 400 mg/l and depends on whether the sulphate is predominantly associated with sodium, potassium, calcium or magnesium, or mixtures thereof.

6.3.2 Economic Considerations: Scaling & Corrosion

Apart from the health and aesthetic effects associated with the presence of sulphate in water, elevated sulphate concentrations also increase the corrosion rate of metal fittings in water distribution systems. Dolomitic water in general is classified as scaling water. This is due to its saturation with calcium and magnesium carbonate. It is also classified as “hard” water for the same reason. This hardness is, however, classified as temporary hardness as it can be removed from solution by boiling of the water. The hardness associated with sulphate salts, originating from the mine void water, is classified as permanent hardness as it is not readily removed from solution by simply boiling the water.

When there are metals dissolved in the water in excessive concentrations, the scaling or corrosion effects of that water would also be increased.

As the water in the Tweelopiespruit progresses downstream, it undergoes several changes. Firstly, due to Reaction 2 and 3 (***Section 3***), the iron(II) (ferrous) is oxidised to iron(III) (ferric), which subsequently precipitated out of solution. The consequence of this is the deoxygenation of the water as all free oxygen is used up. This has probably been the cause of death for the entire fish population that used to live in the stream. The water also becomes progressively more acidic as the iron hydroxide precipitates (refer ***Section 3***).

At least, most of this stream through the game reserve is a gaining stream. Dolomitic water is added to the stream in two distinct areas after entering the game reserve. Firstly, water is added form a fountain (actually, a fountain and a seep zone), where water decants form a dolomitic inlier referred to as the "big toe" of the "giant footprint" (refer ***Figure 4***).

Photo 7 – The fountain draining the "big toe" of the "giant footprint" in the Krugersdorp Game Reserve. Although it was covered with a layer of algae when the photo was taken, the quality was as good as can be expected from uncontaminated dolomitic water.

During the rainy season seepage occurs over a distance of approximately 200m downstream from the fountain, presumably from the same source. At this point, the stream stills flows over mainly quartzite of the Witwatersrand Supergroup. Approximately 1 Km downstream from the fountain the stream flows off the quartzite and onto the dolomite of the Transvaal Supergroup. For the next 2.2 Km up to the Aviary dam, the stream receives additional dolomitic water from various tributaries and diffuse sources along its way. Approximately 500 m after leaving the game reserve's northern border, the stream crosses the Rietfontein fault and rapidly becomes a losing stream. The netto positive effect of the dolomitic water being added to the stream along its length through the game reserve is that the mine void water is diluted with clean, alkaline dolomitic water. The electrical conductivity is reduced from 241 mS/m at the Hippo Dam down to 90 mS/m at the Aviary Dam, while the pH increases from 3.68 to 7.14 between the same two points (refer ***Table 4***). It should, however, be noted that these readings were done right at the end of the dry season of 2005 when there was no mine void water bypassing the collection system on surface. It therefore represents only the mine void water flowing sub-surface. The 2005/2006 rainy season proved that the pumping installation and treatment plant is totally inadequate to handle peak flow conditions and that, for a period of several months, almost all the mine void water flowed down the Tweelopiespruit.

In general, however, the gaining section of the stream does have a beneficial effect on the water quality flowing in the Tweelopiespruit.

6.3.3 Industrial Use of Contaminated Water

In addition to drinking (and watering of livestock), the water in the Zwartkrans Compartment is used for other applications. One important example is discussed briefly hereunder.

An example is the use of sulphate-contaminated groundwater by the Krugersdorp Brick Works (KBW) in the manufacture of pre-stressed concrete lintels and concrete beams. These items are used in the manufacture of buildings and structures. It has been proven that excessive sulphate in water could weaken concrete structures and in a worse-case scenario, could lead to the failure of structures, killing or injuring the occupants.

Mr. John Fourie of KBW Pre-cast Concrete Products raised this item as a result of the public participation process pertaining to the EIA. Their premises is located right at the point where the Tweelopiespruit water enters the Zwartkrans compartment and the borehole supplying water for their operations is located on or very close to the northern-most fault shown in ***Figure 10***. The borehole also locates in the central area, shown in ***Figure 10***.

Sulphate attack on concrete results from a chemical reaction between the sulphate ion and hydrated calcium aluminate and/or the calcium hydroxide components of hardened cement paste in the presence of water. The products resulting from these reactions are calcium sulphoaluminate hydrate, commonly referred to as ettringite, and calcium sulphate hydrate, known better as gypsum. These solids have a very much higher volume than the solid reactants and, as a consequence, stresses are produced that may result in breakdown of the paste and ultimately in breakdown of the concrete.

This process can, to an extent, be mitigated by using sulphate-resistant cement (low in calcium aluminate).

Further studies are required to establish the degree and rate of deterioration/weakening of concrete and cement items manufactured using Zwartkrans Dolomitic water.

7. Suggested Mitigation Measures

It has been shown in the preceding pages that the mine void water has had a definite negative impact on the receiving body of water, the Zwartkrans dolomitic compartment underlying the Cradle of Humankind World Heritage Site. Although Harmony has done a great deal of work in intercepting the mine void water in the vicinity of the decant point, an unquantified volume still escapes downstream into the Zwartkrans compartment via the Tweelopiespruit, mostly sub-surface. It was confirmed that 1.47 Ml/day escapes downstream at the end of the dry season, as this water emerges from the fountain downstream from the Hippo Dam (near the graves in the Krugersdorp Game Reserve) as well as from seepage downstream from the fountain. At the same time, the surface stream was bone dry upstream from the Hippo dam in the game reserve. Previously, while the gold mines were maintaining an artificial low groundwater level, this fountain was always dry, as was the Hippo Dam (then referred to as the Dry Dam). There is only one logical explanation for this fountain to have resumed its flow and that is that the water in the mine void feeds it. The water table in the mine void is some 30 m above the fountain (Fountain = 1 640 mamsl, Decant = 1 665 mamsl, water in void is ±5 m above decant point).

