Long-term Impacts of Gold and Uranium Mining on Water Quality in Dolomitic Regions – examples from the Wonderfonteinspruit catchment in South Africa

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Abstract. A number of gold and uranium mines in South Africa are located in areas where compartmentalised dolomitic rock forms extensive karst aquifers overlaying mined reefs. Apart from dewatering of such aquifers triggering widespread sinkhole formation and impacting on water availability by drying up of springs and boreholes, mining activities also impact on the quality of local water resources. Of particular concern to downstream users is uranium pollution of ground- and surface water often associated with gold in the mined reefs. This paper estimates potential U-fluxes associated with different types of mining-sources assessing their varying significance in past, present and future.

Introduction

Large scale gold mining in South Africa commenced more than a century ago at outcrops of gold-rich Witwatersrand sediments marking the shoreline of an ancient lake. With mined auriferous reefs dipping deeper towards the centre of this lake, mining depth steadily increased reaching maxima of up to 4000m below surface.

In large parts of the Witwatersrand basin gold mining developed below extensive, compartmentalized karst aquifers in dolomitic bedrock hosting large volumes of groundwater, a much needed resource in a water-stressed country such as South Africa.

As a consequence of increasing ingress of dolomitic groundwater into underlying mine workings, it was decided in the early 1960’s to dewater affected dolomitic compartments as a matter of policy for economical and safety reasons. The associated lowering of the groundwater table by up to several hundreds of meters in some compartments, however, unexpectedly triggered massive ground movements in near-surface karst areas in the form of sinkholes and dolines, frequently with disastrous consequences for residents and infrastructure (Jennings et al. 1965).

Apart from the associated land degradation and negative impacts on water availability (drying up of irrigation boreholes and dolomitic springs feeding into the otherwise non-perennial stream), mining also caused pollution of the remaining ground- and surface water resources in the area. Originating from a wide variety of point- and non-point sources, most problems are associated with excessive sulphate (Sulphate mainly originates from oxidized sulphides and sulphuric acid used by many gold mines in the past to leach U from auriferous ore. Although not toxic, high sulphate concentrations severely limit the fitness of water for many usages and contribute to water stress in semi-aid South Africa, where dilution to acceptable limits as practiced in many humid mining countries is not a feasible option due to the lack of water) and nitrate (High nitrate concentrations are mainly linked to the use of explosives for underground blasting. The use of cyanide as leaching agent in gold recovery may also contribute to elevated concentration of N-compounds since the extremely toxic cyanide is believed to soon decay into harmless C/ N-components once exposed to UV radiation (sunlight)) concentrations in mine effluents, acidic mine drainage and a variety of toxic heavy metals including radioactive elements such as uranium.

This paper focuses on sources of mining-related U-pollution in the Far West Rand goldfield 70km south west of Johannesburg where U is found associated with gold in many of the mined reefs. Owing to potential risks for human health, the radioactive heavy metal is of particular concern to downstream users such as local residents and riparian land owners as well as the Potchefstroom municipality depending directly on water from the WFS. Identifying and characterizing all potential sources of U pollution is a first step contributing to current efforts by the government to comprehensively assess the extent of historic, current and possible future water pollution. It forms part of a knowledge base needed to develop appropriate water management strategies for the period during and after successive mine closures in the area.

Mining history and natural conditions of the study area

Gold- and uranium mining

Apart from the FWR goldfield, the catchment of the WFS also includes parts of the much older West Rand (WR) goldfield, which developed soon after the discovery of gold in 1886, mostly located in the non-dolomitic head water region of

