URANIUM POLLUTION OF WATER RESOURCES IN MINED-OUT AND ACTIVE GOLDFIELDS OF SOUTH AFRICA - A CASE STUDY IN THE WONDERFONTEINSPRUIT CATCHMENT ON EXTENT AND SOURCES OF U-CONTAMINATION AND ASSOCIATED HEALTH RISKS

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ABSTRACT

Even though mining-related uranium pollution in the Wonderfonteinspruit (WFS) has been an ongoing concern since the mid 1960s, media attention recently increased considerably focussing on pollution-related health risks that unsettle the general public. In view of recent findings that uranium (U) might be more toxic than previously thought such concerns need to be addressed. This even more so as South Africa has embarked on a nuclear expansion program aimed, amongst others, at extending mining and processing of uranium (U). This paper explores the impacts mining over the past decade had on U-pollution of water resources in the WFS catchment. The analysis is mainly based on close to 3400, mostly unpublished, values on U-concentrations of water samples gathered between 1997 and 2008. Results indicate that U-levels in water resources of the whole catchment increased markedly since 1997 even though U-loads emitted by some large gold mines in the Far West Rand were reduced. This apparent contradiction is explained by the contribution of highly polluted water decanting from the flooded mine void in the West Rand. Over the reference period, an average of some 3,5 t of dissolved U have been released into the fluvial system from monitored discharge points alone. However, since WFS dries up well before it joins the Mooi River this U-load does not usually impact on the water supply system of downstream Potchefstroom directly. It may, however, indirectly reach Potchefstroom since much of the water from the WFS recharges the underlying karst aquifer of the Boskop Turffontein Compartment (BTC) as the single most important water resource for Potchefstroom. Compared to 1997 groundwater in the BTC showed the highest relative increase in U-levels of the whole WFS catchment resulting in some 800 kg of U per year flowing into Boskop Dam as Potchefstroom's main water reservoir. Of particular concern is the fact that U-levels in the WFS are comparable to those detected in the Northern Cape (South Africa) which had been geostatistically linked to abnormal haematological values related to increased incidences of leukaemia observed in residents of the area.

Keywords: Uranium, water pollution, load, gold mining, karst, dolomite, health risks, Wonderfonteinspruit, West Rand, Far West Rand

1. INTRODUCTION: 'DEATH IN THE WATER'

With the above headline on its front page the SOWETAN, in July 2007, drew the attention of its readership to the radioactive water pollution of the Wonderfonteinspruit (WFS). Together with well over 50 articles which appeared between 2007 and 2008 on this topic alone covering double, full and front pages of local and national newspapers, the article illustrates the degree of media attention pollution of the WFS received. The increased awareness on potential dangers associated with U in South Africa coincides with a globally renewed interest in uranium as a climate-neutral source of energy fuelled by an ever widening gap between increasing demand and constant supply. Consequently, the U-spot price rose tenfold between 2003 and 2007 triggering large-scale exploration efforts to find new U-deposits in Africa and southern Africa in particular. During more than a century of gold mining in the catchment of the Wonderfonteinspruit (WFS) deep level gold mining brought more than 100000 t of U_3O_8 from depths of up to 3000 m, to the densely populated surface areas of the West Rand (WR) and Far West Rand (FWR) (Winde in press a and b). Since 1952, U-producing gold mines in South Africa exported a total of some 240000 t of U more than double that amount (ca. 600000 t) is estimated to still be contained in gold mining tailings covering some 400 km² in the Witwatersrand basin. These slimes dams and associated infrastructure such as return water dams, pipelines, metallurgical plants etc. together with unmined uraniferous ore in mine voids constitute a multitude of sources from which U migrates, mostly uncontrolled, into the environment. In addition to wind and water erosion of slimes dams transporting uraniferous tailings particles into adjacent areas, the chemical leaching of U from tailings particles and subsequent, waterborne transport as a dissolved phase into subjacent aquifers and nearby streams often constitutes the single largest source of mining-related water pollution. In mined out areas such as the West Rand and Central Rand of the Witwatersrand basin water flowing out of flooded mine voids may act as another major source of U-pollution affecting surface- and groundwater.

With evidence mounting that the radioactive heavy metal U may pose a more severe health risk than previously thought even at comparably low concentrations, a thorough analyses of the extent of U-pollution in the densely populated catchment of the WFS is needed. This paper attempts to provide a comprehensive overview on available data in order to quantify the extent of U-pollution in the WFS catchment and gain perspective for assessing possibly associated health risks. The focus is on the contamination of surface and groundwater as characterized by data from largely unpublished studies and includes first order approximations of associated U-loads in the WFS. The catchment of the WFS is shown in (Fig. 1).

