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Review

The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province, South Africa

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ABSTRACT

The Witwatersrand has been subjected to geological exploration, mining activities, parallel industrial development and associated settlement patterns over the past century. The gold mines brought with them not only development, employment and wealth, but also the most devastating war in the history of South Africa, civil unrest, economical inequality, social uprooting, pollution, negative health impacts and ecological destruction. One of the most consistent and pressing problems caused by mining has been its impact on the water bodies in and adjacent to the Witwatersrand. The dewatering and rewatering of the karstic aquifer overlying and adjacent to the Witwatersrand Supergroup and the pollution caused by Acid Mine Drainage (AMD) are some of the most serious consequences of gold mining in South Africa and will affect the lives of many South Africans.

Contents

1. Introduction

The Witwatersrand, once occupied by a farming community, was transformed within a few years into the densest populated region in Southern Africa after the discovery of gold. Johannesburg was founded in 1886 after the discovery of the Main Reef. Other parts of the reef were discovered to the east and the west during the next few years and the towns of Germiston and Boksburg were established to the east of Johannesburg and Krugersdorp, Roodepoort, Randfontein and Klerksdorp were established to the west of Johannesburg. Over the next few decades further towns such as Nigel, Brakpan and Carletonville came into existence along the

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Witwatersrand. Black townships such as Orlando, Kliptown (the nuclei around which Soweto grew), Vosloorus, Katlehong and Thembisa were established on the outskirts of the major urban centres.

The settlements along the Witwatersrand initially started off to provide housing for miners. Shortly thereafter other supporting industries were established which attracted people of diverse occupations and an infrastructure was developed including roads, railway lines, telegraph, electricity, gas and water supply. Within a few months these settlements grew from mine camps to shanty towns and ultimately to municipalities where schools, hospitals and businesses opened their doors. Some of these towns grew into cities, in the case of Johannesburg, within a few decades.

The urban centres grew to such an extent that a continuous strip of habitation stretching over a hundred kilometres, from Nigel to Carletonville, was formed within a century. The residents consist of not only a cross-section of the ethnic groups of South Africa, but also people from other African countries such as Lesotho, Swaziland, Botswana, Zimbabwe, Mozambique, Malawi and Zambia.

Squatter camps sprung up in the open spaces between the towns as destitute people from rural areas and neighbouring countries flocked to the cities, and more particularly to the mines and other industries in the hope of finding work. This strip of mines and humanity is separated by farms between the mining region known as the Far West Rand which includes Carletonville and Khutsong southwest of Randfontein and the mining centre of Klerksdorp, Orkney and Stilfontein near Potchefstroom further to the west.

Avarice and opportunism rather than careful planning with an eye to long-term sustainability were the main motives behind the development of the mines and industries and the settlement patterns along the Witwatersrand. One of the first major problems that government and mining houses had to solve was the supply of water for drinking and sanitation purposes for the urban population and for the running of the industries and mines in the area. The water security situation in Gauteng and North West Province has taken a turn for the worse with the efflux over the past decade of mine effluent from the mine void on the Witwatersrand.

2. Water on the Witwatersrand

Johannesburg is one of the few major cities in the world that was not founded near a lake or a river. For the first few decades the small rivers and groundwater along the Witwatersrand were sufficient for the needs of the small but rapidly growing population, but after the Anglo-Boer War the need for additional water became more pressing. The Vaal Barrage Dam, which was an engineering feat at the time, was built in the Vaal River between 1916 and 1923 to supply the Witwatersrand, and especially Johannesburg with water (Tempelhoff, 2001).

By the 1930s the 70 Ml storage capacity of the Vaal Barrage was not enough to meet the needs of the growing population and industries on the Witwatersrand. The Vaal Dam with an original storage capacity of 994 Gl was built upstream at the confluence of the Vaal and Wilge Rivers in 1938. Due to continued population growth, the expansion of industries on the Witwatersrand and the development of the Free State gold fields after WWII, the Vaal Dam wall was raised to increase the capacity to 2330 Gl. Even after the dam wall was raised again in 1985 to increase the capacity of the dam to 3364 Gl the insatiable need for water on the Witwatersrand outstripped supply and additional water had to be piped from Lesotho into the rivers supplying the Vaal Dam by the end of the 20th Century (Turton, 2004).

The Witwatersrand Supergroup lies adjacent to the karstified dolomites of the Malmani Subgroup of the Transvaal Supergroup. The karstic aquifer contains more water than the Vaal Dam. The groundwater from this aquifer is the only reliable source of water for several towns, rural communities and farms located on the karst system that extends from the North West Province, to Gauteng, into Mpumalanga and Limpopo Province. This aquifer could also supply the population and industries of the Witwatersrand with water if it were not for the pollution of the aquifer with sewage, industrial waste and especially effluent emanating from the gold mines of the Witwatersrand.

3. The geology of the Witwatersrand and surroundings

The term Witwatersrand Supergroup was derived from the discovery and description of the auriferous outcrop on the Witwatersrand. Subsequent exploration and research proved that this sequence of gold-bearing sedimentary rocks occurs in a wide arc surrounding the Vredefort Dome and is found in Gauteng, North West and the Free State Provinces. The layers that constitute the Witwatersrand Sequence were deposited as sediments when deltas, fed by large river systems, fed into an inland sea in the Witwatersrand Basin approximately 2.8 Ga (McCarthy and Rubidge, 2005). The resulting 7500 m thick sedimentary sequence forms a syncline as it dips towards the centre of the Vredefort Dome at an angle that mostly varies between 10° and 30°, but in places such as the West Rand it may dip as much as 80° (Truswell, 1977).

The 8000 m thick Witwatersrand Supergroup is subdivided into two main divisions, the lower unit called the West Rand Group and an upper unit known as the Central Rand Group. The West Rand Group is in turn subdivided into three units: the Hospital Hill Subgroup, Government Reef Subgroup and Jeppestown Subgroup. The Central Rand Group is subdivided into the Johannesburg Subgroup and the Turffontein Subgroup. Each of these strata derived its name from the area where it was first described, but is not limited to that area. The Johannesburg Subgroup of the Central Rand Group contained the richest deposit of gold and was mined extensively throughout the Witwatersrand Basin (McCarthy and Rubidge, 2005; Viljoen and Reimold, 2002).

The 1600 m thick lavas of the Ventersdorp Supergroup, which were deposited between 2.714 and 2.665 Ga, overlie the Witwatersrand Supergroup (Schneiderhan, 2008) (Fig. 1). At the base of the Ventersdorp Supergroup, which consists mostly of a sequence of igneous rocks, a layer of sedimentary rock known as the Ventersdorp Contact Reef is found. This gold-bearing layer consists of the sediments that were deposited after the partial erosion of the Witwatersrand Supergroup.

The Transvaal Supergroup overlies the Ventersdorp Supergroup discordantly (Fig. 1). The basal layer of this sequence, called the Black Reef, consists of sedimentary rock which contains limited deposits of gold. The area occupied by the Witwatersrand Basin sediment was eroded heavily by an extensive northwards-flowing river system more than 2.2 Ga (Viljoen and Reimold, 2002). The channels formed by this river system were filled in by the sediments which consolidated into the Black Reef. The average thickness of the Black Reef varies between 1 and 10 m thick, but in the vicinity of Randfontein, it is tens of metres thick and has been mined extensively (McCarthy and Rubidge, 2005).

The Chuniespoort Group of the Transvaal Supergroup overlies the Black Reef Formation. The Chuniespoort Group consists of chemical and biochemical sediments including stromatolitic carbonates and banded ironstone. This unit which is approximately 1200–2000 m thick in Gauteng and North West Province was set down during the transgression of the Transvaal Supergroup epeiric

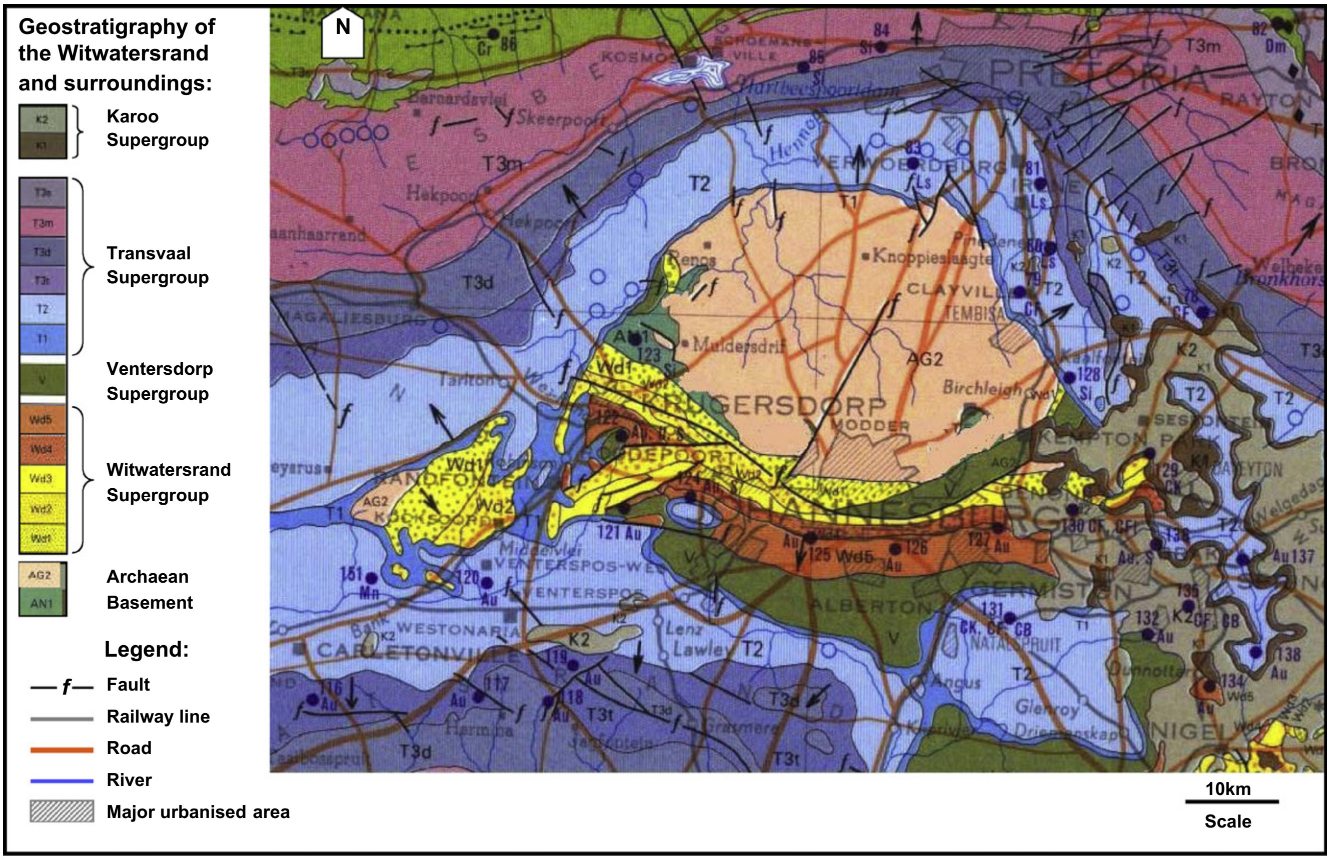

Fig. 1. Simplified geological map to show the relationship between the major geological units on the Witwatersrand and surroundings (adapted from the 1:1,000,000 Geology Map for South Africa, Lesotho and Swaziland, Geological Survey, 1970).

sea approximately 2.67–2.46 Ga (Eriksson et al., 2001). The carbonates which were set down 2.643–2.520 Ga (Obbes, 2000) are subdivided into several formations most of which were dolomitised and partially silicified (Eriksson and Reczko, 1995) (Fig. 2). The Malmani Subgroup, which occurs at the base of the Chuniespoort Group, underlies a large part of southern Gauteng and the gold mining region of North West Province.