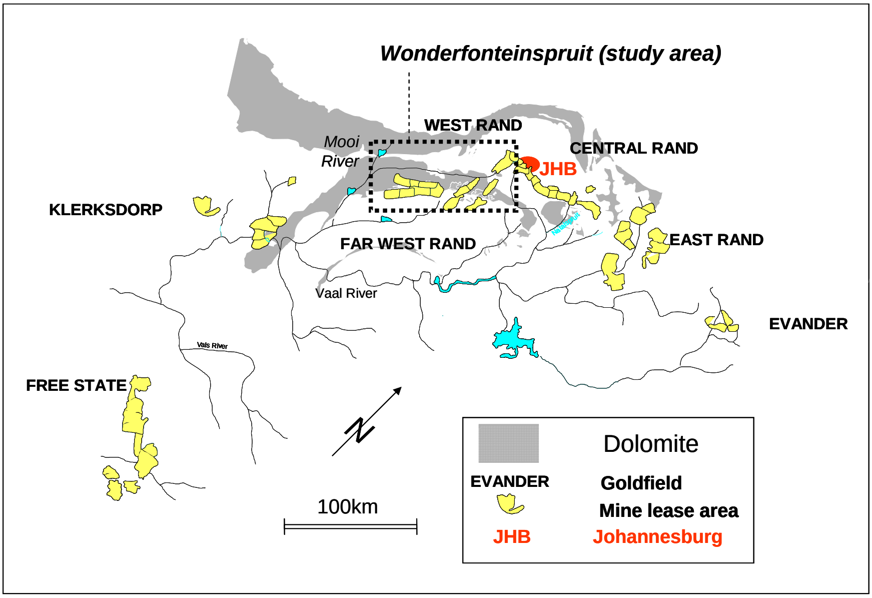

Fig. 1. Location of the study area (Wonderfonteinspruit catchment) within the Witwatersrand basin in relation to the goldfields as defined by lease areas of gold mines, the surface hydrology and outcropping dolomitic limestone.

the catchment (also known as the upper WFS; Fig. 1). Many gold mines in this area are abandoned and associated mining residues such as sand dumps and slimes dams are often several decades old and heavily eroded.

Gold mines in the lower, dolomitic part of the catchment were only developed in the late 1930's after a newly invented cementation technology allowed for sealing of sunken shafts against flooding by dolomitic groundwater.

As part of the global search for uranium resources for atomic weapons initiated by the 'Manhattan Project', the uranium-rich gold reefs of the WR and FWR were used by many gold mines in the area to produce U as a by-product of gold from the early 1950's on. At one stage 9 out of 22 gold mines produced U for a total of 7 metallurgical U recovery plants in the area. The importance of the area for South African U production is illustrated by establishing the Nuclear Fuels Corporation of South Africa (NUFCOR), as one of the world's largest continuous producer of uranium oxide, in the area (upper part of the catchment). After peaking in 1980, U production in South Africa declined steadily, leaving only one gold mine in the area currently (2005) still producing U. At all other mines U is no longer extracted from the milled ore and discarded onto slimes dams together with the leached ore.

Climate and Geology

The study area is part of a semiarid to arid interior plateau (‘Highveld’) ranging in elevation from 1700 – 1400 m a.m.s.l., where potential evaporation exceeds mean annual precipitation (MAP) of 600-750mm by a factor of 2-3. Rainfall occurs mainly as part of convectional thunderstorms in summer (Nov-April), while the winters months are normally dry.

The surface geology is dominated by two 10-15km wide E-W running bands of carbonate limestone (dolomite) covering large parts of the lower catchment. Within the upper 100-150m of the 1-1.5km thick dolomite chemical weathering developed extensive karst systems. The total volume of groundwater stored in the karst aquifers exceeds the storage volume of the Vaal Dam at full capacity by far. Later intrusions of syenite and diabas dykes associated with volcanism hydraulically separated the dolomitic blocks into several sub-units (‘compartments’). Four of the nine compartments within the catchment are dewatered by mining, which also mined through some of the dykes, effectively linking adjacent compartments hydraulically. Since the northern band of the dolomite is not affected by mining it is not discussed further.

Hydrology

The WFS originates just south of the sub-continental divide separating the watersheds of the Indian Ocean (to the north) and the Atlantic (to the south). After passing the quartzite-dominated head water region the WFS traverses seven dolomitic compartments forming the stream bed for more than 80% of its total length of about 90km. Prior to mining the WFS was fed by a succession of springs at the downstream dykes of each compartment where naturally dammed up dolomitic groundwater decanted into the stream.