It has furthermore been shown that the mine void water is undermining a section of the Zwartkrans Compartment and that it has contaminated the groundwater in a part of the compartment. There is very little that can be done about the void already created by the mine water as the void, although centred around an area of most likely impact, is spread over a significant area of the compartment. Grouting of the void is therefore out of the question except in the immediate area of the decanting mine void water entering the compartment. The process of accelerated void formation can, however, be stopped from continuing, by removing the source of the contamination.

The following section will describe one of the solutions to the problem, i.e. to pump the water down to an acceptable elevation as recommended in the SWaMP document. This elevation was referred to as the **Environmentally Critical Level** or the **ECL**.

7.1 Lowering of the Water Level in the Mine Void

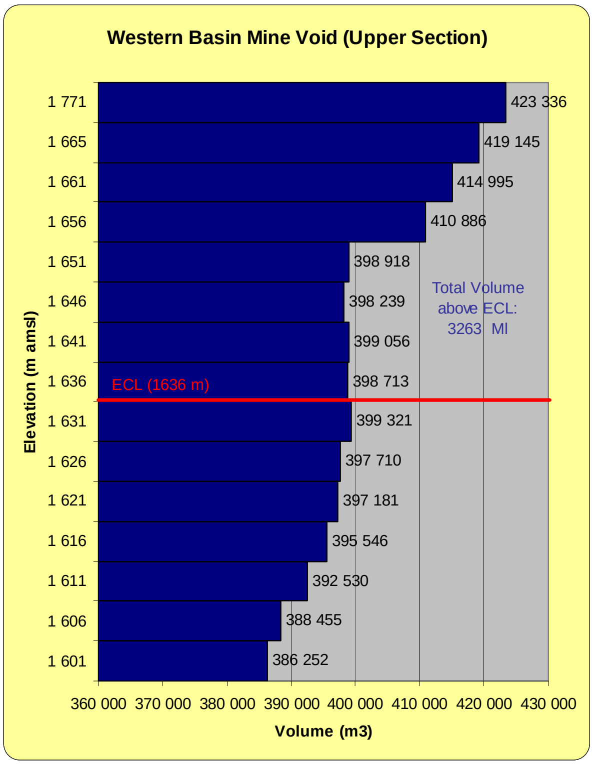
7.1.1 Revised ECL Level

Phase 1

In the SWaMP document, it was recommended that the ECL be fixed at the elevation of the water table in the Zwartkrans compartment adjacent to the Tweelopiespruit. Studies by Parsons, however, indicated that there was not any leakage between the two compartments. From our studies, however, it appears as if there is definitely some near-surface leakage from the mine void towards the Zwartkrans compartment, especially along the fractured area underlying the Tweelopiespruit. This would, however not have impacted upon the water ingress into the mine void while it was filling up, as the water level in the Zwartkrans compartment is lower than the *graves* fountain. The fact that the fountain (*graves* fountain) started flowing again since the mine void water started to decant, confirms that at least some leakage occurs, even across the section of stream crossing the Witwatersrand rocks between the Hippo Pool and the main Zwartkrans aquifer.

The revised ECL (RECL) is therefore set at the elevation of this fountain. The fountain in the Tweelopiespruit, located at South 26.0969550°, East 27.7189403° (WGS84 datum), is immediately downstream from the contact between the dolomitic inlier and the underlying Black Reef and appears to be the lowest known decant point of the dolomitic inlier, through which the Western Basin Mine Void water is currently flowing. The fountain is at an elevation of approximately 1 636 mamsl.

The water level within the Western Basin Mine Void is currently at an elevation of 1771 mamsl, while the RECL is at 1 636 mamsl. ***Graph 1*** shows the volumes in the Western Basin Mine Void down to, and immediately below the RECL. There is a volume of 3 263 Ml between the current water level and the RECL. This represents the volume, which is to be removed from the mine void, in order to lower the water level to the RECL.



Graph 1 – The near-surface volumes of the Western Basin Mine Void in relation to the Revised ECL (RECL) level (*Van Biljon, 2005*).

It has been observed that there is a definite correlation between the local rainfall and the volume of water decanting from the mine void. During 2003, one of the dryer years, it was observed that approximate volumes of 6.9 and 11.3 Ml/day (averaging 9.1 Ml/day) were decanting from the mine void into the Tweelopiespruit East during winter and summer, respectively.

A water balance, created by van Biljon & Krige in 2005, showed that a more realistic volume of ingress into the mine void was 15.5 Ml/day. It is believed that the difference between the two volumes (6.4 Ml/day) could be accounted to water lost through diffuse decant areas as well as the water underflowing the decant interception setup in the Tweelopiespruit East. This would then also account for the volume decanting from the *graves* fountain in the Krugersdorp Game Reserve.

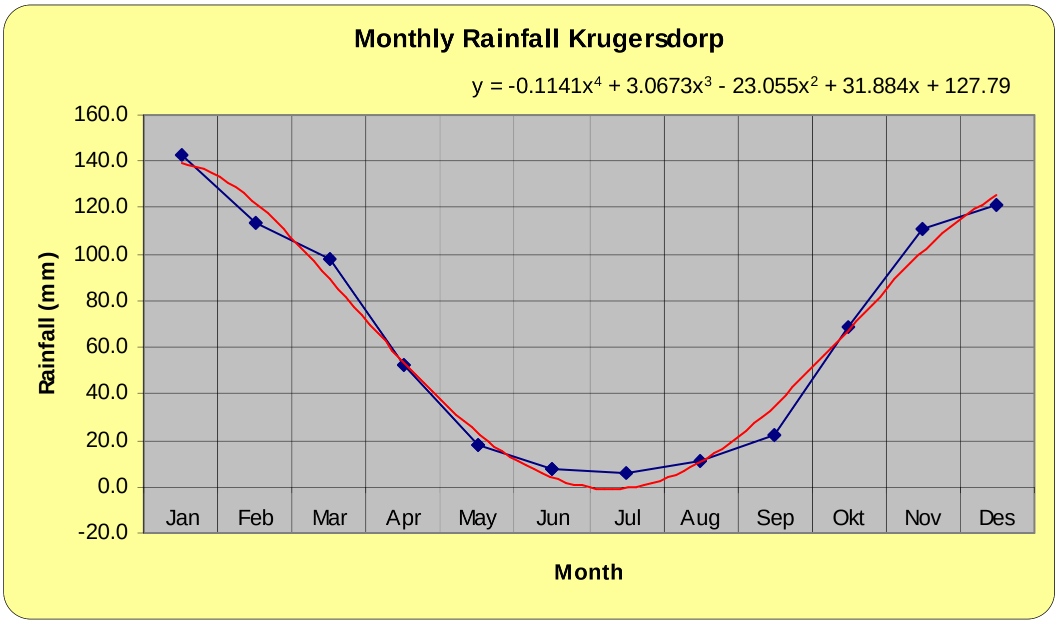
As stated above, the flow rate from the decant point in the Tweelopiespruit is directly related to the amount of rainfall. It was therefore decided that the rainfall pattern and the recorded relationship between the various months would be used to develop a model to simulate the ingress and outflow into and out of the mine void.