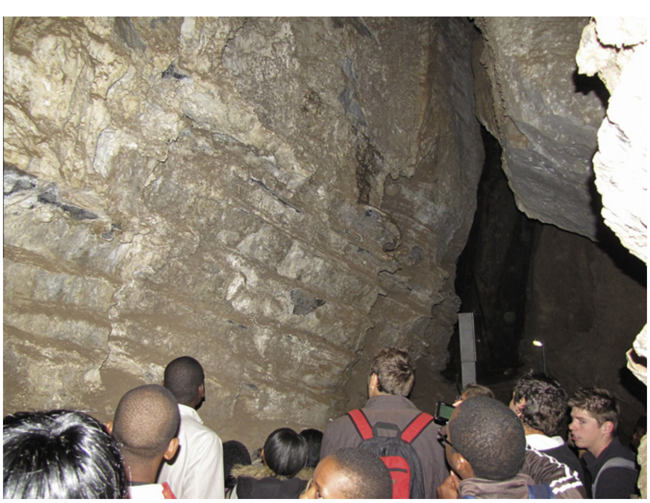

Fig. 2. The Malmani Subgroup exposed in Sterkfontein Cave, Krugersdorp showing alternating layers of dolomite and chert.

4. History of the discovery of gold in Gauteng and North West Province and the establishment of the mines on the Central Rand, West Rand and Far West Rand

Pieter Jacob Marais, the fist official gold prospector of the Transvaal Republic, discovered alluvial gold in 1853 in the Jukskei and Crocodile Rivers in the western Transvaal. Undoubtedly this gold originated from the Witwatersrand, Ventersdorp and Transvaal Supergroups. Marais, like many other prospectors at the time, focussed on the alluvial deposits in the rivers and although they crossed the Witwatersrand Supergroup often, the largest gold deposit in the world remained unknown.

An Australian prospector by the name of Henry Lewis discovered gold-bearing rocks in December 1874, at Blaauwbank in the western part of the Transvaal Republic, now known as the North West Province. The Nil Desperandum Co-operative Quartz Company was floated by Robert Green the following year to mine these deposits and explore for more gold deposits further afield. The town of Magaliesburg was later established adjacent to the mine. This was the first gold mine to be operational in the Witwatersrand region. Although the gold deposit was rich, the extent of the gold-bearing quartz reefs, which form part of the Timeball Hill Formation, were limited, and by 1877 the mine was closed down (Truswell, 1977).

In 1877 the British Empire annexed the Transvaal. The new government was anxious to explore the gold reserves of the country and Alfred Watson Armfield was appointed as "Inspector of Goldfields". Neither Armfield, nor subsequent government-funded prospecting companies could find gold in the Witwatersrand region.

The next most significant discovery of gold took place when David Wardrop discovered gold-bearing quartz veins belonging to the Black Reef Group at Zwartkop north of the Witwatersrand Ridge in 1878. The gold deposit at Zwartkop is situated approximately 10 km to the north of the main geological sequence constituting the Transvaal Supergroup containing the Black Reef Group. This anomaly was caused when a portion of the Witwatersrand and Transvaal Supergroups separated due to faulting from the main sequence and was subsequently displaced to the north.

This discovery, together with others in the vicinity at the time, yielded no economically viable deposits that could be mined. Prospectors found traces of gold which eroded from this portion of the Black Reef in the Bloubankspruit (*spruit* = stream), which led to an intensive search for the mother lode. Prospectors initially thought the gold originated in the Orange Grove Quartzites, because of the thick layers of quartz present in this formation. Although it forms the basal layer of the Witwatersrand Supergroup and contains quartz, it is virtually devoid of gold. This erosion-resistant formation forms the prominent ridge or "rand" in Afrikaans, from which the name Witwatersrand was derived. Several shafts and tunnels in the Orange Grove Quartzites north of Krugersdorp testify to this search, which was funded by the Geldenhuis family, who farmed in the region (Fig. 3).

Eventually the source of the alluvial gold was traced by Stephanus Minnaar to the farm Kromdraai in 1881. The concession for Kromdraai Gold Mine was appointed by the ZAR to Stephanus Minnaar and Jan Gerritse Bandjes, who operated the mine until 1884 (Fig. 4). The concession was taken over by Henry Norse, who erected stamp mills for the crushing of the ore and had the mine proclaimed as a public digging in 1885. The Kromdraai Mine was the second, after Blaauwbank Mine, to be operational close to the Main Reef of the Witwatersrand Supergroup (Viljoen and Reimold, 2002).

The prospectors Fred and Harry Struben made the first discovery of gold-bearing Witwatersrand Supergroup rocks in January 1884 on the farm Sterkfontein near Kromdraai. They discovered gold-bearing conglomerates on the farm Groot Paardekraal, to the south of Sterkfontein, in the same year. These deposits were however not economically viable and were abandoned.

Fred Struben discovered a rich gold-bearing reef on the Wilgespruit River in September 1884 to the north of the Witwatersrand Ridge, which he named Confidence Reef. The Struben brothers decided to mine this reef, which forms part of the Witwatersrand Supergroup, and erected a stamp mill on the site in 1885. This site delivered disappointing results and was abandoned shortly after.

Fig. 3. Entrance to prospectors' tunnels in the Orange Grove Quartzite near Krugersdorp.

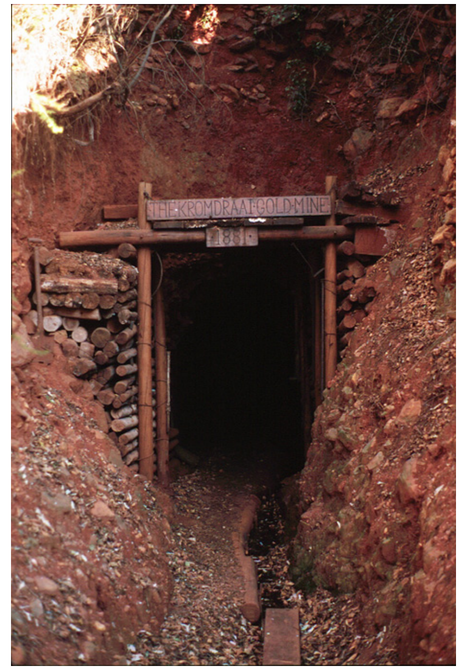

Fig. 4. Entrance to Kromdraai Gold Mine, Krugersdorp.

The gold miners George Walker and George Harrison stayed over on the Witwatersrand, en route to Barberton. Walker was in the employ of the Strubens and Harrison was building a house for Willem Oosthuizen on the farm Langlaagte. Although there is some controversy as to which of the two miners discovered the Main Reef, it is now generally accepted that George Harrison discovered the gold-bearing conglomerate, which turned out to be the richest and most extensive gold deposit in the world, on the farm Langlaagte in February 1886. George Harrison received a reward and was awarded discoverer's rights from the Transvaal government, while Walker received two claims on Langlaagte from G.C. Oosthuizen (Mendelsohn and Potgieter, 1986).

During subsequent exploration the Main Reef was traced by Jan Bandjes and Fred Struben to the farm Vogelstruisfontein, by Henry Nourse to the farm Doornfontein, by Dirk Geldenhuis to the farm Turffontein, by the Strubens brothers to the farm Elandsfontein, by P.J. Kilian to the farm Leeuwpoort and by Adolf Vogel to the farm Vogelfontein.

In September 1886, a few months after the initial discovery of the Main Reef, nine farms from Vogelfontein in the east to Roodepoort in the west were proclaimed as public diggings. These farms were Elandsfontein, Driefontein, Doornfontein, Turffontein, Randjieslaagte, Langlaagte, Paardekraal, Vogelstuisfontein and Roodepoort, forming the main focus of the gold industry that would become known as the Central Rand. Shortly thereafter, in March 1887 Leeuwpoort and Vogelfontein to the east of Elandsfontein were also proclaimed as public diggings (Viljoen and Reimold, 2002).

In September 1886, the town of Johannesburg was established on the triangular shaped farm Randjieslaagte, situated between the farms Doornfontein, Braamfontein and Turffontein, to house the thousands of people who converged on the newly discovered gold reef. Many of these mine workers came from the almost depleted goldfields of the eastern part of the Transvaal Republic, now known as Mpumalanga. The majority of these mine workers were of European, mainly British origin, laying the foundation of political dissidence which would eventually culminate in the Jameson Raid and the Anglo-Boer War.

The town of Roodepoort grew from a camp which housed miners working on the farms Roodepoort and the adjacent farms Wilgespruit to the north and Maraisburg and Florida to the east. The first stands in Roodepoort were sold in February 1887. Krugersdorp, named in honour of President Paul Kruger, was founded in April 1887 on the farm Paardekraal. This town originally served as the central administrative centre for the Witwatersrand gold fields. Germiston was originally established as a mine town to house the workers employed by the Simmer and Jack Gold Mining Company on the farm Elandsfontein in May 1887. Boksburg, named after Eduard Bok, the Attorney-General of the Transvaal Republic, was established on the adjoining farms Leeuwpoort and Vogelfontein that same year (Mendelsohn and Potgieter, 1986).

The ox-wagon trail connecting the diggings along the Witwatersrand became the Main Reef Road. This road, which is one of the main connecting routes running from the East Rand to the West Rand, was the artery around which townships, central business districts, industries and mines grew. The urban topography bisected by the Main Reef Road is striking – the majority of the high-rise buildings of Johannesburg and other cities along the Witwatersrand rise to the north of the Main Reef Road while small industries and townships dominate the region south the road. This phenomenon is due to the fact that the area south of Main Reef Road is literally undermined by mine tunnels and stopes which implies that tall or heavy buildings would collapse if the supporting substrate caved in. The original diggings along the Central Rand were established where the Main Reef outcrops. The miners followed the reef which dips at an angle of 10–30° to the south, creating in the process stopes supported by pillars, some of which can still be seen in George Harrison Park (Mendelsohn and Potgieter, 1986).

An example of this threat can be witnessed in the basement of the Standard Bank Building in Simmonds Street where some of the old mine tunnels of the Ferreira Mine had to be backfilled with concrete to stabilise the foundations of the structure that was built on top of it (Viljoen and Reimold, 2002).

Soon after commercial mining of the Witwatersrand commenced in 1887, it became clear that it was not a venture that could be successfully undertaken by individual miners or small companies as in Barberton and Pilgrim's Rest, due to the nature of the gold ore. Whereas gold occurred as alluvial deposits and nuggets in Mpumalanga, the gold of the Witwatersrand was more difficult to extract and called for special crushing equipment and chemical extraction processes. Mining companies, specialised industries and an organised work force were established to meet this challenge. In addition, the infrastructure to handle the people, ore and goods, which included roads, railways, buildings and water supply, had to be financed.

Financiers such as Joseph Benjamin Robinson, William Knight, George Goch, Hans Sauer, Cecil John Rhodes and Charles Dunell Rudd arrived on the Witwatersrand after the discovery of the Main Reef. Much of the money invested in the development of the Witwatersrand originated from capital generated from the Kimberley diamond fields (Mendelsohn and Potgieter, 1986).

William Knight registered the first mining company on the Witwatersrand, the Witwatersrand Gold Mining Company, in September 1886. Goch founded the George Goch Gold Mining Company in 1886 and the Wemmer Gold Mining Company in 1887. Rudd and Rhodes floated the company Gold Fields of South Africa Limited on 9 February 1887. Robinson registered the Randfontein Estates Gold Mining Company in April 1887. This operation, which was started with a £2 million investment and employed 20,000 mine workers, was the largest mining operation on the Witwatersrand at the time. Alfred Beit, Hermann Eckstein and Lionel Phillips established Rand Mines Limited in 1888.

