Radionuclides and toxic elements transfer from the Princess Dump to the surrounding vegetation in Roodepoort South Africa: Potential radiological and toxicological impact on humans

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Dissertation submitted in partial fulfillment of the requirements for the degree of Master of Science in Applied Radiation Science at the Mafikeng Campus of the North-West University

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November 2014

DECLARATION

I declare that this dissertation, Radionuclides and toxic elements transfer from the Princess Dump to the surrounding vegetation in Roodepoort South Africa: Potential radiological and toxicological impact on humans, carried out in the laboratories at the Centre for Applied Radiation Science and Technology (CARST) of the North-West University, Mafikeng Campus, is my work in design and has not previously been submitted for the Master's degree to any University in the Republic. All authors of the material contained in this work have been fully acknowledged.

Signature: ..... Date: .....

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ACKNOWLEDGMENTS

I take this opportunity to express my sincere gratitude to the supervisor of this study Prof. Manny Mathuthu as well as my co-supervisor Prof. VM Tshivhase for the immense time and advice. Without their guidance and supervision this work would not have been completed.

I would also love to thank Prof. Dr. Arnaud Faanhof for always being there for me when I needed him. His guidance, immense experience and expertise were very much instrumental in the completion of the dissertation.

I thank my mother, my family and my dear friend Reabetswe for the immense emotional and financial support while doing my research work.

The financial assistance of the National Research Foundation (NRF) towards this research is hereby acknowledged by the corresponding student author. Opinions expressed and conclusions arrived at, are those of the author and are not necessarily to be attributed to the NRF.

I would also like to express my gratitude to the Centre for Applied Radiation Science and Technology, North-West University (Mafikeng Campus) for allowing me the opportunity to do my research within their facilities and the personnel, both students and stuff for the assistance. The Department of Animal Health of the North-West University, Mafikeng is also acknowledged for their assistance in the ICP-MS analysis of soil and vegetation samples.

Finally I would love to thank God for being with me throughout the research and for opening doors for me.

LIST of Abbreviations

α	Alpha particle
β	Beta particle
γ	Gamma ray
GM	Geometric Mean
GSD	Geometrical Standard Deviation
HPGe	High Purity Germanium
IAEA	International Atomic Energy Agency
ICP-MS	Inductively Coupled Plasma Mass Spectroscopy
ICRP	International Commission of Radiological Protection
K_d	Distribution coefficient
NORM	Naturally Occurring Radioactive Material
NNR	National Nuclear Regulator
TENORM	Technologically Enhanced Naturally Occurring Radioactive Material
UNSCEAR	United Nations Scientific Committee on the Effect of Atomic Radiation
WHO	World Health Organisation
MTL	Maximum Tolerable Limit
LET	Linear Energy Transfer
NCRP	National Council on Radiation Protection

Abstract

South Africa is a mining country, and one of the leading gold mining countries in the world. Mining activities tend to bring other minerals and elements to the surface in addition to the desired mineral. In gold mining, one of these metals is Uranium which is both toxic and radioactive. Uranium decay to form other radioactive daughters and the radioactivity may be high enough to cause some health concerns to the public residing next to where this waste material is being dumped.

In this study, soil and vegetation samples were collected from the Princess Gold mine dump in Roodepoort, South Africa, to evaluate the transfer of radionuclides and toxic elements from the mine dump to the vegetation at and around the dump. The samples were analyzed and the data was then used to estimate the potential radiological and toxicological impact of the mine dump to the community located next to it. The concentration of all essential elements in plant leaves of three species, A. *pycnatha*, E. *globulus* and *Hyparrhenia* spp. were within the normal levels found in the species. The concentrations of toxic elements were slightly elevated, especially that of uranium and lead.

There is a transfer of radionuclides and toxic elements from the mine dump to the plants and the transfer rates vary from species to species and from one sampling point to the other. The potential toxicological impact of both essential and toxic elements was estimated using default transfer parameters from the IAEA and the essential elements were within acceptable limits in leafy vegetables grown in home gardens while the concentration of uranium and lead were high, 1.88 and 0.144 µg/g, respectively. The MTL in food for the two metals are 0.3 and 0.005 µg/g respectively.

The potential exposure of the population from ingestion of meat and milk from cattle feeding on pasture contaminated by radionuclides from the mine dump, as well as the consumption of sheep feeding in the same pasture was estimated. The study showed that consumption of milk and meat from such cattle will lead to a dose of 3.6 ± 2.0 mSv/a and 2.6 ± 1.6 mSv/a respectively. The dose received from consumption of leafy vegetables grown in contaminated soil was insignificant for people above the age of 1 year and 278 µSv/a for those below 1 year.

Key Words

Naturally occurring radioactive material, gold mining, toxic elements, essential elements, radioactivity, dose, potential radiological impact, potential toxicological impact

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CHAPTER 1: INTRODUCTION AND JUSTIFICATION

1.1 Introduction

South Africa is one of the leading mining countries in the world (Yager, 2007) and has been for many decades. Gold is one of the principal mining products of South Africa. In 2005 South Africa was the world leader in gold production, producing 337 223 kg of gold (George, 2007). In Witwatersrand and in most gold deposits in South Africa, gold is associated with uranium. The ratio of uranium to gold in these mines varies between, 5:1 and 500:1 (Yager, 2007). Large amounts of uranium are brought to the surface during gold mining. Uranium in most cases is thrown away in the mine dumps with the rest of the rock material. ^{238}U, ^{235}U and ^{232}Th are all radioactive and occur in significant concentrations in nature due to their long radioactive half-lives (Bucham, 1993; Noz & Maguire, 2007)

There are three types of nuclear decay that are common, and these are; beta decay, alpha decay and spontaneous fission (Radford, 1986). When the atoms decay via these modes, they are usually left at higher energy levels, and they release the energy in the form of gamma radiation. In addition to gamma radiation there is alpha and beta radiation from NORMs (Naturally occurring radioactive materials), and all these types of radiation are called ionizing radiation, which is radiation that is capable of producing ion pairs in biological material(s) (IAEA, 2007). Ionizing radiation is harmful to biological material and to humans (Leiser, 1995; Ward, 1988).

When radionuclides migrate from a mine dump, they are deposited at various distances from the mine dump and enter into the natural environment; water and land (Desmet, Nassimbeni & Belli, 1990). This leads to the transfer and accumulation of radionuclides within food chains in the ecosystems. Animals that graze on the ground absorb them directly from the soil, from the water they drink and from the plants that they consume (Bhattacharyya, 1998). Humans get the radionuclides from the water that they drink and from the consumption of plants and animals. As the radionuclides are being transferred from one organism to another within the food chains they become accumulated. This process is called bio-accumulation (Qiao-qiao, Guang-wei & Langdon, 2007). This is mainly because most living organisms including humans do not have a

very efficient method of getting rid of heavy metals from their bodies. In this way the radionuclides and other heavy toxic metals are selectively concentrated as they go up the food chain (Russell, 1965). Once these minerals are dissolved in water, they are taken up through absorption by plant roots, as the plants attempt to absorb water and nutrients from the soil. The degree to which this absorption occurs depends on the chemical form and properties of the radionuclides and the kind of plant involved. The interaction of plants with radionuclides occurs at two levels: either in the aerial (shoot portion of the plant), or in the rhizosphere (soil-root zone of the plant) (Al-Kharouf, Al-Hamarneh & Dababneh, 2008).

1.2 AIM AND OBJECTIVES OF THE STUDY

1.2.1 Aim

The main aim of the study is to measure the environmental impact of the Princess Dump in Roodepoort. The study is a multi-faceted one, which will cover a thorough assessment of the radiological and toxicological impact of the gold mine dump. The study will cover assessment of the soil at and around the mine dump, the vegetation at and around the dump and the water in the vicinity and flow-direction of run-off from the dump. It will ascertain the level of radiation of the Princess Dump and abandoned gold mine tailings facilities in Roodepoort. Report will include exposure assessment based on the radiation levels measured in solid material and water. This study will concentrate on the transfer of the toxic and radioactive elements from the soil to the vegetation.

1.2.2 Objectives

The objectives of the study were to:

- Generate a qualitative and quantitative analysis report of all the elements found in the mine dump and in the vegetation using Inductively Coupled Plasma-Mass Spectroscopy (ICP-MS);
- Evaluate the potential toxicological impact of toxic elements on humans via the plants pathway;
- Generate a qualitative and quantitative report of radioactive isotopes from the soil samples from the mine dump using a High Purity Germanium gamma detector;

- Estimate the potential radiological exposure to humans via the plants pathway.

1.3 Justification of the research project

There are considerable concerns surrounding the introduction of NORM into the biosphere as a result of human activities. The creation of very large residues of mining and processing of uranium-bearing ores, the resulting heaped slag and waste water giving rise to considerable health and environmental concerns is a classic example (Al-Kharouf, Al-Hamarneh & Dababneh, 2008). It has been estimated for instance that about 1 GBq of ^{222}Rn is released per ton of ore containing 1% U_2O_8 (International Committee on Radiation Protection, 2008).

