Assessing Health Risk Associated with Uranium in Rietspruit Water, Far West Rand Goldfield, South Africa

Iyioluwa Busuyi Raji (rajiiyioluwa@gmail.com)
North-West University Potchefstroom Campus: North-West University
https://orcid.org/0000-0002-7110-3715

Emile Hoffmann
North-West University Potchefstroom Campus: North-West University

Ewald Erasmus
North-West University Potchefstroom Campus: North-West University

Adeline Ngie
North-West University Potchefstroom Campus: North-West University

Frank Winde
North-West University Potchefstroom Campus: North-West University

Research Article

Keywords: uranium, dose, exposure, pathways, cancer, risk, hazard, gold, mining

Posted Date: December 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1177732/v1

License: ☎️ This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Abstract

Uranium, U, as a toxic element has detrimental radiological and chemical impacts on human health when ingested at elevated concentration in water. The establishment of gold mining operations upstream to the Rietspruit is assumed to be a source of uranium into this water body which flows through residential and agricultural land. Water samples from the stream were collected and analysed using inductively coupled plasma mass spectrometry to determine the concentration of U. Uranium concentrations above South African regulatory limit were recorded in the stream water which is used for domestic, agricultural and religious activities as observed during field visits. Results from calculations showed that the maximum annual effective dose within this mining environment was above 1 mSv/year for all age groups. Furthermore, the probability of radiological risk is lower than the chemical risk which is due to the ingestion of U in the Rietspruit water. The chemical risk analysis showed that within 24 km of this mining environment, stream users are in danger of U chemical toxins therefore, it is important to educate the stream users about their health risk of U and recommend adequate interventions by relevant government agencies to this effect.

Introduction

The quality of most South African water has deteriorated over the years which poses serious health risks to humans and livestock (WWF-SA, 2016). The main source of South Africa water input is rainfall, however, with annual average rainfall below 50% of world average rainfall, the country is regarded as a water-scarce country. Despite the scarcity, 62% of South Africa’s water is used for irrigation, 11% is used for mining and industrial use (WWF-SA, 2016; DWAS, 2020). Poor communities like residents of informal settlements have the extreme problem of insufficient water services and consequent water-related ailments. This is because they depend on nearby surface water to meet their water needs. In gold mining areas, most of the surface water was polluted with heavy metals, uranium inclusive.

Uranium, U, has been reported to have health impacts on humans exposed to the element (Adams et al., 2010; ATSDR, 2014; Bjørklund et al., 2020; Bleise, Danesi, & Burkart, 2003; Winde, 2011; Zamora, Tracy, Zielinski, Meyerhof, & Moss, 1998). Depending on the solubility of the uranium compound, exposure route, and concentration, kidneys, lungs, bones are among the targeted vitals that could be damaged by U (ATSDR, 2014; Dewar, 2019; Keith et al., 2013; WHO, 2001). Uranium is mined in South Africa in most cases as the by-product of gold mining (Ford, 1993; Krige, 1966; Tutu, Cukrowska, McCarthy, Mphephu, & Hart, 2003; Winde & de Villiers, 2002). High concentrations of U have been found within gold mines in water and sediment (Durand, 2012; Fashola, Ngole-Jeme, & Babalola, 2016; Caspah Kamunda, Mathuthu, & Madhuku, 2016; Raji, Hoffmann, Ngie, & Winde, 2021).

Gold mining has been a contributing factor to the economy of South Africa, however, large volumes of mine wastes have been deposited as a result (Fedderke & Pirouz, 2002; McCarthy, 2011). In the Witwatersrand Basin, one of the richest gold deposits worldwide (Tutu, McCarthy, & Cukrowska, 2008), high concentrations of U have been recorded in some of the mined gold reefs. About 70 years ago, the Far
West Rand became the first goldfield in South Africa where commercial production of U was established (Coetzee, Winde, & Wade, 2006). Winde (2001) reported an average U concentration of about 110 mg/kg in gold tailings across seven goldfields of the Witwatersrand Basin. Winde (2004) concluded that for each ton of gold produced, more than 10 tons of U were brought to the earth's surface. Mined gold reefs are therefore regarded as the primary source of U (Winde & Sandham, 2004).