Since inception of dewatering, however, all springs in the four dewatered compartments dried up, significantly reducing stream flow in affected reaches. Instead, the stream now receives groundwater pumped from underground mine workings and discharged into the WFS downstream of the dewatered compartments via an extensive network of pipelines and canals. Furthermore, dewatering also caused massive losses of stream water to the underground through the many sinkholes that occurred in the stream channel due to dewatering. In order to reduce these losses and the increased costs for pumping this water from the mine void back to the surface, a 30km-long stretch of the WFS where its crosses the three (lower) dewatered compartments was diverted into a pipeline of 1m diameter.

After its confluence with the upper Mooi River the WFS provides a significant proportion of the drinking water supply for approximately 250,000 residents of the Potchefstroom municipality 20km downstream of the confluence.

Sources of uranium contamination

Types of sources

U pollution in the WFS catchment is mainly caused by sources associated with gold mining activities. However, possible contributions of not directly mining-related sources cannot be excluded. These include the production of uraniferous fertilizer (phosphates) and its application on agricultural land, impacts from the U concentrate refinery NUFCOR via several possible pathways including air- and waterborne migration and road transport as well as natural ore bodies in contact with free moving water. However, in view of the contribution of mining operations to U-pollution in the area these sources are of marginal significance.

Mining-related sources of U pollution can further be divided into 'on-site sources', comprising all possible pollution originating from the actual mine property (lease area) and 'off-site sources' comprising mining-related pollution sources outside the mine boundaries e.g. eroded tailings particles transported into the adjacent environment, tailings material used to fill sinkholes of karst aquifers, contaminated mining material used for construction purpose in nearby communities, etc. From a water management point of view a division of sources according to their spatial extent into point and non-point (diffuse) is often useful. Typically, point-sources relate to a somehow controlled release of U (e.g. discharging mine effluents via pipelines) and commonly affect surface water bodies. In contrast, U release from non-point sources often cannot be controlled and mainly affects subjacent aquifers.

Point sources of U pollution

A comprehensive overview of potential point sources of U contamination associated with gold and uranium mining in the WFS catchment is given in Winde (2004). In this paper the focus is on three major types of point sources namely:

- Mining effluents (consisting of process water from metallurgical plants, fissure and service water from underground, surplus water from tailings storage systems, outflow of settlings ponds, etc.)
- Domestic waste water from mining-related sewage works and
- Polluted run off from storm water drainage systems of mines and adjacent municipalities.

Mining effluents

For the period of active U-production between the early 1950's and the mid 1980's it is likely that point sources contributed significantly to water pollution since U was leached from the ore and therefore present at much higher concentrations in water circuits of metallurgical plants. Low recovery efficiency in the early days of the newly introduced U leaching technology and frequent process failures allowed for much of the leached U to leave the metallurgical plant along with the waste water stream (Mc Lean 1994). However, increasing recycling and reuse of process water later on caused increased U concentration in process water that finally needs to be discharged. In the early 1990's, after U production in many gold mines had ceased, Pulles (1991) reported an average U-concentration of 0.74mg/l for mining effluents across the Witwatersrand basin. Based on associated discharge volumes it is conservatively estimated that point sources of gold mines in the study area discharge about 12t U/a mostly into the WFS (Winde 2004).

To be added to this are contributions of point sources that are not controlled, including spillages, leakages from pipeline and water treatment systems and surface run-off from contaminated areas such as ore piles, slimes dams etc. draining into storm water systems. Leakages from damaged reticulation systems in the area are likely to be above average due to increased seismic activity repeatedly damaging even surface buildings, and due to karst-related ground movements (sinkholes and subsidences) still occurring in the area several decades after dewatering commenced.

Apart from process water and contaminated surface run off, groundwater seeping into underground mine workings (usually referred to as 'fissure water' since it migrates into the mine void via cracks and fissures connected to he dolomitic aquifer several hundreds to thousands of meters above), also must be considered. Being in contact with oxidized ore bodies and other possible U-sources such water was found to contain up to 11mg/l U_{nat} (Deelkraal Gold Mine 1991). However, the vast majority of fissure water, pumped by mines into the WFS, is of good quality frequently diluting waste loads from upstream in the WFS.