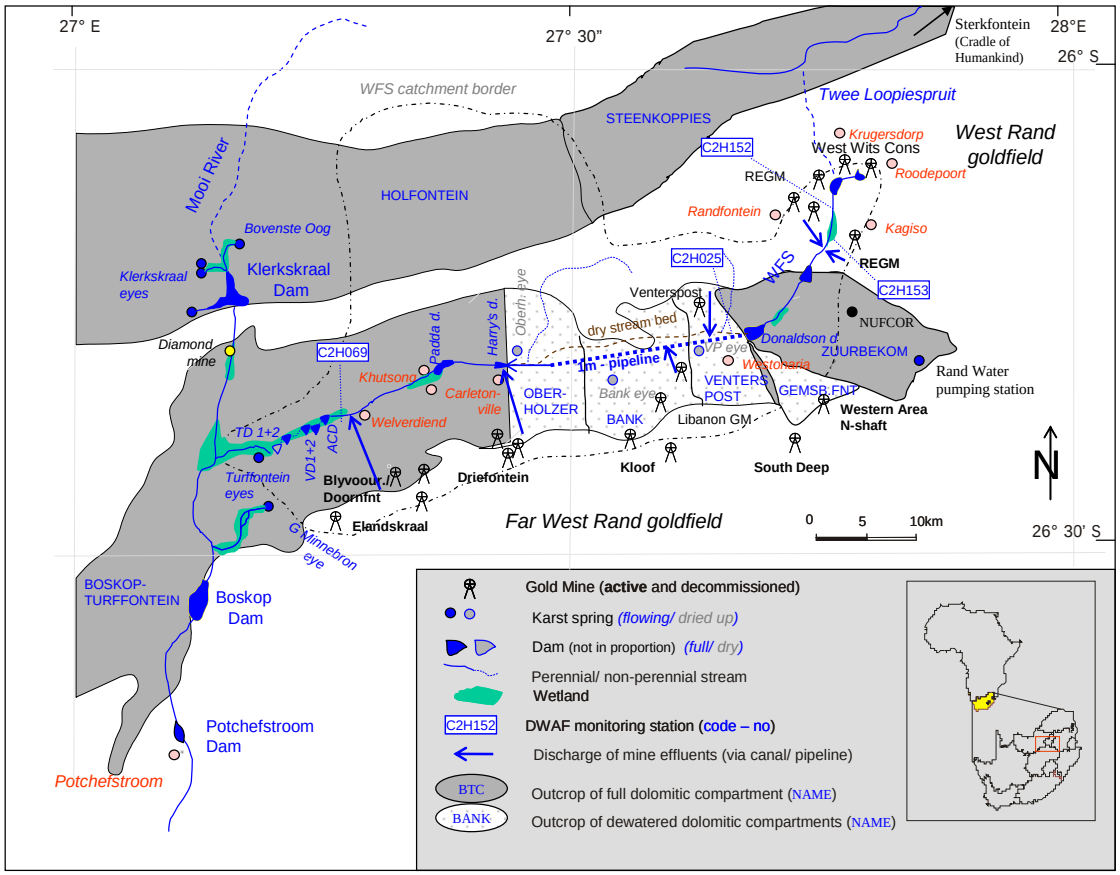

Figure 1. The Study area (VD – Visser dams, ACD – Andries Coetzees dam, d. – dam)

A detailed description of the relevant hydrological and geohydrological features of the study area are provided in Winde (in press a and b).

2. U-POLLUTION OF STREAM WATER IN THE WFS

Underlying data: The most extensive study on waterborne U-pollution in the WFS catchment conducted to date is IWQS (1999) which is based on several hundreds of water samples taken between January and December 1997 at 28 different sites across the study area. Taking IWQS (1999) as a baseline study on the extent of U-pollution of water resources in the WFS area, a second set of data sources is used to characterise subsequent changes. The DWAF started monitoring U-levels soon after completion of the IWQS study (DWAF 2004). For the upper part of the WFS these data are complemented by a more recent water monitoring program of Harmony Gold Mine (Dorling 2008). In the lower part of the WFS the monitoring program of the Blyvooruitzicht GM complements monthly U-data from DWAF with weekly U-analyses (Blyvooruitzicht 2008). A third monitoring program is conducted by the Potchefstroom municipality focusing on the lower WFS and the Mooi River in the vicinity of the municipal water works. For some of the monitored sites U-data gathered by various *ad hoc* investigations are also included (Barthel 2007, Coetzee *et al.* 2006, Coetzee *et al.* 2002, Winde 2000 & 2008). For calculating U-loads gauging records of the DWAF could be used for some of the sites while for others alternatives sources and methods had to be applied. A comprehensive overview of the data used and an assessment of their consistency and comparability is provided in Winde (in press a and b).

Extent of U-pollution in 1997: Fig. 2 depicts the average U-concentration for different sampling points along the WFS and selected mine effluent discharge points for the period January to December 1997.