Other sources of U pollution include mine waste deposits such as slime dams and mine dumps often located close to streams or rivers. In many cases, these waste deposits are the primary source of U pollution of the nearby water bodies. The process includes the transport of dissolved U via seepage into underlying alluvial aquifers (Winde & van der Walt, 2004) and of U-bearing tailings particles by wind and water erosion (Winde & Sandham, 2004). Uranium can be emitted from point sources or from non-point (diffuse) sources. Point source pollution includes the discharge of fissure and processed water through canals and pipelines into nearby streams or dams as witnessed in this study. Despite the fact that the mine has been decommissioned about 5 years ago, dewatering of underground shafts is still ongoing. Another example of point source pollution is the storm-water run-off from contaminated mining environments such as slime dams, retention dams, rock and sand dumps. A typical example of diffuse sources of pollution includes seepage from slime dams, run-off from mine dumps.

Uranium is released into the environment in a number of ways which include erosion of slime dams by wind and water leading to eroded slimes settling on dams, wetland, irrigation channels and agricultural land etc. (Coetzee et al., 2006). In addition, there are spillages of tailings associated with burst pipelines, partial dam failures etc.

High concentrations of U have been found several kilometres from the mining site in river sediment, wetlands and dams as a result of precipitation, adsorption, co-precipitation and bioaccumulation (Winde, Wade, & van der Walt, 2004). Wetlands and dams have been identified as sinks for U and other toxic heavy metals such as mercury, lead, cadmium, arsenic (Coetzee, Wade, & Winde, 2002; Ross & Dudel, 2008; Schöner, Noubactep, Büchel, & Sauter, 2009). Raji et al., (2021) recorded high concentrations of the aforementioned heavy metals above the acceptable limit in a wetland and dam located about 3 km and 6 km respectively away from a mining site. These sites can be a secondary source of U pollution and other heavy metals if there is a change in the water chemistry which could be influenced by the water’s pH, electric conductivity, redox state and seasonal changes (from winter to summer).

The focus of this study is on the Rietspruit, a small stream draining the south-eastern part of the Far West Rand (FWR) goldfield that is impacted by mining-related water pollution. The study explores the main pathways of U entering the Rietspruit system including the leaching of U from mine wastes, aqueous transport of dissolved uranium from on-site sources and mechanisms governing the transport of dissolved U within the fluvial system which include immobilisation and remobilisation to and from fluvial sediments, respectively.

Uranium is released from mine waste during a rain event and transported to Peter Wright dam (Rietspruit headwater). A concentration of about 52.7 µg/l of U was recorded in the fissure water discharged by the
mine into the PW dam. (Raji et al., 2021). According to Kritzinger (2017), about 68 Ml of fissure water is pumped into the PW dam per day, this means the amount of U discharged into the PW dam is about 52 700 mg/l of U per day. Thus, the discharge of fissure water into the PW dam is the most significant U source into the Rietspruit. The outflow from the PW dam into the Rietspruit makes the Rietspruit a perennial one. Observations during field sampling indicated that the Rietspruit water is used for drinking, cooking, bathing (especially by the residents of informal settlements within the area and religious worshippers) and animal watering and dam water is used for irrigation of farmland. Plant’s uptake of U from the soil could be a result of air pollution from slime dams and water used to irrigate such plants (Anke, Seeber, Müller, Schäfer, & Zerull, 2009; Gupta & Walther, 2020).

Due to human exposure witnessed during fieldwork, and the lack of information on the level of U these people could be exposed to, it is imperative to assess potential health risks associated with the concentration of U found in the Rietspruit. This study will be used to sensitize the locals about the danger involved with the use of the water for domestic, agricultural and religious purposes. Since the most regular human exposure pathway witnessed was the ingestion of the water from the stream, both carcinogenic and non-carcinogenic risk assessments were carried out.

The objectives of this study are;

1) To determine the concentration of U in the Rietspruit water.

2) To assess the health risk posed by U level in the Rietspruit water.

3) Propose general recommendations.