By the end of 1887 there were 68 registered gold mining companies on the Witwatersrand. As with Kimberley it was time for takeovers, consolidation and centralisation. Gold Fields of South Africa Limited was amalgamated with other smaller companies into the Consolidated Gold Fields of South Africa Limited in 1892. Robinson sold his shares in Randfontein Estates Gold Mining Company, worth £250,000, to the Wernher–Beit Company, which was an affiliate of the De Beers group and the forerunner of Rand Mines.

Seven mining companies, including the Robinson Mine and the original Crown Mine were amalgamated into Crown Mines Limited on 1 July 1909 which became the largest gold producer in the world. When mining ceased in 1977 it had over 1600 km of underground tunnels and stopes, some which were more than 3 km below the surface and extended over a surface area of more than 42 km^2. This mining company which employed nearly 28,000 people at its peak, yielded over 1400 tons of gold in its lifetime. The no. 14 shaft of Crown Mines is a historical landmark today and forms part of the open air museum at Gold Reef City (Viljoen and Reimold, 2002).

As the larger mining companies were cannibalising smaller ones, the mining strategies changed from small-scale pick and shovel operations to industrialised processes aided by more sophisticated technology. The focus shifted from opencast and shallow pit mining methods to underground mining as new techniques had to be developed to access the rich gold deposits that extended far underground.

The Jubilee Gold Mining Company sank the first shallow shafts into the Witwatersrand Supergroup in 1887. J.B. Robinson sank five shafts on the farm Langlaagte to access the Main Reef and in so doing, laid the foundation of modern deep mining – one of these shafts was over 30 m underground and was connected to the others by means of side tunnels. J.S. Curtis sank the first deep exploration borehole for the Village Main Reef Mine in 1890 which intersected with the Main Reef at a depth of 177 m. The Turffontein East borehole, drilled in 1901, intersected the Main Reef at a depth of almost 1.5 km below the surface, 2.5 km south of the outcrop (Mendelsohn and Potgieter, 1986).

Deep mining implies that the gold-bearing reefs are mined out, leaving concrete, wood and natural rock pillars to support the roof, or hanging wall. The sections following the reef that are mined out are called stopes. The stopes are connected via incline and vertical shafts. This mining technique has been perfected on the South African gold fields and is still the proven way to extract gold. Western Deep Levels Gold Mine near Carletonville, which currently has tunnels 4 km underground, is the deepest mine in the world and there are plans to extend this mine to more than 5 km underground.

After it was established that the Main Reef was consistently present underground, albeit at great depths, and had a predictably high yield of gold, the major gold mining companies, headed by Eckstein's Corner House and Rhodes's Gold Fields of South Africa, started buying up large tracts of land to the south of the Main Reef outcrop.

The nature of the ore changed, the deeper it occurred beneath the surface. The original gold extraction process of amalgamation proved to become progressively less effective and more costly, the deeper the ore was mined underground. A team of Scottish chemists invented the MacArthur-Forrest cyanidation process in 1890, by means of which gold is extracted from the crushed ore by means of solution by cyanide. This process was first employed by the Robinson mine and thereafter by the rest of the mines on the Witwatersrand, and it remains the main extraction process of gold today.

By 1895 there were 2870 stamps crushing ore along the Witwatersrand, of which eight mines had more than 100 stamps each, producing approximately 25% of the world's gold. By 1913 the three largest gold mines in the world were Crown Mines, ERPM and Randfontein Central, together producing approximately 10% of all the gold in the world. In 1922 the Rand Refinery became operational in Germiston. It remains the largest gold refinery in the world (Mendelsohn and Potgieter, 1986).

The first discovery of radioactive metals in the gold-bearing conglomerates of the Witwatersrand occurred in 1915, during the First World War. A pilot uranium oxide extraction plant was built in 1949 at Blyvooruitzicht, followed by the uranium extraction plant at West Rand Consolidated Mines Limited in 1952. This plant, which was the first in the world to produce uranium commercially, was developed as the strategic importance of nuclear weapons and the economical advantages of nuclear-driven power stations became clear.

Many mines reached their operational limits during the previous century and had to close down. These include Cinderella, Spes Bona, Jumpers and Treasury Mines which closed in 1913. On the Witwatersrand many mines including Van Ryn, Wes Vlakfontein, Langlaagte Estate, Modderfontein Deep Levels, New State Areas, Modder B, Nigel and Welgedacht Exploration closed down. Several mines, many of which were operational in the East Rand, closed down in the 1960s including the Government Areas, Springs, Brakpan, Simmer and Jack, East Champ d'Or, Robinson Deep, New Kleinfontein, Van Dyk Consolidated, Spaarwater and Vogelstruisbult Mines. After World War II East Daggafontein, Venterspost, Western Reefs, Vlakfontein and Blyvooruitzicht opened along the Witwatersrand. More mines opened along the periphery of the Witwatersrand Supergroup in the 1950s particularly in the Free State, Far West Rand and Evander as the gold deposits of the Central Rand were depleted or production costs became too high (Mendelsohn and Potgieter, 1986).

The increase in the price of gold has motivated companies over the past three decades to develop more advanced gold extraction processes to extract the traces of gold that remained in the old mine dumps. Carbon-in-leach or carbon-in-pulp plants were erected by East Rand Gold Operations, Anglo American and Crown Gold Recoveries for the processing of old mine dumps. The process involves liquidising the sand or slimes, then the pumping of the resulting slurry to the plant for the extraction of the gold.

Although the Witwatersrand Supergroup is exposed mainly in the southern part of Gauteng and North West Province, economically viable parts of it were also discovered in the Free State in 1946. The towns of Welkom and Virginia were established near Odendaalsrus to house the growing mining community in that region.

5. Dewatering and rewatering of the karst aquifer

It is noticeable that the names of many of the farms on the Central and West Rand have been derived from the word "fontein", the Afrikaans word for fountain or spring – eg. Vogelfontein, Elandsfontein, Driefontein, Doornfontein, Turffontein and Vogelstuisfontein, and then there is of course the town Springs. This is due to the proximity of the Witwatersrand Supergroup to the karstic dolomite-rich Transvaal Supergroup. Groundwater issues from the karst along the length of the Witwatersrand, from which the name "White Water Ridge" was derived. Groundwater was the mainstay of small farms along the Witwatersrand, but was not sufficient to supply the growing population, industries and mines with water.

The logistical problems increased as the depth of gold mines increased. There were problems in supplying the miners with air, the cooling of the operational tunnels and especially the pumping of water that flooded the mines. The Witwatersrand gold mines have to be dewatered constantly to allow mining due to the proximity of the dolomites of the Malmani Subgroup (Morgan and Brink, 1984; Warwick et al., 1987). The dolomites of the younger Transvaal Supergroup overlie the gold-bearing Ventersdorp Supergroup and Witwatersrand Supergroup, with the result that many of the gold mines on the Central and West Rand are situated beneath karst aquifers which flood the mines continuously. When the gold mines on the East Rand, Central Rand, West Rand and Far West Rand were operational, millions of litres of water was pumped from the mine void daily.

The first reports of the ingress of water into the mines date back to the beginning of the previous century (O'Flaherty, 1903). Although the gold mines on the Witwatersrand started off as separate entities, the tunnels and stopes of adjacent mines met up eventually, either directly or via cracks and fissures in the rock. In so doing a continuous mine void extending from the East Rand to the West Rand was formed over time. Originally, mines were responsible for their own dewatering, but as the mines were worked out and were abandoned, dewatering of the mine void became the responsibility of fewer and fewer mines. The state became involved by subsidising the pumping costs when it became too expensive for the remaining mines (Scott, 1995).

Groundwater levels were maintained on the East Rand until 1991 by the extraction of water from the mine void at Sallies No.1 Shaft and Grootvlei Nos. 3 and 4 Shafts at 64.5 Ml per day. The groundwater level on the Central Rand has been maintained since 1990 through the extraction of water from the mine void at Hercules Shaft at ERPM Mine, SW Vertical Shaft servicing the central mines (CMR to Simmer and Jack) and from Rose Deep and DRD mines. Almost 36 Ml per day was pumped from the Central Rand mines in the 1990s (Scott, 1995). At the peak of mining activities the Harmony Gold Mine on the West Rand pumped an average of 32 Ml of water daily from its Randfontein Operations into the Tweelopiespruit and Wonderfonteinspruit (Krige and Van Biljon, 2010).

The large scale abstraction of water by the mines caused a drop in the water tables in and adjacent to the mining region with the result that the springs which inspired the name Witwatersrand dried up (Enslin et al., 1996, Dreybrodt, 1996). The drop in the water table also caused surface subsidence, especially in the North West Province from the 1960s onwards (Kleywegt and Pike, 1982). Surface subsidence manifested as sinkholes and dolines, some of them more than 100 m in diameter, appearing over a wide area (Swart et al., 2003).

The rewatering of the dolomites also contributes to karstification. Some sinkholes that formed during the dewatering of the dolomites were reactivated, while new ones formed when the water table returned to its original pre-mining level (Beukes, 1987). The recharge rate of the groundwater is also accelerated by the swallow holes and sinkholes which formed during dewatering. Surface water run-off flows into sinkholes and swallow holes such as those in the stream bed of the Lower Wonderfonteinspruit (Swart et al., 2003).

The dewatering of the mines also interferes with the natural flow of groundwater (Enslin et al., 1976; Dreybrodt, 1996). The flow of groundwater in the karst system in Gauteng and North West Province was primarily in a westerly direction before the 20th Century. Decantation of the groundwater originally took place over the dykes forming the boundaries of the dolomitic compartments, as a series of springs. The flow from most of these springs decreased and many dried up after the dewatering of four of the karst compartments associated with the Witwatersrand Supergroup. The perforation by mining activities of the north-south syenite dykes that partitioned the karst aquifer into compartments

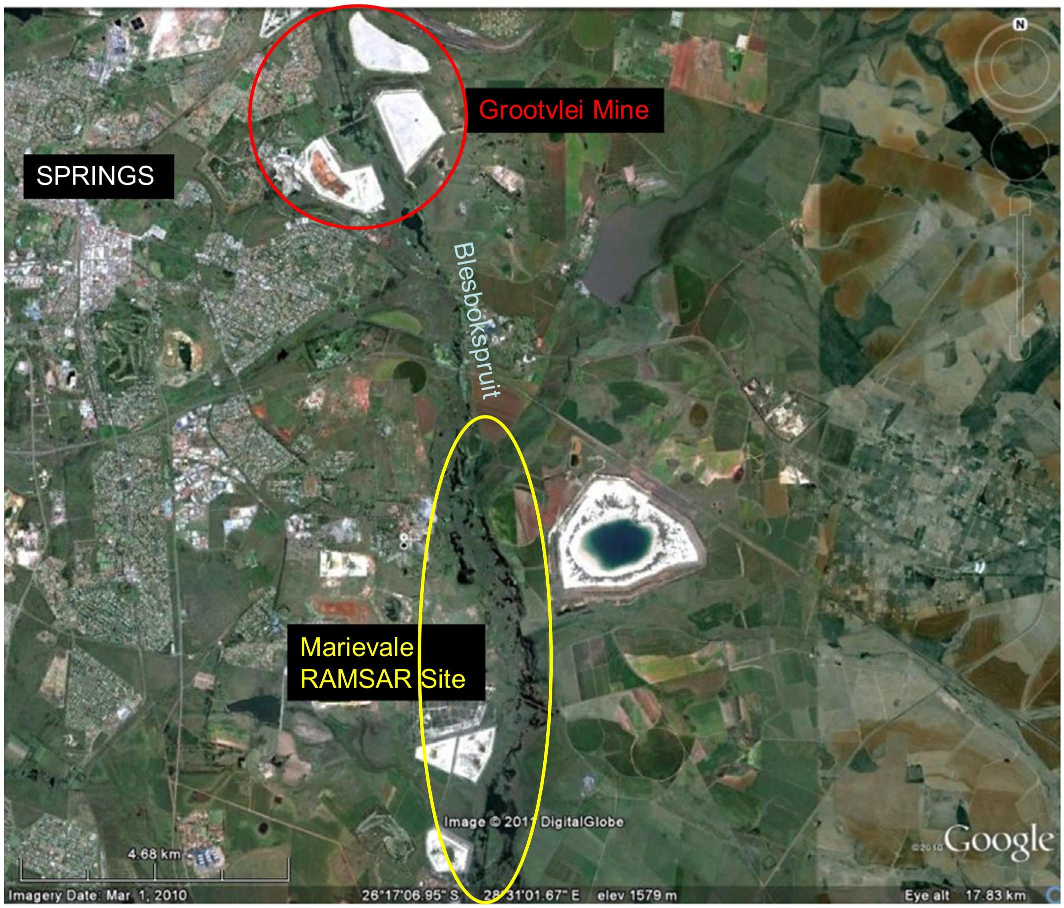

Fig. 5. Marievale RAMSAR Site, downstream of Grootvlei Mine, Springs (East Rand).

further interfered with the natural flow of groundwater in Gauteng and North West Province (Swart et al., 2003).