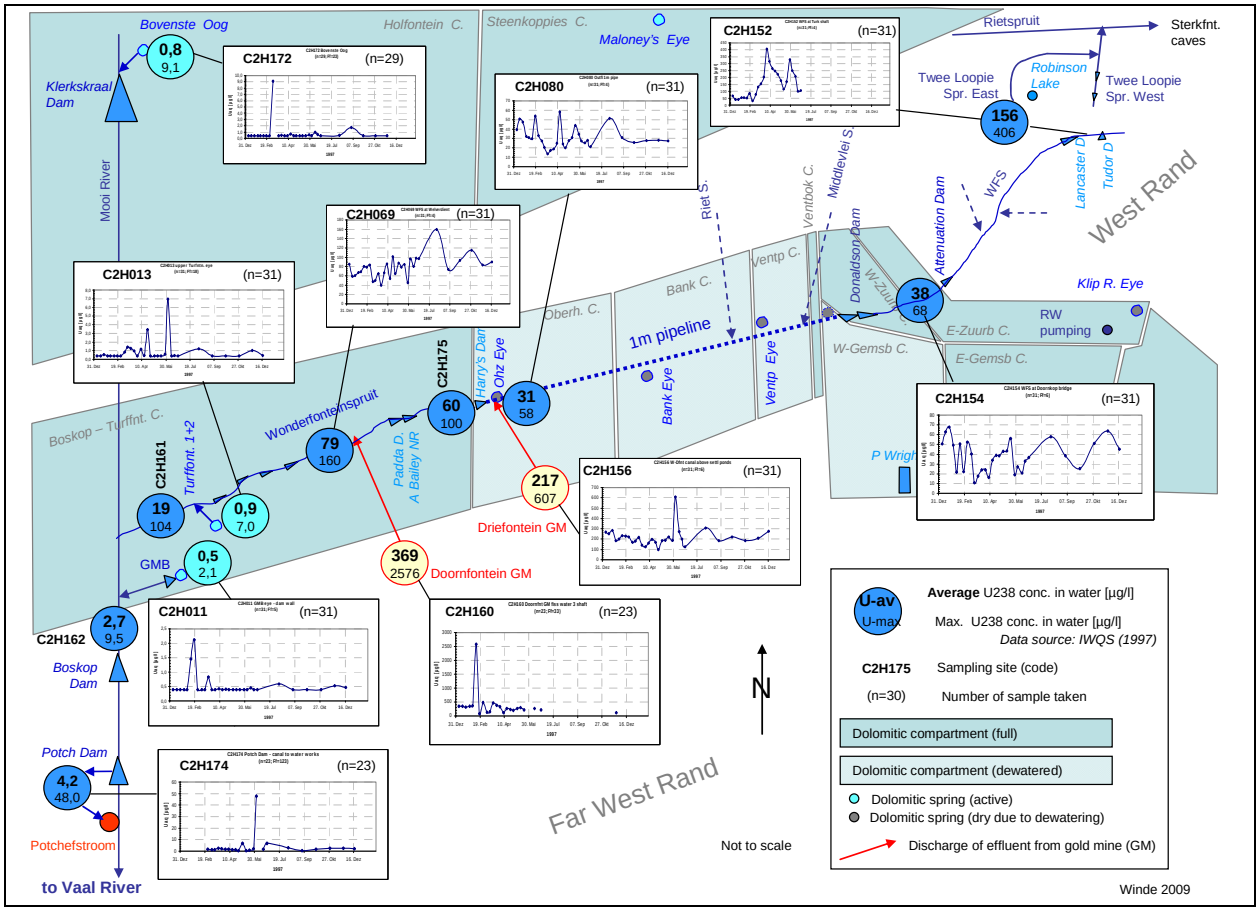

Figure 2. Schematic representation of average and maximum U-concentration in water as well as its temporal variability for selected sampling sites in the Wonderfonteinspruit catchment based on raw data generated during the IWQS (1999) study (raw data are not contained in cited report and had to be retrieved separately)

U-levels along the course of the WFS display distinct differences. By far the highest in-stream U-concentrations occur at site C2H152 right in the head waters illustrating the higher potential of the (older) WR goldfield for direct stream pollution. Owing to dilution by large volumes of mainly U-free sewage effluents the U-level in the WFS drops significantly before the stream enters the 1m pipeline.

After receiving discharge from Driefontein GM at the end of the 1m pipeline the U-level in the WFS doubles and further increases with effluents from two more gold mines (Blyvooruitzicht and Doornfontein) entering the WFS via canals. With 79 µg U/l the *average* U-level in the WFS at the outflow of the catchment exceeds the SA drinking water limit for most of the time. Compared to the regional natural background of 0,8 µg U/l measured at Bovenste Oog (C2H172), a dolomitic spring regarded as largely unaffected by gold mining, this suggests a mining-related increase of U-levels by a factor of 100.

While concentration values are commonly used to assess, for example, potential health effects they are not sufficient to quantify (long-term) impacts on the receiving environment. This is particular true for discharges containing non-biodegradable contaminants such as U and other heavy metals which tend to accumulate in sediments, soil etc. through secondary enrichment. In order to quantify the potential of U for such off-site enrichment the total mass of discharged U ('U-load') needs to be determined. Loads associated with the above discussed U-concentrations are displayed in Fig. 3.