**Material And Method**

**Study area**

The Rietspruit is located in Gauteng Province, South Africa about 1 km away from a gold and uranium mine. The gold and uranium mine (coordinate: 26°21’46”S 27°42’52”E) was operational for about 56 years before it was decommissioned in August 2016 discharge their fissure and process water into the Peter Wright dam (PW dam). The outflow from the PW dam is the source of the Rietspruit. It is believed that the Rietspruit will be a non-perennial river if the mine should stop discharging water into the PW dam.

The river flows for about 60 km southwardly before joining the Vaal river (Figure 1). The associated drainage region name is C22H according to the Department of Water Affairs and Sanitation (Figure 2) comprising a catchment area of about 454 km². Contributing tributaries include the Leeuspruit, Evaton Rietspruit and Klein-Rietspruit. While Leeuspruit is also polluted with U as a result of a gold mine located upstream of the confluence with Rietspruit, the Evaton Rietspruit and Klein-Rietspruit are not polluted as they drain areas without mining activity. The Leeuspruit is located in the C22J Quaternary Catchment (Figure 2) draining some 668.7 km² (Department of Water Affairs and Sanitation, 2011). As a result of the
absence of mining or industrial activities upstream of both the Evaton Rietspruit and Klein-Rietspruit, the concentration of U in the water of these streams was used as the natural background concentration of U. Farms are located within the area and most of them depend on the water from the Rietspruit for irrigation.

The climate of the study area is temperate, defined by moderately cold winters (April to August) and hot summers (October to March). Annual rainfall occurs between October to March and with an average of about 664 mm. Evaporation is about twice the annual rainfall (about 1700 mm). In winter, the average temperature is 13 °C and 24 °C in summer (Caspah Kamunda et al., 2016).

The Ezulwini gold and uranium mine is located in the Witwatersrand Basin, a sedimentary basin of about 2.7 billion years of age containing a stratigraphic sequence about 6 km thick made of quartzites, conglomerates and lava (Phillips & Law, 2000). Underlying the mine, gold is found in the upper Elsburg in the form of native gold and is associated with sulphide minerals (e.g pyrite). Also, gold is found in the middle Elsburg reefs associated with pyrite underlying the mine and U is mined in the middle Elsburg reef (Kritzinger, 2017) and it is found in the form of uraninite.

**Field work**

A total of 28 water samples were collected on the 28th of August 2020 across the entire length of the Rietspruit (Figure 2). Water samples were collected in a 100 ml water bottle below the water surface. The water bottle was rinsed three times with the river water and decanted away from the sampled site. Water samples were taken in the middle of the river, depending on the depth of the site, to avoid sampling the banks of the river. Each water bottle was labelled accordingly and kept in a cooler box. The samples were all taken to the laboratory the following day for chemical analysis. Samples were analysed in the laboratory to determine the concentration of U using inductively coupled plasma mass spectrometry (ICP-MS).

**Lab analysis**

The chemical analysis of the water samples was done at the Eco-analytical laboratory in North-West University, Potchefstroom Campus, South Africa. Each water sample was first filtered using a 0.45 µm pre-nylon sieve to remove suspended particles. 1 mL of the filtered water was measured and 9 mL of nitric acid was added to remove any dissolved organic material in the water. An Agilent 7500 CE ICP-MS with Collision Reaction Cell (CRC) technology for interference removal was used to determine the concentration of U in the water. In order to achieve a quantitative result, the instrument is calibrated using ULTRASPEC certified custom mixed multi-element stock standard (De Bruyn Spectroscopic Solutions, Midrand, South Africa) solutions containing all the elements of interest.

**Exposure assessment**

According to the US EPA (1992), exposure assessment can be defined as the determination of the magnitude, frequency and duration of exposure and exposure dose. Exposure assessment includes identification of all important sources of pollutant, routes of exposure (exposure pathways), potentially exposed population, mechanism of pollutant transportation, quantification of exposure, toxicity
assessment of pollutant, and risk characterisation. Exposure assessment is one of the most essential steps in human health risk assessment, hazard identification, dose-response assessment and risk characterization are the other steps (NRC, 2009).