Dangerous levels of radioactivity in Gauteng's mine dumps will take decades and billions of rands to clear, say the scientists who blew the whistle on the province's acid mine drainage problem. Mariette Liefferink, the chief executive of the Federation for a Sustainable Environment, said the tailings dumps and dams were historically sited on unlined dolomite, resulting in heavy metals and uranium seeping into groundwater reported Macleod (2011) in the Mail & Guardian online. Among other headlines to grace the local and international media were reports about, high radiation levels in informal settlement built on radioactive mine waste dump in Krugersdorp (Business Day, 2010), acid mine drainage, tailings seepage, settlements on radioactive mine waste, and bricks being made from radioactive tailings (Mammburu, 2010). The NNR distanced itself from a report called the WRC 1214 report (Coetzee *et al.*, 2006) which was responsible for most of the media attention to the issue. The NNR cited the assessment methodology as the basis of the rejection and decided they will instead conduct their own assessment on the matter. The report, known as the Brenk-Report, identified several sites along the WFS catchment with significant radiological risk, in some cases, exceeding applicable guidelines by several magnitudes (Barthel, 2007).

Radiation is dangerous if it is not monitored very well. It is true that most gold mine dumps in South Africa contain a lot of Uranium which is radioactive (Yager, 2007). The dose rate of the mine dump may happen to be above the world average of 60 nGy/hr which is the population weighted average dose rate and have damaging effects on the environment as well as the

human population living next to the mine dump. But if the activity of the mine dump is low and the radionuclides don't migrate from the dump, then the dump is as safe as any other pile of rock and sand. This study will determine if the mine dump is safe or not. If the mine dump is hazardous to the residents, then measures can be taken to ensure the safety of the people. If the mine dump does not pose a significant health risk to the environment and the residents, then that is also important because it means that the government will save a lot of money which can be used in rehabilitation works elsewhere.

CHAPTER 2: LITERATURE REVIEW

2.1 Gold mining

Gold mining is a very old activity because gold has been around for centuries. The initial mining strategies might have been very simple and basic but as science and knowledge increased, the mining and recovery process improved and involved the use of advanced technology. Nowadays the mining and processing of gold involves the use of heavy machinery and advanced chemical treatment to extract, concentrate and purify the gold (Yager, 2007).

Gold deposits are places where the amount of gold in a soil or rock mass occurs in higher concentrations than normal. These deposits were formed millions of years ago by a number of geochemical processes. These processes include erosion of mineral rich rock, deposition of sediments, climate change and tectonic plate movement. There are two hypotheses that attempt to answer the deposition of gold in the Witwatersrand basin (Kirk, Ruiz, Chesley & Titley, 2003). The models agree on the fact that the sediments of the Witwatersrand were originally carried by rivers that were eroding highlands and depositing their sediments in an inland sea or huge lake. When deposition occurred in the large water body the high density elements/metals got deposited first, and thus were closer to the shore of the water body, while the rest were deposited more into the water body.

This preferential deposition of the heavier sediments at the shore of the lake helped in concentrating the heavier elements at specific points. The theories further suggest that due to change in climate and position of the water bodies these shoreline sediments were covered by sand which formed layers and more sand forming even more layers and eventually sedimentary rocks leaving the deposits buried deep into the crust of the earth. Some of the deposits have been brought closer to the surface by geo-mechanical possesses (Kirk *et al.*, 2003). The depth of the deposits determine the mining method used.

The process of gold production can be divided into six main phases:

- Finding the ore body;
- Creating access to the ore body;
- Removing the ore by mining or breaking the ore body;
- Transporting the broken material from the mining face to the plants for treatment;

- Processing;
- Refining.

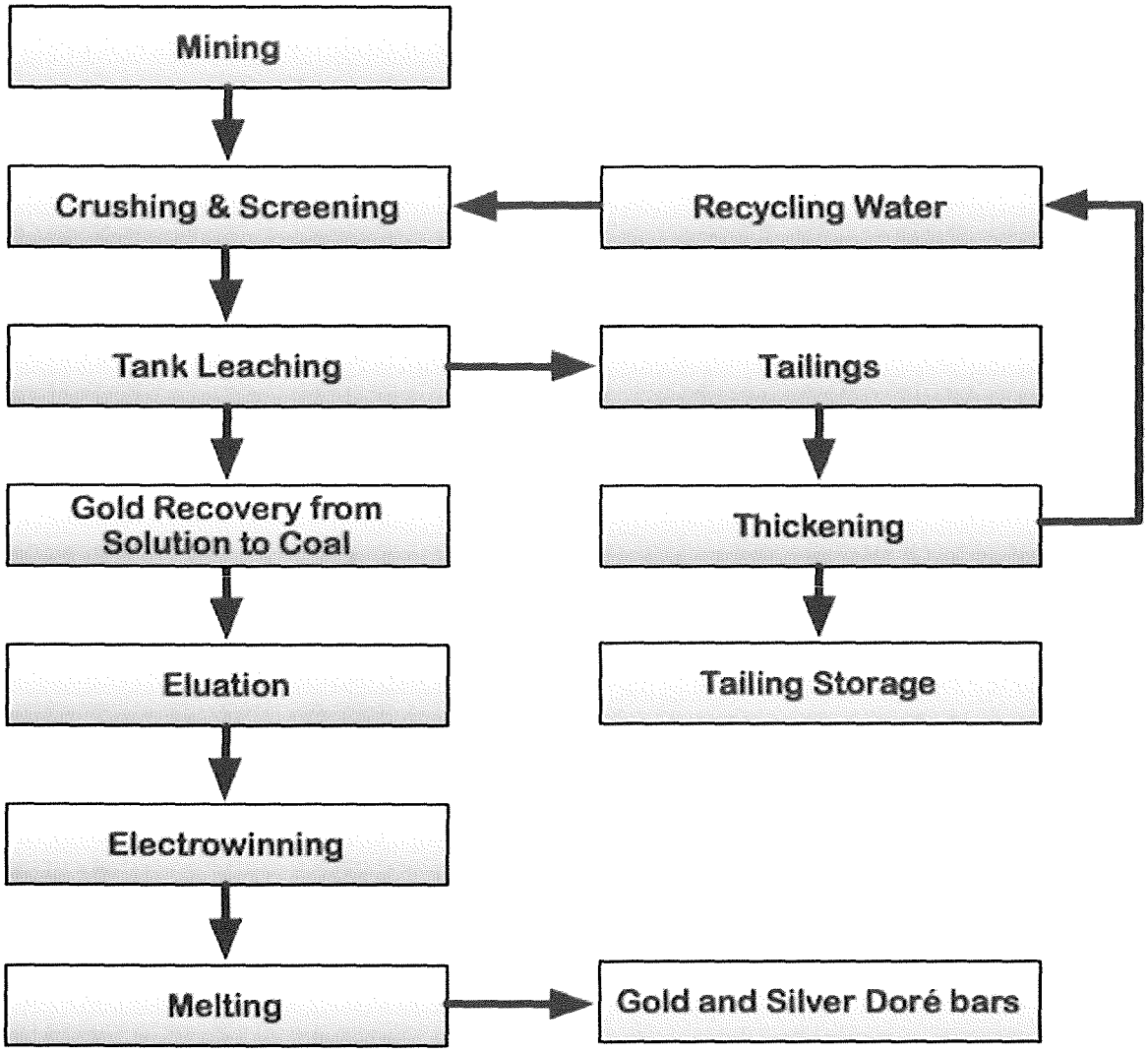

Figure 1 Gold mining flow chart as illustrated by GeoProMining (n.d.)

Although the process can take different routes at processing, they all lead to the production of pure gold and a lot of unwanted waste material.

2.2 Associated concentration of radionuclides and heavy toxic metals

From the theories about the deposition of gold in the Witwatersrand basin (Kirk *et al.,* 2003), one can actually note that the deposits of gold in the lithosphere will almost always go with some uranium and other heavy elements, especially for the scenario in the Witwatersrand basin. The theories claim that the deposition occurs according to density of the element, with the more dense elements being deposited first and the lighter one later. This therefore means that the deposition of the heavy metals like gold, silver, mercury, uranium and others will take place almost at the same position.

Therefore, in the case of the Witwatersrand basin and other deposits formed like them, the gold will always be found with deposits of other heavy elements. This partially explains why most gold deposits are associated with uranium and other heavy metal elements.

The mining of gold doesn't just bring the gold to the surface but it also brings the other heavy metals to the surface. Like gold, the concentrations of these heavy metals are slightly enhanced compared to those on the surface of the earth.

2.3 Toxic elements

Most heavy metals are not good for human health especially when they are in high concentration. The high concentration mentioned here is relative to the human body or most living organisms. The concentration may just be less than 1 ppm but it is considered to be high concentration, for example 0.3 ppm of mercury in the body is considered very bad for human health (Eck & Wilson, 1989). It is worth noting also that minerals needed in lesser amounts are quite toxic when in excess. For example copper, iron, manganese, selenium and vanadium, even calcium and sodium are quite toxic when in excess (Wilson, 2013).