The initial ratio between the 2003 volumes decanting from the mine void was used to determine the summer-to-average and winter-to-average ratios.

These were 1.2 and 0.8 respectively. Using these ratios, the new revised summer and winter decant volumes were calculated to match the 15.5 Ml/day of water entering the mine void. The revised winter and summer volumes were hence calculated at 11.8 and 19.2 Ml/day respectively.

The next step was to obtain accurate local rainfall figures. The rain station most representative of the catchment area of the Western Basin Mine Void is the station at Coronation Park in Krugersdorp (*Station No. climn 0475456 8 LAT: 2606 LON: 2746 HEIGHT: 1699*). The data used to calculate the monthly average rainfall volumes were obtained from the SA Weather Services and covered the period from 1903 up to 1999.

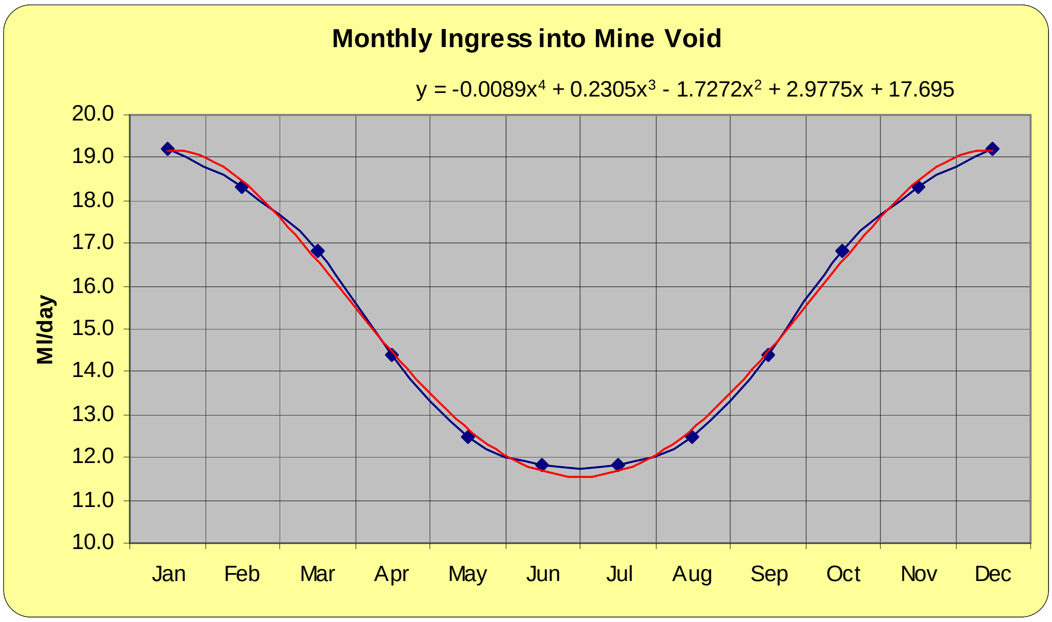
The 96 years of rainfall records were used to calculate average monthly rainfall volumes. These volumes were then plotted in a graph to determine the relationships between the month and the rainfall intensity. ***Graph 2*** shows the rainfall graph (Dark blue line).



Graph 2 – A graphic representation of the rainfall in Krugersdorp.

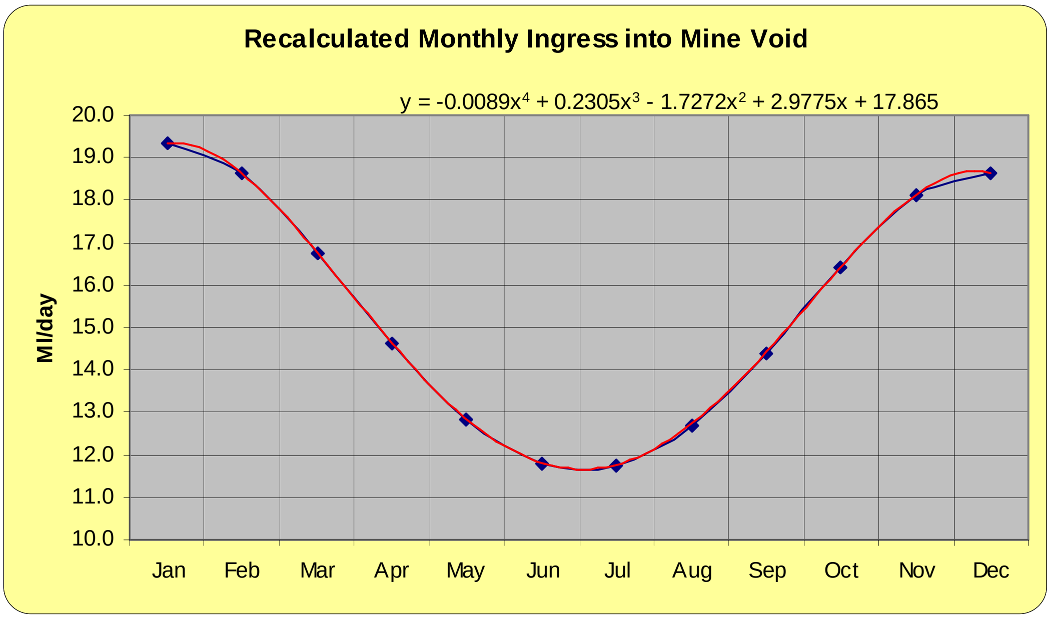
A trend line (in red – ***Graph 2***) was included to match the rainfall pattern as closely as possible. It was found that a polynomial curve, expressed by the equation, $y = -0.1141x^4 + 3.0673x^3 - 23.055x^2 + 31.884x + 127.79$, fitted the rainfall curve the best. It was observed, however, that the curve actually crossed the zero-line during July with a value of -0.06 mm. This is an impossible value when modelling rainfall values, but due to the very small negative value, the equation was still considered to fit the rainfall profile close enough. The average total measured rainfall for the entire period was 770.5 mm, while the polynomial equation shown above, would produce a slightly lower average total of 769.1 mm. The slightly lower values would be corrected in subsequent calculations and would also get rid of the negative rainfall values during July.