Source of uranium pollution

The main source of uranium, as a contaminant of concern, in the Rietspruit is the Ezulwini Gold and Uranium mine (Figure 3). Slimes and waste rock are deposited on the surface. Oxidised mine wastes release U when in contact with water (in the form of rain, pore-water and seepage), which then runs-off into PW dam inflow. The mine also discharges fissure water with elevated concentration of U into PW dam, Rietspruit headwater. Fissure water is mainly water from underground mine workings that was in contact with oxidised uranium ore (Winde, 2004). Another source of U in the Rietspruit includes the settling of tailings materials transported by wind to surface water.

Exposure pathway

In this study, the pathways include the usage of the water for domestic, religious and agricultural purposes. Domestic and religious activities observed in the Rietspruit include drinking of the Rietspruit water, using the water for cooking, bathing in the river, as well as fishing in the dam located downstream of the river (Figure 4). The water is also used for the irrigation of farmlands. The commercial wheat plantation located a few kilometres from the mine uses the water from the dam for irrigation (Figure 4C). Several studies have been done on the uptake of U and other heavy metals by plants (Dzoma, Moralo, Motsei, Ndou, & Bakunzi, 2010; Edayilam et al., 2020; Genthe, Kapwata, Le Roux, Chamier, & Wright, 2018; Gupta & Walther, 2020; Hakonson-Hayes, Fresquez, & Whicker, 2002).

Wind erosion is another pathway. The deposition of tailings materials on nearby farmland could potentially introduce U into the food chain due to the uptake by plants. The consumption of animals that were fed with plants irrigated with polluted water is also another route for indirect consumption of U by humans (Figures 4A & B). Formal and informal settlers within the immediate environment of the slime dams could also be exposed as a result of inhaling dust particles (Figure 4F).

The only exposure pathway considered in this study is the oral ingestion of U from drinking water. This is the most prevalent exposure pathway experienced in the Rietspruit by different population groups that depend on the water for both domestic and religious activities (Figure 2E) and the primary objective of this study.

Mechanism of transport

The major mode of transportation of U from the source pollutant to the Rietspruit is through water and air.

Exposed population
The majority of the inhabitants around the study area live in informal settlements, e.g. Lawley (Figure 1). Informal settlements are housing areas often built illegally on municipal land by people who cannot afford to live in urban areas of the country (Huchzermeier, 2009). Most of the houses in an informal settlement are built out of metal sheets and other materials (Figure 4F).

Other exposed populations are the worshippers using the water from the river for their various religious activities which include drinking. On a visit to site 6, 7, 8, 9 and 11, cooking activities using water from the river was also witnessed as well as bathing in the river. The worshippers are of different age groups and sex.

**Annual effective dose (radiation dose) due to the ingestion of uranium in Rietspruit water**

Whenever there is human contact with a hazardous chemical as U in this study, there is exposure (Means, 1989). Residents and worshippers using the water for drinking, cooking, bathing are therefore exposed. In order to screen the area that could constitute a health risk, radiation doses for all the sampled sites were calculated and compared with the radiation dose limit prescribed by UNSCEAR (2000) for U$^{238}$ in water.

Annual effective dose is the estimated value of radiation energy received or absorbed by the human body as a result of an intake of a certain amount of radioactivity in a year (DWAF, 2002). In order to calculate the annual effective dose, equation 1 was used.

$$\text{Annual effective dose} = C \times \text{AWI} \times \text{DCF} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \text{equation 1}$$

Where C is the activity concentration of U (Bq/l), DCF is the dose conversion factor for a specific age group (Sv/Bq) and AWI is the age-dependent annual water intake. The annual water intake default values for different age groups and the dose conversion factor values were obtained from the Department of Water Affairs handbook (DWAF, 2002). The concentration of U recorded in the water was converted to activity concentration using 1 µg/l = 0.025 Bq/l as the conversion factor.

