Peat deposits as natural uranium filters? - First results from a case study in a dolomitic gold mining area of South Africa

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Abstract. Associated with a karst spring which drains a large system of interconnected dolomitic aquifers the studied peatland is the single most important water source for a downstream municipality. Owing to the reported ability of peat to remove U and other heavy metals from polluted waters it is anticipated that the GMB peatland may potentially serve as a natural buffer between polluting mines upstream and downstream users. Based on long-term water quality trends, real-time observations and geochemical data indications for U-pollution at the peatland are presented and associated sources, pathways and transport mechanisms discussed.

Introduction

Peat consists of partially decomposed wetland plants accumulating in waterlogged environments where complete mineralization cannot be achieved. With 99 % of all known peat deposits being located in humid regions of the northern hemisphere peat in southern Africa is a generally scarce resource. This is particular true for the semiarid interior plateau of South Africa where the studied peatland is located. The peatland owes its existence mainly to a strong perennial discharge of groundwater from the Gerhard Minnebron (GMB) Eye (spring) and can thus be classified as a karst fen. The water is mainly used by local farmers and feeds into the domestic water supply system of Potchefstroom with some 300.000 people.

The GMB eye is one of the lowest lying outflow points of an extensive system of interlinked dolomitic karst aquifers (called ‘compartments’) a number of which is severely impacted on by deep level gold mining operations. Apart from large-scale dewatering of three of the compartments which lowered the groundwater table by up to 1000 m in places this also includes pollution of dolomitic groundwater through filling caves and sinkholes connected to the aquifer with uraniferous tailings, discharging polluted effluents into the Wonderfonteinspruit (WFS) as main drainage of the dolomites as well as through significant volumes of seepage flowing from tailings deposits directly into the underlying karst aquifer. While the possibility of mining-related water pollution of the GMB spring has been discussed in previous studies, the actual extent, exact sources as well as pathways and mechanisms are still largely unknown (Wolmarans 1978, Grundling 2002, Bredenkamp 2007).

Using C^{14}-based age determination fairly consistent accumulation rates of around 0,3mm/a were found with the oldest sample at 4,5m depth dating back almost 11.800 years. Since 1993 an estimated 60% of the peat has been extracted from the wetland mainly for mushroom production (casing substrate) and as enhancer for horticultural soil. In view of the rapid destruction of a potentially beneficial resource the Department of Water Affairs and Forestry (DWAF) commissioned a study to assess associated environmental impacts (Winde 2007).

Of particular interests in this regard is a potential function of peat to buffer possible mining-borne pollution through its widely reported ability to remove U and other contaminants from the water phase (Owen and Otton 1995; Brown *et al.* 2000, Ringquist and Oeborn 2001, Ringquist *et al.* 2001, Coggins *et al*. 2005, Van Roy et al. 2006). Such buffer function could be vital in a possible (worst case) post-mining scenario where the GMB eye is expected to be one of only three karst springs through which large volumes of highly contaminated mine water may surface from a vast system of flooded underground mine voids (Winde *et al.* 2006).

In this paper first results of the study are presented including a brief characterisation of the hydrogeological setting of the GMB peatland and potential U-loads affecting the associated karst aquifer. Based on this indications for U-pollutions as found in previous studies are presented and compared to own findings. The latter include a preliminary quantification of the total contribution of the peatland system to the downstream water supply system, geochemical data and *in-situ* observations of hydrodynamic processes including responses to events such as heavy rainfall.

Hydrological and hydrogeological conditions

The GBM eye together with the upper and lower Turffontein eyes is one of three major outflow points of dolomitic groundwater from a large karst aquifer called ‘Boskop-Turffontein Compartment’ (BTC). This compartment is the largest and lowest lying one in a succession of several others located further up in the Wonderfonteinspruit (WFS) catchment. Separated from each other by near impervious, north-south trending syenite and dolorite dykes these compartments used to feed large volumes of dolomitic groundwater via so-called eyes (karst springs) into the WFS as reflected in its Afrikaans name (‘Miraculous Fountain Stream’). Originating south of the sub-continental divide near Krugersdorp the 90 km-long WFS runs over approx. 80 km across several dolomitic compartments to finally join the upper Mooi River. The GMB peatland, however, falls outside the (surface) catchment of the WFS and feeds via an unnamed stream (here called GMB-stream) also in to the upper Mooi River, some 4 km upstream of Boskop Dam as main reservoir for the water supply of some 300.000 people of the Potchefstroom municipality (Fig. 1).