The next step was to find an equation that would produce a curve similar to the rainfall curve, but which would fit the water ingress volume into the mine void. A curve as shown in ***Graph 3***, was found to fit the profile of the rainfall, as well as the profile representing the ratio between the winter and summer volumes measured at the decant point of the mine void, the closest.



Graph 3 – A graph representing the relationship between the water decanting from the Western Basin Mine Void and the rainfall over its catchment.

The red line on the graph represents the trend line for the curve. As was the case with the rainfall, however, the trend line with a polynomial equation of, $y = -0.0089x^4 + 0.2305x^3 - 1.7272x^2 + 2.9775x + 17.695$**,** produced slightly lower values than the actual values used to produce the curve. The equation was then amended slightly (by a value of +0.17) to produce a curve that would produce an average decant volume of 15.5 Ml/day. This curve is represented by the formula, $y = -0.0089x^4 + 0.2305x^3 - 1.7272x^2 + 2.9775x + 17.865$, and is shown in ***Graph 4***.



Graph 4 – An amendment of the curve shown in ***Graph 3*** to eliminate the negative rainfall during July. The curve produced by the recalculated polynomial equation at the top of the graph matches the actual line almost exactly.

As can be seen from the graph, the actual line (in dark blue) and the trend line (in red) match each other almost exactly. The recalculated polynomial equation also produced a curve with properties closer to the original rainfall curve. In the rainfall graph, it can be seen that the value for December is somewhat lower than the value for January. In ***Graph 2***, however, the values were the same. The recalculated curve is therefore more representative of the rainfall than the curve in ***Graph 2***.

The equation represented by the graph produced the following monthly average values for ingress into the mine void:

Month	Ingress into mine void (Ml/d)
Jan	19.3
Feb	18.6
Mar	16.8
Apr	14.6
May	12.8
Jun	11.8
Jul	11.8
Aug	12.7
Sep	14.4
Oct	16.4
Nov	18.1
Dec	18.6
Average:	15.5

Table 5

It is believed that there is somewhat of a lag period between the time of rainfall and the water reaching the mine void. Actual observations during and shortly after a period of heavy rainfall during the beginning of 2005, however, indicated that this lag period might be as short as a day or two. This may be due to the relatively large surface area covered by open pits that are connected directly to the mine void in the vicinity of the decant point. When water falls into these pits, it would reach the mine void water within a very short period compared to rainwater percolating through undisturbed geology. It was decided that, at least for this exercise, a lag period would not be incorporated into the water balance.

We have now established a formula that would produce realistic flow rates into the mine void. The next step would be to apply these values to develop a management plan for pumping of mine void water in order to lower the water level down to the RECL.

A total volume of 3 263 Ml will have to be removed in a scenario where there is an average ingress of 15.5 Ml/day. Furthermore, there is a bottleneck in the form of the limitations of the treatment plant. The treatment plant can only treat a daily volume of 15 Ml. The Directive from DWAF also limits the volume of mine void water released from the Cooke Attenuation Dam to a maximum of 15 Ml/day. This would not have been too much of an obstacle if the treatment plant could handle a greater volume. In that case, the Attenuation Dam could be used to release water under controlled conditions. The Cooke Attenuation Dam has a total capacity of 2 100 Ml with an attenuation capacity of 1 800 Ml, about half the water in the mine void above the RECL. If the plant could treat a greater volume, all the water could be stored in the Cooke Attenuation Dam and released under controlled conditions in a manner that would not exceed the volumes prescribed in the DWAF Directive. Due to the limitations of the treatment plant, however, this option cannot be exercised.

It is believed that, the actual bottleneck in the treatment plant is the settlers. Water is treated through aeration and the addition of lime (to correct the pH and to precipitate the Fe^{2+} in the mine void water as Fe^{3+}, in the form of gypsum. This precipitate has to be settled out in settling tanks, and it is these settling tanks that do not have the capacity to treat a greater volume of water.

It is understood, however, that limed water could be irrigated directly onto the nearby tailings dams without having been settled first. Capacity exists to irrigate a volume of 4 Ml/day. As it stands at present, the lime sludge underflow from the settlers is deposited onto the tailings dams anyhow; therefore it would not change the method of disposal dramatically, apart from spreading the sludge over a greater surface area. However, if the water were irrigated continuously, the chances of increasing the windblown dust, resulting from the sludge in the irrigated water, would not increase significantly until the RECL has been reached and the irrigation operations cease. The cessation of irrigation operations could lead to the increase in windblown dust. This problem will be addressed at a later stage and does not form part of this particular exercise.