**Lifetime cancer risk (Carcinogenic risk assessment)**

The lifetime cancer risk (risk factor) estimates the likelihood of developing cancer due to exposure to a carcinogen (Bleam, 2012). In order to calculate the lifetime risk factor due to the consumption of the Rietspruit water, equation 2 was used. The concentrations of U in the Rietspruit water were converted to uranium activity concentration (Bq/l). 1µg/l = 0.025 Bq/l.

$$\text{Lifetime cancer risk} = \text{Uintake (Bq/l)} \times \text{risk coefficient} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \text{equation 2}$$

The calculation is based on the assumption that the activity concentration of U at each site remains constant and the resident consumes the water at the specified rate throughout their lifespan. This method was designed by the US EPA (USEPA, 1986) and has been used in several studies (Bleam, 2012; Giri & Jha, 2012; Okeyode & Jibiri, 2013).
In order to calculate lifetime cancer risk, the activity intake of U has to be determined using the concentration of dissolved uranium quantified in the water samples collected at each site. Equation 3 was used to calculate the uranium activity intake:

\[ \text{Uranium intake (Bq/l)} = C \times IR \times EF \times ED \]  

Where C is the uranium activity concentration (Bq/l), ED is the lifetime exposure duration (70 years), and EF is the exposure frequency (365 days per year). Lifetime cancer morbidity and mortality risk coefficients for uranium are 1.3E-09 and 1.73E-09 respectively (EPA; Radiation, 2000).

**Hazard quotient (Non-carcinogenic risk assessment)**

Hazard quotient (HQ) is the ratio of the lifetime average daily dose at each site and the reference dose for U (0.6 µg/kg/day) through the ingestion of drinking water. A reference dose (RfD) is the estimate of the dose level considered safe for human consumption (ATSDR, 2014). It relates the dose at the exposure point to a toxicological endpoint (Bleam, 2012). Hazard quotient below 1 signifies no risk while above 1 means there is sufficient risk. Hazard quotient has been used to assess the health risk of U in some studies (Giri & Jha, 2012; C Kamunda, Mathuthu, & Madhuku, 2018; Njinga, Tshivhase, & Mathuthu, 2016).

\[ \text{Hazard quotient} = \frac{\text{lifetime averaged daily dose}}{\text{reference dose}} \]

**Results And Discussion**

**Concentration of U in collected water samples**

The highest concentration of U (781.9 µg/l) in the water was recorded at the inflow of PW dam (Rietspruit headwater) (Table 1). The concentration of U decreases gradually with distance from the mine. This is similar to the study of Davidson (2003) which also reported a gradual reduction in the concentration of U moving downstream from the source pollutant.