Stream flow and groundwater recharge are altered due to the discharge of particle-rich effluent which is voided together with the discharge of water from the gold mines. This mine sediment causes flooding and clogging of surface streams, the clogging of aquifers responsible for the recharge of groundwater and the altering of wetlands. The massive discharge of groundwater into surface streams such as the Wonderfonteinspruit, Tweelopiespruit, Klip River, Blesbokspruit, Rietspruit, Suikerbosrand River, Mooi River and many others altered the nature of these water courses. In many cases non-perennial streams were turned into sizable rivers or permanent swamps containing mine effluent.

An example which illustrates this situation is the Blesbokspruit on the East Rand, which was a meandering non-perennial stream without reeds. The release of megalitres of water from the neighbouring mine, industries and sewage plant, in conjunction with the construction of roads and embankments across the stream, dammed the flow and turned it into a permanent wetland with reeds (Fig. 5). This area was declared a RAMSAR site due to the bird life that flourished in the newly formed wetland. Unfortunately, due to the accumulation of pollutants in the discharge from the mine, industries and sewage works in addition to the run-off from tailings and slimes dams in the vicinity, the site was placed on the Montreux Record in July 1996 (DEA, 1998).

6. Acid Mine Drainage (AMD)

The US Environmental Protection Agency recognised already in 1987 that "...problems related to mining waste may be rated as second only to global warming and stratospheric ozone depletion in terms of ecological risk. The release to the environment of mining waste can result in profound, generally irreversible destruction of ecosystems."

Gold occurs in the Witwatersrand Supergroup in association with pyrite (FeS_2) (Fig. 6). Pyrite, which may constitute up to 3% of the gold bearing reefs, and other sulphates remain stable underground, but produce iron hydroxide and sulphuric acid when exposed to water and oxygen ($4FeS_2 + 15O_2 + 14H_2O = 4Fe(OH)_3 + 8H_2SO_4$) (Scott, 1995). This acidic solution dissolves the surrounding ore in the flooded parts of the mine, slimes dumps and rock

Fig. 6. Gold ore containing pyrite from the Witwatersrand Supergroup.

piles, releasing the metals it contains, which may include manganese, aluminium, iron, nickel, zinc, cobalt, copper, lead, radium, thorium and uranium (Kleywegt, 1977; Jones et al., 1988; Venter, 1995; Scott, 1995; Naicker et al., 2003).

The effluent produced by Acid Mine Drainage (AMD) enters the surface water bodies and the groundwater and poses a threat to humans, domesticated animals and ecosystems alike. Many of the slimes and holding dams along the Witwatersrand and Far West Rand were purposefully built on the dolomites because it was observed that this practice resulted in more structurally stable dams and minimised collapses. The reason for this structural stability was because the water drained directly into the karst system below, resulting in a drier, more stable slimes dam above (Fig. 7). The groundwater in the karst system in Gauteng and North West Province could have provided an additional water supply to the region as demand for drinking water in the region grows. Unfortunately, due to the whole-scale pollution of the groundwater in these regions with AMD, this may not be possible.

The efflux of AMD from the Eastern Basin Mine Void was predicted as early as 1995 (Scott, 1995), while that of the Western Basin Mine Void was predicted in 1996, but largely ignored (Krige and Van Biljon, 2010). The threat of AMD has worsened over the past decade as the situation regarding the release of mine effluent from the gold mines in Gauteng and North West has been deteriorating. Most of the mines on the East Rand, Central Rand and West Rand have been closed down, leaving only three productive mines on the West Rand and Far West Rand.

The pumping of water from the gold mines on the Witwatersrand over the past century caused the dewatering of overlying dolomitic compartments and the surrounding rock formations up to depths of three kilometres underground. The water table slowly returned to its original level as the daily pumping of many megalitres of water ceased in 1998 and the mines beneath Krugersdorp and Randfontein started to flood. The combined void created by the mine tunnels and stopes of Randfontein Estates Ltd., West Rand Consolidated Mines Ltd., Luipaardsvlei Ltd. and the East Champ D'Or mines, known collectively as the Western Basin Mine Void, constitute 45 Gl (Krige, 2006). Springs originally fed by the groundwater started flowing again after a century, but this time it was not water that issued from them but an effluent containing a toxic and radioactive concoction of sulphuric acid, sulphates and heavy metals.

The first decantation from the flooded gold mines in Krugersdorp and Randfontein was recorded in August 2002, when AMD started to issue from boreholes and an old shaft of Harmony Gold Mine (Pty) Ltd. (Randfontein Operations) into the Tweelopiespruit in the Krugersdorp Nature Reserve. Subsequently two dry springs also started to issue AMD into the Tweelopiespruit. Mine effluent is already issuing from the 15 active and 29 closed mines to the north of the Vaal Barrage (Fig. 8).

The water treatment plant at Harmony Gold Mine was designed to partially treat 15 Ml of water per day by elevating the pH before it was released into the Tweelopiespruit. Several attempts were made to treat the mine effluent including the filtering of part of the mine effluent through a product called *Supasorb*, a cedar needle compost packed in burlap bags, and the filtration of the water through lime pebble beds (Fig. 9). The increase of mine effluent emanating on the mine grounds due to higher rainfall and the cessation of pumping at Harmony Gold Mine overran the capacity of the treatment plants and untreated mine effluent of approximately 36 Ml per day is presently entering the Tweelopiespruit. During periods of high rainfall this may increase to approximately 80 Ml per day. The effluent enters the Tweelopiespruit wetland on the mine grounds via surface seeps while megalitres of water decant from the old Black Reef shaft. An unqualified volume of water is entering the groundwater of the Zwartkrans dolomitic aquifer below the mine area (Fourie 2006, Hobbs and Cobbing, 2007).

The AMD-affected mine effluent emanating from the mines on the East and Central Rand drains into rivers such as the Blesbokspruit, Rietspruit, Elsburgspruit and Natalspruit flowing into the Vaal River to the south (Scott, 1995; Naicker et al, 2003). Due to the fact that the West Rand mines were built on the continental water divide, the effluent emanating from these mines affects both the Vaal River to the south and the tributaries of the Limpopo River to the north (Coetzee et al., 2006; Hobbs and Cobbing 2007). The efflux of AMD is considered to be an enormous threat if remediation is not implemented. The potential volume of mine effluent which may emanate from the Witwatersrand Goldfield alone is estimated at approximately 350 Ml per day (Manders, 2009).

The structural stability of the dolomitic region in Gauteng and North West is threatened by the sulphuric acid contained in AMD. Dolomite and limestone are highly soluble in acid, posing the threat of excessive karstification in this area with the formation of subterranean cavities in the dolomite. As the water containing AMD flows through the karstic aquifers in the dolomites, fissures may widen and sinkholes and dolines may result when the surface collapses into the void below (Hodgson et al., 2001; Swart et al., 2003; Krige, 2006).

Fig. 7. Irrigation of crops using water from a dolomitic aquifer covered by Cooke Slimes Dam (West Rand) seen in the background.

Fig. 8. Mine effluent issuing from a mine shaft on the West Rand.

Fig. 9. The defunct water treatment plant at Harmony Gold Mine, Randfontein.

7. Sulphates

The salinity of river systems that receive mine effluent is greatly affected by the volumes of sulphates contained in the effluent. The mine effluent discharged from the Witwatersrand mines to the south of the watershed accounts for only 5% of the volume of water in the Vaal River but it accounts for 20% of the salts entering the system (DWAF, 2009).

Sulphate salts form when sulphuric acid reacts with the alkaline dolomite and limestone in the region. AMD is often treated with limestone in order to push up the pH of the effluent to make it more acceptable to consumers downstream. However, the resulting water, although closer to neutral than untreated water, contains high levels of sulphates and metals.

Besides the ingestion of other toxins in AMD-polluted water, the ingestion of sulphates in itself is dangerous. Consumption of sulphates in excess of 200 mg/l by humans may lead to vomiting and diarrhoea in sensitive individuals. Sulphates in excess of 600 mg/l will lead to vomiting and diarrhoea in most individuals. This is especially the case when sulphate forms a bond with a cation such as magnesium, which is present in high quantities in areas where AMD dissolves the dolomite of the karst system. In 2005, the mine effluent that decanted from Harmony Gold's Randfontein Operations contained 4500 mg/l sulphates (Fourie, 2005), while Robinson Lake which is used as a holding dam by Harmony Gold Mine in Randfontein contained 5055 mg/l sulphates in 2007.

Plants are generally sensitive to excessive amounts of salt in the soil. The plants growing along the riparian zone are exposed to high levels of sulphates and are replaced by the pollution-resistant reed *Phragmites*. The decimation of plant life around water bodies that contain high levels of sulphate is obvious in places such as Robinson Lake in Randfontein on the West Rand (Fig. 10). The rocks, soil and plants on the river banks affected by mine effluent are often encrusted with sulphate salts (Fig. 11). The water in the Zwartkrans dolomitic compartment contains sulphate concentrations of over

Fig. 10. Robinson Lake in Randfontein, the source of the Tweelopiespruit, note the absence of riparian plants.

150 mg/l due to the AMD pollution emanating from Harmony Gold's Randfontein Operations (Bredenkamp and Xu, 2003, Krige and Van Biljon, 2010) (Fig. 12). Similar results were reported by Hobbs and Cobbing (2007).

Fig. 11. Sulphate salts encrusting the rocks and soil adjacent to the Tweelopiespruit.

8. Metals

Metals enter the river systems through the run-off from slimes dams and rock dumps and from the mine void via seeps and decanting. It also enters the groundwater by means of seepage of rainwater through mine dumps and the decanting of mine effluent from the slimes dams into the groundwater (Kleywegt, 1977; Jones et al., 1988; Naicker et al., 2003). AMD containing metals can also seep through swallow holes and cracks in the dolomites linking the surface run-off to the water table, and directly from the mine void into the karst system above as the groundwater level rises (Swart et al., 2003).

The AMD issuing from the gold mines in Gauteng and West Rand contains high concentrations of metals such as manganese, aluminium, iron, nickel, zinc, cobalt, copper, lead, radium, thorium and uranium (Venter, 1995; Coetzee et al., 2006). Depending on the concentration of the metal and the duration of exposure to the metal, exposure to any of these metals may be fatal to organisms, including humans (Smith and Heath, 1979; Venter, 1995; Adendorff, 1997; Jooste and Thirion, 1999).