2.3.1 Functioning of toxic elements in the body

Toxic metals replace nutrient minerals in enzyme binding sites. When this occurs, the metals inhibit, over-stimulate or otherwise alter thousands of enzymes. An affected enzyme may operate at 5% of normal activity. This may contribute to a number of health conditions. Toxic metals may also replace other substances in other tissue structures. These tissues, such as the

arteries, joints, bones and muscles, are weakened by the replacement process. Toxic metals may also simply get deposited in many sites, causing local irritation and other toxic effects. They may also support development of fungal, bacterial and viral infections that are difficult or impossible to eradicate until this cause is removed. The mineral replacement process often involves the idea of preferred minerals. For example, the body prefers zinc for over 50 critical enzymes. However, if zinc becomes deficient - and our soil and food are very low in zinc today – and the exposure to cadmium, lead or mercury is sufficiently high, the body will use these in place of zinc (Kutsky, 1981).

Cadmium and mercury, in particular, are located just below zinc in the periodic table of elements (all group IB elements), so their atomic structure is very similar to that of zinc. It almost fits perfectly in the zinc binding sites of critical enzymes such as RNA transferase, carboxy-peptidase, alcohol dehydrogenase and many others of great importance in the body. The ability to replace a vital mineral, however, means that toxic metals are not completely harmful. Indeed, they can extend life. They keep bodies functioning when vital minerals are deficient. Many people limp along on grossly deficient diets, and some are even born deficient and with high concentrations of toxic elements. Depending on where toxic metals accumulate, the resulting effects may be given names such as hypothyroidism, diabetes or cancer (Schroeder, 1973). The different essential and toxic elements as well as their uses and toxicities are presented in Annexure A.

2.4 Radioactivity

Irradiation of the human body from external sources is mainly by gamma radiation from radionuclides of the ^{238}U and ^{232}Th series and from ^{40}K present at different levels in soils. Natural environmental radioactivity and the associated external exposure due to gamma radiation depend primarily on the geological and geographical conditions. The specific levels of terrestrial environmental radiation are related to the type of rocks from which the soils originate (Momcilovic´, Kovacevic´ & Dragovic, 2010).

Natural radioactivity exists on earth; contributed by primordial radionuclides (present when the earth was created), and cosmo-genic radionuclides (formed as a result of cosmic ray

interaction). Radioactivity is defined as the spontaneous emission of subatomic particles (α-rays and β-rays) and high-frequency electromagnetic radiation (γ-rays and X-rays) by radioactive elements (ICRP, 2008; Tykva & Sabol, 1995). An emission of this type is referred to as 'radioactive decay' or, nuclear transition. Reason for the phenomenon of radioactivity is the quest for nuclear stability. It was Becquerel who discovered radioactivity in 1896 through the fogging of photographic plates by an unknown radiation emanating from a uranium bearing rock (Eisenbud & Gesell, 1997). All food contains some natural radioactivity - radionuclides such as ^{40}K, ^{210}Po, ^{226}Ra which occur naturally in the soil, are incorporated metabolically into plants and ultimately find their way into food and water (Eisenbud & Gesell, 1997). The three major decay series of naturally occurring radionuclides are shown in table 1

Table 1 The ^{238}U, ^{235}U and ^{232}Th decays series showing both the major decay mode and the half-life of the radionuclides.

Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation	Nuclide	Half-life	Major radiation
^{238}U	4.5×10^9 a	α	^{235}U	7.03×10^8 a	α	^{232}Th	1.41×10^{10} a	α
^{234}Th	24 d	β	^{231}Th	25.5 h	β	^{228}Ra	5.75 a	β
^{234}Pa	1.2 m	β	^{231}Pa	3.3×10^4 a	α	^{228}Ra	6.1 h	β
^{234}U	2.4×10^5 a	α	^{227}Ac	21.8 a	α, β	^{228}Th	1.91 a	α
^{230}Th	7.5×10^5 a	α	^{227}Th	18.7 d	α	^{224}Ra	3.66 d	α
^{226}Ra	1.600 a	α	^{223}Ra	11.4 d	α	^{220}Rn	55.6 s	α
^{222}Rn	3.8 d	α	^{219}Rn	3.96 s	α	^{216}Po	0.15 s	α
^{218}Po	3.1 m	α	^{215}Po	1.78 ms	α	^{212}Pb	10.6 h	β
^{214}Pd	27 m	β	^{211}Pd	36.2 m	β	^{212}Bi	60.6 m	α, β
^{214}Bi	20 m	β	^{211}Bi	2.17 m	α	^{212}Po	0.3μs	α
^{214}Po	160 μs	α	^{207}Th	4.77 m	β	^{208}Th	3.1 m	β
^{210}Pb	22 a	β	^{207}Pb	(stable)		^{208}Pb	(stable)	
^{210}Bi	5 d	β						
^{210}Po	140 d	α						

Radionuclides released to the environment as a result of human activities add to the exposure received from natural radionuclides. These radionuclides are called TENORM for technologically enhanced naturally occurring radioactive material. Ionizing radiation is a health hazard and contributes towards adverse biological effects. Once present in the environment, these radionuclides can make their way into the food chain through two general pathways (Figure 2): the aquatic pathway, which involves entry into the food chain via water (IAEA, 1989); these radionuclides move along with water through lakes, the underground water, rivers and get

deposited on the surrounding soil or rocks. Plants and fish absorb the radionuclides in water the same way they absorb minerals, depending on chemical properties of the nuclides. The second pathway through the environment is the atmospheric pathway when radionuclides are released into the air by human activities. They later fall back on land and may settle on the surface of plants. Animals may eat these plants; they therefore ingest the radionuclides on these leaves. Eventually the plants and animals will become food for people and therefore they provide a pathway for radionuclides to humankind (Sedumedi, 2003).

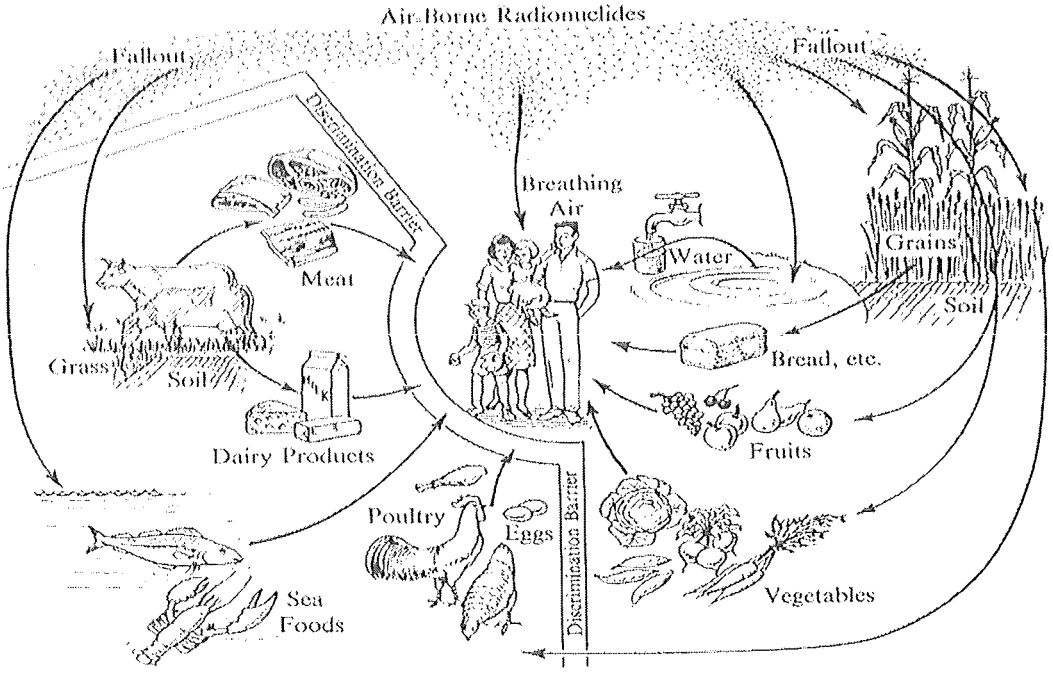

Figure 2 Different pathways that radionuclides travel in the environment and into the food chain as illustrated by Sedumedi, (2003)

The radioactive dose received by any individual depends upon a number of factors, such as time, location, the pathway taken by the radionuclides through the environment and the characteristics of the individual. These characteristics include physiological parameters (e.g. breathing rate), dietary information (e.g. consumption rate and type of food), residence data (e.g. ventilation of house), use of local resources (e.g. agricultural resources), recreational activities (e.g. swimming), and any other individual-specific information that is necessary to

estimate annual dose. In the assessment on doses, a specific set of these characteristics is referred to as an exposure scenario (ICRP, 2005).