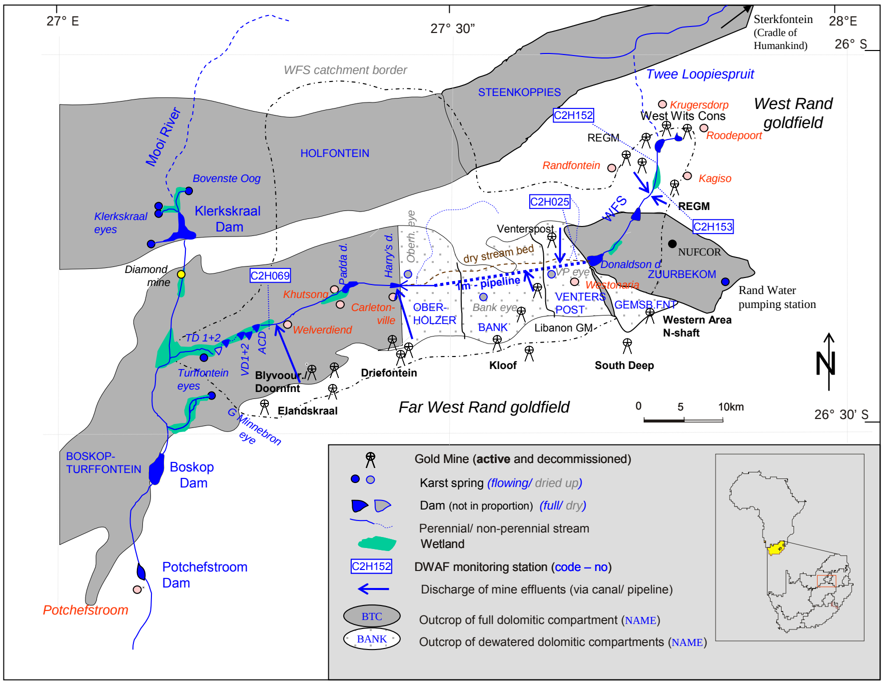

Fig. 1: The Study area

Most of the groundwater is stored in the upper 40 - 100 m of outcropping Malmani dolomite in what is termed the ‘cavernous zone’. This zone consists of a network of caves and cavities interconnected by solutions slots, underground channels and fractures totalling a storage capacity which exceeds that of the full Vaal Dam (as second largest dam in SA) by several times. The 2,6 bn years old dolomite has been subject to exceptionally extensive karstification resulting in the five longest caves in southern Africa being in the WFS catchment and a number of eyes (karst springs) which are amongst the strongest in the southern hemisphere (Swart *et al.* 2003a and b).

Owing to large volumes of dolomitic groundwater pushing into underlying mine workings deep level gold mines soon embarked on the ‘dewatering’ of dolomitic compartments in order to reduce the excessive costs for pumping the water from depths of up to 3km back to surface. Dewatering was effected by pumping out more water from the receiving mine void than the karst aquifer could naturally be recharged lowering the groundwater table by up to 1000m in places. Consequences of the large-scale dewatering included the drying up of four springs with a total discharge of approximately 135 Ml/d as well as irrigation boreholes as predicted but also some unforeseen effects such as the wide-spread occurrence of sinkholes and dolines often with disastrous effects on people's live and infrastructure (Swart *et al.* 2003 b). During an above average wet period in the mid 1970s many sinkholes had formed right in the stream channel of the WFS diverting large volumes of stream water directly into the underlying mine void partly defeating the original purpose of dewatering. In order to counteract the increased recharge in 1977 the stream was diverted into a 32 km-long pipeline carrying the water across the three dewatered compartments (Venterspost, Bank and Oberholzer) to the non-dewatered BTC. From here on the WFS runs for the last 35km or so in its original stream bed (Fig. 1).

Currently gold mines pump approximately 113 Ml/d back into the WFS while using some of the abstracted groundwater for internal purposes such as tailings disposal.

Apart from severe impacts on the surface water system through the drying up of springs, diversion of stream flow and changing natural runoff characteristic, deep level gold mining also irreversibly changed the hydrogeological system by mining through the dykes that compartmentalise the aquifer.

With more than 43km of tunnels, through fares etc. running through dykes mining hydraulically linked previously separate compartments (derived from Swart *et al.* 2003a). This also applies to the full (non-watered) BTC which is now connected to three dewatered compartments upstream forming one single Mega-compartment'. In a future rewatering scenario this results in the final water level being controlled by the elevation of the lowest lying springs i.e. the two Turffontein eyes, the GMB eye and possibly some smaller eyes near Boskop dam. With the GMB spring being the largest low lying spring it will form a major decant point for polluted mine water, which after the cessation of mining and subsequent rewatering, will emanate from the vast network of flooded mine voids. While the three springs together currently yield a total of approx. 80 Ml/d (of which close to 80% come from the GMB eye) this could well rise to over 200 Ml/d. Judged by the extreme poor water quality of water decanting from the flooded mine void in the head water region of the WFS where pH values <2 and U-concentrations of 16 mg/l have been measured, such concentrated outflow could have catastrophic consequences for downstream water users and the environment (Winde *et al.* 2006).