The concentration of U in the water is above WHO guideline limit in drinking water (30 µg/l) and South Africa standards (10 µg/l in water used for irrigation and 30 µg/l in drinking water) for about 24km away from the source pollutant. The concentration of U in the water used for the irrigation of the wheat plantation (Figure 4C) is 52.7 µg/l. Hakonson-Hayes et al (2002), concluded that the concentration of U in plants is directly proportional to the concentration of U in the water used for the irrigation of the plant. The consumption of such plants by humans and animals that fed on the plant could be detrimental to human health (ATSDR, 2014; Bjørklund et al., 2020; Corlin et al., 2016).
<table>
<thead>
<tr>
<th>Site number</th>
<th>Site name</th>
<th>Field number</th>
<th>Distance from PW dam (km)</th>
<th>U water (µg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>PW dam inlet</td>
<td>1</td>
<td>0</td>
<td>781.9</td>
</tr>
<tr>
<td>Site 2</td>
<td>Channel water</td>
<td>*1</td>
<td>0</td>
<td>52.7</td>
</tr>
<tr>
<td>Site 2</td>
<td>Corner of dam</td>
<td>*2</td>
<td>0</td>
<td>55.8</td>
</tr>
<tr>
<td>Site 3</td>
<td>PW dam outflow</td>
<td>2</td>
<td>1</td>
<td>181.2</td>
</tr>
<tr>
<td>Site 4</td>
<td>Wetland 1</td>
<td>3</td>
<td>2</td>
<td>101.4</td>
</tr>
<tr>
<td>Site 5</td>
<td>Wetland 2 inflow</td>
<td>*8</td>
<td>3</td>
<td>62.0</td>
</tr>
<tr>
<td>Site 5</td>
<td>Wetland middle</td>
<td>*7</td>
<td>3</td>
<td>63.4</td>
</tr>
<tr>
<td>Site 5</td>
<td>Wetland outflow</td>
<td>*6</td>
<td>4</td>
<td>65.6</td>
</tr>
<tr>
<td>Site 6</td>
<td>Damlit outflow</td>
<td>4</td>
<td>6</td>
<td>49.2</td>
</tr>
<tr>
<td>Site 7</td>
<td>Between damlit</td>
<td>5</td>
<td>6</td>
<td>104.9</td>
</tr>
<tr>
<td>Site 8</td>
<td>Religious site</td>
<td>5B</td>
<td>8</td>
<td>103.3</td>
</tr>
<tr>
<td>Site 9</td>
<td>Post religious site</td>
<td>6</td>
<td>8</td>
<td>103.8</td>
</tr>
<tr>
<td>Site 10</td>
<td>Post bridge</td>
<td>7</td>
<td>12</td>
<td>70.2</td>
</tr>
<tr>
<td>Site 11</td>
<td>Poortjie</td>
<td>8</td>
<td>14</td>
<td>74.5</td>
</tr>
<tr>
<td>Site 12</td>
<td>Pre Evaton</td>
<td>9</td>
<td>24</td>
<td>71.1</td>
</tr>
<tr>
<td>Site 13</td>
<td>Evaton Rietspruit</td>
<td>10</td>
<td>NA</td>
<td>0.3</td>
</tr>
<tr>
<td>Site 14</td>
<td>Post confluence</td>
<td>11</td>
<td>32</td>
<td>4.9</td>
</tr>
<tr>
<td>Site 15</td>
<td>Pre confluence Rietspruit &amp; Leeuspruit</td>
<td>13</td>
<td>37</td>
<td>6.0</td>
</tr>
<tr>
<td>Site 16</td>
<td>Leeuspruit</td>
<td>12</td>
<td>NA</td>
<td>17.4</td>
</tr>
<tr>
<td>Site 17</td>
<td>Post confluence Rietspruit &amp; Leeuspruit</td>
<td>14</td>
<td>39</td>
<td>6.2</td>
</tr>
<tr>
<td>Site 18</td>
<td>Post confluence Rietspruit &amp; Leeuspruit</td>
<td>15</td>
<td>43</td>
<td>6.9</td>
</tr>
<tr>
<td>Site 19</td>
<td>Rietspruit (Potch rd)</td>
<td>16</td>
<td>49</td>
<td>5.1</td>
</tr>
<tr>
<td>Site 20</td>
<td>Pre-confluence Rietspruit &amp; Klein-rietspruit</td>
<td>18</td>
<td>53</td>
<td>3.7</td>
</tr>
<tr>
<td>Site 21</td>
<td>Klein-rietspruit</td>
<td>17</td>
<td>NA</td>
<td>0.7</td>
</tr>
</tbody>
</table>
The reduction in the concentration of U from the source pollutant downstream could be attributed to the dilution effect from unpolluted water (e.g., discharge from water treatment plants and tributaries), infiltrating groundwater and the river water-sediment interplay. Despite the reduction in the concentration of U in water downstream, the site used for religious activities have U concentration more than twice the guideline limit of U in water. This is about 6 km from the source of the pollutant.

The concentrations of U at the sites designated as this study natural background concentration of U were 0.3 µg/l at the Evaton Rietspruit and 0.7 µg/l at the Klein-Rietspruit. As mentioned earlier, these sites were selected as the natural background concentration of U because there is no mining activity or industrial operation upstream of the river. At the Leeuspruit tributary, the concentration of U in the river was 17.4 µg/l. A gold mine is located about 24 km upstream of the sampled site (Figure 1). Besides the grazing of cattle and the location of farmlands along the Leeuspruit, no human exposure was witnessed. The source of the water used for irrigation of the farmlands is unknown. However, Leeuspruit water might be used by the residents of the informal settlements within this area.