The levels of aluminium, cobalt and nickel in the Tweelopiespruit/Rietspruit/Bloubankspruit system are far higher than those accepted in water quality regulations. The maximum concentration of aluminium in drinking water has been set in the South African Water Quality Guidelines at <0.5 mg/l (DWAF, 2006a). Neither the South African Water Quality Guidelines, nor

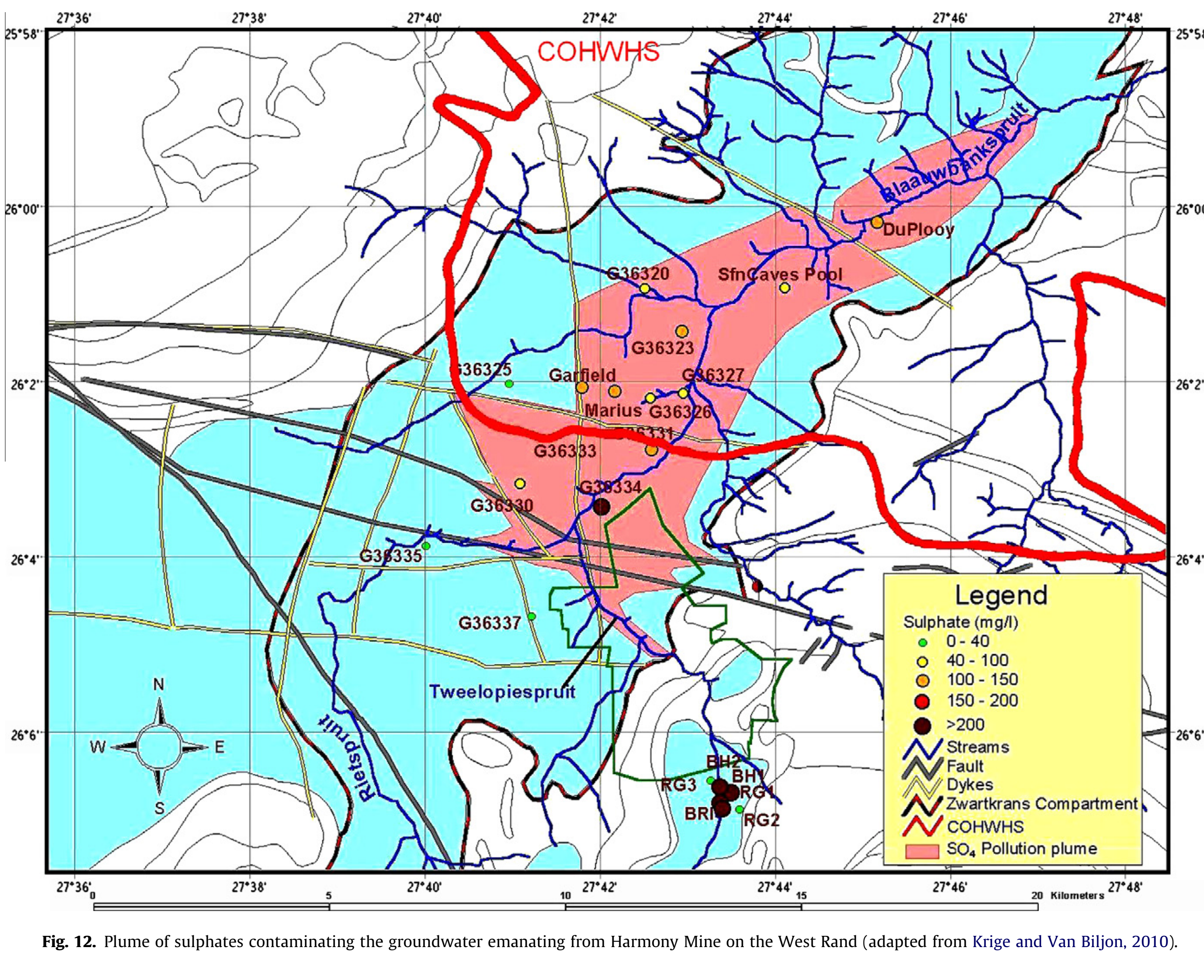

Fig. 12. Plume of sulphates contaminating the groundwater emanating from Harmony Mine on the West Rand (adapted from Krige and Van Biljon, 2010).

Table 1
Values of pH and metals sampled in the Tweelopiespruit/Rietspruit/Bloubankspruit river system on 2011-02-26 (values of metals indicated as ppm).

Sample site	pH	Al	Ca	Co	Fe	Mg	Mn	Ni	U	Zn
1.	7.6	0.100	61	<0.025	0.510	30	2.80	0.090	<.001	<0.025
2.	7.3	0.100	63	0.060	1.01	33	5.29	0.110	<.001	<0.025
3.	3.6	0.680	124	0.230	51	57	16	0.420	0.007	0.160
4.	3.0	0.610	140	0.280	70	51	17	0.500	0.008	0.150
5.	2.6	1.60	367	0.980	233	158	60	1.69	0.024	0.410
6.	2.6	2.51	497	1.37	438	237	92	2.47	0.036	0.600

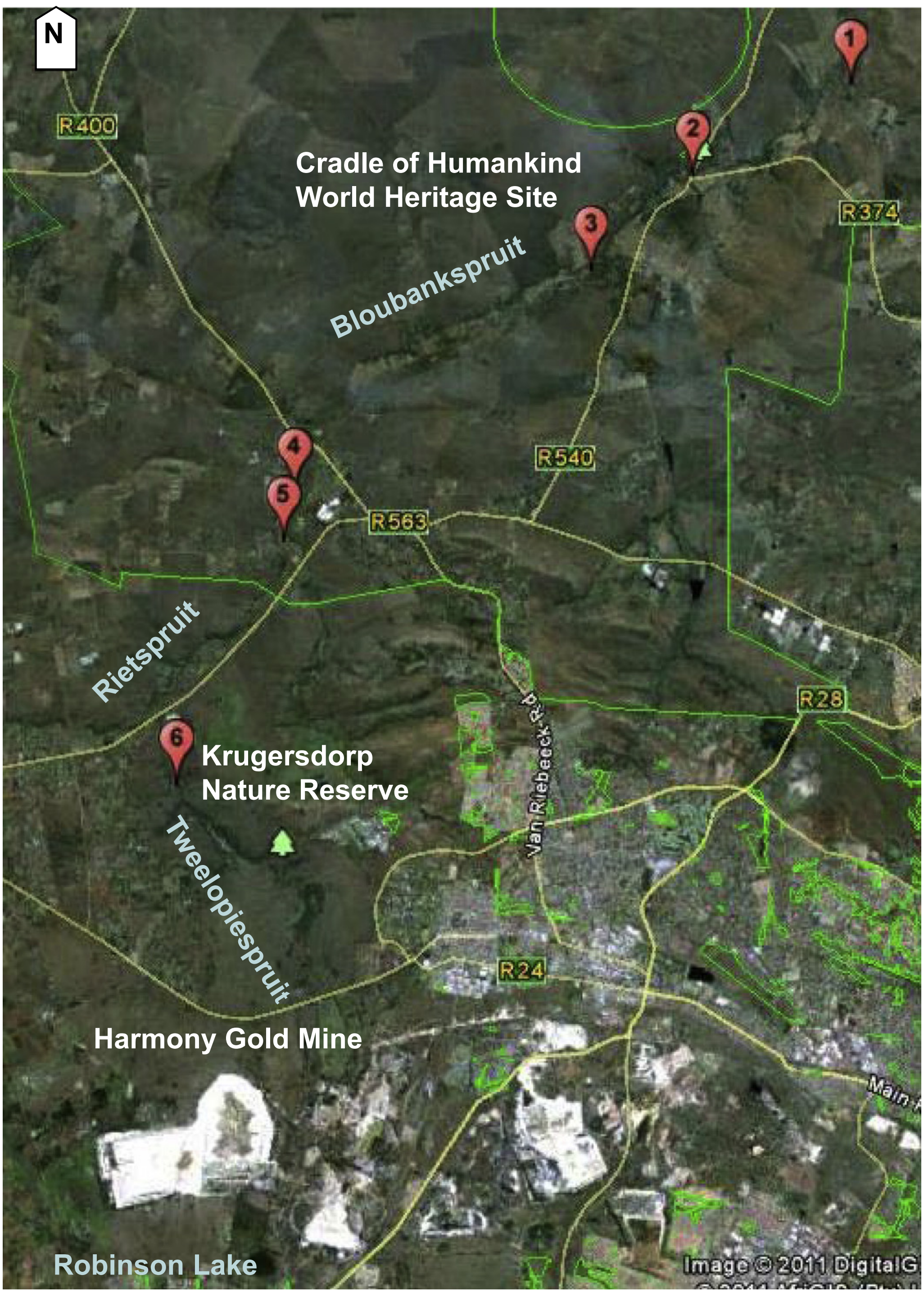

Fig. 13. Metal sampling points in the Tweelopiespruit/Rietspruit/Bloubankspruit river system (2011-02-26).

the World Health Organisation has determined the acceptable levels of cobalt in potable water. However, the US Environmental Protection Agency however sets the maximum level of cobalt at 40 μg/l (US EPA, 2007). The World Health Organisation sets the maximum for nickel in drinking water at 70 μg/l (WHO, 2005). The levels of zinc in the Tweelopiespruit and Rietspruit exceed the accepted maximum levels of zinc at 0–3 mg/l and will cause acute toxicity with gastrointestinal irritation causing nausea and vomiting if ingested.

High levels of calcium, magnesium and iron have been measured in the Tweelopiespruit/Rietspruit/Bloubankspruit system (Table 1, Fig. 13). The amount of calcium, magnesium and sulphates which are released into the rivers and groundwater indicates the rate of dissolution of the dolomites by AMD containing sulphuric acid. The South African Water Quality Standards set the maximum levels of iron at 1–10 mg/l for sensitive individuals such as children (DWAF, 2006a). The iron levels of the Tweelopiespruit and Rietspruit will cause acute toxicity, while chronic toxicity may occur if water from the Bloubankspruit is ingested.

Metals are absorbed after exposure or ingestion in different parts of the bodies of organisms that are exposed to it. Metals that accumulate in the tissues vary from species to species. In general, iron, zinc, nickel, copper, manganese and lead are absorbed by freshwater organisms (Adendorff, 1997). The rates of accumulation and toxicity of these metals are determined by the salinity, acidity and hardness of the water (Moore and Ramamoorthy, 1984). The absorption of metals may cause necrosis, tumours, cancer and general impairment of the digestive system, cardiovascular system and urogenital system of vertebrates (Venter, 1995; Adendorff, 1997; Jooste and Thirion, 1999). Even at low concentrations, heavy metals may have an endocrine-disrupting effect on organisms (Konietzka et al., 2005).

9. Radioactivity

The Witwatersrand Supergroup contains more uranium than gold and the Witwatersrand gold mines are in fact also uranium mines. Uranium was originally mined as a by-product of the gold mining industry in Gauteng and the West Rand (Von Backström, 1976). South Africa also had one of the first uranium extraction plants in the world, which provided the uranium used in the making of the atom bombs dropped on Hiroshima and Nagasaki. As the strategic importance of uranium was realised, other countries mined and refined their own uranium, causing the price of uranium to drop. Subsequently most of the uranium extracted as part of the gold mining process is dumped in slimes dams on the Witwatersrand and Far West Rand which already may contain more than 100,000 tons of uranium (Coetzee et al., 2006).

The slimes dams and rock dump sites of Gauteng and North West all leach uranium and its daughter products. The AMD issuing from mines, the run-off from mines and the dust that blows from the mine dumps and slimes dams, contain uranium, thorium, radon/radium and lead. It is estimated that as much as 50 tons of uranium is discharged annually into the rivers into which effluent drains from the slimes dams drain. The slimes pumped into sinkholes on the West Rand and Far West Rand will also add to the contamination of the groundwater as the water table is restored (Coetzee et al., 2006).