2.4.1 Radioactive equilibrium

Radioactive equilibrium is a term that is applied to a decay chain series, that is, a parent with all of its daughter nuclei. Radioactive equilibrium is when all the daughter nuclei in a decay chain series, decay at the same rate as they are produced (Prince, 1979). One very common and useful state of equilibrium is the secular equilibrium. When a decay chain series is in a state of secular equilibrium all the daughter nuclei decay at the same rate as the parent nuclei. Figure 3 shows one of the oldest radioactive equilibria in nature, the secular equilibrium between ^{238}U and its daughters. In secular equilibrium the parent has a very long half-life compared to all its daughters and therefore its decay constant is much lower compared to its daughters, $\lambda_P << \lambda_D$ (Burcham, 1973; Cember & Johnson, 2009; Faires & Boswell, 1981; Krane, 1988). λ_P can be estimated to be zero. The activity of radioactive nuclei is given by equation (1) and that of daughter nuclei in a decay chain series is given by equation (2) (Lapp & Andrews, 1972; Lilley, 2001);

$$A = N\lambda \quad (1)$$

Where: A= Activity, N= number of radioactive nuclei and λ= decay constant

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D-\lambda_P}(e^{-\lambda_P t} - e^{-\lambda_D t}) \quad (2)$$

In secular equilibrium this equation can be simplified into equation (3) (Krane, 1988; Lapp & Andrews, 1972);

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D}(1 - e^{-\lambda_D t}) \quad (3)$$

With time the $e^{-\lambda_D t}$ term will become negligible and the number of daughter nuclei will decay at a constant rate as illustrated by equation (4) (Cember & Johnson, 2009; Lapp & Andrews, 1972; Turner, 2007);

$$N_D(t) = N_P(t_0)\frac{\lambda_P}{\lambda_D} \quad (4)$$

Thus at a state of secular equilibrium the daughter and parent have the same activities as can be seen in equation (5);

$$N_D\lambda_D = N_P\lambda_P \quad (5)$$

Where:

N_D = number of daughter nuclei

N_P = number of parents nuclei

λ_D = decay constant of daughter

λ_P = decay constant of parent

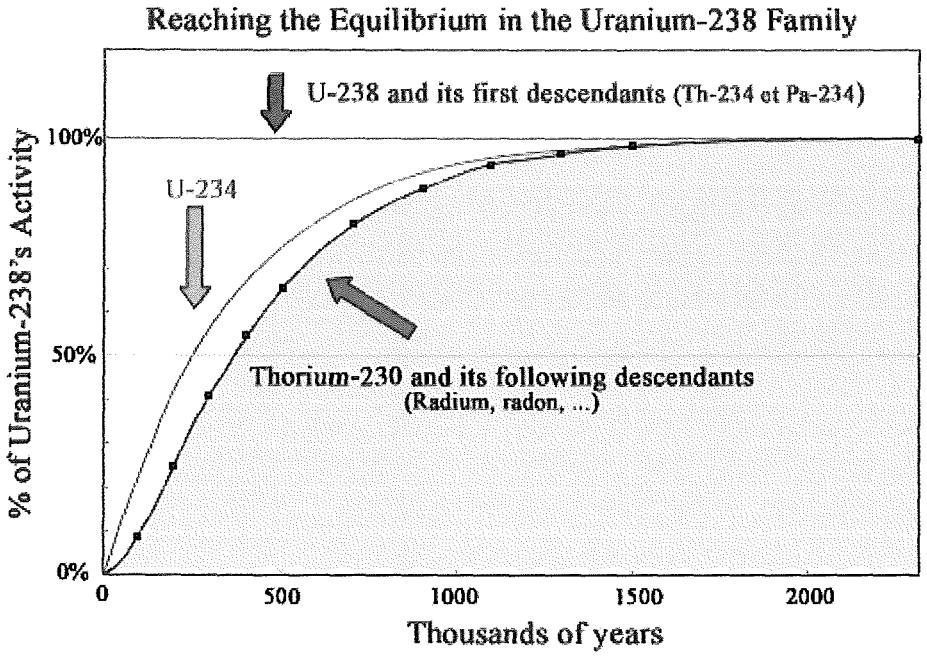

Figure 3 Secular equilibrium between ^{238}U and its daughter nuclides (la radioactivite, 2014)

2.4.2 Radioactivity detection and measurement

A fundamental feature of nuclear processes is that the energy released is larger than the binding energies of atomic electrons. Any emitted particles will have sufficient energy to ionize atoms. Nuclear radiation is called "ionizing radiation" and detecting this ionization allows us to observe nuclear processes. Radiations that interact with matter via the electromagnetic force, i.e., electrons, charged particles and photons, can directly ionize or excite atoms. These radiations are readily detected (Oregon State University, 2010).

There are various types of instruments used to detect radiation and all of them depend on the ionizing nature of 'ionizing radiation'. Even though these detectors differ in their fundamental functioning, several common criteria are used to evaluate and compare them. These are as follows:

1. The sensitivity of the detector- this property has to do with what type of radiation and the energies the detector can detect. For example solid scintillation detectors are used for α-particles from radioactive-decay because they can't penetrate the detector covering.
2. The energy resolution of the detector- this has to do with the ability of the detector to measure the energy of the particle striking it as accurately as possible, say for example if two gamma-rays of energy 1.10 MeV and 1.15 MeV strike the detector, will it be able to distinguish between them?
3. The time resolution of the detector or its pulse resolving time- addresses things like the dead time, how long the detector takes to process an incident hit and get ready for a new one. The shorter, the better.
4. The efficiency of the detector- if for example 1000 gamma-rays strike the detector, how many will be detected. High efficiency reduces uncertainty and allows for shorter counting times (IAEA, 2004; Oregon State University, 2010).

2.4.3 Types of detectors

a) Gas Ionization detectors- these detectors take advantage of the fact that radiation ionizes gases and produces ion pairs. These pairs can be separated and collected.

Application of a potential gradient between the two electrodes in a gas-filled ion chamber causes the cations move to the cathode and the anions move to the anode and this creates a measurable pulse (IAEA, 2004; Knoll, 1989).

b) Semiconductor detectors- in these detectors the incident radiation interacts with the detector material, a semiconductor, usually Si or Ge, to create hole-electron pairs. The hole-electron pairs are collected by charged electrodes and the electrons move to the anode and holes to the cathode, creating a measurable electric pulse. The important feature of semiconductor detectors is their superior energy resolution (Bertolini & Coche, 1968; Goulding & Pehl, 1974; IAEA, 2004).

c) Solid Scintillators- the energy of incoming radiation is transferred into fluorescent molecules in a crystalline solid. The absorbed energy causes excitation of the orbital electrons in the material. The electrons lose the excitation energy as light in the visible or near ultra-violet range of the electro-magnetic spectrum. A photomultiplier tube is used to convert the photons into photo-electrons, which are amplified through a series of secondary electron emission via a series of dynodes. The result is a big enough pulse to be measured (Ortec-Online n.d.; IAEA, 2004; Oregon State University, 2010).

d) Liquid scintillators- similar operation to solid scintillation detectors, only difference being that the radioactive sample and the fluorescent material are dissolved in a liquid medium, usually a non-polar solvent. The energy of nuclear radiation first excites the solvent molecules. This excitation energy eventually appears as photons emitted from the fluor (fluorescent material) following an intermediate transfer stage. The photons are then detected using a photomultiplier system as in solid scintillators (Flakus, n.d.; IAEA, 2004; Oregon State University, 2010).

e) Nuclear emulsions- ionizing radiation from a sample interacts with the silver halide grains in a photographic emulsion to cause a chemical reaction. Subsequent development of the film produces an image and so permits a semi-quantitative estimate of the incoming radiation (IAEA, 2004).

2.4.4 Radiation dosimetry

Radiation is always around us, from the sun, the dust and other sources, even inside us, as we inhale some radioactive particles in dust and ingestion of material (Harvey, 1969; Turner, 2007). Radiation exposure is described as the amount of ionization that X- or γ radiation produces in air, and its unit is the roentgen (R) and it is equivalent to 2.58×10^{-4} C/kg (IAEA, 2007). Exposure is not very important in radiation dosimetry because it doesn't have any indication of the biological effect in living tissue.

Absorbed dose is defined as the amount of dose absorbed by a specific mass of target organ. The absorbed dose is expressed in the unit, gray (Gy), where 1 Gy is equal to I joule of absorbed energy per 1 kg of irradiated target (Cember & Johnson, 2009; Lilley, 2001; Noz & Maguire, 2007). The absorbed dose can also be expressed in the form of equation (6) (IAEA, 2007);

$$D = \frac{d\bar{e}}{dm}, \qquad (6)$$

where d*e* is the mean energy imparted by *ionizing radiation* to matter in a volume element and d*m* is the mass of matter in the volume element. The absorbed dose can be expressed in another unit called the '*rad*'(radiation absorbed dose). The *rad* is the original unit and is defined as an absorbed energy of 100 erg per gram. Equation (7) shows its relationship to the *gray* (Martin & Harbison, 2006);

$$1\,rad = 0.01\,Gy = 1\,centigray\,(cGy) \qquad (7)$$

The absorbed amount of energy just gives a very small idea of the biological effect of the radiation absorbed by the target. The biological effect depends on other factors that are related to the type of radiation and the target organ where the radiation is being absorbed (Cember & Johnson, 2009). Different types of radiation have different effects on living organisms. High LET (linear energy transfer) radiation like alpha particles will cause more damage than gamma rays because they will deposit a large amount of their energy over a very short distance and thus over a very small volume, while gamma rays which are low LET will deposit very little energy

over a longer path and thus less energy per unit volume (Lilley, 2001). Relative biological effectiveness (RBE) was introduced as a dimensionless quantity of the amount of absorbed dose of ionizing radiation relative to that of X-ray or gamma radiation of a particular energy to provide the same biological response (Noz & Maguire, 2007). The RBE is a complicated factor and has been normalized into the radiation weighing factor (W_R) by the ICRP and NCRP. Table 2 shows a list of radiation weighing factors for different radiation types and different energies (ICRP, 1991).