Analyses of recent satellite imagery have revealed that the WFS over the past few years did not reach the Mooi River but dried up some 12 - 16 km upstream of the confluence. Entering the BTC with an average flow rate in the region of >100 Ml/d it is suspected that most of the stream water is lost to the underground karst aquifer in the form of so-called 'bed loss' recharging the BTC (losses through evaporation are assumed to be counterbalanced by sewage effluent discharge from several municipalities such as Carletonville, Khutsong and Welverdiend).

It was further established that the GMB spring is not the only source of water for the downstream peatland but that artesian groundwater discharge in the upper part of the wetland through sub-aquatic springs and diffuse seeps also contributes significantly. With approximately 100 Ml/d this contribution is of the same order of magnitude as the actual spring flow rendering the GMB peatland system the single most important water source for Potchefstroom (Winde 2007).

In view of the relatively high levels of U-pollution detected in the WFS catchment (IWQS 1999, Wade *et al.* 2002, Coetzee *et al.* 2002, Du Toit 2006, Barthel 2007, Coetzee *et al*. 2006) such filter function may be of importance under current conditions. Under the extreme conditions of the above-mentioned worst case re-watering scenario, however, it is questionable whether the remaining peat deposits at GMB could retain any significant amount of the large contaminant load, which in the case of U alone could initially amount to approximately 1000 kg/d (100 Ml/d at 10 mgU/l). Given the very limited hydraulic conductivity of peat it is also questionable whether volumes totalling >200 Ml/d could effectively filter through the peat in the first place.

Uranium pollution: extent, sources and pathways

The Wonderfonteinspruit

U in the WFS area mainly originates from mined gold reefs (ore bodies) where it is associated with Au. Owing to above average U-grades compared to other (also low grade) ore bodies in SA many gold mines in the West Rand and Far West Rand also produced U as a by-product. Recently local gold mines receives competing offers from various national and international interest groups participating in the current U-renaissance to rework their tailings dams and extracting U. While uraniferous slimes dams (as tailings deposits are called in SA) were generally seen as an environmental liability in the past with not much reference to the actual U-levels being made, they are now perceived as assets highlighting their above-average U-grades (Hill 2007, 2008 a and b).

This coincides with mining related U-pollution in the WFS catchment receiving extraordinary media attention often sensationalizing alleged health effects on residents, downstream water users, animals and crops. While effects of U-pollution on health are still largely un-quantified and mainly based on anecdotal and circumstantial evidence sound scientific evidence exists for the significantly elevated levels of U especially in aquatic environment of the WFS catchment (Faanhof *et al.* 1995, Kempster *et al.*, 1996, IWQS 1999, Wade *et al.* 2002, Coetzee *et al*. 2006, Du Toit 2006, Barthel 2007).

An overview of U concentrations as found in a screening survey is shown in Fig. 2.

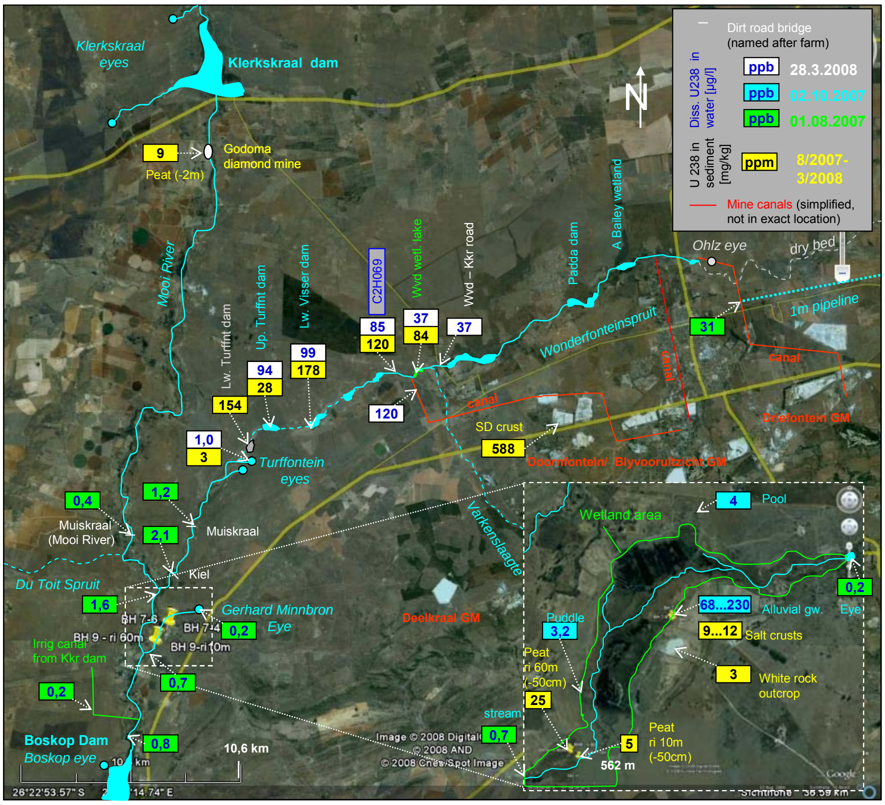

Fig. 2: Uranium concentrations in water and sediment samples taken during screening surveys conducted between August 2007 and March 2008 (map base: Google Earth, 14.6.2008)