The mine effluent in Gauteng and North West Province contains radium, polonium, thorium, uranium and some isotopes of lead which, besides their toxic nature, are also radioactive. Due to the lack of municipal services, people in the rural areas adjacent to the mines and downstream of the mines use groundwater for drinking purposes, to water their cattle and to irrigate their crops. Most people resident in proximity to rivers in Gauteng and the West Rand use water, either from streams or boreholes contaminated by these elements (Coetzee et al., 2006; National Nuclear Regulator, 2007). Uranium accumulates in the river sediment and soil in this region, with a serious negative impact on the vegetation surrounding the water bodies, and poses serious threats to the farming industry adjacent to mining areas (De Wet, 1996; Winde and Van der Walt, 2004; Coetzee et al., 2006).

Humans and other animals may be exposed to these heavy radioactive metals though ingestion, inhalation and absorption through the skin. ^{238}Uranium and its daughter elements ^{234}Thorium, ^{234}Protactinium, ^{234}Uranium, ^{230}Thorium, ^{226}Radium, ^{222}Radon, ^{218}Polomium, ^{214}Lead, ^{214}Bisthmuth, ^{214}Polonium, ^{210}Lead, ^{210}Bismuth and ^{210}Polonium are alpha and beta particle emitters that cause damage to tissues (Durakovic, 1999; Coetzee et al., 2006). These elements may also be parenterally absorbed through the skin. The absorption of uranium through ingestion leads to the destruction of the kidneys (Hursh and Spoor, 1973), affects the neurological system causing blindness, paralysis and loss of coordination, causes chromosome aberrations in sperm and causes blood and other connective tissue diseases, changes in the immune and endocrine systems and prevalence in malignant diseases, including cancer (Zhu, 1994; Au et al., 1996, Baur et al., 1996, Zaire et al., 1996; Zaire et al., 1997).

According to the World Health Organisation, the recommended maximum limit for uranium in drinking water for humans is 30 μg/l (WHO, 2011). The German Federal Parliament passed legislation in 2006 which limits the uranium in bottled water to 2 μg/l, which it considers safe for the preparation of baby food based on research that uranium has endocrine-disrupting characteristics even at very low concentrations (Konietzka et al., 2005). In South Africa the maximum uranium concentration recommended in drinking water is 70 μg/l (DWAF, 1996a). The uranium concentration in Robinson Lake was 14.8 mg/l in 2009.

The irrigation of crops poses a significant risk to human health due to the fact that metals are accumulated in plants to levels significantly higher than in the water with which they are irrigated (Van Biljon, 2007). For this reason the maximum allowable concentration for uranium in water used for irrigation is 10 μg/l (DWAF, 1996b). Heavy metals, including radionuclides accumulate in the sediment affected by mine effluent (Coetzee et al., 2006; National Nuclear Regulator, 2007). Plants, including grass, vegetables, fruit and other agricultural products, readily absorb metals through their roots where they are exposed to the metals in the soil (Fig. 14) (Dushenkov et al., 1997). In a study done on the accumu-

Fig. 14. Dairy farmer cutting hay on mine grounds adjacent to a slimes dam on the West Rand.

lation of uranium in vegetables grown on farms near mines on the Witwatersrand, it was found that both carrots and beetroot accumulated up to 1.7 μg/g of uranium (Bain et al., 1994). In another study it was found that a wide range of agricultural products including milk, meat and vegetables from farms near mining areas and polluted rivers contained radium (De Wet, 1996).

Fig. 15. Subsistence farmer's food garden on the West Rand irrigated with mine water runoff.

The sediment in the Andries Coetzee Dam in Blyvooruitzicht which receives water from the Wonderfonteinspruit, contained levels of uranium of 900 mg/kg. Levels of 1100 mg/kg were measured in sediment in the upper Wonderfonteinspruit (Coetzee et al., 2006; Van Eeden et al., 2009). The use of this water for drinking or irrigation purposes may pose serious health risks to people living and farming near these water bodies (Fig. 15). The use of groundwater which is recharged by the affected Wonderfonteinspruit and Tweelopiespruit/Rietspruit/Bloubankspruit system may be equally dangerous (Fig. 16).

The concentration of uranium in the sediments in certain areas along the Wonderfonteinspruit in North West Province exceeds the maximum limit set by the National Nuclear Regulator at 16 mg/kg of uranium in sediment (which has a radioactive level of 0.2 Bq/g). The Water Research Commission Report No. 1214/1/06 (WRC, 2006), noted however that the U-238 concentration of the sediment in the Tudor Dam had radioactive readings of 10,000–100,000 Bq/g and 1000–10,000 Bq/g at the Andries Coetzee Dam and 100–1000 Bq/g in the Donaldson Dam. The average dose of

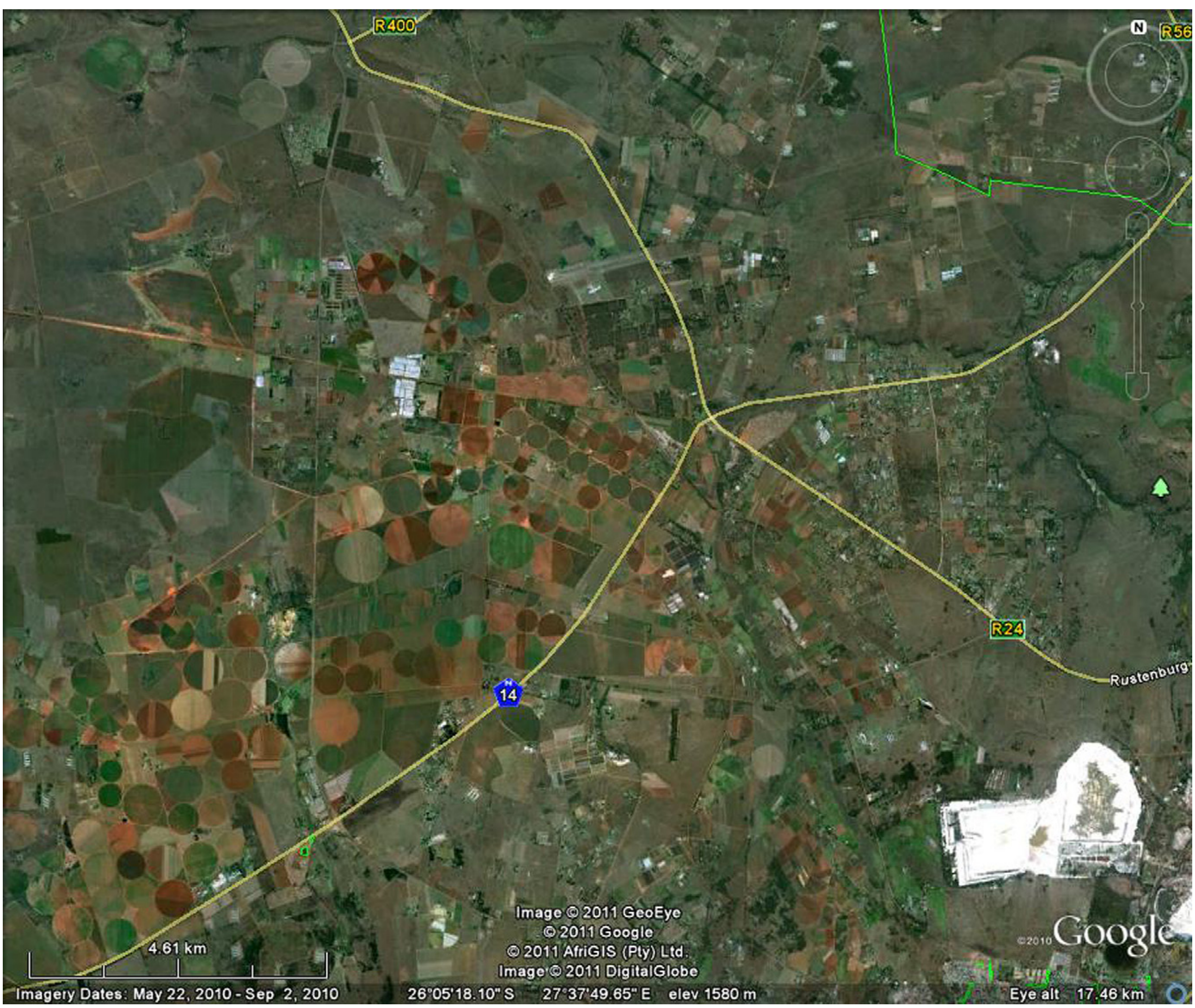

Fig. 16. Farms on the West Rand using water from the AMD contaminated Zwartkrans dolomite compartment for irrigation.

radiation to which an adult may be exposed is 1 mSv per year. A sample from the Blyvooruitzicht Mine in Carletonville on the Far West Rand had a value of 548 mSv (National Nuclear Regulator, 2007).

10. Cyanide

The cyanide process for the extraction of gold may have saved the mines a century ago, but simultaneously it posed a major environmental and health impact. The gold extraction process with cyanide involves the exposure of crushed gold-containing rock or sand to cyanide, treatment with active coal, heating, treatment with some more chemicals and lastly ore electrolysis (Korte and Coulston, 1998). During the ‘‘Heap Leach’’ treatment, a cyanide solution is percolated through large piles of low grade ore, in some cases covering hundreds of hectares, to dissolve the gold it contains. After months of treatment the liquid containing the gold is drained into storage ponds from which gold was is extracted (Sternkamp, 1992).

Both the ‘‘Carbon in Pulp’’ (CIP) and the ‘‘Carbon in Leach’’ (CIL) methods are used to extract gold on the West Rand mines. These processes involve milling of the ore into a fine powder to which cyanide is added. Activated carbon is then added to slimes in order to adsorb the gold solubilised by cyanide. After the extraction of the gold bearing particles from the slimes, ferrous sulphide or ferrous chloride is added to the slimes to neutralise the cyanide. The slime is then pumped to tailings dams, from which a variety of chemicals, including the remaining cyanide, may leach into the soil, rivers and groundwater (Krige, 2006).

Although great care is taken to line the storage ponds and ore piles with thick plastic sheets to prevent seepage, they often tear, causing cyanide to escape into the environment, invariably finding its way into the streams and groundwater. Cyanide gas also evaporates constantly from the heap leach works where it has a half-life of 267 years (Atkinson, 1985). Cyanide in the form of NaCN may remain in anaerobic soil for up to two years (Wolf et al., 1988). The use of cyanide to extract gold poses a serious threat to the ecology, both aquatic and terrestrial (Albersworth, 1992; Marquardt and Schäfer, 1994; Korte and Coulston, 1998).

Cyanide is a deadly substance that can damage the nervous, cardiovascular and respiratory systems of animals that ingest or inhale it (ATSDR, 1993). The lethal dose for humans is 1–3 mg per kilogram of body weight (Korte and Coulston, 1998).

11. Ecological impacts

The water quality of the river systems, wetlands and groundwater has deteriorated noticeably over the past decade due to mine effluent issuing from mines in Gauteng and the North West Province. Certain rivers are devoid of macroscopic organisms and the riparian vegetation has suffered a loss of biodiversity in affected areas (Fig. 17).

Although many deaths and miscarriages of the animals in the Krugersdorp Nature Reserve have been reported since decanting started in 2002 (Fourie, 2005), no epidemiological studies or autopsies have been done and the cause of death remains speculative (Du Toit, 2006). There are uncontaminated springs in the Krugersdorp Nature Reserve which serve as alternative sources for water for these animals.

