The transfer and accumulation of trace metals from the Wonderfonteinspruit into the surrounding environment

D. Hamman & L. Van Rensburg
Unit for Environmental Research, North West University, South Africa

Abstract

The Wonderfonteinspruit flows through the richest gold mining region in the world and has subsequently been exposed to the related pollution for more than a century. The issue of pollution in the WFS catchment was raised in 1967 and lingered on with varying intensity ever since, mostly focussing on radioactive pollution. This study attempts to detect and quantify the transfer and accumulation of trace elements and heavy metals from the WFS into the soil, vegetation, water from dams and boreholes and cattle grazing in the area. ICP-MS analysis was used to quantify the differences in the elemental concentrations within the different organs and structures of the cattle and the environment. The possible associations between the elemental concentrations of the water sources, vegetation and that of the soil were determined by using Redundancy analysis. Additional objectives were to assess the water quality of the WFS and the adjacent boreholes for livestock watering purposes. The results illustrate that elements such as uranium, cadmium and chromium, amongst others, are found at levels much higher than the normal levels found in the control group and accumulate in the soil, vegetation and cattle grazing in the area. This suggests that there is a transfer and accumulation of elements from the water into the surrounding environment of the WFS.

Keywords: trace elements, heavy metals, ICP-MS, cattle, gold mining, uranium mining, mining pollution, Wonderfonteinspruit.

WIT Transactions on Ecology and The Environment, Vol 153,© 2011 WIT Press
www witpress com ISSN 1743-3541 (on-line)
doi:10.2495/WS110191

1 Introduction

1.1 Background

The Wonderfonteinspruit (WFS) originates at the Continental Divide near Krugersdorp in the Gauteng Province and flows into the Mooi River, close to Potchefstroom in the Northwest Province of South Africa [1]. The name Wonderfonteinspruit, means "Wonderful-fountain-stream", a name it derives from the large volumes of dolomitic groundwater that once fed the stream via karst springs [1]. It drains a catchment area of approximately 1600 km^2 and flows for approximately 90km through an area known to have the richest gold deposits in the world. Subsequently, it has been exposed to gold mining activities for more than a century [2]. During the 1930s deep level gold mining commenced, which resulted in the world's deepest mine, West Wits Operations, with current mining activities close to 4 km below the surface [1]. The gold reefs in the WFS area contained high concentrations of uranium, which resulted in uranium exploitation during the1940s after an American expert group screened sediment samples that would later be used in the "Manhattan Project" to develop the nuclear bomb [1].

The uraniferous gold ores that were brought to the surface for processing contained significant levels of pyrite. The pyrite, which is oxidised in the presence of oxygen and water, is able to produce sulphuric acid or Acid Mine Drainage (AMD) as it is more commonly known [3]. AMD solubilises heavy metals from the waste rock that is produced by mining activities and these soluble metals are then able to enter surface and ground water systems [3]. Apart from contaminated run-off water entering the WFS it is estimated that mining companies are pumping an additional 140Mℓ/d into the WFS [2].

The issue of mining pollution impacting on the WFS was first raised in 1967 and has lingered on with varying intensity since then, making the WFS the contentious issue it is today [2]. Various Governmental bodies such as the Department of Water Affairs and the National Nuclear Regulator as well as many scientific specialists have studied the effects of mining pollution on the WFS with emphasis being placed on radioactive pollution and human health hazards due to the presence of uranium [1]. Although the WFS is not directly used for drinking water, it does flow through agricultural land and is used for livestock watering with possible effects that have not been studied before. This paper presents the results of the transfer and accumulation of uranium (U), cadmium (Cd) and chromium (Cr) from the WFS into the soil, grass and cattle grazing in the adjacent area. Iron (Fe), manganese (Mn) and (Se) were also found to be elements of concern and although they do appear in some of the figures, they will not be discussed.

1.2 Literature review

1.2.1 Chromium

Chromium is a naturally-occurring element found in plants, soil and animals. Absorbed chromium distributes to nearly all tissues, with the highest concentrations found in the kidney and liver [4]. Most of the absorbed chromium is excreted via the urine within 4 days [4].