In case of bed loss from the WFS constituting a major water source for the BTC the possibility of associated U-pollution of the receiving aquifer is a major concern. In the most comprehensive study to date in terms of water analyses, weekly water samples (later monthly) were taken over a period of a full year at several point along the WFS. Maximum U-concentration detected in stream water of the WFS ranged from >400µg/l in the head water region (C2H152) to >200 µg/l in the lower WFS (C2H157) (Fig. 1). U-concentrations in mine effluents, as a major U-source reached up to 2600 µg/l (IWQS 1999). A survey conducted as part of the project between August 2007 and March 2008 confirmed that little has changed regarding the overall patterns of water contamination along the WFS (Fig. 2).

Owing to the diversion of approx. 30 Ml/d of highly polluted decant water from the flooded mine void of the West Rand goldfield (also known as 'Western Basin') into the WFS (after treatment) U-levels in the head water region recently rose again resulting in an estimated 1400 kg U/a (60 µg/l at 65 Ml/d) being exported via the 1m-pipeline directly onto the BTC (based on data from Dorling 2008). Compared to a load of approx. 500 kg/a in 1997 (31,4 µg/l at 45 Ml/d) this is an increase of some 900 kg U/a (IWQS 1999). The contribution from decant water is in addition to U originating from mining residues that cover a large proportion of the head water catchment.

Right where the WFS starts flowing on the BTC it receives a second major U-input in form of mines effluents from the Driefontein gold mine adding another 1200 kg U/a (estimated based on average U-concentration of 126 µg/l in 1997 as per IWQS 1999 and an exceptionally low discharge of only 26 Ml/d in this year). Based on the normal discharge of some 50 Ml/d the associated U load is well over 2300 kg/d.

The last direct U-input into the WFS is received via two canals from the Blyvooruitzicht and Doornfontein GM area discharging mine effluents as well as stormwater run off. The latter frequently also carries considerable amounts of eroded tailings material. Based on 2008 data this area adds some 400 kg/a to the total load of the stream (120 µg/l at 10Ml/d). Counting only the U-input associated with the direct discharge from the three major mining areas mentioned the WFS receives over 4000 kg of dissolved U per annum.

In view of the recent discovery that most of the time the stream flow does not reach the Mooi River it can be concluded that all of the received U must either be stored in the fluvial systems (i.e. immobilized in aquatic sediments and floodplain soils etc.) or be diverted into the karst aquifer underlying the stream bed or both. Several sampling programmes recently conducted in the lower WFS indicated that significant amounts of U indeed accumulated in fluvial sediments especially in dams downstream of Welverdiend (Fig. 1). With close to 1000 ppm U such sediments by now display higher U-levels than the mined ore and the tailings as original sources of the U-pollution. Winde (2006 b) discusses a number of site-specific mechanisms enabling shallow farm dams to remove dissolved U from stream water more effectively than other parts of the stream resulting in above average sediment contamination. Sediments in the Coetzee dam downstream of Welverdiend contain an estimated 6t of U (based on data in Coetzee *et al.* 2002). Compared to the estimated load it received over the past 40 years of its existence (some 64t, 100 µg/l at 44 Ml/d) this constitute approx. 9 % of the total U-influx. Owing to site specific peculiarities it is likely that this rate of U-immobilisation is exceptionally high compared to other parts of the fluvial system. With most of the >100 Ml/d of the WFS stream flow gradually disappearing into the cavernous dolomite it can thus be estimated that some 90 % of the U-load also enter the BTC aquifer (i.e. 10 % are retained in sediments). This would result in close to 2200 kg of dissolved U polluting the dolomitic groundwater of the BCT.