Table 2 Radiation weighting factors for different radiation types and energies (ICRP, 1991; Noz & Maguire, 2007)

Type of radiation	Energy range	Weighting factor (W_R)
Photons, electrons, positrons, muons	All energies	1
Neutrons	<10 keV	5
	>10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	>2 MeV to 20 MeV	10
	>20 MeV	5
Proton	<20 MeV	5
Alpha particles, fission fragments, non-relativistic heavy nuclei	<20 MeV	20

In order to determine the effect of the nature of the radiation by the weighting factor in Table 2, a unit called the ***equivalent dose (H_T)*** is specified. This is the amount of the dose ($D_{T,R}$) absorbed over a tissue or organ (T) due to radiation (R) and is given equation (8) (Cember & Johnson, 2009; Eisenbud & Gesell, 1997; Lilley, 2001);

$$H_T = \sum_R w_R D_{T,R} \qquad (8)$$

The '***Sievert***' (*Sv*) is used to express the equivalent dose when the absorbed dose is in units of *gray* (*Gy*); thus one Sievert is also equal to one joule per kilogram (Choppin, Liljenzin & Rydberg, 2002; Eisenbud & Gesell, 1997; Knoll, 2000). In addition to the radiation types and energy, the biological effect to radiation is concerned with the sensitivities of irradiated organs or tissues. The variation of radiation sensitivity of each organ is taken into account in the contribution of the equivalent dose in all tissues and organs of the body. The new terms the ***effective dose* (*E*)** and the ***tissue weighting factor* (w_T)** are introduced and given in Table 3. The definition of the effective dose is the sum of the equivalent doses weighted by the tissue weighting factors for each tissue, as given in equations (9) and (10) (Cember & Johnson, 2009; Martin & Harbison, 2006);

$$E = \sum_T w_T H_T \qquad (9)$$

And can also be written as;

$$E = \sum_T w_T \sum_R w_R D_{T,R} \qquad (10)$$

Table 3 Tissue weighting factors (ICRP, 1991; Martin & Harbison, 2006)

Tissue or Organ	Tissue Weighting factor, w_T
Gonads	0.20
Colon	0.12
Lung	0.12
Red bone morrow	0.12
Stomach	0.12
Bladder	0.5
Breast	0.5
Oesophagus	0.5
Liver	0.5
Thyroid	0.5
Skin	0.1
Bone surfaces	0.1
Remainder	0.5

2.4.4.1 Dose limits

ICRP has done some research on the dosage that people receive and calculated all the risk factors. Those calculations led to recommendations on the amount of dose that different groups of people may receive to keep the risk factors as low as reasonably possible. Table 4 shows those recommendations made;

Table 4 Recommended occupational and public dose limits (Cember & Johnson, 2009; ICRP, 1991; Noz & Maguire, 2007)

Application	Dose limit	
	Occupational	Public
Whole body	20 mSv per year, averaged over a defined period of 5 years	1 mSv per year
Annual equivalent dose in		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hand and feet	500 mSv	–

2.3.4.2 Dosage

The most important parameter in radiological impact assessment is the yearly dose received by an individual. The dose rate in air can be calculated from the radioactivity concentrations of the natural radionuclides in soil samples. The mean activity concentrations of ^{238}U, ^{232}Th and ^{40}K ($Bq.kg^{-1}$) in the soil samples are used to calculate the absorbed dose rate given by equation 11 (Beck, 1972; Belivermis, Kikic, Cotuk & Topcuoglu, 2010; Turhan & Gundiz, 2008):

$$D = (0.462A_{Ra} + 0.604A_{Th} + 0.0417A_K) \quad (11)$$

D is the absorbed dose rate in $nGy.h^{-1}$, A_{Ra}, A_{Th} and A_K are the activity concentration of ^{226}Ra (^{238}U) assuming secular equilibrium in the ^{238}U decay-series, ^{232}Th and ^{40}K, respectively. The dose coefficients in units of $nGy.h^{-1}$ per $Bq.kg^{-1}$.

The absorbed dose can be considered in terms of the annual effective dose equivalent from outdoor terrestrial gamma radiation which is converted from the absorbed dose by taking into account two factors, namely the conversion coefficient from absorbed dose in air to effective dose and the outdoor occupancy factor. The annual effective dose equivalent can be estimated using equation (12) (Beck, 1972; Turhan & Gundiz, 2008; Chang, Koh, Kim, Seo, Yoon, Row & Lee, 2008);

$$AEDE\ (\frac{\mu Sv}{yr}) = D(\frac{nGy}{h}) \times 8760\ h \times 0.2 \times 0.7\ Sv.Gy^{-1} \times 10^{-3} \qquad (12)$$

AEDE is the Annual Effective Dose Equivalent in μSv/yr, D is the dose rate in air, 8760 h is the number of hours in a year, 0.2 is the outdoor occupancy factor and 0.7 is a dose conversion factor for adults.

The yearly dose from the ingestion of radionuclides also contributes to the amount of dose received per annum. It can be calculated using equation (13);

$$Yearly\ Dose\ =\ Yearly\ Consumption\ x\ Specific\ Activity\ \ x\ \ Dose\ Conversion\ Factor \qquad (13)$$

2.4 Interaction of radionuclides in the soil

The solid-liquid distribution concept is one of the major concepts used in the study and understanding of radionuclide mobility in the soil. Dissolved radionuclides in the soil can bind to different solid phases found in the soil through different mechanisms that can be classified under the broad term, sorption. The chemical form in which a particular radionuclide exists in the soil, i.e. either dissolved, complexed or in solution and the speciation of that radionuclide are the key determining factors for the mobility in the soil and the eventual uptake by plants (IAEA, 2010).

The degree to which radionuclides are bound in the soil phases can be estimated using the solid-liquid distribution coefficient, K_d. Since the sorption of radionuclides to soil surfaces depends on this distribution coefficient, it can therefore be used to estimate the mobility of radionuclides in the soil as well as determine the amount of time that radionuclides will stay in

a particular layer of the soil profile. The distribution coefficient can be calculated using equation (14) (Konoplev, 1993)

$$K_d = \frac{activity\ concentration\ in\ solid\ phase\ (Bq\ kg^{-1})}{activity\ concentration\ in\ liquid\ phase\ (Bq\ L^{-1})} (L\ kg^{-1}) \quad (14)$$

The K_d approach takes no explicit account of sorption mechanisms but assumes that the radionuclide on the solid phase is in equilibrium with the radionuclide in solution and that exchange between these phases is reversible and can go either way depending on the soil environment and species concentration.

Importance of the K_d factor on uptake of radionuclides by plants

The radionuclides soil-to-plant transfer is assessed by measuring the soil to plant concentration factor (F_v), defined as the ratio of the radionuclide content in the plant to that in the soil; (Bq/kg) dry weight plant tissue per (Bq/kg) dry weight soil. The concentration factor can be assumed to be mostly controlled by the root uptake, since other sources of plant contamination are often of lesser significance (except for mosses).

The radionuclide concentration in plants (C_v) is assumed to be linearly correlated to the radionuclide level in the soil solution (C_{ss}). The relationship is controlled by the selectivity of the plant-root system represented by the bioaccumulation factor (Bp) given by equation (15):

$$C_v = B_p \times C_{ss} \quad (15)$$

Where: B_p is the radionuclide plant-soil transfer factor (Bq/kg plant tissue / Bq/L soil solution). The process of ion uptake from the soil solution to the plant by its roots includes physiological aspects of the plant related to nutrient uptake and selectivity, and depends on both the plant and the element considered.

Therefore, the plant to soil solution bioaccumulation factor is assumed to be dependent on the concentrations of competitive radionuclide species in soil solution which is in-turn controlled by the liquid-solid distribution coefficient.

2.5 Accumulation of elements and radionuclides by plants

The transfer of artificial radionuclides along terrestrial food chains has been studied extensively during the last 40 years. Apart from the obvious presence of naturally occurring radionuclides (NORs) in uranium deposits, a wide range of uranium- and thorium-bearing minerals (and their daughters) are being mined and processed commercially (IAEA, 2003; Vandenhove, *et al.*, 2000). The processes by which radionuclides can be incorporated into vegetation can either be (1) through activity interception by external plant surfaces (directly from the atmosphere or from re-suspended material), or (2) through uptake of radionuclides via the root system. The soil-to-plant transfer factor (F_v) is defined as the ratio of the concentrations of radionuclides in plant (Bq kg^{-1} dry mass) to that in soil (Bq kg^{-1} dry mass) (Chakraborty, Azim, Rahman & Sarker, 2013; Vandenhove, *et al.*, 2000). It is calculated according to equation (16) (International Union of Radioecologists, 1994).

$$F_v = \frac{Activity\ of\ radionuclide\ in\ plant\ (Bq\ kg^{-1}\ dry\ weight)}{Activity\ of\ radionuclide\ in\ soil\ (Bq\ kg^{-1}\ dry\ weight)} \qquad (16)$$

The soil-to-plant transfer factor is widely used for calculating the dose to humans from environmental radiation via the ingestion pathway. The soil-to-plant transfer factor is regarded as the most important parameter in environmental assessment programs. It is very important for the compilation of environmental transfer models used for estimating human dose from environmental radiation.