Mine effluent affected by AMD decimates the aquatic life in the water bodies into which the effluent is discharged (Roback and Richardson, 1969; Adendorff, 1997; Jooste and Thirion, 1999). The acidity, salinity, turbidity, toxicity and radioactive value of the receiving water body are affected. The aquatic macroinvertebrate studies in the Tweelopiespruit determined that the diversity

Fig. 17. The AMD-polluted Tweelopiespruit in the Krugersdorp Nature Reserve.

and number of invertebrates diminished with the deteriorating water quality the closer one got to the mine (Heyl, 2007). The Wonderfonteinspruit, which receives water from the Tweelopiespruit via the Rietspruit, is in a worse state today than Tweelopiespruit was in 2007 (Fig. 18). The macroscopic life in the Tweelopiespruit and Rietspruit was severely diminished in 2011 due to mine effluent.

In addition to the toxicity, salts and acid that kill organisms, the iron hydroxide that settles on the river bed turns it into a crust which is impenetrable to the invertebrates that have to live in the sediment (Fig. 19). It also excludes bottom feeders like certain fish and water birds. Animals that have to drink water from these water bodies will also perish if they do not have alternative water sources such as in the Krugersdorp Nature Reserve. The impact of AMD on the wetlands, rivers and lakes affects not only the aquatic invertebrates, but also those organisms dependent on them like frogs, water birds and fish (Fig. 20). The rivers affected by AMD on the West Rand are virtually devoid of vertebrate life as well.

Metals and other toxins produced by AMD that are ingested by animals or absorbed by plants will impact on every successive herbivore, predator or scavenger. Toxins will be passed through the food web in this way. One of the most serious consequences of this is that toxins tend to become more concentrated as they travel up

Fig. 18. The Tweelopiespruit in the Krugersdorp Nature Reserve (sample point no. 6). Note the precipitation of iron hydroxide. This water flows into the Rietspruit.

Fig. 19. Rietspruit (sample point no. 5). The Rietspruit, like the Tweelopiespruit, has been devoid of macroscopic life since 2009. The bottom of the river is encrusted with iron hydroxide, known as yellowboy, which excludes all bottom-dwelling organisms.

the food chain and may have a fatal effect on higher trophic levels due to bioaccumulation (Kang et al., 1997).

The same ecological destruction seen in the Wonderfonteinspruit (Coetzee et al., 2006) is unfolding at the Tweelopie/Riet/Bloubankspruit river system (Durand et al., 2010). The demography and land use bordering of the rivers differ. The Tweelopie/Riet/Bloubankspruit river system flows through two major natural areas in Gauteng – the Krugersdorp Nature Reserve on the one hand and the Cradle of Humankind World Heritage Site on the other, where it serves as the major water source of many vertebrates. The Wonderfonteinspruit, on the other hand, is flanked by farming communities that depend on the water for drinking water and for farming purposes.

The Cradle of Humankind is home to the largest collection of hominid fossils in the world. This unique World Heritage Site has yielded hundreds of thousands of vertebrate fossils, including thousands of fossils belonging to four different hominid species. Thousands of stone artefacts, mostly of the Oldowan Industry or the early Stone Age, were also discovered here. The fossils were found in many localities, of which 13 major sites have been inscribed by UNESCO as part of this World Heritage Site. Some of the fossil sites are only tens of metres away from the AMD effluent-containing Bloubankspruit. One has to wade or drive through Bloubankspruit to get access to Swartkrans, which yielded the oldest proof of the controlled use of fire (dated at 1.8 Ma) and the remains of hundreds of apeman individuals. When tourists become aware of the nature and scope of the AMD problem, this may be detrimental to the reputation of this educational facility and tourist attraction (Durand et al., 2010).

12. Legal implications

The efflux of AMD-contaminated water is the most costly environmental and socio-economic problem in South Africa (Oelofse et al., 2007). Attempts by government departments to involve the mining companies in the rehabilitation of the areas impacted by mining activities have been frustrated because of the mine companies' refusal to accept responsibility for the situation (Funke et al., 2007). Mine companies usually claim that they inherited the situation which already existed before they took over the mine properties.

Most gold mines, particularly on the Central Rand, East Rand and West Rand, were abandoned or liquidated before the environmental and health impacts caused by them became evident. Many of the remaining mines have experienced changes in ownership or been amalgamated into larger companies such as DRD Gold which is an amalgamation of Mintails and Blyvooruitzicht Gold Mining Company. In some instances, surface infrastructure such as rock dumps and slimes dams were sold to third parties such the founding of Rand Uranium when Harmony Gold sold the Cooke section of its Randfontein Estates Mine to Pamodzi Resources Fund (a black economic empowerment initiative).

Government departments also do not take the mining companies to court, despite the existing legal framework (Van Eeden et al., 2009). The government of the day has always been lenient

Fig. 20. Macroinvertebrate sampling in the Bloubankspruit at sample site 4 (left) and 3 (right). This river flows through the Cradle of Humankind World Heritage Site.

towards the mines due to the mutual working relationship between government and the mines – from the period of British rule in the first half of the 20th century, during the apartheid era in the last half of the 20th century and today under ANC rule (Van Eeden, 2008). This is even more evident today than in the past where powerful government officials, their spouses or close family members are directors of mining companies.

The gold economy in South Africa has been mainly an extracting enterprise since the British government took over the rule of South Africa after the Anglo-Boer War and this is still the case today. Mining costs are kept artificially low by the mines by deflecting responsibility for their environmental and health impacts to the state and third parties in order to maximise profits (Adler et al., 2007). Approximately 57% of the profits generated by mines are paid to government in the form of taxes and levies.

Reports on environmental pollution by mines are often withheld from the public which is directly affected by the pollution by the government which treats them as "secret" or "confidential". On 4 June 2008 the Federation for a Sustainable Environment, through appeals to the Parliamentary Portfolio Committee on Water Quality and Pollution, forced government to respond to its concerns about the contamination of the Wonderfonteinspruit. The Minister of Minerals and Energy, Bulyewa Sonjica said in her Budget Speech before Parliament on 6 June, 2008: "Following reports of possible radiological contamination in the Wonderfonteinspruit catchment area, the National Nuclear Regulator instituted an investigation. The investigation indicated that the situation does not pose a radiological risk to the surrounding communities" (Van Eeden et al., 2009).

The cooperation between government and mining companies incapacitated government from enforcing the laws which are designed to protect the public and environment. The economic benefit derived from this collusion enables the mines to operate with little regard to health or environmental issues while the government turns a blind eye towards the health and environmental transgressions of the mines. There is, for instance, even legislation in place which protects mine companies against claims by miners who have suffered injuries or diseases while working in the mine. According to the Compensation for Occupational Injuries and Diseases Act (RSA, Act 130 of 1993): "No action shall lie by an employee or any dependant of an employee for the recovery of damages in respect of any occupational injury or disease resulting in the disablement or death of such employee against such employee's employer, and no liability for compensation on the part of such employer shall arise save under the provisions of this Act in respect of such disablement or death."

Thembekile Mankayi, who worked at AngloGold Ashanti as a gold miner, sued the company after he contracted silicosis, claiming that it had failed to provide a safe and healthy work environment according to the legal statutes of South Africa. AngloGold Ashanti claimed that they it was exempted by law to pay him compensation according to the Compensation for Occupational Injuries and Diseases Act. The High Court of South Africa ruled in favour of AngloGold Ashanti on 26 June 2009. After appeal in March 2010, the Supreme Court Appeal of South Africa upheld the High Court's ruling. Mankayi then approached the Constitutional Court of South Africa, which reversed the previous courts' rulings in favour of Mankayi on 3 March 2011. Mankayi had however died of silicosis on 25 February 2011 (Business and Human Rights Resource Centre, 2010).

Despite having some of the most progressive legislation with regard to human rights, environmental management and conservation, the efforts of government departments that are involved in monitoring mine activities are frustrated due to the "cooperative governance clause" in the Constitution, which does not allow any department to challenge another. For instance, mining rights are awarded by the Department of Mineral Resources, but are subject to a water permit issued by the Department of Water Affairs only after the Department of Environmental Affairs has done an environmental impact study to determine what the effect of the mine will be on the environment. There are presently 104 mines operating with the full knowledge of government without having a water certificate, some of them owned by family members of government officials.

The South African Government has launched an investigation to assess the situation regarding the efflux of AMD from the gold mines. Researchers were appointed from the Council for Geoscience, Department of Water Affairs, Department of Mineral Resources, Council for Scientific and Industrial Research, Mintek, Water Research Commission as well as leading geology experts from four South African universities to report on the matter. The report entitled: *Mine water management in the Witwatersrand Gold Fields with emphasis on Acid Mine Drainage* was presented to an Inter-Ministerial Committee on Acid Mine Drainage consisting of representatives of the Department of Mineral Resources, the Department of Water Affairs, the Department of Science and Technology and the National Planning Commission of the Presidency (Inter-Ministerial Committee on Acid Mine Drainage, 2010).

In this report the two sets of risks were identified: the consequences of the flooding of the mines by AMD and the consequences of the impact of AMD on the environment. The report pointed out that the flooding of the mines would contaminate the groundwater used for agriculture and human consumption and compromise the underground infrastructure in urban areas. There will also be an increase of seismic activity in areas above and adjacent to flooded mines that may damage property and infrastructure. The risks owing to the decant of the AMD to the environment includes the serious impact on the ecology, regional impact on major river systems and the flooding of low-lying areas in the vicinity of the mines.

Some of the most important recommendations made by the team of experts include that:

- Water must be pumped from the three main basins – East Rand, Central Rand and West Rand, to maintain water levels at least below the relevant environmental critical levels or, after consultation with stakeholders, the lowest level of underground activity within the basin.
- Steps must be implemented to reduce the ingress of water into the underground workings as far as possible. This will reduce the volumes of water which need to be pumped and treated to more acceptable levels and consequently reduce the operational costs of AMD management.
- The pumped water is treated in the short-term by neutralisation and the metals removed to increase its quality for productive use or to discharge it into the river systems. It is also proposed that the salinity of the major river systems should be addressed in the medium- to long term.
- The monitoring of mine water, groundwater, surface water, seismicity, subsidence and other impacts of mine flooding should be improved. The monitoring should be done by a multi-institution monitoring committee which will facilitate the implementation of monitoring programmes. Targeted research on these aspects should also be done.
- Other sources of AMD, in particular mine residues, must be monitored and remediated.
- The feasibility of an environmental levy to be paid by operating mines in order to cover the costs of the legacies of past mining should be investigated.

This report was awaited with anticipation by many concerned citizens and NGOs but, as in the case of the report on the radioactivity levels of the water and sediment of the Wonderfonteinspruit

(National Nuclear Regulator, 2007), it was initially kept under wraps by government. The report was only made public after NGOs such as the Anti Privatisation Forum, Biowatch South Africa, the Centre for Environmental Rights, the Coalition against Nuclear Energy and private individuals threatened to take legal action against the Inter-Ministerial Committee on Acid Mine Drainage for not making the information public.

The frustration of the public with the efficacy of the Inter-Ministerial Committee on Acid Mine Drainage and indeed the Departments of Water Affairs and Mineral Resources may be summarised as follows: most of the information in the report has been known for many years. This rate of the flooding of the mine void, the efflux of AMD and even the decanting points where AMD would exit from the mine were determined decades ago. The impact of AMD on the environment has been studied and reported on years before the release of the report.

For many years NGOs and concerned individuals attempted to petition the government to acknowledge the seriousness of the AMD problem, to force it to take action against the mines in order to limit the decant of AMD and to remediate the impact of AMD on the environment. These efforts have been mostly in vain (Van Eeden et al., 2009). Although the 2010 report recommended that AMD should be urgently addressed, more than a year has passed and very little progress has been made. Another point of concern is that the costs for the pumping, treating and monitoring of AMD, which will run into the billions of Rand, will be paid by the taxpayers and would not be carried by the mines as legislation demands.