Boskop-Turffontein Compartment – Gerhard Minnebron peatland

With an est. 400km² of surface catchment area and corresponding groundwater recharge potential the BTC has an appreciable potential to dilute U-inputs from the WFS (Winde 2007). However, data for the Turffontein eyes, which are the closest to the WFS channel system and thus most likely to be affected first, suggest that U-levels are temporarily elevated to 10 - 20 times the natural background level reaching maxima of up to 7 µg/l (average 0,9 µg/l; n = 31; IWQS 1999). Moreover, in our screening survey it was found that the U-concentrations steadily increase downstream of the eye from 1µg/l to 2,1µg/l possibly through contributions of groundwater diffusely exfiltrating in the lower lying parts of the stream channel near the confluence with the Mooi River. U-concentration measured in a weekly monitoring program of the Blyvooruitzicht GM for the period February 2003 to March 2006 displays significantly higher U-levels fluctuating from 1 to 172 µg/l. On average the groundwater-fed stream in this lower part of the BTC contained 13 µg/l (n = 105) (Blyvooruitzicht GM 2008). With 18,7 µg/l an even higher U-level was measured in 1997 at the nearby station C2H161 (at Muiskraal bridge, Fig. 2) in 1997 (IWQS 1999). This constitutes an estimated U-load of >200 kgU/a (est. flow rate of 30 Ml/d), equaling some 5% of the estimated load the BTC receives further upstream through seepage from the WFS. The wide range of U-levels at this point fluctuating between 2,9 and 104 µg/l could be indicative of an event-driven pollution regime. This is supported by most U-peaks occurring during the rainfall season (Fig. 3)

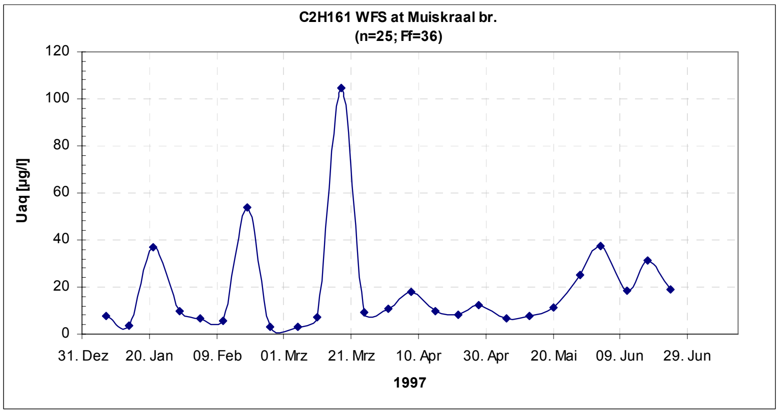

Fig. 3: Dynamic of U-concentration of exfiltrating groundwater in the lower WFS (Muiskraal bridge, C2H161; Data source: IWQS 1999)

In the absence of flow data U-concentration in the different stream components can be used to assess mixing ratios. With 1,6 µg/ l U in stream water after the confluence with the Mooi River the contribution of water from the WFS catchment is close to 75% of the total flow in the combined stream (at the time of sampling) and this despite the fact the WFS dried up well above the Turffontein springs. It is therefore likely that in the confluence area additional groundwater discharge from the BTC occurs which increases stream flow in the lower Mooi River. Such discharge of groundwater is also suggested by satellite imagery showing significantly darker wetlands commonly associated with inundated areas (Winde 2007).

Originating from the oxidation of sulphides in mined reefs sulfate is commonly used as an indicator for mining-related impacts. With sulfate being dominant in many mining-impacted waters close relations exist between sulfate concentrations and EC. However, relying only on the EC might be misleading in instances where decreasing sulfate levels are compensated by other salts from alternative sources. Using therefore the proportion of sulfates on the total concentration of dissolved solids (TDS) Fig. 4 indicates continued deterioration of water quality at the upper Turffontein eye at least since 1979 (when the monitoring started) with a first peak in 1967. From the mid 1980s, however, water quality started to improve.

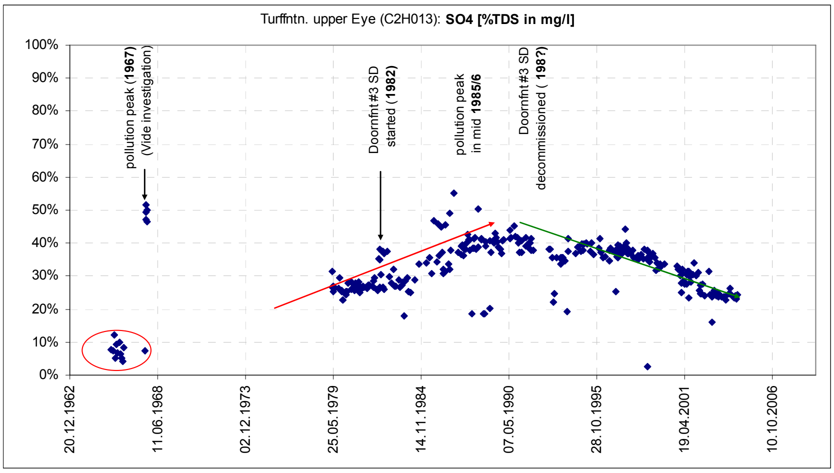

Fig. 4: Changes in the proportion of sulfate at the Turffontein upper eye as indication of mining-related impacts on groundwater quality in the BTC (Data source: DWAF)

Higher levels of mining-borne pollution in the past may have been associated with higher levels of U-pollution as well. A possible means of indirectly detecting such historic pollution peaks is the analyses of sediments which act as geochemical memory of the river. More importantly though it needs to be analysed what the actual reasons for the improvement are as this could help to identify exact sources and pathways of U-pollution. It has also been suggested that the commissioning and decommissioning of a nearby slimes dam at the Doornfontein GM coincides with the deterioration and improvement respectively of the spring water (Stoch L 2007 personal communication). Should this be correct it could provide an opportunity to not only identify sources of U-pollution other than the WFS (i.e. individual slimes dams in this case) but also alternative underground pathways within the karst system.