Domestic waste water from mining-related sewage works

Workforces of gold mines in the order of tens of thousands of people cause sewage volumes comparable to those of many medium-sized towns in the area. The treated wastewater mainly originates from imported tap water bought from a water service provider ('Rand Water'), although some mines also use treated fissure water. Higher U-concentrations in domestic wastewater from mines were linked, amongst others, to miners drinking U-contaminated water, such as chilled cooling water in underground mine workings, resulting in elevated U-levels in urine (Deelkraal Gold Mine post-1990). Samples from toilet drains of changing rooms at shafts taken at several gold mines displayed U-concentrations of 0.4 - >13 mg/l (Pulles 1991).

Surface run off from storm water drainage systems

Although being a natural non-point source by nature, rain water run-off becomes a point source of water pollution once it enters storm water drainage systems discharging the water collected from a much larger area spatially concentrated via several outlets into receiving water courses. Storm water drainage systems collect mainly rainwater run-off from sealed surfaces such as tarred roads, concrete covered areas and roofs. Due to much higher run-off coefficients this can result in almost 100% of the rainwater from such areas flushing untreated into nearby streams. Containing a wide range of heavy metals such as Pb (originates in petrol), Cd (abrasion of tyres), Zn and Cr (corrosion of cars, gutters, roof material) run-off from roads and other sealed surfaces constitutes a significant source of stream contamination (Winde 1996). In addition, frequently windblown dust from adjacent slimes dams is also washed off from sealed surfaces nearby. Based on measured dust concentration, the size and mean annual run-off volumes of affected areas, a sediment load of approximately 100,000t/a was estimated to be discharged from storm water drainage systems into receiving water courses. With wind blown tailings material containing on average U concentration >100mg/kg, storm water-drainage systems discharge >10t particle bound U per year mainly into the WFS (Winde 2004). Other sources likely to contribute to the U contamination of storm water include run-off from ore piles, rock and sand dumps as well as from U-plants where possible spillages of process water, dust and U-concentrate may occur. In addition, tailings particles eroded from nearby slimes dams are also transported into storm water drainage canals. Rainstorms exceeding an intensity of a 1:50a event will in most cases result in additional spills of run-off from slimes dams overflowing the prescribed 0.8m high free board of storm water retention dams. In some cases storm water-drainage channels are also illegally used to dispose of highly contaminated process water from gold mines (Parker 1982).

Non-point sources of U-pollution

Seepage from slimes dams

Owing to their large surface area and content of contaminants slimes dams are likely to be the single largest source of diffuse water pollution by mining.

Along with some 1.1 billion t of gold ore that was milled by mines in the West Rand and Far West Rand up to 1998 more than 150,000t of uranium were brought to the surface. With only a quarter of it being extracted and sold the majority of the mined U remains in tailings. The slimes dams of the West Rand and Far West Rand contain a total of well above 100,000t of uranium (1998), reaching average concentrations in some mines of up to 300ppm. The mass-weighted mean U_{nat}-concentration in all tailings of about 100ppm is about two orders of magnitude above the natural background in soils and surface rocks of the area rendering slimes dams a potential source of U-contamination (Winde 2004).

Seepage from slimes dams frequently displays significantly elevated concentrations of uranium and other toxic heavy metals as well as dissolved salts such as sulphates. In tailings where sulphide oxidation leads to acid mine drainage (AMD) the leaching rate for uranium and other heavy metals can increase by orders of magnitude. This results in concentrations of dissolved U reaching maxima of several hundred mg/l (Mrost & Loyd, 1970) compared to a discharge-unweighted mean of global background concentration for uranium in freshwater of 0.0003mg/l (DWAF 1995). Based on surface area covered by slimes dams, average U concentration in tailings and seepage and rainfall, flow rates of seepage from slimes dams only in the WFS catchment are estimated to be in the order of 12 million m^3/a (Winde 2004). Assuming an average U-concentration in tailings seepage of 1mg/l about 12t/a of dissolved U are transported from slimes dams into ground- and surface water of the WFS system (up to 30mg Unat/l were found; Winde & de Villiers 2002). With many gold mines having abandoned U-production in the mid 1980's, the associated increase of U-concentration in tailings by a factor of ten is likely to be reflected in the long-term increases of U concentrations in seepage from such slimes dams (U-leaching by sulphuric acid on average had an extraction efficiency of some 90%).