1.2.2 Cadmium

Cadmium is emitted to soil, water, and air by non-ferrous metal mining and refining e.g. gold mining, and is not usually found in water at concentrations greater than 1µg/L [5]. Most of the cadmium that enters the body goes to the kidney and liver and can remain there for many years [5]. A small portion of the ingested cadmium is excreted in the urine and faeces [5].

1.2.3 Uranium

Uranium is radioactive and the heaviest naturally occurring element that is found in varying but small amounts in soil, rocks, water, plants and animals [6]. Less than 0.1–6% of the uranium is absorbed by the digestive tract, depending on the solubility of the uranium compound [7]. The highest levels of uranium are found in the bone, liver, and kidney. It takes 11 days for half of the uranium to leave the bones, and 2–6 days for the kidneys [7]. Most of the absorbed uranium is excreted via the urine [7].

The major route of exposure to these trace metals is through ingestion of water from the WFS, grass that grows adjacent to the stream and grass that is irrigated from the stream. Another important route is the ingestion of soil, which could be accidental or a result of mineral seeking behavior by the cattle called geophagia. Studies indicate that cattle ingest 0.5–0.9 kg of soil per day [8, 9].

2 Materials and methods

2.1 Area description

The study was conducted on the farm Blaauwbank in the Gauteng province of South-Africa. The farm is situated approximately 45 km Northeast of Potchefstroom towards Carletonville at an altitude of 1445m above sea level.

2.2 Soil

A soil auger was used to take three samples of soil at each of the eight designated sites in the study area. The soil was sampled at an approximate depth of 20 cm and the organic matter was removed from the soil sample. The samples were prepared using the EPA 3050B method and analysed separately. The average for the three samples was calculated to obtain a single representative value for each of the sites.

2.2 Grass

Samples of the dominant grass species at each of the eight sites were collected for analysis during August 2010. Three samples of approximately 100g of the grass were sampled at each of the sites. The samples were prepared using the

EPA 3050B method and analysed separately. The average for the three samples was calculated to obtain a single representative value for each of the sites.

2.3 Water

Three water samples were collected at ten different sites during the winter and summer. The sites included seven sites in the WFS and three boreholes on the farm. Approximately 600 ml of water was sampled at each of the sites and analysed separately.

2.4 Cattle

Samples were taken from ten non-pregnant, non-lactating cows that were of the same breed and age. The cattle grazed along the WFS and drank water from the WFS and the bore holes. Approximately 100 g of the kidneys, liver, spleen, three tissue (muscle) types, bone and hair were collected during the slaughtering of the animals. The collected samples were cut up into fine pieces and freeze dried. Each tissue sample was prepared according to the EPA 3050B method and analysed accordingly.

2.5 Milk

A one litre representative sample of milk was collected from the milking herd on the farm and analysed.

2.6 Chemical analysis

All the samples were prepared separately as required to enable analysis with an Inductively Coupled Plasma Mass Spectrometer (ICP-MS).

2.7 Statistical analysis

Statistical analyses were performed in Microsoft Excel and Canoco 4.5 for Windows. Excel was used to determine the variation, deviations, mean values and averages of the elemental concentration in the specific areas. Canoco was used to do redundancy analyses (RDA). The results of a RDA analysis would indicate the association between the different samples according to their different scores they receive during the procedure. The distance between the various vectors on the RDA diagram indicate the strength of association, the closer the two vectors are, the greater the association.

3 Results and discussion

3.1 Water

Results for water samples from this study (Table 1) were compared with the Target Water Quality Range (TWQR)* for livestock watering purposes established by the Department of Water Affairs and Forestry of South Africa. The chromium exceeded the TWQR in all samples except in borehole 3. The cadmium concentration in all the samples fell within the TWQR and it was undetectable in all the boreholes. The uranium concentrations of all the samples were within the TWQR.

Table 1: Cr, Cd and U concentrations found in the boreholes and in the WFS.