2.5.1 Foliar intake

Plants can accumulate radionuclides through their leaves. These radionuclides are usually airborne particles that have been blown by wind from areas of high nuclides concentration like mine dumps, nuclear power stations and other nuclear facilities, or fallout from a nuclear accident. Plant leaves vary from one plant to the next. Leaf physiology is such that the leaf structure of a plant differs, the top from the bottom. The amount of leaf hairs, cuticle and number and density of stomata differs greatly. When the radionuclides are deposited on plants, they are deposited on the upper part of the leaf, which usually has a cuticle, which is both waterproof and definitely radionuclide-proof (Pröhl, 2009). This therefore means that most of

the contamination in plants from areal deposition is superficial and in most cases adds to the food chain when the leaves are eaten by farm animals and game. Intake of radionuclides occurs either through the cuticle and epidermis, with the latter highly specific. Most stomata intake is for gaseous radionuclides like Radon (Koranda & Robison, 1978; Romney, Lindbergh, Hawthorne, Bystrom & Larson, 1963; Russell, 1965).

2.5.2 Root intake

Radionuclides get deposited into the soil through areal deposition by gravity or precipitation. It is then transferred from one point to another by water, usually run-off during rains. Thus from a dump the radionuclides are transported to other areas through the wind and by water. Once they are in the soil, they are in a position to be taken up by plants, which either can be plants eaten by animals or humans. There are a number of factors that determine the absorption of radionuclides and other elements by plants from the soil, such as (Sanzharova, Fesenko & Reed, 2009; Chakraborty, Azim, Rahman & Sarker, 2013):

- The form in which the activity enters or is present the soil;
- The physicochemical properties of the radionuclide;
- Time after entry into the soil;
- Type of soil and the physicochemical characteristics of the soil environment e.g. exchangeable potassium and pH;
- Type of crop;
- Crop management practices (application of fertilizers, irrigation, ploughing, liming, etc.);
- Climate conditions.

This is schematically represented in Figure 4

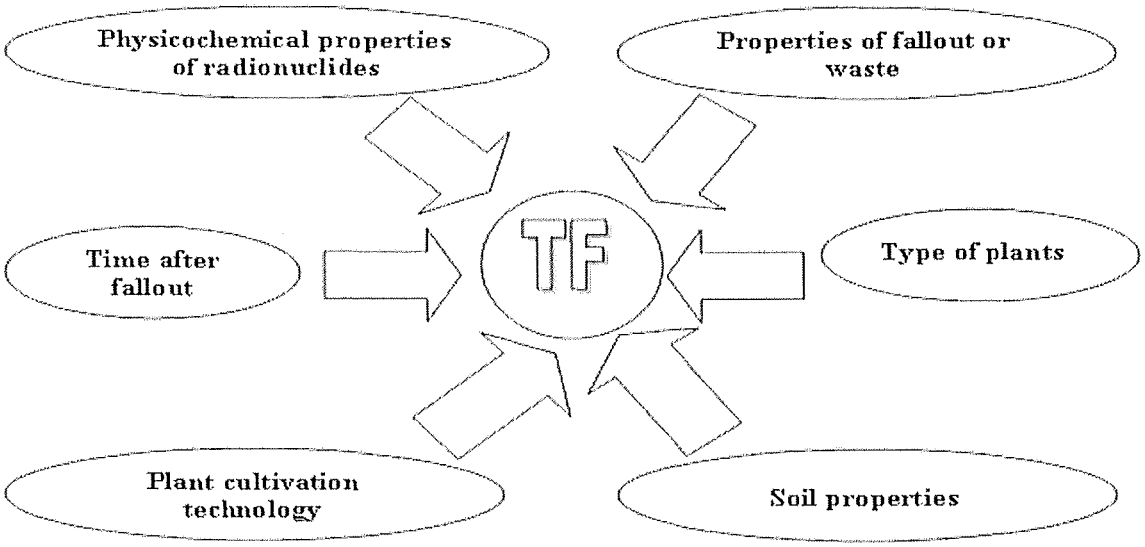

Figure 4 Factors influencing radionuclide root uptake as illustrated by IAEA (2003)

Tome *et al.* (2003) studied the soil to plant transfer factors of natural radionuclides and stable elements in a Mediterranean area. The transfer factor of ^{238}U, ^{234}U, ^{232}Th, ^{230}Th, ^{228}Th, and ^{226}Ra were obtained in plant samples (grass-pasture) collected around the soil of a disused mine. In the study, it was observed that the transfer of radium to plants is greater than the transfer of uranium and thorium and that there was no linear relationship between the concentration in plants and the substrate for the stable elements. The results also showed the preferential uptake of ^{226}Ra and some essential elements such as Ca, Mn, and P in contrast to uranium and thorium. Shtangeeva (2010) studied the uptake of uranium and thorium by native and cultivated plants. In the study he concluded that soil type, parent rock, climate and vegetation season had an effect on the transfer of radionuclides and stable elements from the soil to plants. It was noted that there is a variation in the concentration of radionuclides in the different compartments of the plant and that it was highest in the roots and the rate of radionuclide translocation from roots to shoots is probably species dependent. The study also showed that the concentrations of radionuclides in plants are rarely linearly correlated to the concentration of radionuclides in the soil. The temporal variation of both uranium and thorium in plants was also discussed and it was noted that the concentration of the elements in tissues can vary with the vegetation season. The concentration of other elements in plants may be controlled by light and the biological clock; however, this variations maybe species-specific. It

was then concluded that the plants grown in radionuclide enriched soils demonstrate significant increases in concentration of uranium and thorium in the roots compared to that in the upper plant parts. Thorium was less available for uptake by plants than uranium and that the relationship between uranium and thorium in soil and in plants depends significantly on the soil type.

Vegetables produced in kitchen gardens in Canas de Senhorim, including locations close to the mining tailings of Barragem Velha, did not show extreme enhancement of radioactivity. The highest concentrations were measured in lettuces grown with water from Ribeira da Pantanha. In general, ^{226}Ra is the radionuclide more concentrated by vegetables and through ingestion, may be the main contributor to the dose to local population (Carvalho, Oliveira & Malta, 2009).

CHAPTER3: METHODOLOGY

3.1 Study Area

The study was carried out at Princess gold mine tailings facility in Roodepoort, South Africa [26° 9' 37.606 South and 27° 51' 19.461 East]. The general location of the study area is marked as point A in Figure 5. The top of the mine dump is particularly devoid of vegetation, but there are plenty of trees and grass around it.

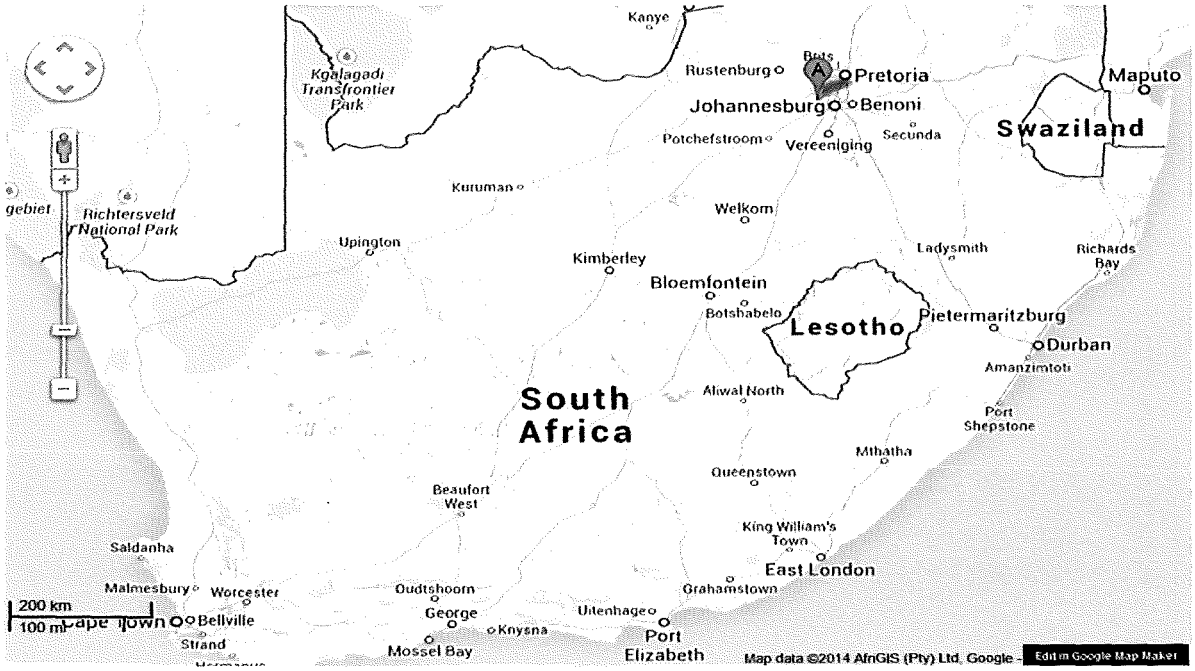

Figure 5 The location of the study area in the Gauteng province, South Africa, marked with the letter A.