In this context it is important to note that slimes dams in the area are frequently covered with a greenish-yellowish crust which in case of a SD at Blyvooruitzicht contained 588 ppm U. Readily dissolvable on contact with water these crusts are a major U-source for polluting surface run off from slimes dams. In view of the fact that drainage lines downstream of the Doornfontein slimes dams are dotted with open sinkholes a rapid transport of highly polluted stormwater via sinkholes directly into the underlying karst aquifer is possible.

At the GMB eye a similar tendency of the water quality is discernable albeit at a generally lower level. Weekly monitoring data from DWAF covering some 40 years suggest that the sulfate proportion at the GMB eye steadily increased indicating increasing impacts of pollution from upstream mining (Fig. 4).

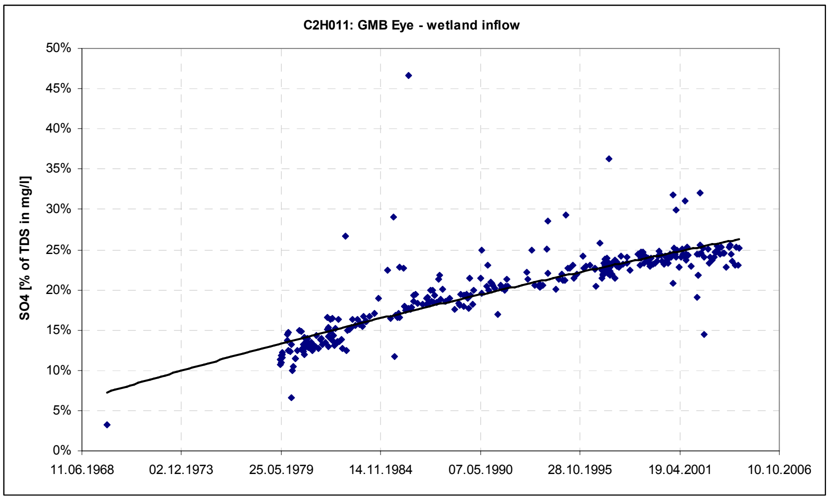

Fig. 4: Proportion of sulfate at the GMB eye as indication of mining-related impacts on groundwater quality in the BTC (with logarithmic trend line added) (data source: DWAF)

Wolmarans (1984) suggested in this context that seepage from the polluted WFS forms a pollution plume below the stream bed which gradually mixes with underlying groundwater on its way towards the lower lying GMB eye (even though this falls outside the surface catchment of the stream). Owing to the associated dilution, advection and dispersion pollution levels at the GMB eye are considerably lower than in the stream. Since the Turffontein eyes are located directly in the stream channel of the WFS such plume would naturally effect them first which is consistent with the fact that EC levels at GMB in 1969, i.e. 2 years after first pollution peaks occurred at Turffontein, still indicate pristine conditions. Owing to a gap in monitoring data it is not possible to determine when exactly water quality at GMB started to deteriorate. In 1979 when monitoring was re-started SO_4-levels had already risen considerably from 3 % of the TDS to well over 10 % and continue to do so ever since. With current levels of 25 % of the TDS SO_4-levels at GMB are still below the maximum of >40 % reached at Turffontein eyes some 20 years ago (Fig. 4). At EC maxima of 75 - 80 mS/m (750 - 800 µS/cm) and SO_4 levels of >20 % TDS water quality is now approaching levels at the Turffontein springs. However, in contrast to Turffontein no clear tendency of improvement is yet discernable even though the increase seem to follow a logarithmic function starting to flatten out (Fig. 4). This could be indicative of a slow moving plume which already passed Turffontein and whose centre (i.e. the most polluted part) is now approaching GMB. Should the trend of flattening continue it seems possible that GMB may reach the turning point (i.e. the maximum pollution from where on water quality improves again) below the peak pollution level of Turffontein, i.e. with SO_4 levels well below 40 % of the TDS. This, in turn, would be consistent with the higher dilution through unpolluted groundwater at GMB which has a significant larger flow rate than the Turffontein eyes.

Data from IWQS (1999) suggest that U-levels at GMB in 1997 were still mostly around 0,4 µg/l and thus in the region of global U-background values for (discharge-unweighted) freshwater (DWAF 1996). However, on at least two occasions U-levels in the weekly samples increased significantly reaching a maximum of 2 µg/l (i.e. 500 % of its normal U-concentration) (Fig. 5).