	TWQR* mg/kg	Borehole One	Borehole Two	Borehole Three	WFS avg. Winter	WFS avg. Summer
Cr mg/kg	0–0.01	0.0138	0.014	0.01	0.011	0.022
Cd mg/kg	0–0.01	0	0.00	0.00	0.004	0.001
U mg/kg	0–0.2	0.109	0.046	0.09	0.097	0.058

3.2 Soil and grass

Results for analyses of grass and soil samples are indicated in Table 2. The chromium concentrations found in the soil was significantly higher in the Dam 1 area compared to the control site. The chromium concentrations found in the grass does not show much variation between the different sites indicating that the capacity of the grass to absorb chromium was not affected by higher concentrations of chromium in the soil.

Table 2: Cr, Cd and U concentrations found at the different sites.

	Dam 1 Inflow	Dam 1 Middle	Dam 1 Outflow	Irrigated pastures	Wetland	Control site
Cr_Soil	64.175	87.5	82.5	44.175	28.325	43.325
Cr_Grass	2.75	2.225	2.425	4.425	2.075	2.3
Cd_Soil	0.175	0.075	0.775	0.05	0.075	0.025
Cd_Grass	0.175	0.05	0.175	0.025	0.05	0.025
U_Soil	97.475	66.325	167.5	2.05	20.75	3.725
U_Grass	22.175	11.5	125	73.175	3.825	7.575

The cadmium concentrations in the soil were higher in the Dam 1 area, especially at the Dam 1 Outflow once compared to the other site. The cadmium concentrations in the grass was also much higher in the Dam 1 area indicating that the grass is able to absorb higher levels of cadmium in soils with higher cadmium concentrations.

www witpress com ISSN 1743-3541 (on-line)

The uranium concentrations in the soil were significantly higher in the Dam 1 area, with Dam 1 outflow being close to 45 times higher than the control site. The uranium concentrations in the grass were also much higher in the Dam 1 area compared to the control site. The Irrigated pastures show a very interesting result with low uranium concentrations in the soil and much higher concentrations in the grass. This could be explained by one of two phenomena: The grass in the Irrigated pasture has an exceptionally high absorption capacity for uranium or, the uranium compounds that are present in the water which is used for irrigation are of the more soluble types.

3.3 Results from multivariate statistical analysis

3.3.1 Water and soil association

From the RDA ordination data of the concentrations of the different elements quantified in the eight respective sampling sites. It is evident that there is a strong association between both the chromium and uranium concentrations in the soil and water. The cadmium concentration in the soil and water shows a weak association.

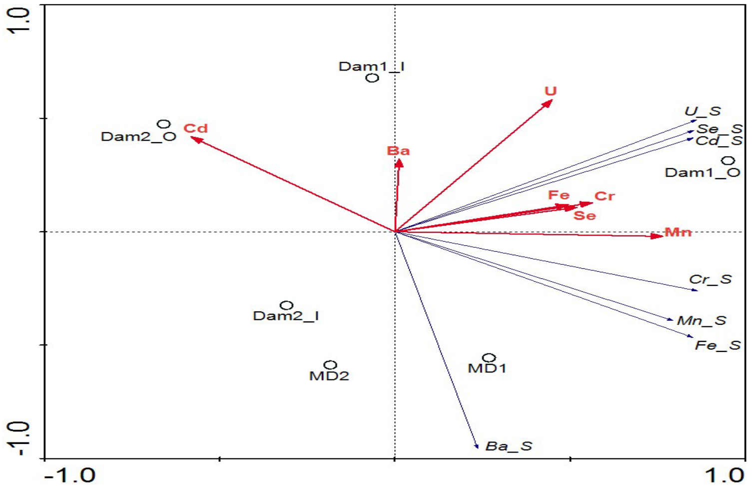

Figure 1: RDA of the soil and water samples at the different sites. The elements in the soil were indicated with vectors marked with a _S, e.g. U_S, element in the water were indicated with vectors marked only with the element abbreviation, e.g. U.

3.3.2 Water and grass association

From the RDA ordination data of the concentrations of the different elements quantified in the eight respective sampling sites. It is evident that there is a strong association between both the cadmium and uranium concentrations in the soil and water. The chromium concentration in the soil and water shows a weak association.