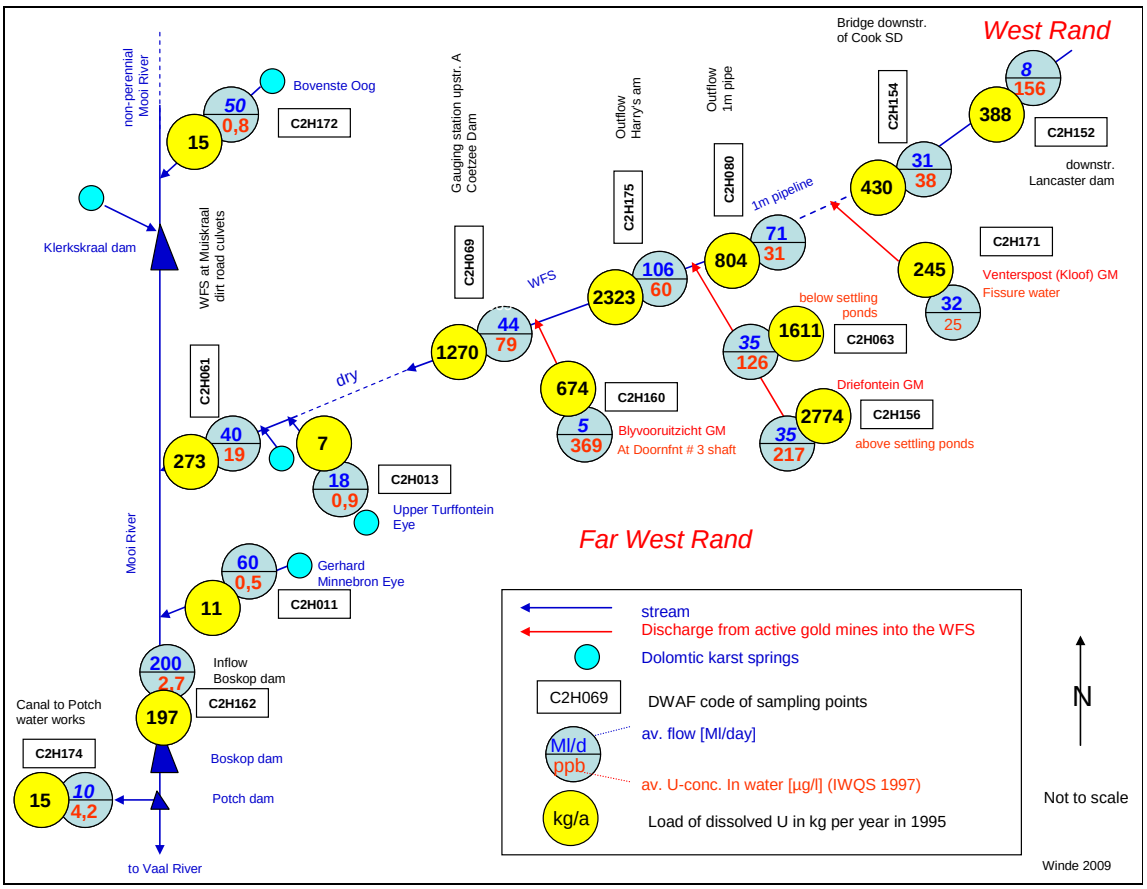

Figure 3. Estimated loads of dissolved U (i.e. not including U bound to particulate matter such as suspended sediment, spilled and eroded tailings or windblown tailings dust) in the WFS based on U-concentrations measured in 1997 (IWQS 1999)

While based on U-concentration the WR appears to be the main source of stream pollution (the highest U-levels are found in the upper reaches of the WFS) this changes when U-loads are used as base of comparison. Load values indicate that mines in the FWR release significantly more U into the WFS than all sources in the WR together (Fig. 3). Considering only U released from the three monitored mine discharge points in the FWR (there are others which are not monitored or monitored but not included here) a total load of over 3,6 t U per year was discharged into the river. While being transported in the river parts of the dissolved U are attenuated in sediments especially those of shallow farm dams where specific conditions promote above average U-immobilization as pointed out by Winde (2006). However, such quasi-natural U-removal contributes only marginally to the general decrease of the U-load observed between Harry's dam (C2H75) and gauging station C2H069 that amounts to almost 1800 kg U per year (2323 kg/a leaving Harry's dam plus the 674 kg/a the stream receives from Blyvooruitzicht GM) (Fig. 3). Most of the 'loss' is due to a significant reduction in flow (from some 106 Ml/d at Harry's dam to an average of 44 Ml/d at C2H069) rather than decreasing U-concentration. In the absence of large-scale water abstraction the cause of this drastic flow reduction still needs to be researched. Especially since the extent of stream loss appears to have increased in recent times. In 2005, close to 90% of the water (89 Ml/d) 'disappeared' between Harry's dam and C2H069 compared to 60 Ml/d in 1997.[1]

Changes in U-pollution levels since 1997: Data from Dorling (2008) indicate a significant rise in average U-levels at the outflow of the Donaldson Dam, representing an increase by over 60 %. Of particular concern is the drastic increase of the U-maximum exceeding 1997 levels by an order of magnitude. In view of the rather large dilution capacity of the dam (maximum storage capacity of 1000 Ml) such U-peaks are indicative of large pulses of polluted water moving through the dam and subsequently into the 1m-pipeline. Another increase of U-levels appears at C2H023 located in the upper reaches of the WFS where the average in-stream concentration more than doubled between 1997 and 2000 (from 156 µg/l to 319 µg/l). A similar trend is noticeable for the U-maximum which increased from 406 µg/l to 705 µg/l exceeding the TWQR for irrigation water by a factor of over 70 and for drinking water by a factor of 10. A possible cause for this drastically increased U-influx is the discharge of large volumes of semi-and untreated water decanting from the flooded mine void of the West Rand R (the void is also referred to as 'Western Basin'). Following a DWAF directive this water was diverted from the point of decant located outside the WFS catchment via a former mine water reservoir known as Robinson lake into the WFS. Between January 2004 and May 2005 the average U-concentration in Robinson lake was 1219 µg/l with a detected maximum of 3100 µg/l (Dorling 2008). The increase of U-levels in water

[1] Considering that sewage works at Carletonville and Khutsong add additional volumes of sewage effluents to the WFS between Harry's dam and C2H069 the actual loss is even higher.

at the inflow of the 1m-pipeline is, for some reason, not reflected at the outflow of the pipe. In fact, the average U-concentration at the outflow decreased by almost 20 %. It must be noted, however, that the DWAF data end in January 2004, possibly before the decant water was diverted into the WFS. Since the diversion of decant water into the WFS was later abandoned, samples taken by the mentioned studies (December 2006 and early 2008) might well have missed previous decant-related U-peaks. For sampling sites located further downstream the trend of slightly decreasing average U-levels continues including C2H069 for which a comparably large set of data is available. DWAF data suggest that the average U-level dropped by almost 40 %. Comparing this with the more recent, high-frequency sampling data from Blyvooruitzicht GM for A Coetzee's Dam, which represents more or less the same water, confirms this drop of average U-levels even though the reduction is significantly smaller (11 % instead of 40 %). Still, with an average concentration of 71 µg/l U, the WFS at the outflow of mining areas continues to exceed SA-guideline values