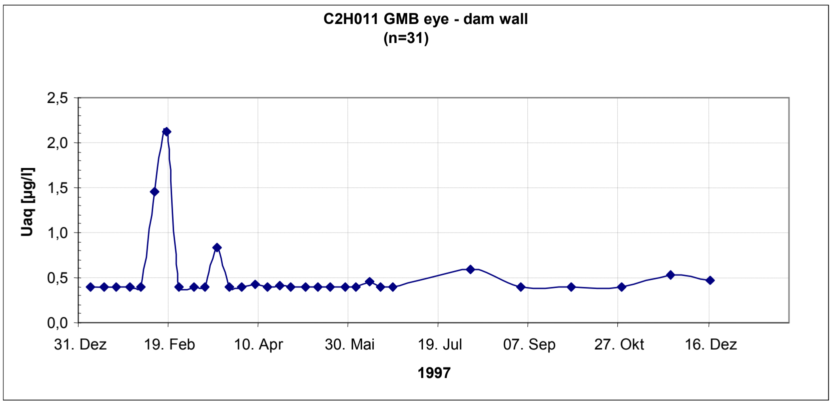

Fig. 5: U concentration at the GMB eye (data: IWQS 1997)

While such isolated peaks could possibly be ascribed to analytical errors and treated as irrelevant outliers real time *in-situ* observations of water quality in the spring suggest that such peaks may indeed occur as a result of storm events in the area. Changes in pH and EC at the GMB eye in response to a storm event observed through *in-situ* datalogger clearly indicate a drop in pH and a corresponding rise in EC some 6d after the rain storm. Given that acid mine drainage causes exactly the observed changes (dropping pH due to high acidity and rising EC due to high salt load esp. sulphates) this could well indicate a rainfall-triggered impact by upstream mines. Acid rainfall which also lead to dropping pH values even in well-buffered dolomitic water (Winde *et al.* 2004) can be eliminated as cause of the observed response since this is accompanied by dropping EC values (quasi 'distilled' rain water with low mineral content). Such rather isolated events may also explain the six exceptionally high EC values at GMB found in the monthly monitoring program (Fig. 4).

These relative low U-concentrations at GMB are confirmed by Grundling (2002) reporting U-levels in grab samples of water from the GMB wetland ranging from 0 to 1,5 µg/l (n = 5) corresponding with in/ near-stream sediments (not peat) displaying between 4 and 40 ppm U (n = 3). Derived from semi-quantitative ICPMS scans the sediment concentrations are likely to contain a significant analytical error. A similar range of U-levels was found by Smuts (1997) in peat from the GMB wetlands ranging from 5ppm (3,25 m below surface) to 15 ppm in 4 m depth and the maximum of 35 ppm in 2,8 m depth. With no clear depth gradient it remains unclear in how far this relates to the rather recent mine pollution given that peat at 4m depth formed some 11,000 years ago. In order to determine the extent to which surface and/or groundwater may move through undisturbed peat *in-situ* porewater dynamics in peat are currently observed using quasi-continuous datalogger controlled measurements in two different transects comprising a total of nine boreholes.

Longitudinal profiles of water quality parameters in the wetland revealed that generally the quality of water deteriorates as it flows through the wetland displaying considerably higher EC values at the outflow than at the eye. The total salt load increases by some 6t/d, while the U-concentration more than triples rising from 0,2 to 0,7 µg/l. Owing to the drastic increase of flow associated with the discovered sub-aquatic groundwater discharge in the upper reaches of the wetland the U-load increases by a factor of 35 (2 to 70 g/d). With a total export of approximately 26 kg U per year the peatland would contribute less than 10% of the total U-load reaching Boskop Dam (>200 kg come from the Turffontein eyes area) as main drinking water reservoir for Potchefstroom. While this is still a relatively small pollution load compared to several tons of U per year found in the WFS it may indicate a future problem.

In view of the frequently reported ability of wetlands and peatlands in particular to aid the natural purification of polluted water this finding is somewhat unexpected. It was further found that at a number of sites poor quality groundwater enters the wetland from its fringes (Fig. 2). In an un-mined area with no peat deposits present located between two peat mining operations shallow groundwater was found displaying EC values of 3000 to 6000 µS/cm which even exceed EC-levels in tailings seepage of the upstream mining area. This water also contains between 50 and 70 µg/l U which rose to 230 µg/l after the first spring rain (Fig.2). Why the influx of (clean) rainwater resulted in an increase of U in the near surface part of the groundwater is not entirely clear. One possibility is the dissolution of salt crusts (mainly consisting of $MgSO_4$ and some 5% of NaCl) which formed during the dry winter period over large areas on dry vegetation and sediment. Containing 9 to 12 ppm U the redissolution of these crusts may well have resulted in higher U-levels in near surface groundwater.