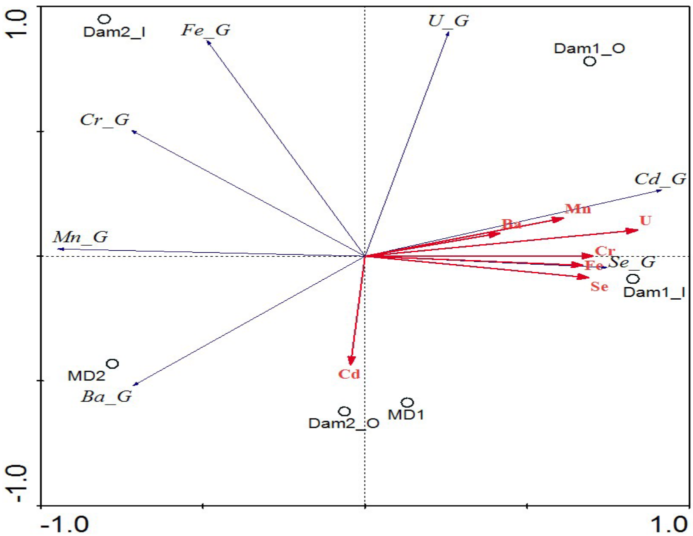

Figure 2: RDA of the grass and water samples at the different sites. The elements in the grass were indicated with vectors marked with a _G, e.g. U_G, element in the water were indicated with vectors marked only with the element abbreviation, e.g. U.

From the RDA ordination data of the concentrations of the different elements quantified in the eight respective sampling sites. It is evident that there is a strong association between both the cadmium and uranium concentrations in the soil and water. The chromium concentration in the soil and water shows a weak association.

3.3.3 Soil and grass association

From the RDA ordination data of the concentrations of the different elements quantified in the eight respective sampling sites. It is evident that there is a strong association between both the cadmium and uranium concentrations in the soil and water. The chromium concentration in the soil and water shows a weak association

3.3.4 Cattle

The results from samples that were collected from the cattle which include tissue, liver, kidney, bone, hair and milk samples. is compared with a representative sample of water and grass. Soil sample values were not included here due to the much higher elemental concentrations detected, making it near impossible to incorporate into the graphs. Milk is not presented with a standard deviation as the sample taken was representative of a different herd of cattle, the milking herd. The high standard deviation found in the data does not necessarily indicate poor repeatability or low accuracy. It is believed to illustrate the fact that the cattle were able to ingest water, soil and grass with different levels of contaminants as the cattle were not confined to graze exclusively along the WFS.

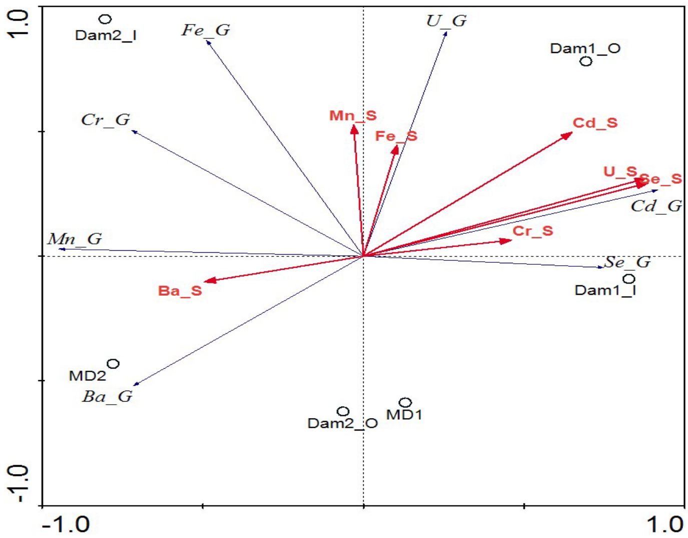

Figure 3: RDA of the grass and soil samples at the different sites. The elements in the soil were indicated with vectors marked with a _S, e.g. U_S, element in the grass were indicated with vectors marked with a _G, e.g. U_G.