Associated groundwater contamination is exacerbated by the fact that most slimes dams in the area are not lined and deliberately placed - in the FWR area - on top of (permeable) karstic dolomite in order to enhance natural drainage of tailings porewater und reducing the risk of dam failure. However, this practice allows for highly contaminated seepage to enter directly into underlying groundwater.

Different problems are found in the non-dolomitic head water region of the WFS where large parts of the (small) catchment are covered by heavily oxidized old sand dumps and slimes dams. Here much of the baseflow feeding into the WFS actually consist of acidic seepage from slimes dams migrating along shallow aquifers into the stream, as indicated by low pH values (3-4) and high electrical conductivity of the stream water. In dry winter months when no uncontaminated rain water dilutes such seepage, particular high U levels in stream water of the WFS are likely. This even more so since the very source of the WFS is buried under tailings deposits.

Sinkholes filled with tailings material

Soon after dewatering commenced a large number of sinkholes occurred within and near the stream bed of the WFS where it crossed the dewatered compartments. By 1987 some 271 sinkholes with a total volume of 2.45 million m^3 had occurred within a narrow band alongside the 30km-long stretch of the stream channel of the WFS where it flows over the three lower dewatered dolomitic compartments (Swart et al. 2003).

In order to reduce the infiltration of stream water and associated cost for pumping it from the mine void back to the surface, affected gold mines attempted to close these conduits by filling some of the larger sinkholes with tailings produced from nearby metallurgical plants. However, in several instances large volumes of slimes pumped into the sinkhole for several months, suddenly disappeared into underlying karst receptacles (cavities). In one particular sinkhole at Venterpost compartment a total volume of 77 000m^3 of tailings and waste rock was dumped , of which 35 000m^3 of tailings disappeared into the underlying karst aquifer. However, waterborne erosion associated with intense rain fall and flood events in many cases reactivated sinkholes filled in that manner (Swart et al. 2003).

Tailings also entered the underlying karst aquifer via sinkholes occurring in slimes dams placed on dolomite. Slimes directly injected into the dewatered aquifer may act as potential source of U pollution once mining ceases and groundwater tables recover. Using geochemical modelling Dill & James (2003) estimate that seepage from tailings material filled into sinkholes may contain U concentrations between 60mg/l and 310mg/l.

Summary and conclusions

Hosting large volumes of scarce groundwater close to the extremely water-stressed metropolitan areas of Johannesburg and Pretoria, dolomitic karst aquifers in the Far West Rand are of increasing significance as future sources of water supply. However, impacts of deep level gold mining on water availability and quality currently restrict the utilization of these resources. While the cessation of mining and rewatering of dolomitic compartments might cause water availability in the Far West Rand to improve, water quality is likely to remain poor.

The presented analyses of potential U-sources associated with mining suggest that, over time, the significance of different sources for the overall pollution changed. While many contributions to pollution from point sources of U-contamination ceased or will cease, those from many non-point sources will remain significant in the medium to long-term future. This is especially true for seepage from extensive deposits of uraniferous tailings often impacting directly on groundwater. This is of particular concern since high flow rates and low adsorption capacity typical for karst systems allow for far-reaching downstream transport of contaminants. Owing to close interactions between groundwater and surface in dolomitic regions this is also associated with the pollution of surface water systems currently used for drinking water supply (Winde 2005).

In addition, groundwater decanting from the flooded underground mine may in future contribute considerably to U-pollution of surface water. In the head water region of the WFS acidic groundwater currently decants from a flooded mine void with considerably elevated U-levels. Assuming that pre-mining spring flow at all dewatered dolomitic compartments will be re-established after all mining in the area ceased, approximately two thirds of the future dolomitic spring flow into the WFS (some 133Ml/d) will consist of contaminated groundwater decanting from mine voids of the four rewatered compartments. With current pumping rates in these compartments significantly exceeding rates of pre-mining spring flow, considerably higher decant volumes (some 230Ml/d) are possible (Winde 2005).

In view of the different spatial and temporal characteristics of mining-related sources contributing to U-pollution in dolomitic aquifers, further research into transport mechanisms in karst aquifers with very complex surface and groundwater interactions and into associated health risks for downstream user is needed. Based on this strategies on how to manage these important water resources after mining have ceased can be developed.

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