**Annual effective dose due to the ingestion of uranium in Rietspruit water**

There are many human exposure pathways for U, however, the major pathway witnessed during the field survey was considered in this study, ingestion through drinking of water. From Figure 5, it was confirmed that an individual annual radiation dose limit of 0.1 mSv/year (for members of the general public) prescribed by UNSCEAR (2000) was exceeded at the PW dam inlet for all the age groups. At PW dam outflow, the radiation dose limit was exceeded by the 15 years’ age group while the rest of the age groups’ annual effective dose was equal to the radiation dose limit (0.1 mSv/year). This means the ingestion of the water at the observed U activity concentration will cause a proportional increase in the chance of a health effect. Given the numerous exposure pathways that may cause radiation exposure, it was
recommended by the International Commission on Radiological Protection (ICRP) to keep individual exposure doses to a minimum. This is essential in order to keep the total dose received by an individual below the annual dose limit.

At sites where human exposure was observed, the annual effective dose was equal to 0.1 mSv/year for all the age groups (site 6 to site 9). The maximum effective dose was recorded at the PW dam inlet for all the age groups (Table 3). This coincided with the maximum concentration of U recorded in this study. The annual effective dose is in the order 15 years age group as the highest > adults > 1 year > infants > 5 years and 10 years.

In Table 2 below, the values of annual water intake (AWI) and dose conversion factor, (DCF) used to calculate the annual effective dose were given. Also included in Table 2 are the minimum, maximum, average and standard deviation for each of the studied age groups.

<table>
<thead>
<tr>
<th>Age group (years)</th>
<th>AWI (L/year)</th>
<th>DCF (Bq/Sv)</th>
<th>minimum mSv/year</th>
<th>Maximum mSv/year</th>
<th>Average mSv/year</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 12 months</td>
<td>200</td>
<td>1,40E-07</td>
<td>2,00E-04</td>
<td>0,55</td>
<td>0,05</td>
<td>0,1</td>
</tr>
<tr>
<td>1 - 4</td>
<td>260</td>
<td>1,20E-07</td>
<td>2,00E-04</td>
<td>0,61</td>
<td>0,06</td>
<td>0,11</td>
</tr>
<tr>
<td>5 - 9</td>
<td>300</td>
<td>8,00E-08</td>
<td>2,00E-04</td>
<td>0,47</td>
<td>0,04</td>
<td>0,09</td>
</tr>
<tr>
<td>10 - 14</td>
<td>350</td>
<td>6,80E-08</td>
<td>2,00E-04</td>
<td>0,47</td>
<td>0,04</td>
<td>0,09</td>
</tr>
<tr>
<td>15 - 17</td>
<td>600</td>
<td>6,70E-08</td>
<td>3,00E-04</td>
<td>0,79</td>
<td>0,07</td>
<td>0,15</td>
</tr>
<tr>
<td>Adults</td>
<td>730</td>
<td>4,50E-08</td>
<td>2,00E-04</td>
<td>0,64</td>
<td>0,06</td>
<td>0,012</td>
</tr>
</tbody>
</table>

**Lifetime cancer risk (Carcinogenic risk assessment)**

According to US EPA, 1991, lifetime cancer risk ranging from 1.0E-06 to 1.0E-04 is acceptable and above 1.0E-04 require immediate remediation while a cancer risk below 1.0E-06 are not considered to pose any significant health effect (Fryer, Collins, Ferrier, Colvile, & Nieuwenhuijsen, 2006; Hu et al., 2012). Using equation 2 above, the result of the cancer risk is displayed in table 3 below.

The highest mortality cancer risk recorded was 1.1E-03 and 1.7E-03 for morbidity cancer risk. These values were the only values above the radiological risk limit (1.0E-03) in this study. From the result above, (Figure 6), downstream users of the Rietspruit water are below the cancer risk limit and can be considered safe. Similar to the exposure dose result, the PW dam inlet has the highest cancer risk (Figure 6). This means the sites require immediate intervention. However, as mentioned earlier, a high concentration of a pollutant in an environment is harmless until there is human contact. Since no human contact was
witnessed in this environment, possible human exposure to U will be the consumption of cattle that graze within this environment (Dzoma et al., 2010).