Should the above option prove to be feasible, the pumping of 19 Ml/day would result in the revised ECL being reached within 31 months. The pumped water would be disposed of as follows:

Water pumped from Mine Void:	19 Ml/day
Water to Treatment Plant:	19 Ml/day
Water through Treatment Plant's settlers:	15 Ml/day
Partially treated water, bypassing settlers in Treatment Plant:	4 Ml/day
Treated water pumped to Wonderfonteinspruit:	15 Ml/day
Partially treated water to irrigation of tailings dam:	4 Ml/day

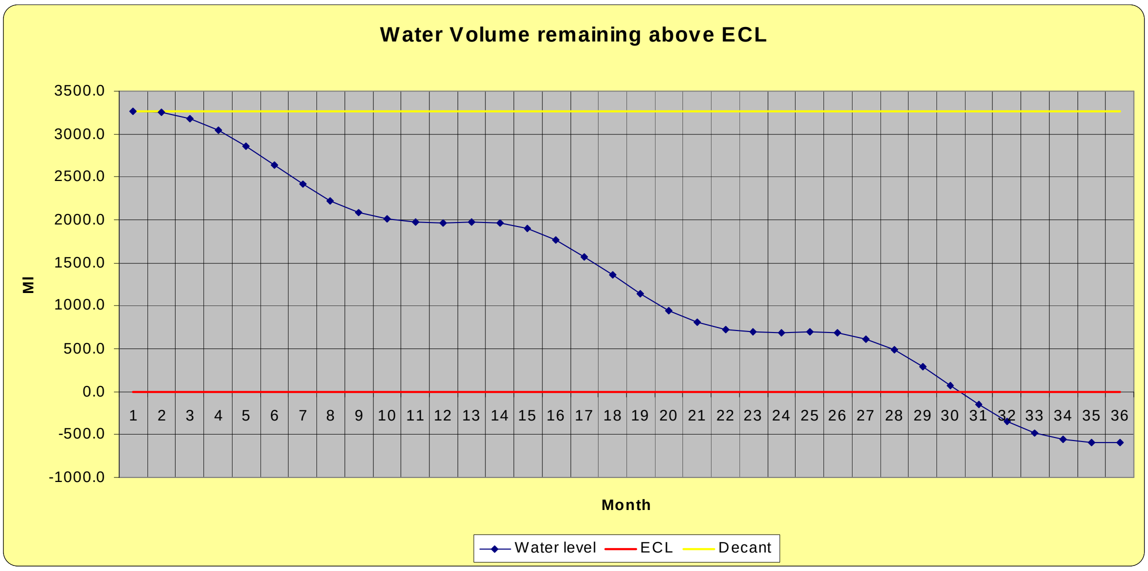
The daily pumping of a volume of 19 Ml, would lower the water table in the mine void as shown in ***Table 6***.

Year	Year 1											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ingressinto mine void Ml/day)	19.3	18.6	16.8	14.6	12.8	11.8	11.8	12.7	14.4	16.4	18.1	18.6
Ingressinto mine void Ml/month)	599.4	521.2	519.4	438.4	397.5	354.1	364.8	393.9	432.0	509.0	543.5	577.6
Water volume pumped from mine void Ml/day)	19	19	19	19	19	19	19	19	19	19	19	19
Water volume pumped from mine void Ml/month)	589	532	589	570	589	570	589	589	570	589	570	589
Balance (negative values indicate nett loss from mine void) Ml/month	10.4	-10.8	-69.6	-131.6	-191.5	-215.9	-224.2	-195.1	-138.0	-80.0	-26.5	-11.4
Initial volume above ECL = 3263 Ml												
Volume remaining in mine void above ECL (Ml)	**3273.4**	**3262.6**	**3193.0**	**3061.4**	**2869.9**	**2654.0**	**2429.8**	**2234.7**	**2096.7**	**2016.8**	**1990.3**	**1978.9**
Year	Year 2											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ingressinto mine void Ml/day)	19.3	18.6	16.8	14.6	12.8	11.8	11.8	12.7	14.4	16.4	18.1	18.6
Ingressinto mine void Ml/month)	599.4	521.2	519.4	438.4	397.5	354.1	364.8	393.9	432.0	509.0	543.5	577.6
Water volume pumped from mine void Ml/day)	19	19	19	19	19	19	19	19	19	19	19	19
Water volume pumped from mine void Ml/month)	589	532	589	570	589	570	589	589	570	589	570	589
Balance (negative values indicate nett loss from mine void) Ml/month	10.4	-10.8	-69.6	-131.6	-191.5	-215.9	-224.2	-195.1	-138.0	-80.0	-26.5	-11.4
Volume remaining in mine void above ECL (Ml)	**1989.3**	**1978.5**	**1908.9**	**1777.3**	**1585.8**	**1369.9**	**1145.7**	**950.6**	**812.6**	**732.6**	**706.1**	**694.7**
Year	Year 3											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ingressinto mine void Ml/day)	19.3	18.6	16.8	14.6	12.8	11.8	11.8	12.7	14.4	16.4	18.1	18.6
Ingressinto mine void Ml/month)	599.4	521.2	519.4	438.4	397.5	354.1	364.8	393.9	432.0	509.0	543.5	577.6
Water volume pumped from mine void Ml/day)	19	19	19	19	19	19	19	19	19	19	19	19
Water volume pumped from mine void Ml/month)	589	532	589	570	589	570	589	589	570	589	570	589
Balance (negative values indicate nett loss from mine void) Ml/month	10.4	-10.8	-69.6	-131.6	-191.5	-215.9	-224.2	-195.1	-138.0	-80.0	-26.5	-11.4
Volume remaining in mine void above ECL (Ml)	**705.2**	**694.3**	**624.7**	**493.1**	**301.6**	**85.8**	**-138.5**	**-333.6**	**-471.6**	**-551.5**	**-578.0**	**-589.4**

Table 6 – The relationship between the water ingress into the mine void, water pumped from the void and water levels in the Mine Void over a period of 3 years.

As can be seen from ***Table 6***, the RECL will be reached during July of Year 3, provided that pumping operations commenced during January of Year 1. It is recommended that pumping of 19 Ml/day continue for at least another month or two to create a volume below the ECL to accommodate the excess water encountered during January of each year. This will prevent water from decanting at the ECL fountain (*graves* fountain) during months of excess rain.

Table 6 is represented graphically in ***Graph 5***. A spreadsheet was developed and simulations of various scenarios are now simple. The spreadsheet allows for the alteration of the volumes pumped and the month started.