3.2 Sampling

Multiple sampling points were selected from the mine dump and the surrounding environment. The sampling points were identified using a GPS and then they were marked on a map using pins as shown in Figure 6.

Figure 6 The study area showing the sampling points marked with letters and the surrounding communities

An auger drill was used to extract samples to a depth of a metre, and the top 15 cm of the soil. At every sampling point, two soil samples were collected, one from the top soil and the other from the bottom soil. Leaf samples of the vegetation were collected and a corresponding soil sample was also collected closest to the plant. All samples were labelled using letters, A, B, C, etc. with the top and bottom samples for the soil differentiated by subscripts i.e. A_1 for the top 15 cm and A_2 for the 100 cm sample.

The soil samples were collected into plastic bags, marked on the surface with the sample name, closed completely using cable ties and taken to the laboratory. The vegetation samples were put into perforated plastic bags to avoid the build-up of moisture that could damage the samples. Different species of plants found next to the mine dump were collected and these included *Eucalyptus globulus*, *Acacia mearsii* and *Hyparrhenia* spp. The samples were then air dried for 2 weeks. Organic material was removed from the soil samples, and 1kg of each of the soil samples was sealed into a Marinelli beaker using black masking tape for 26 days. This was done to allow ^{226}Ra to be in equilibrium with all its daughters for gamma analysis.

3.3 Gamma spectroscopy

A HPGe detector was used for gamma analysis of the radioactive elements in the samples. The major advantage of the HPGe detector is its unparalleled resolution of different energy peaks. The detector model used was HPGe GCD-35 190, with an efficiency of 36% relative to a 3"×3" NaI detector and a FWHM of 0.850 keV at 122 keV (Co-57) photon energy.

3.3.1 Efficiency Calibration of the HPGe GCD-35 190

For calibration, a powdered source of ^{133}Ba and ^{152}Eu with activities of 5.97 and 13.06 kBq was mixed with one of the soil samples in a sample bottle that was exactly the same as the ones used for counting of the actual samples. The sample into which the source was mixed had already been counted and the activities of the two radionuclides were recorded to ensure that it was as low as possible. The prepared standard was sealed for a period of 26days like all the other samples that were being counted to ensure that all conditions of the sample and the standard were the same. After 24 days the standard was counted for 24 hours and the following ^{133}Ba and ^{152}Eu gamma emission lines were considered; ^{152}Eu gamma lines (keV) 40.11 keV, 45.37 keV, 121.77 keV, 367.79 keV, 1085.88 keV, 1408 keV and ^{133}Ba gamma lines (keV) 53.14 keV, 80.98 keV, 160.6 keV. For each gamma line the ratio of the calculated activity into the actual activity ($\frac{actual}{calculated}$) was calculated and plotted against the gamma energy. For the lower energies (0-160 keV), a logarithmic data fit was done and for the higher energies (160-1408 keV) a polynomial data fit was done. The efficiency curve is shown in figure 7.

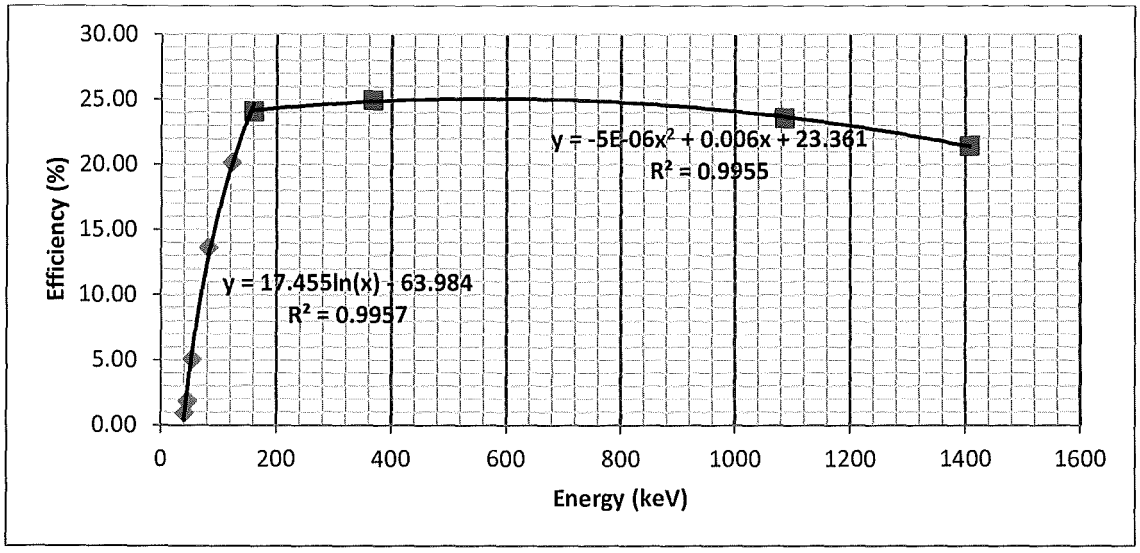

Figure 7 HPGe detector efficiency curve

3.3.2 Data acquisition

Data acquisition was done using, Winspec for automation and the spectra obtained was analyzed using the software, IDENTIFY. ^{226}Ra concentration was calculated as the weighted average of the activity determined using the gamma lines 295.1 (19.2%) and 351.9 (37.1%) keV gamma-rays from ^{214}Pb and 609.3 (46.1%) gamma-ray from ^{214}Bi (Boukhenfouf and Boucenna, 2011).The gamma-ray photo-peaks used for the determination of the ^{232}Th contents were 338.4 (12%), 911.2 (29%), 964.6 (5.05%) and 969.0 keV (17%) of ^{228}Ac, 238.6 keV (44.6%) of ^{212}Pb. ^{40}K was directly determined using 1460.8 (10.7%). The 186.2 keV gamma line of ^{226}Ra was not used due to interference from the 185.7 keV gamma emission line associated with ^{235}U. The correction may lead to some measurable error.

3.4 ICP-MS for soil and vegetation

3.4.1 Soil samples preparation

The aqua regia digestion method was used for complete digestion of the soil samples. A gram of each soil sample was mixed with 9 mL dilute hydrochloric and 3 mL dilute nitric acid. The solutions were then digested in a microwave oven and then filtered through Whitman paper number 42. After filtration the samples were diluted into 100 mL of de-ionized water and then appropriate aliquots were taken for ICP-MS analysis.

3.4.2 Vegetation samples preparation

The vegetation samples were ground using an electric mill after air-drying and they were stored for ICP-MS. To remove all moisture from the samples, 1 gram of each sample was dried in an oven at 600 °C for a period of 18 hours. The oven dry weight was collected and recorded, and then the samples were ashed in an oven at 800 °C for another 18 hours and the ash weight was also recorded. The ashed samples were each digested using the aqua regia method, filtered through the Whitman number 42, diluted into 100 mL de-ionised water and an aliquot of that was taken for ICP-MS analysis.

Soil/Sediment Sample Concentration by ICP-MS:

The concentrations, calculated using equation (17), determined in the digestate were to be reported on the basis of the dry weight of the sample, in units of µg/g:

$$concentration(dry\ weight)\left(\frac{\mu g}{g}\right) = C \times \frac{V_f}{W \times S} \times \frac{DF}{1000} \qquad (17)$$

Where,

C = Instrument value in µg/L (The average of all replicate integrations).

V_f = Final digestion volume (ml)

W = Initial aliquot amount (g)

S = % Solids/100

DF = Dilution Factor

Table 6 Concentration of toxic elements in soil and their potential concentration in leafy vegetables growing on the soil

	Element	soil conc.	TF	conc. Plant	MTL
Toxic	Pb	23.5±1.36	0.08	1.88±0.08	0.30
	Co	7.27±0.37	0.17	1.24±0.06	NA
	Ni	4.10±0.142	0.027	0.111±0.007	0.20
	Th	2.36±0.07	0.0012	0.003±0.0002	0.005
	U	7.19±0.58	0.002	0.144±0.014	0.005

4.1.2 Concentration of radiotoxic elements in plants

Table 7 shows the concentration of thorium and uranium in three different plant species. The vegetation samples were collected at and around the Princess mine dump. Figure 4 demonstrates the variation of the concentration of thorium among the samples. The concentration ranges from 0-0.1345 µg/g, with average concentration 0.0498 µg/g. A. *mearsii* generally has a slightly higher thorium concentration, with an average of 0.074µg/g while *Hyparrhenia* spp. has a low concentration, with an average of 0.0065µg/g.