**Hazard quotient (Non-carcinogenic risk assessment)**

The lifetime average daily dose (LADD) of U due to the ingestion of Rietspruit water ranged from 0.0 to 22.3 µg/kg/day of uranium with an average of 2.1 µg/kg/day. As mentioned earlier, the HQ was estimated for uranium using a reference dose of 0.6 µg/kg/day as recommended by EPA OGWDW (2000). The result of the non-carcinogenic risk (chemical risk) ranged from 0 to 37.2. The minimum HQ was recorded at sites selected as the natural background concentration of U in the study area. Similar to the U concentration in the Rietspruit, the maximum HQ was recorded at the PW dam inlet.

In this study, HQ was above 1 for about 24 km from the mining environment. With human exposure observed within this radius, it means people drinking from the water could be exposed to chemical toxins as a result of ingesting U in the water.

**Recommendation**

Due to the high concentration of U found in the study area, the usage of the water for domestic, agricultural and religious activities should be discouraged. This could be achieved by educating the inhabitants of the informal settlements, farmers and worshipers about the health impacts of U and the concentration of U in the water used for these activities.

Mining companies in conjunction with relevant government agencies should work together in order to remediate this situation. This will help in reducing human exposure to the U.

**Limitations**

Risk assessment is based on the assumption that the concentrations of U will remain constant and people consume only the Rietspruit water at the given quantity per day throughout their lifespan. Individual risk can be influenced by genetic, age, sex, diet, state of health and lifestyle factors, as a result, lifetime cancer risk does not estimate the actual risk for any individual.

**Conclusion**

Uranium has been introduced into the Rietspruit as a result of a gold and uranium mining plant established upstream of the stream. Due to different human exposures observed within the environment, water samples covering the entire Rietspruit were taken for analysis using ICP-MS to quantify the concentrations of U in the stream. The results from the laboratory analysis were used to characterise both radiological and chemical health risks of U as an element of concern.

The concentration of U in water within 24 km from the source pollutant (gold mine) at all the sampled sites is higher than WHO and South Africa regulatory limit of U in water (30 µg/l = 0.03 mg/l). The
concentrations of U in the Rietspruit water decrease as the distance from the mining site increases.

The annual effective dose values due to the consumption of the Rietspruit water are above the safe limit within the mining environment, 0.1 mSv/year. Where human exposure was observed, the annual effective dose values for all the age groups were equal to the safe limit. Due to several exposure pathways that contribute to radiological dose, it can be concluded that the Rietspruit water is not safe for consumption.

Radiological (lifetime) cancer risks of mortality and morbidity due to Rietspruit water consumption are above the safe limit of 1.0E3 within the mining environment. The grazing of cattle within this environment and the use of the water for irrigation activity could be an entry point for the introduction of U into the food chain. Also, people observed drinking water at these sites and fetching the water for domestic purposes are at risk of radiological exposure.

The chemical toxicity of U$^{238}$ in the Rietspruit has values above the standard limit. The HQ is above 1 for about 24 km away from the mining environment. These are sites where human exposure, cattle grazing, and farmland were observed. This study revealed that the probability of carcinogenic risk is low, however, the non-carcinogenic risk may be due to the chemical toxicity of U$^{238}$.

References


**Tables**

Table 3 is not available with this version

**Figures**
Figure 1

Geological map of the study area.

Figure 2

Study area catchment showing the sampled sites

Figure 3

Google Earth image showing the mining site
Figure 4
Exposure pathways witnessed in Rietspruit; A: Cattle grazing in the Rietspruit river B: Cattle grazing next to the canal used by the mine to discharge water C: Wheat plantation irrigated by water from PW dam, D: Local residents fishing in PW dam, E: Religious site, F: Informal settlement within the study area.

Figure 5
Annual effective dose for different age groups: via drinking untreated stream water only at site-specific U - concentrations observed on 28th August 2020
Figure 6

Mortality and morbidity cancer risk: via drinking untreated stream water only at site-specific U-concentrations observed on 28th August 2020
**Figure 7**

Non-carcinogenic risk: via drinking untreated stream water only at site-specific U - concentrations observed on 28th August 2020