Graph 5 – The water level in the mine void should water be pumped from the void at a constant rate of 19 Ml/day.

<u>Phase 2</u>

Once the ECL has been reached, pumping operations will continue, but the volume will return to the volume entering the Western Basin Mine Void, i.e. 15.5 Ml/day. By this time and in accordance with the Directive from DWAF, a water licence application for the continued disposal of water from the Mine Void would have been applied for and issued. Under the current circumstances it is unclear as to the ultimate use of the treated water. In the short to medium term, it could be used in the metallurgical plants of Harmony and Mogale Gold. The mines will, however, not produce indefinitely and another solution of the treated water will have to be found. The answer lies in a water utility company as recommended at the *Western Basin Technical Committee* by Atomaer.

7.2 Monitoring of Water Quality in the Zwartkrans Compartment

The Zwartkrans compartment has been contaminated by the discharge of mine water for over a century. Recently, however (2002 onwards), the magnitude of the contamination has increased as a consequence of the water, from the flooded mine void, decanting on surface and flowing via the Tweelopiespruit into the Zwartkrans Compartment.

As part of the groundwater study by Mr. Marius van Biljon of Rison Groundwater Consulting (part of the EIA study of the Zwartkrans Compartment), a number of boreholes (including boreholes drilled by DWAF in 1986, part of a study by Bredenkamp, *et. al. 1986*) were sampled. The sulphates in these boreholes were plotted on a map of the area and a pollution plume was drawn around the areas with elevated sulphate concentrations. For the purposes of this exercise, it was assumed that natural dolomite would not contain sulphate concentrations in excess of 40 mg/l. In fact, under normal conditions, dolomite would contain less than half that concentration, but due to the proximity of the Witwatersrand quartzites and the Black Reef to the south, both containing pyrite and both in the catchment of the aquifer, it was decided to choose a conservative concentration of 40 mg/l. The results are shown in ***Figure 11***.

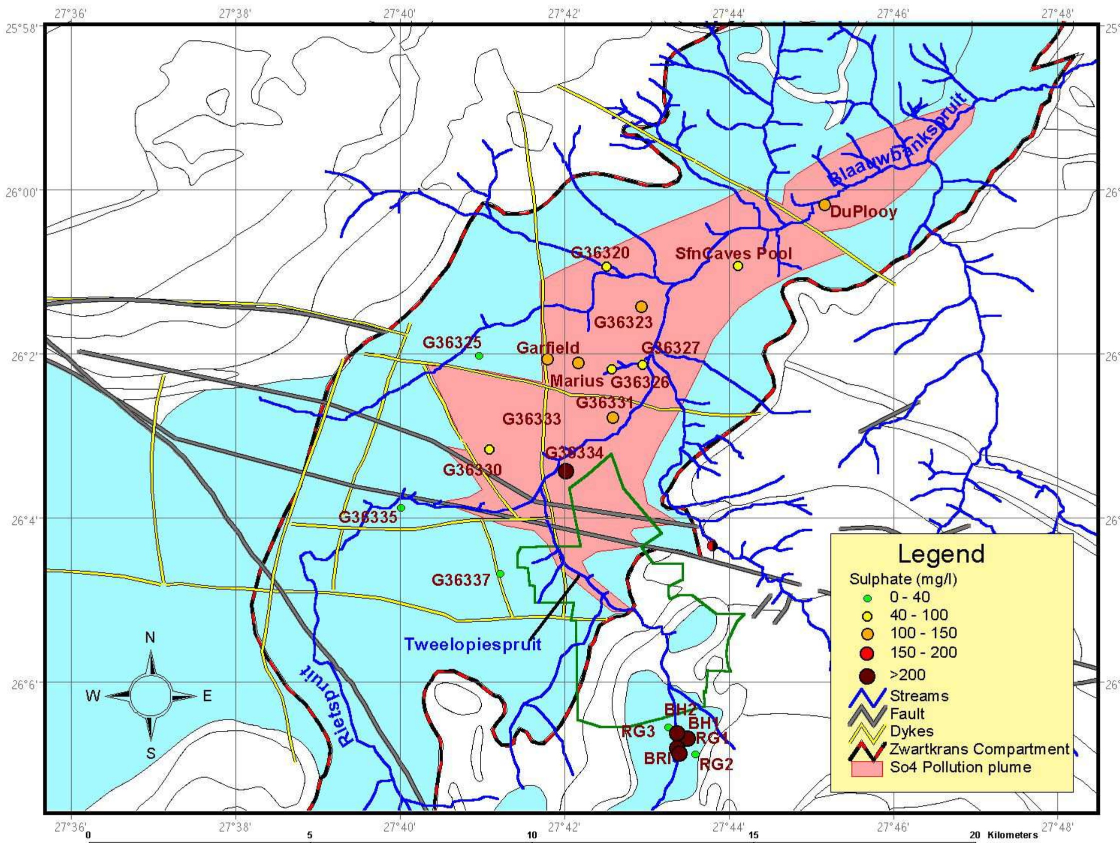


Figure 11 – The pollution plume containing excessive concentrations of Sulphate.

The pollution plume in ***Figure 11*** included all the boreholes with sulphate concentrations in excess of 40 mg/l. Sulphate was chosen as an indicator determinand, as the Witwatersrand rocks mined for their gold content, also contains significant quantities of pyrite, which cause sulphate pollution (refer ***Section3*** – Acid Mine Drainage). It appears as if some of the dykes play a role in containing the pollution, while the fact that there is no contamination to the west indicates that the groundwater flow mimics the surface water flow, i.e. it flows from southwest to northeast. The last dyke (to the northeast), shown in ***Figure 11***, is believed to be a barrier dyke. This is the reason there is a spring on the dyke (refer ***Figure 8***). The fact that the pollution continues beyond this dyke can be attributed to surface water carrying the contaminants over the dyke. The description of the groundwater environment is, however, beyond the scope of this report and will be covered in detail in the groundwater report. The purpose of including this section here is merely to show the extent of the pollution plume.