While U-levels in the lower WFS might have been more or less constant over the past 12 years or so, this seems to be different in case of the dolomitic groundwater in the Boskop Turffontein Compartment (BTC). Issued from two karst springs known as upper and lower Turffontein eyes the groundwater allows perennial stream flow to resume in the lowest reach after the WFS dries up some distance upstream (Fig. 1). A third karst spring, the largest of the three, is located outside the WFS catchment and known as Gerhard Minnebron (GMB) eye. While in 1997 all springs displayed U-levels close to the natural background concentrations later rose significantly. Rising U-levels also occurred downstream of the two springs increasing the average U-concentration at Boskop Dam by almost five times (from 2,7 µg/l to 11 µg/l). Of particular concern is the comparably high U-maximum of 142 µg/l which exceeds the 1997-value by almost 16 times. A similar trend of rising U-levels is evident for the Potchefstroom dam where the average U-concentration at the water works inlet rose more than 300% (from 4,2 µg/l to 14 µg/l). Associated changes in U-loads between 1997 and the post-1998 period are depicted in Fig. 4.

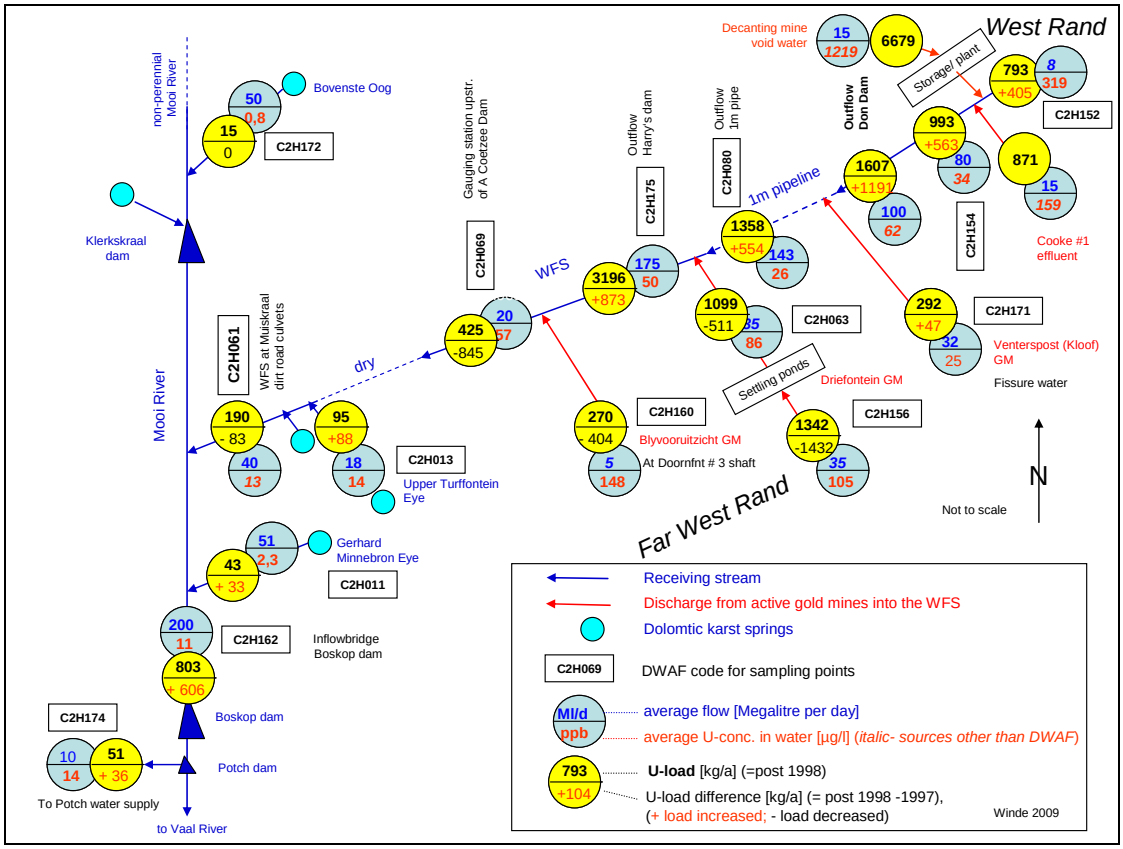

Figure 4. U-loads for selected sampling sites in the WFS catchment post 1998 and load changes since 1997

While U-loads at some sampling points declined since 1997 (negative values) they increased at others (positive values) (Fig. 4). Fluvially transported U reaching the Potchefstroom area via the Mooi River increased to 606 kg/a (Fig. 4, C2H162). This increase is mainly attributable to a significant rise in U-loads emitted by the WR goldfield which increased almost four fold from 430 kg to 1,6 t per year (Fig. 4). A large part of this increase is presumably caused by the discharge of considerable volumes of partly treated mine water from the flooded Western Basin, which carries an U-load of close to 7 tons per year out of the mine void. In contrast to the significant increase of the U-load imported from the upper catchment, U-loads emitted by major discharging mines in the FWR decreased considerably from a approx. 3,7 t in 1997 to 1,9 t for the period 1998-2008 of which only some 87 % (1661 kg) actually reach the WFS. The remainder appears to be trapped in settling ponds of Driefontein GM (243 kg/a). Compared to the 1997 data, the removal rate of the settling ponds appears to have significantly decreased from 1163 kg U/a to only 243 kg/a. While reasons for this drop are unknown, Driefontein GM (according to DWAF 2004 data) reduced the total U-load discharged into the WFS by approximately one third compared to 1997. An even larger reduction is observed at

Blyvooruitzicht GM where U-loads decreased by 60 % (from 674 kg/a to 270 kg/a) over the same period (Fig. 4).