Water use by mines is classified separately from that of other industries. Adequate mine closure plans were never developed and regulatory measures were never enforced but rather seen as "amicable agreements" (Adler et al., 2007). The regulatory legislation dealing with the environment, water and health has been redrafted since 1994 but never implemented in the case of the mines. The lack of a unifying policy on the treatment of mine waste and water pollution and the non-cooperation between government departments is also abused by the mining companies. There are presently four acts and three government departments to address mine water management (Adler et al., 2007).

One of the Acts that should protect the public is the National Environmental Management Act, No. 107 of 1998 (NEMA). If any party is convicted of an offence under an Act listed in Schedule 3 of the NEMA (which includes the National Water Act No. 36 of 1998), and it appears that such a party has caused loss or damage to any other party, the court may determine the amount of loss or damage caused, and may award damages or compensation equal to that amount, in addition to other punishment such as the rehabilitation of the environment and taking steps to ensure that such damage will not occur again. Court costs may be claimed from the guilty party. Parties in such proceedings may rely on the common law remedies, including those available in terms of the law of delictual liability and the law of damages.

NEMA and the National Water Act (RSA, Act 36 of 1998) both state that a party has to take all reasonable measures to prevent water pollution or degradation of water resources as a result of mining operations for which they are responsible (Van Eeden et al., 2009). The prevention and remedy of the effects of pollution are addressed in Section 19, where it is stated that "an owner of land, a person in control of land or a person who occupies or uses the land on which – (a) any activity or process is or was performed or undertaken; or (b) any other situation exists, which causes, has caused or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring."

The Mineral and Petroleum Resources Development Act (RSA, Act 28 of 2002) addresses the responsibilities of the holders of mining rights and states that the mine permit holder must take responsibility for the rehabilitation of the environment affected by mining to its natural state or to comply with the principle of sustainable development as far as is reasonably practical. This Act states that a mine permit holder whose actions cause or result in pollution, environmental degradation or health risks "...is responsible for any environmental damage, pollution or ecological degradation as a result of his or her operations and which may occur inside and outside the boundaries of the area to which such right, permit or permission relates", and in terms of Section 43(1), "remains responsible for any environmental liability, pollution or ecological degradation and the management thereof until a closure certificate has been issued."

The responsibilities of holders of mining rights, with regard to pollution, ecological degradation or environmental damage are stipulated in the Mineral and Petroleum Resources Development Act (RSA, Act 28 of 2002) which states that a mining rights holder is responsible for "any environmental damage, pollution or ecological degradation as a result of his or her operations and which may occur inside and outside the boundaries of the area to which such right, permit or permission relates" and "remains responsible for any environmental liability, pollution or ecological degradation and the management thereof until a closure certificate has been issued".

The mine permit holder is responsible under these acts for any pollution, environmental destruction or ecological degradation, regardless whether the mining permit is held by directors of a company or members of a close corporation or whether the impact was advertently or inadvertently caused by the company or close corporation which they represent or represented. The National Environmental Management Act states that any person who is or was a director of a mining company at the time of the transgression will be held responsible in their personal capacities for the offence and is liable on conviction to the penalties imposed. NEMA also states that if more than one person is liable for the transgression "...the liability must be apportioned among the persons concerned according to the degree to which each was responsible for the harm to the environment resulting from their respective failures to take the measures required."

In a review of Mine Environmental Management Programme Reports it was apparent that none of the gold mining companies on the West Rand and Far West Rand (DRD Gold, AngloGold Ashanti, GoldFields, Harmony Gold) operated according to an approved Environmental Management Plan in terms of the Mineral and Petroleum Resources Development Act.

To date no legislative action has been taken against any of the gold mine companies, and it seems unlikely that this will ever happen. This unwillingness or inability of government to hold the mining companies responsible for their impact on the environment is in conflict with the Constitution of South Africa (RSA, Act 108 of 1996) which supersedes any other act of Parliament. According to the Constitution it is the legal and moral duty of the state to oppose the actions of individuals or organisations that threaten the wellbeing of the citizens of South Africa (Van Eeden et al., 2009).

13. Conclusion

Mine closure and especially the rehabilitation of the environment need to be addressed urgently. According to the Department of Mineral Resources there are over 8000 derelict and ownerless mines in South Africa which would take approximately 800 years to rehabilitate at a cost of billions of Rands (Brown, 2007). If one adds the rehabilitation of the water bodies affected by AMD, the health impacts on humans, the disruption of societies and the destruction of the biodiversity, the cost becomes incalculable.

Mines have a limited lifespan and the closer they come to mine closure, the less money they have due to a reduction of the revenue generated. Virtually no money would be available either for the rehabilitation of the environment or for compensation to people with health claims against the mine company.

New mine permit applicants will pay lip service to making financial provision for remediation of the negative environmental impacts caused by the mine under the Mineral and Petroleum Resources Development Act in order to obtain a mining permit, knowing full well that there will not be enough money to do so. Environmental and social costs are kept from investors to make the mine companies seem more financially viable. It seems as if the South African public ultimately will have to foot the bill for the environmental impact caused by the mines. Already taxpayers' money has been used to assist in the funding of the treatment of mine effluent at Grootvlei Mine on the East Rand.

Many thousands of people in the Tweelopiespruit/Rietspruit/Bloubankspruit and Wonderfonteinspruit depend on the rivers and groundwater for drinking and farming. The ongoing urbanisation of the Witwatersrand has had the result that people are living and working only tens of metres away from slimes dams, rock dumps and AMD-polluted water where they too come into contact with pollutants from the mines through inhalation, ingestion or skin contact. The removal and relocation of the people from the informal settlement at Tudor Shaft illustrates this problem (Fig. 21). The wetland on which they built their shacks is affected by the efflux of AMD from the Tudor shaft nearby. Only after the dire situation of this settlement made news headlines and the National Nuclear Regulator confirmed that the grounds were indeed radioactive, the Parliament decided to relocate this community. This action has set a precedent and would probably have to be repeated many times because of the threat to the health of many thousands of people living in similar circumstances on the Witwatersrand and Far West Rand. It would probably be a different matter if people living in brick houses, rather than shacks, had to be moved.

Although mine companies agree that their slimes dams issue AMD, it is often claimed by them that the AMD effluent will decrease after mine closure. The more than 270 slimes dams on the Witwatersrand and Far West Rand cover an area of approximately 400 km^2 and will continue to pollute the surroundings for as long they take to erode away. The situation is exacerbated by the fact that many slimes dams were built on the continental divide and on top of a very large karst aquifer and therefore pollute two separate river systems and the groundwater on which millions of people depend. The negative and cumulative impact of mines on the

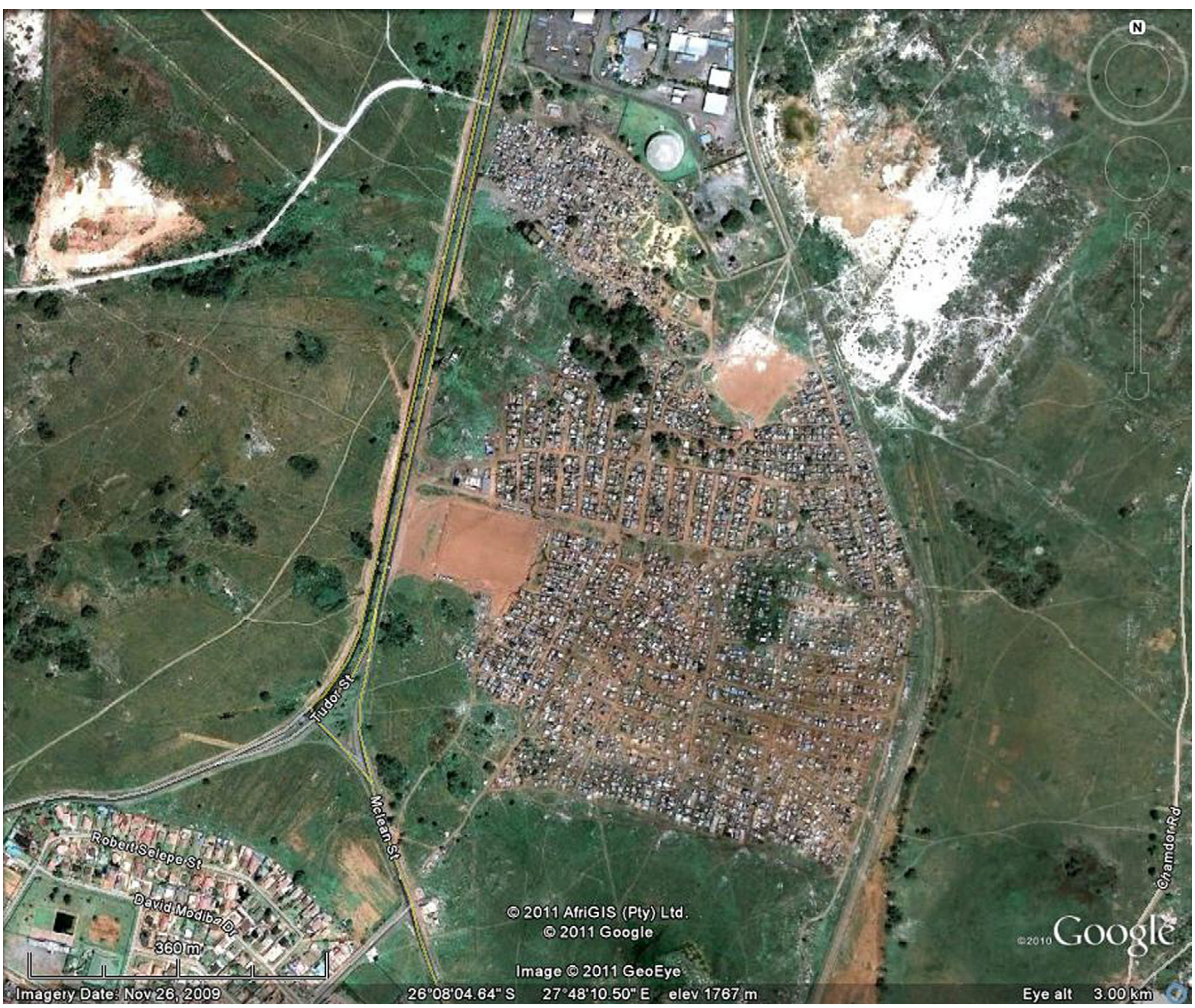

Fig. 21. Tudor Shaft Informal Settlement on mine property polluted by radioactive effluent.

environment may only reach its climax over decades if not centuries (McCarthy, 2010).

Although many studies have been done by many researchers on the problem of mine effluent, they have accomplished very little due to the fact that most work in isolation from one another and seldom with specialists from other fields of study or the community. The solution to this problem, which is considered to be one of the greatest environmental threat ever faced by South Africans, requires cooperation between geologists, hydrologists, engineers, biologists, ecologists, environmentalists, health and legal practitioners, sociologists and the community.

Little has changed from the time the German scientist and physician Georgius Agricola stated in his book *De re metallica* (1556): "The fields are devastated by mining operations, for which reason Italians were formerly warned by law that no one should dig the earth for metals and so injure their very fertile fields, their vineyards, and their olive groves. Also, they argue that the woods and groves are cut down, for there is need of an endless amount of wood for timbers, machines and the smelting of metals. And when the woods and groves are felled, then are exterminated the beasts and birds, very many of which furnish a pleasant and agreeable food for man. Further, when the ores are washed, the water which has been used poisons the brooks and streams, and either destroys the fish or drives them away. Therefore the inhabitants of these regions, on account of the devastation of their fields, woods, groves, brooks and rivers, find great difficulty in procuring the necessaries of life, and by reason of the destruction of the timber they are forced to greater expense in erecting buildings. Thus it is said, it is clear to all that there is greater detriment from mining than the values of the metals which the mining produces."

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