As part of this study, the elevation of the water level in the Sterkfontein Caves was surveyed accurately. It has now been shown that the Sterkfontein caves pool is at an elevation above the regional groundwater, yet it contains elevated sulphate concentrations (61 mg/l). These sulphates are probably attributable to the bat population living in the cave rather than to mining pollution. Apart from the Sterkfontein Caves pool, however, it is unlikely that the other boreholes containing elevated sulphate concentrations are contaminated by sources other than from mining origin. *The water level in the Sterkfontein Caves on 06/02/2006 was 1 450.883 meters above mean sea level (mamsl), while the water in the Blaauwbankspruit adjacent to the cave was at 1 445 (± 1 m) mamsl. At the same time, the water level in the borehole located on the property of the Sterkfontein caves was at 1 437.48 mamsl*.

It should also be kept in mind that the sulphate concentration in all but one of the boreholes still meets the SABS 421 Class 0 (*Ideal*) standard for drinking water. The only borehole with sulphate concentrations over the Class 0 limit is Borehole G36334, but with a concentration of 220 mg/l, it still falls within the Class 1 (*Acceptable*) standard.

In spite of this, however, the fact that elevated sulphates are present in the groundwater shows that mining contamination has already had an impact on the aquifer. It is recommended that these, and other boreholes in the general vicinity of the pollution plume, be monitored on a regular basis, not only for sulphates, but also for all the other potential contaminants associated with gold mining, and that the residents and users of water be warned of the contamination of their water.

7.3 Ground Stability

In ***Section 6.2*** the subject of accelerated void formation in the dolomite of the Zwartkrans compartment was discussed. The area most likely to be affected was shown in ***Figure 10***. There are people living and operating businesses in the area shown in ***Figure 10*** and these people should be warned about the potential ground instability in their area. The potential greatest disaster, however, could occur if part of the N14 Roadway collapses. This road carries a high traffic load, as it is the main arterials between Johannesburg and Botswana. The stability of this road is of paramount importance.

It is recommended that the stability of the N14 roadway crossing the area of most likely ground instability discussed in ***Section 6.2*** and shown in ***Figure 10***, be subjected to geotechnical surveys on a regular basis, to identify potential sinkholes before the road collapses. The same goes for the residences and businesses in the area. In short, a thorough geotechnical survey is recommended in the affected area.

8. Conclusions

The study, culminating in this report, was conducted between October 2005 and March 2006. It starts by giving a description of the surface- and groundwater environments and shows that, in the study area, there is no definite distinction between surface- and groundwater as is the case in most other areas. Apart from the fact that the water flows on surface or below ground level, the only distinction between surface- and groundwater is the fact that, on surface, the water can be seen, it flows in a known channel and it can be measured and tested, while in the groundwater environment it cannot be seen, the mechanisms governing its flow is still to a great extent unknown and we only get snapshots of its character by examining water pumped from boreholes sunk into the aquifer.

Across the study area water flowing on surface becomes groundwater and *vice versa* several times. We have given the streams names such as losing and gaining streams and we talk about surface- and groundwater environments, but in reality, the streams do not change, they merely move from one medium to another abiding by the simple physical law stating that all water is subjected to gravity and that it will always flow downhill following the route of least resistance. However, surface water entering the groundwater environment, emerges further downstream bearing a totally different chemical character form what it had before entering the groundwater environment, but in essence, the water is still the same water entering the groundwater environment.

Our report provides a short history of the gold mining industry in the West Rand and its relationship with acid mine drainage with specific reference to the water decanting from the Western Basin Mine Void.

This is followed by a detailed description of the flow rates into and out of the Zwartkrans Dolomitic Compartment and how the methods we used in measuring these flow rates. This section culminates in a water balance of the compartment.

We then looked at a simple salt load balance of the in- and outflows of the compartment.

The section following the water and salt balance is probably one of the most important sections in this report. This section discusses the chemistry and the chemical reactions between the mine void water and the dolomite in the aquifer. Some quantification of the impacts is described and recommendations are made. The toxicity of the mine void water is described and their impacts on downstream users are discussed.

The final section describes a number of mitigating measures that can be used to reduce the impacts of the mine void water on the environment.

The water in the Western Basin Mine Void could probably not have chosen a worse place to decant. Of all the places in the world, the acid water chose to decant into a carbonate aquifer which in itself is a formula for disaster insofar the formation of sinkholes goes, but even worse, the entire area downstream from the decant point has been declared a world heritage site (Cradle of Humankind World Heritage Site) in order to preserve its very important caves and fossil finds for future generations. Furthermore, the area immediately downstream form the mine water decant point is a game reserve and the stream flowing through it and which also conveys the mine void water across the length of the game reserve, is the only drinking water source for the animals living in the game reserve.

Although most of the water decanting from the flooded mines emerges from a old shaft, a significant amount of water daylights across a large area downstream from the decanting shaft making interception of all the water extremely difficult. A significant volume bypasses the interception structures put in place by the mines and enters the dolomite. One of the reasons that this interception is made so difficult is that the area from which the mine void water emerges is underlain by severely leached dolomite, making surface dams and interception structures almost useless.

To make things even worse, the problem only manifested itself after the productive lives of the contributing mines had lapsed and after all the profits gained from mining the gold-bearing reefs in the area had been spent elsewhere. It can be assumed with a great deal of confidence that none of the contributing mines have enough money in their environmental trust funds to properly address the matter. Although the problem was predicted many years back, it was mostly ignored and when it finally manifested, it seemingly caught everybody by surprise, the mining houses and the authorities.

Some recommendations to mitigate the problems associated with the mine void water are discussed in the next section.

9. Recommendations

The problem of intercepting the mine void water after it reaches the surface, discussed in the last paragraphs of the previous section (***Section 8***), has placed yet another challenge on the gold mining industry of the West Rand.

It was described that it is virtually impossible to intercept all the water decanting from the mine void. Furthermore, the rainy seasons experienced over 2004/2005 and 2005/2006 showed that the pumping and treatment facilities put in place by Harmony was inadequately sized to cope with the peak flow rates experienced during the average rainy seasons. At the same time, the plant and pumping facilities are under-loaded during the dry season.