Similar salt crusts with an increased proportion of NaCl (>30%) were found in the unmined part of the peatland near a groundwater puddle containing 3,2 µgU/l (Fig. 2). Elevated U-levels (4 µg/l) were also detected in water of a pool near the northern bank of the upper peatland ('willow seep pool', Fig. 2). This fits in a trend of steadily increasing U-concentration in groundwater surfacing along or near the drainage line downstream of the Turffontein springs: 1,0 ppb (Turffontein upper eye) --> 1,2 ppb at Muiskraal --> 2,1 ppb at Kiel --> 4 ppb at GMB willow seep and 3,2 ppb at GMB lower part of the wetland port 9. This again appears to be quite different from groundwater at the GMB eye which has on average a U-level which is about ten times lower. However, with a 5-6 day delay after rain events similar high U-concentration sporadically occur.

Summary and conclusion: Hydrogeological model

Despite the sketchy data and large uncertainties a first approximation of a hydrogeological model is attempted in order to synoptically combine available information. The following, preliminary model therefore is a mere tool for further research than for making predictions of any kind.

Running some 25 km or so over cavernous dolomite of the BTC the WFS loses more than 100 Ml/d on average to the underlying aquifer. Owing to U-pollution that originates from several gold mining areas this is associated with a U-load of some 4 t/a affecting groundwater in the BTC as the single largest resources supplying Potchefstroom municipality. Apart from three distinct outflow points in the form of karst springs (Turffontein and GMB eyes) large areas of diffuse groundwater discharge exist in lower lying areas around the confluence of the Mooi River and the WFS as well as the GMB peatland. Groundwater discharged in these low lying areas (i.e. stratigraphically deeper sourced groundwater) displays higher U-levels than (more shallow) groundwater discharged at higher levels e.g. at the GMB eye. Apart from a possible internal stratification of groundwater within a karst channel (i.e. lighter, unpolluted rainwater floats on top of denser, polluted groundwater) such vertical differentiation could also be caused by groundwater moving in separate karst channels developed on top of each other at different depths. For the WFS catchment at least three of these levels have been found (Erasmus E, personal communication, 2006).

However, with a lag of 5 - 6 days intense rain events in the upstream catchment also seem to cause pollution of the more shallow groundwater. With easily dissolvable and highly uraniferous salt crusts covering many slimes dams stormwater runoff from tailings entering nearby sinkholes is a possible explanation for such event-related pollution. These sinkholes are located well above the stream channel of the WFS and could link to a karst system on a higher level which is only activated after rainfall feeding highly polluted runoff to the Turffontein and GMB eyes. With a distance of some 18 km and a time lag of 6 days in the case of GMB (for Turffontein no high resolution time series are available) this would require an average flow speed of some 3 km/d (3,3 cm/s) which does not seem unreasonable for flow in a multiporosity karst system. Such direct link between slimes dam run off, sinkholes and springs would also explain the many U-peaks observed at Turffontein (Fig. 3).

In this context it needs to be stressed that karstification of dolomite is confined to the outcrop of chert-rich formations. According to Erasmus E (2008, personal communication) interlayered sequences of chert-rich and chert-free formations in a gently south dipping column possibly resulted in three to four hydraulically largely disconnected karst systems running more or less parallel to the WFS separated from each other by unweathered chert-free dolomite and up-faulted low permeable quartzite lithologies underlying the dolomite. In such a system it is conceivable that different sources affect different parts of the aquifers in the same compartment without necessarily interacting with each other.

The superimposition of vertical pollution gradients within the groundwater of the BTC with horizontal differences in the density of U-sources impacting on the individual quasi-parallel channel systems could explain the observed large differences of pollution levels between different locations in the same compartment. The existence of hydraulically disconnected sub-systems within the karst aquifer could for example explain the isolated occurrence of an area with almost pristine groundwater found at the northern banks of the upper GMB wetland in direct neighborhood to groundwater at much lower quality.

What remains unclear, however, is the origin of the highly polluted groundwater found at the left bank between the two peat mining operations. Owing to the extremely elevated EC it is unlikely that a distant mining source is responsible. Currently investigations are underway to explore if a nearby outcrop of anomalously deeply weathered carbonate could be a potential natural U-source.

U-levels in the peat at GMB indicate above natural background levels of U in certain areas without displaying clear spatial patterns. So far it seems that higher than mean earth crust U-levels found in peat samples (5-10 ppm) are mainly of naturally origin since such levels were also found in peat from the upper Mooi River (Fig. 2) not impacted on by gold mining.

In exceptionally wet years it was observed that the WFS reaches the confluence with the Mooi River. Together with water from the non-perennial du Toit Spruit (Fig. 2) entering the system near the confluence this may even result in an overland inflow of flood water into the GMB peatland. Such inflow however is unlikely to be a major source of U-pollution owing to the large dilution by unpolluted runoff from non-mining areas.

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