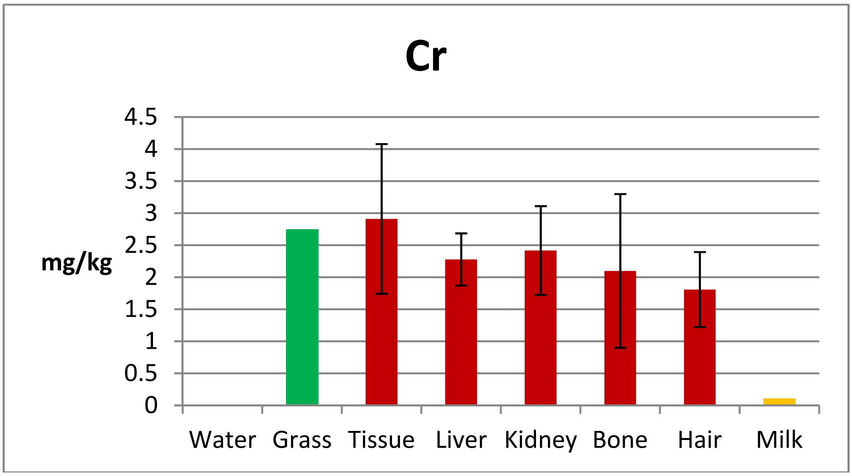

Figure 4: Chromium concentrations found in the different sample types.

As was expected, the chromium is deposited throughout the body and showed a higher concentration in the cattle than in the grass and water which could point to suggesting that a portion of the absorbed chromium is excreted via the milk.

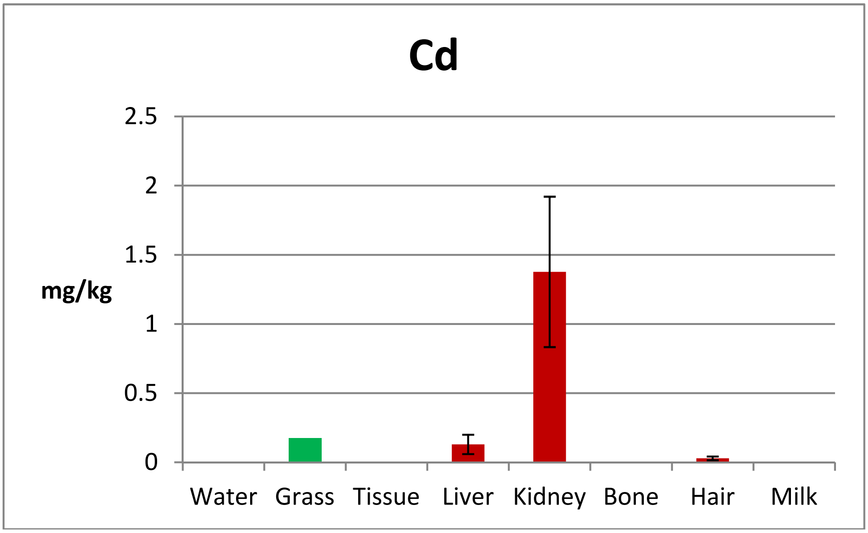

Figure 5: Cadmium concentrations found in the different sample types.

Although the cadmium concentrations were low in the grass and exceptionally low in the water, there is a great bioaccumulation found in the kidneys. The average concentration found in the kidney is 13.75 times higher than the highest observed cadmium concentration in water, 7.9 times higher than the highest observed cadmium concentration in grass and 1.8 times higher than the highest observed cadmium concentration in soil. This indicates that cadmium has a biomagnifications effect in the kidneys and to a lower extent, the liver.