There are three methods of coping with this situation.

Firstly, the pumping and treatment facilities would have to be increased in size to accommodate the greatest peak a rainy season can produce. This exercise would be extremely costly and would mean that the pumping/treatment installation would, for most of its life, be under-loaded. This option is not recommended.

Secondly, a balancing facility should be created. During the dry season, the water level in this balancing facility will be lowered in order to accommodate the higher inflow in the mine void during the following rainy season.

From a practical point of view, the upper section of the mine void itself can act as a balancing facility. In ***Section 7.1*** it is shown that this is easily achievable; all that is required is to install a pumping facility in one of the existing shafts. A spreadsheet was developed to assist the simulation of various pumping scenarios. This spreadsheet is included on the CD accompanying this report.

Thirdly, all ingress points, where rainwater gains access into the mine void, should be sealed where possible. A document prepared by van Biljon and Krige (*2005*) relating to the cost apportionment of costs for pumping and treating the mine void water showed that on each of the mining areas there are different ingress points or ingress areas. Some of them are controllable while some are not. However, a significant volume of rainwater can be prevented from entering the mine void by sealing some of the manageable ingress points. The simplest type of ingress point to seal is an open pit. If all open pits are backfilled, their surfaces shaped into a dome, the surface capped with an impervious layer and then covered with a final layer of topsoil and vegetated, these ingress points will cease to exist. This would then score points in the formula used to determine the cost to each of the mines responsible for the mine void in the first place and should become an incentive for the mines to rehabilitate these ingress points.

The next problem to be addressed is the toxicity in the water of the Zwartkrans compartment, caused by the decanting mine void water, but also attributable to the historic pumping of water over a period of almost a century. This problem was discussed in ***Sections 6.3.1*** and ***7.2***. Our report merely determines that there is a problem, but does not quantify the extent of the problem. More research is required. It is recommended that a representative number of boreholes be monitored on a regular basis across the entire area of impact for as long as it may be necessary or until it can be proven beyond any doubt that the impact from the mine no longer exists. In the meantime, where necessary, people should be warned of the hazard and provided with an alternate, clean, water supply.

In ***Section 6*** it was shown that the mine void water has and still is causing an ever-increasing void volume in the area of the Zwartkrans Compartment where the mine water first comes into contact with the dolomite. It can be assumed that sooner or later, sinkholes will appear. Apart from the obvious loss of life and property that would be associated with a sinkhole underneath a residence or business, the N14 roadway crosses the area where sinkholes are most likely to form as a result of the mine void water. This road carries a heavy traffic load between the greater Johannesburg and Botswana. The collapse of a portion of this road could have severe economic implications in addition to the potential loss of life.

In the light of the above paragraph it is recommended that the entire area under discussion be subjected to a proper geophysical examination to assess whether there are potential points of ground instability and that mitigation measures be taken timeously where these are identified.

The contamination of the groundwater in the Zwartkrans Compartment could also negatively affect other users of the water. In ***Section 6.3.3***, the effect of sulphate on concrete was discussed. There are industries using contaminated groundwater in the manufacture of pre-cast concrete beams and bricks. These items are used in the manufacture of building structures, the failure of which could have dire consequences. It is recommended that these users of groundwater are warned and that a full investigation into the matter be launched. Where necessary, users of groundwater should be provided with an alternative source of water.

Finally, historically, the Tweelopiespruit used to contain clean water decanting from the dolomitic inlier from which the mine void water is now decanting. Some flow should ideally be restored to this stream in the upper sections of the Krugersdorp Game Reserve. It will, however, not be possible to restore the entire stream, as water discharged into the stream upstream from the "graves" fountain would recharge back into the mine void if the water level were maintained below the revised ECL level. However, there should not be any problem if water is added to the stream downstream from this point provided that the water quality meets dolomitic water standards.

Before this can happen, however, the stream will have to be cleaned out as, over the period of mine void water decanting into the stream, considerable amounts of toxic sediment have accumulated in its benthic zone of the stream. Most of this sediment would be made up of ferric hydroxide, which has smothered the benthic vegetation zone. For a stream to be restored to its natural state, this sediment must first be removed. Once this has been done and provided that the water level in the mine void is always kept below the RECL level, the benthic vegetation in the stream will be restored automatically. Once this happens, the stream can be stocked with fish representing its original ichthyo-fauna population.

This study has shown how easily a karst environment in South Africa has become threatened. If no remediation measures are taken this could lead to the permanent destruction of a very important ecosystem and aquifer. This is not the only place in the country where this is occurring. Karst systems all over are under threat, be it from receiving of poor quality water, be it form overexploiting of its groundwater resources or from mining of peat often found in great quantities in karst systems. In the study area, the gold mining industry is by no means the only polluter of the water entering the karst environment. Although the two sewage plants discharge water that meets the General Effluent Standard (Government Notice No. 991 of 18 May 1984, DWAF, as amended by G.NR.1930 of 31 August 1984 and G.N.R.1864 of 15 November 1996), into the aquifer, the General Standard is just not good enough for a karst system. Nor is the Special Standard. It is recommended that a "Special Standard For Karst Catchments" be incorporated into these standards.

As part of the EIA, there are two reports being produced concurrently, the surface water report (this report) and the groundwater report. Rison Groundwater consulting is producing the groundwater report. From the first paragraphs of ***Section 8***, it is shown that there are no clear-cut dividing lines between these two disciplines, especially within this particular area. There may be areas of overlap between the two reports, but more importantly, there may be areas omitted from either report as the one author may have thought that the other would incorporate it in the other report. As an example, the surface water report does not deal with the impact the mine void water may have on the karst formations and the integrity of the caves in the Cradle of Humankind World Heritage Site. A discussion on this aspect should be included in a geology report or possibly in the groundwater report. Then again, our report discusses the mechanisms of carbonate dissolution by sulphuric acid. Although these reactions occur as a result of the surface water entering the groundwater environment, the actual damage is done within the groundwater environment.

It is therefore recommended that a knowledge gap analyses be done on all the reports produced for this EIA and that further studies and corrective action be launched to fill in these gaps.

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