For the reach of the WFS that runs on the non-dewatered BTC from Harry's dam (near the outflow of the 1m-pipeline) to below Welverdiend, a similar situation as in 1997 prevails. Again large amounts of U are lost from the stream over this stretch, this time amounting to over 3 t per year (3196 kg/a at C2H175 + 27 kg/a from Blyvooruitzicht GM – 424 kg/a still passing C2H069) (Fig. 4). The highest (relative) increase of U-loads, however, occurs in dolomitic spring water from the BTC which, in 1997, was still largely unpolluted. U-levels in the upper Turffontein eye, for example, rose by more than an order of magnitude. While the absolute mass of U injected into the fluvial system is still comparably small (88 kg/a), the increasing trend of U-levels is of concern.

3. U-TOXICITY: LATEST FINDINGS

Like most non-essential heavy metals[2], U is chemo-toxic to humans and has been reported to cause irreversible damage to kidneys (nephrotoxic) if consumed above certain concentrations (UBA 2005, WISE 2001). Schnug and Hahneklaus (2008) point to possible links between elevated U-levels in increasingly consumed mineral water and the prevalence of kidney cancer. Exposing rats to uranium in drinking water IRSN (2005) identified that, apart from kidneys, also the brain is targeted by U-toxicity. being possibly as sensitive as the kidneys. In how far such neurotoxic effects may cause behavioural changes is still unclear. In this context it is however interesting to note longstanding rumours in the gold mining town of Carletonville (South Africa) linking U-polluted drinking water to an abnormally high number of children with learning problems in a mining community that relied on pumped groundwater from the mine (Tempelhoff 2007, Stoch L pers. commun.).

IRSN (2005) and Henner (2008) demonstrated that U is also genotoxic causing damage to the DNA of exposed fish. Investigating a community living in a uranium mining area William *et al.* (1995) found such effects also in humans. Using algae Henner (2008) found that U-toxicity increases if Cd is present. As part of investigating possible links between armour-penetrating ammunition containing depleted uranium (DU) and severe health problems observed in DU-exposed soldiers (collectively known as 'Gulf War Syndrome'), Busby (2005) proposes a new mechanism explaining why and how the even less radioactive DU (approx. 60% of the original radioactivity of U_{nat}) is able to damage DNA[3]. Recently Raymond-Wish *et al.* (2007) added U to the long list of known endocrine disruptive compounds (EDC), which rapidly emerge as a major threat to water quality worldwide. Mimicking the effects of estrogen in the body, U could possibly increase the risk of fertility problems and reproductive cancers at levels so far regarded as safe in drinking water.

A major source of uncertainty is the incomplete scientific knowledge for setting U-limits, especially regarding the effects of chronic exposure to low concentrations typically found in the environment. So far almost all U-limits in drinking water are based on data gathered after short-term exposure of animals (experiments). For higher dosages of radioactivity this is supplemented by data from exposure of humans resulting from nuclear accidents and life span studies on the Hiroshima atomic bomb survivors (Jacobi and Roth 1995). Specifically addressing this gap the French research initiative 'Environhom' for the first time in radioprotection demonstrated that *"biokinetics and toxicity of radionuclides after chronic exposure may not be simply extrapolated from data acquired after acute exposure"* and *"... (results) ... showed that many deterministic effects may be induced after ingestion of small amounts of radionuclides ..."* (IRSN 2005). The limited reliability of existing models is illustrated by the fact that after incorporating additional epidemiological data on effects of internal alpha emitters Jacobi *et al.* (1997) found a 20 – 70 times higher risk of contracting liver cancer from occupational U-exposure than indicated in their previous study, which only used extrapolated data from the atomic bomb survivor study.

The U-limit of the WHO as well as those of the US-EPA, Health Canada and the Umweltbundesamt (Federal Environmental Bureau) in Germany are all based on the nephrotoxicity of U observed in two 1998-studies exposing rats and rabbits for up to 91 days to uranium contaminated drinking water [4] (von Soosten 2008, WISE 2001). This approach leaves uncertainty not only regarding the transferability of results from rats/ rabbits to humans and effects of speziations other than uranyl nitrate but also regarding the impacts of exposure times exceeding a three months period. The previous WHO limit for U in drinking water (2 µg/l) is now proposed by the Bundesanstalt für Risikobewertung (Federal Institute for Risk Evaluation) in Germany for mineral waters used to prepare formula-based baby food, while for drinking water the Umweltbundesamt (German Federal Environmental Bureau) proposes a limit of 10 µg/l for life-long exposure to be legislated in the European Union (EU) (von Soosten 2008). Both values are significantly lower than

[2] In contrast to essential heavy metals such as Zn which are needed for the human metabolism and only toxic above certain threshold levels, no such benefits of U exist. Ideally U and other non-essential metals and half metals such as mercury, arsenic or cadmium for example should thus not be in the drinking water at all. However, owing to their natural abundance in the environment, the associated costs to completely remove all potentially dangerous metals would render tap water unaffordable to many.