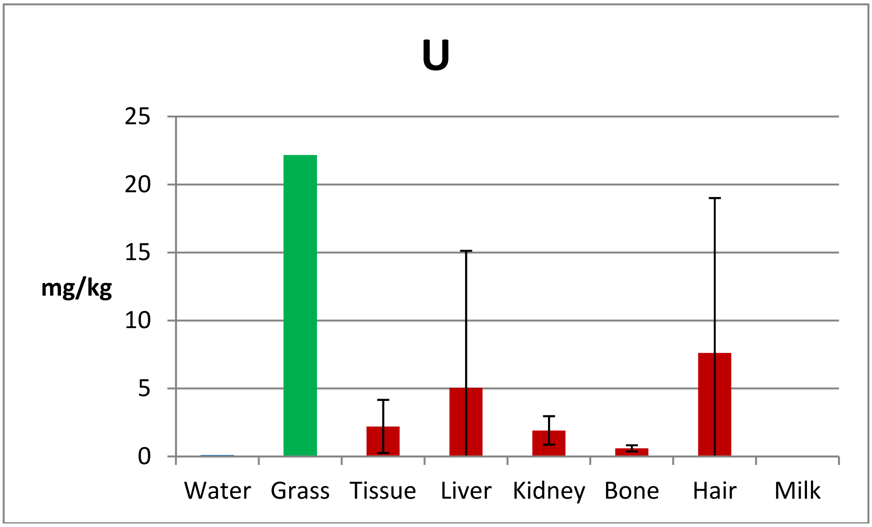

Figure 6: Uranium concentrations found in the different sample types.

The highest uranium concentrations were expected to be in the bone, liver and kidney. The results indicate that the highest concentrations were found in the hair, liver and tissue which proves to be very interesting. It seems that the uranium is also excreted via hair and deposited in the muscle tissue. The bone shows the lowest deposition in the slaughtered cattle. The data indicates that no uranium was excreted via the milk.

4 Conclusions

The aim of this study was to detect and quantify the transfer and accumulation of chromium, cadmium and uranium from the Wonderfonteinspruit into the surrounding environment and the cattle grazing in the area.

The results shown in this study indicate that there is evidence that chromium, cadmium and uranium transferring and accumulating from the WFS into the surrounding environment and into various tissues and excretions of cattle grazing in the area. Uranium was found to accumulate in the cattle muscle tissue and hair and not only the bone, liver and kidney.

Chromium was found throughout the cattle samples and the milk was revealed as an important excretion pathway.

Even though cadmium was present at very low concentrations, biomagnification was evident in the kidney.

5 Recommendations

A control group for the cattle samples would allow greater comparison and may provide more answers than what could be deducted from this study alone.

References

[1] Wade, P., Winde, F., Coetzee, H.: Risk assessment. In: Coetzee, H (compiler): An assessment of sources, pathways, mechanisms and risks of current and potential future pollution of water and sediments in gold-mining areas of the Wonderfonteinspruit catchment. WRC Report No 1214/1/06, pp 1-5, 2004.

[2] Winde, F., Uranium pollution of the Wonderfonteinspruit, 1997-2008 Part 1: Uranium toxicity, regional background and mining-related sources of uranium pollution. *Water SA*. 36 (3), pp 239–256, 2010.

[3] Rios, C.A., Williams, C.D., Roberts, C.L., Removal of heavy metals from acid mine drainage (AMD) using coal fly ash, natural clinker and synthetic zeolites

[4] Agency for Toxic Substances and Disease Registry (ATSDR). 2008. Toxicological profile for Chromium (Draft for Public Comment). Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

[5] Agency for Toxic Substances and Disease Registry (ATSDR). 2008. Toxicological profile for Cadmium (Draft for Public Comment). Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.
[6] Barillet, S., Adam, C., Palluel, O., Devaux, A., Bioaccumulation, oxidative stress, and neurotoxicity in *Danio Rerio* exposed to different isotopic compositions of uranium. *Environmental Toxicology and Chemistry.* 26 (3), pp 497–505, 2006.
[7] Agency for Toxic Substances and Disease Registry (ATSDR). 2011. Toxicological profile for Uranium (Draft for Public Comment). Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.
[8] Mayland, H.F., Shewmaker, G.E., Bull, R.C., Soil Ingestion by Cattle Grazing Crested Wheatgrass. *Journal of Range Management*. 30 (4), pp 264–265, 1997.
[9] Mayland, H.F., Florence, A.R., Rosenau, R.C., Lazar, V.A., Turner, H.A., Soil Ingested by Cattle on Semiarid Range as Reflected by Titanium Analysis of Feces. *Journal of Range Management.* 30 (6), pp 448–452, 1975.