[3] The proposed mechanism is based on the observation that adsorption of natural background radiation is proportional to the fourth power of the atomic number of an element. Thus, DNA contaminated with an element of high atomic number such as U, absorbs several tens of thousands of times more gamma radiation than uncontaminated DNA. Based on this observation, Busby and Schnug (2008) suggest that the above normal adsorption rate explains why U and other elements with high atom numbers are not naturally used as building blocks in organisms.

[4] Based on this a tolerable daily intake (TDI) of 6 µg/kg bodyweight per day was defined by the WHO and subsequently reduced to 0,6 µg/kg x d to allow for variations in vulnerability of exposed populations i.e. between adults and children.

the one of the USA (EPA: 30 µg/l) or South Africa (70 µg/l) as two major U-producers [5]. Preceding a globally renewed interest in U mining the WHO, in January 2003, increased the U-limit from 2 µg/l to 9 µg/l and once more in September 2004 to 15 µg/l [6]. Coincidentally, from 2003 onwards, the spot price for U rose by more than 1000 % from 10 US$/ lb U_3O_8 to a peak of 136 US$/ lb in June 2007 sparking questions on possible links between the two developments [7].

In situations where radioactivity is not the only or the dominant stressor but acts in conjunction with other factors such as malnutrition, air pollution, chemical and bacteriological water pollution, even larger knowledge gaps on health effects through U exposure exist. This is of particular concern since U was found to be immunotoxic (adversely affecting the immune system) observed in chicken lymphocytes exposed to low concentrations of uranyl nitrate (Shukla *et al.* 2007). In view of the prevalence of HIV infections and AIDS in many of the mining towns of the study area (following the outcomes of a medical investigation Carletonville was apparently dubbed *'the AIDS capital of South Africa'*, L Stoch pers. Communication) such impact on humans could further strain the already compromised immune systems of many residents. Other stressors particularly affecting poor communities in informal settlements include lack of basic infrastructure incl. water and sanitation promoting the use of contaminated water from unsafe sources, poverty-related stress, substance abuse and inadequate access to much needed health care. Under such scenarios 'safe' U-levels may need to be set significantly lower than those appropriate for less vulnerable populations elsewhere.

Employing a GIS[8]-based, spatial correlation technique Toens *et al.* (1998) found a statistically significant correlation between U-concentration in groundwater from 69 boreholes (used as source of drinking water in this remote, arid farming area) and high counts of abnormal lymphocytes in peripheral blood from 418 people (16 years and older) sampled at 52 different locations in the Kenhard district west of the 20°E meridian. These abnormal haematological values have been linked to leukaemia, from which many residents of the area suffer and which was the very reason why the study has been initiated by medical doctors from the University of Stellenbosch (Toens *et al.*(1998). Uranium, in this area, mainly originates from uraniferous gneisses leading to concentrations in associated groundwater ranging from 10 µg/l to a maximum of 478 µg/l. These range is comparable to that found in the WFS. Reported cases of leukemia occurred at farms with U-levels as low as 40 µg/l -70 µg/l (Toens *et al.* 1998)[9]. These levels are almost continuously exceeded in most reaches of the WFS, in some instances by up to an order of magnitude. With over 300 µg/l the average U-concentration in the upper most WFS is almost three times higher than the average U-concentration in groundwater of the Poffadder area.

Furthermore, U-peaks moving down the WFS are well above the maximum U-level found in the Poffadder groundwater. Therefore, in cases where people in informal settlements may continuously use stream water as main or even sole source of drinking water this could pose a significant health risk. An even greater risk exists for people using water directly from mining sources such as canals. This is especially true for inhabitants of informal settlements with no formal water supply, which were frequently observed to use untreated water (IWQS 1999, Barthel 2007). In some cases such mine water exceeds levels observed in the Poffadder area by an order of magnitude. From a water user survey conducted along the entire course of the WFS as part of the IWQS study it can be established that a minimum of some 350 people, at the time, were likely to be using untreated water directly from the WFS or from adjacent mine canals for domestic purposes. For some of these people, polluted stream water or mine effluent was reported to be the only source of water. Some 150 people living next to the Driefontein canal were reported to use untreated water directly from the canal for domestic purposes (IWQS 1999). Other exposure pathways discernable from the survey include the use of mine effluent and stream water for irrigating garden vegetables (for own consumption) and commercial crops as well as for watering of livestock used for own consumption and commercial production. Another pathway along which U may enter the food chain is the frequently encountered consumption of fish caught not only in the stream and its dams but apparently also in mine water canals. For this exposure pathway alone annual doses exceeding the 1 mSv/a limit by up to 180 % were calculated for all age groups except the 1-2 year old (IWQS 1999). In view of continued population growth in the area since 1997 the number of potentially affected people has most likely increased, especially in lower

[5] In case of the US-EPA the originally determined limit of 20 µg/l was finally set at 30 µg/l to cater for cost considerations in water treatment.

[6] Maintaining the original TDI value of 0,6 µg U/ kg x d this was justified by raising the assumed contribution of drinking water to the total U-intake from originally 10 % (i.e. assuming that 90 % of the U-intake comes from other sources) first to 50 % and later to 80 % resulting in higher 'tolerable' U-concentration in drinking water since additional U-loads from other sources have been reduced first to 50 % and later to 20 %.

[7] Such link may relate to an 1959-agreement between the International Atomic Energy Agency (IAEA) and the WHO, which according to Bertell (1999) constitutes a serious conflict of interest. It may constrain the work of the WHO by stipulating the following: *"... whenever either organisation proposes to initiate a programme or activity on a subject in which the organisation has or may have a substantial interest, the first party shall consult the other with a view to adjusting the matter by mutual consent"* (WHO 1999). Established by the United Nations in 1956 the IAEA was originally tasked to prevent the proliferation of nuclear arms while promoting the peaceful use of nuclear energy. However, according to Bertell (1999), since established the promotional goals of the IAEA frequently took priority over regulatory aspects. This may explain why the U-limits set by the WHO were significantly lowered twice during a comparably short period when more U-mining was needed to satisfy a growing global demand.

[8] Geographical Information System

[9] It must be noted that, according to Toens *et al.* (1998), despite a generally low residential mobility, migration across farm boundaries sporadically occurs. In a follow up study for DWAF Wullschleger *et al.* (1998) established that groundwater with elevated U-levels was used for domestic purposes in many more settlements of the N-Cape. Triggered by these report and a related article in the Cape Times (February, 1999) in April 1999 another DWAF study was conducted sampling ten boreholes five times between April 1999 and August 2000 (Sekoko *et al.* 2005). Sekoko *et al.* (2005) confirmed elevated radioactivity levels in some boreholes of the N-Cape while finding little or none in others and remained vague and inconclusive regarding associated health risks.

and lowest income groups as most exposed and most vulnerable parts of the population.

4. CONCLUSIONS

Recent findings regarding the toxicity of U significantly extended the list of possible adverse health affects humans may suffer as a consequence of prolonged exposure to above-background levels of U. Apart from the long-known nephrotoxicity (kidney damage) on which the majority of international U-guidelines is based, a surge of research triggered by the DU-related 'Gulf War Syndrome' and newly available large cohorts of former uranium miners from East Germany and the Czech Republic extended the list of possible adverse health effects of uranium significantly. Data from animal experiments as well as epidemiological data now suggest that U may not only be nephrotoxic but also neurotoxic (targeting the brain), genotoxic (causing DNA damage related to cancer), immunotoxic (weaken the immune system) and disrupt hormone balances by mimicking estrogen at levels below currently existing drinking water limits. This is of particular concern since drinking water limits for U in South Africa are well above international standards. Of particular concern are findings of a 1997 South African study which links naturally elevated U-levels in domestically used groundwater to increased incidences of hematological abnormalities related to leukaemia amongst residents of a Northern Cape farming community. While causal relationships between ionizing radiation in general and leukaemia are well established for above-average exposed populations such as of uranium miners, nuclear workers and lately also residents of DU-contaminated war zones, no such link was previously reported for the drinking water pathway. In view of these findings public concerns about uranium pollution in the WFS catchment are to be taken seriously even though some concerns may have been exaggerated and sensationalized in the media.

All major sources of U-pollution in the study area are mining-related with U originating from auriferous ore (reefs) where it is commonly associated with gold. Tailings deposits in the WR and FWR alone contain well over 100000 t of U_3O_8 constituting large, long-term reservoirs from which U migrates largely uncontrolled into adjacent environs. In mined-out areas highly polluted acidic water flowing from flooded mine voids constitutes another major source of waterborne U-pollution. Owing to a much larger void volume in the FWR, a similar uncontrolled decanting of mine water as experienced in the Western Basin and unmanaged rewatering of the four dewatered compartments could have drastic consequences for downstream water users such as the Potchefstroom Municipality. Owing to deepening projects many gold mines recently decided to embark on, rewatering and associated impacts may, however, only realize in several decades from now. This leaves sufficient time to address the issue of rewatering and its associated consequences in a comprehensive and responsible manner.

While, for geological reasons, tap water in some areas of Canada and Scandinavia displayed higher U-maxima than found in the WFS, the average level of pollution present over the entire length of the WFS is well above most international guidelines and comparable to those found in groundwater of the Northern Cape (South Africa) which have geostatistically been linked to abnormal hematological values related to leukemia. For a limited number of people, especially those living in informal settings along the WFS, long-term exposure resulting from the continuous use of untreated stream water or mine water (even though it may be illegal) cannot be excluded. However, owing to a generally higher residential mobility for many of the migrant workers and job seekers duration of exposure may, on average, be less. It also needs to be stated in this context that the overwhelming majority of residents in the WFS catchment have access to good quality tap water provided by Rand Water and are thus much less, if at all, exposed to polluted drinking water.

Considering all possible exposure pathways it is estimated that currently several hundreds, if not thousands, of mainly poor people may be directly affected by water pollution at various degrees of intensity. Immediate intervention should be considered for situations were polluted water is the only sources of drinking water and where such water finds its way into the food chain of subsistence farmers either via irrigation of gardens or livestock watering. Such intervention is particularly urgent, since the most exposed population is commonly the one most vulnerable. This is due to a range of poverty-related stress factors including malnutrition, prevalence of infectious diseases related to sub-standard sanitation, lack of medical health care and high HIV infection rates to name but a few. In view of the fact that U-pollution of stream water is still ongoing and likely to continue for some time into the future intervention should preferably target the habits, economic and living conditions of the most vulnerable groups. This should be based on an updated, sufficiently detailed and comprehensive survey of people currently using polluted water in the catchment. It is believed that this would be more effective in terms of health protection than currently suggested attempts of isolated clean-up operations involving removal of polluted sediments from a few selected sites along the WFS (Ilisio Consulting 2008).

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