Table 7 ICP-MS results for vegetation samples grouped according to species, showing thorium and uranium (radionuclides) concentrations only in µg/g ashed vegetation sample

	E. *globulus*							A. *mearsii*					*Hyparrhenia* spp.	
Element	L	D	E	N	E	BG	G	L	R	N	Y	O	J	S
Th	6.29E-02	0.00E+00	7.80E-02	3.33E-02	4.51E-02	3.80E-02	4.99E-02	5.50E-02	7.51E-02	1.35E-01	2.41E-02	8.84E-02	2.05E-04	1.28E-02
U	4.16E+00	5.36E-03	3.30E+00	2.29E+00	5.38E-01	6.38E+00	1.10E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.47E-02	4.45E-03
Pb	9.86E-01	1.07E+00	1.85E+00	1.40E+00	9.77E-01	2.57E+00	8.25E-01	2.79E+00	1.03E+00	1.07E+00	9.16E-01	1.10E+00	1.04E+00	9.77E-01
Bi	2.52E-03	2.21E-03	7.26E-03	3.65E-03	4.53E-03	6.41E-03	5.19E-03	5.60E-03	3.75E-03	3.83E-03	2.20E-03	6.33E-03	2.25E-03	5.39E-04

Table 7 shows the concentration of thorium and uranium in three plant species collected at and around the Princess mine dump. The concentration ranges from 0-0.1345 µg/g, with average concentration 0.0498 µg/g. A. *mearsii* generally has a slightly higher thorium concentration, with an average of 0.0754µg/g while *Hyparrhenia* spp. has a low concentration, with an average of 0.0065µg/g. The concentration of uranium is generally higher within the E. *globulus* species than all the other species, having an average of 2.40µg/g. The leaf samples from A. *mearsii* have uranium concentrations below the detection limit of the ICP-MS instrument and therefore the values of the concentration are not recorded. This shows that this species has extremely low accumulation capacity for the radionuclide, while the E. *globulus* can accumulate the radionuclide. *Hyparrhenia* spp. shows some accumulation of uranium, even though it is quite low.

Metal uptake by plants can be affected by several factors including metal concentrations in soils, soil pH, cation exchange capacity, organic matter content, types and varieties of plants, and plant age. It is generally accepted that the metal concentration in soil is the dominant factor (Alloway, B.J. and Davies, B.E., 1979). The vegetation samples that were collected were of different ages, even within the same species and they were collected at different sampling points. The chemical properties of the soil at the different sampling points were different and therefore should have an effect on the bio-availability of the radionuclide to the plants. The texture of the soil and the structure of the soil where the samples were collected differed wildly. Some samples were collected on the actual mine dump where the soil is not too compact and is generally sandy in texture while other samples were collected from vegetation growing on very compact soil with a loamy texture. These variations in physical and chemical properties of the sampling sites accounts for the variability in the concentration of the metals within the plant species analyzed. Different plant species have different physiology and different mechanisms when it comes to the absorption of nutrients from the soil. Plant species also vary in the way in which they translocate and store heavy metals. Some plants store them in the leaves, others in the bark, in the stem or roots while other plants selectively avoid certain heavy metals (Myung, 2008). The plant rhizosphere also plays a huge role in the absorption of radionuclides and metals by plants. Plant roots produce organic exudants, which can change

the micro-environment of the rhizosphere and change the bio-availability of radionuclides. Different plant species produce different exudants and therefore the bio-availability of the radionuclides will vary from one species to the next.

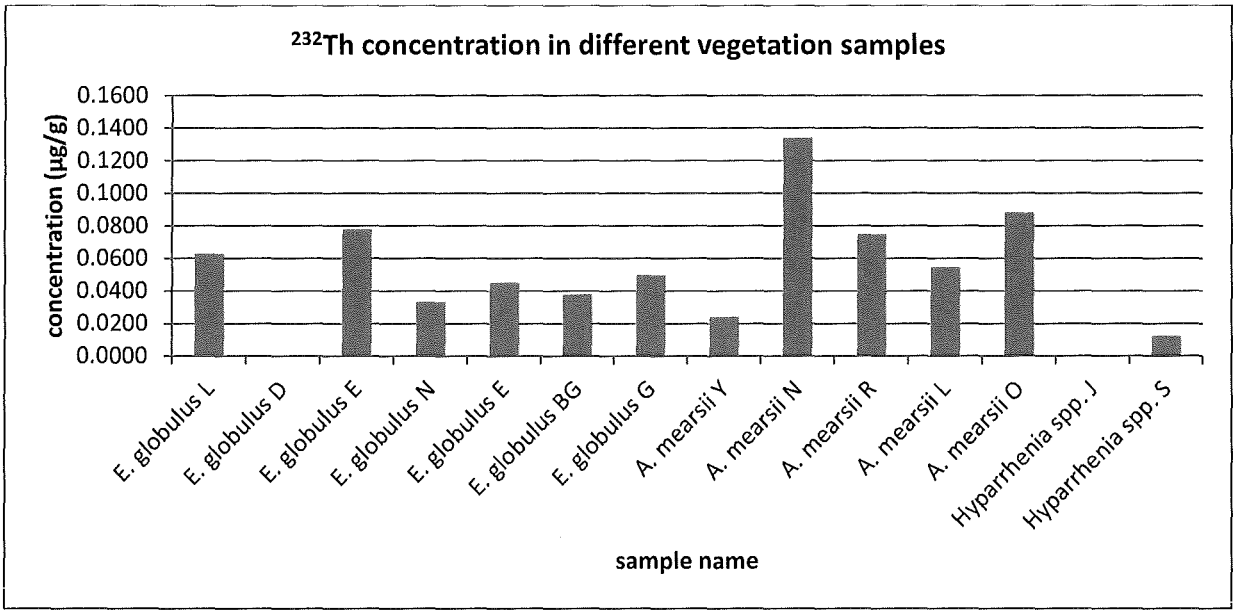

Figure 8 Graph showing the concentration of ^{232}Th among the samples

Figure 8 demonstrates the low variation in the concentration of thorium within the same plant species and among the different plant species. The amount of thorium that is in the soil is not above normal levels of uranium in the soil. This then means that the concentration of thorium in the immediate environment of the mine dump was not significantly enhanced by the mining process. That therefore partially explains why there is low variability in the concentration of the radioactive element in the plant leaves.

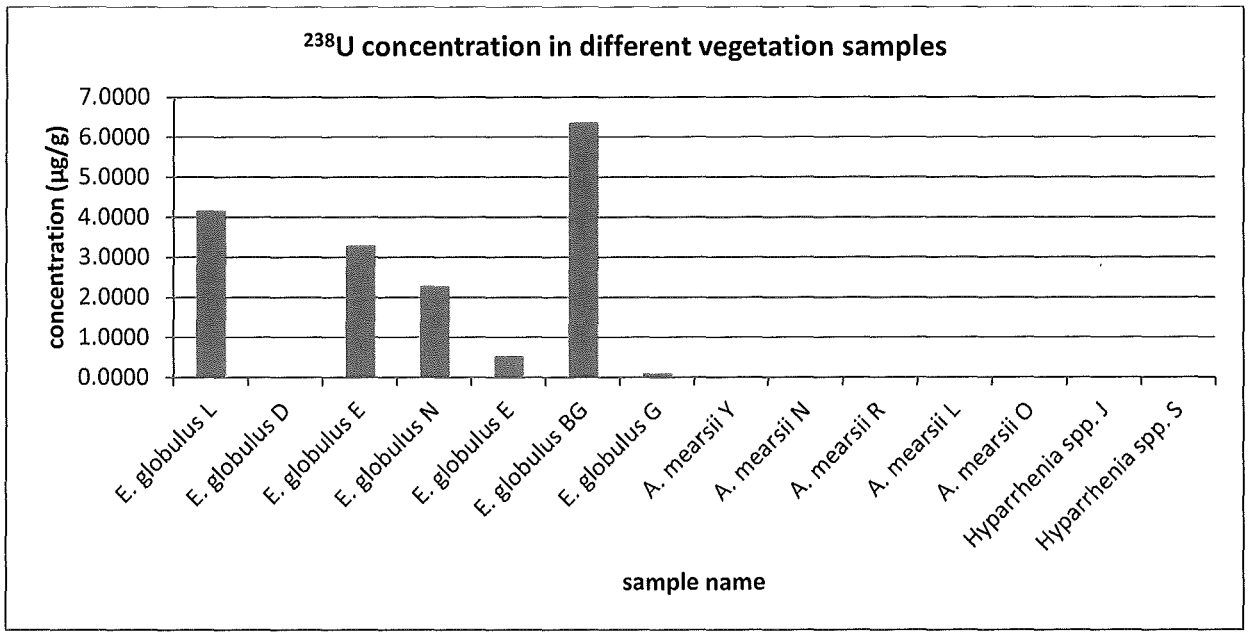

Figure 9 Graph showing the concentration of ^{238}U in different samples

The concentration of uranium varies widely as shown in figure 9. The concentration of uranium is generally higher within the E. *globulus* species than all the other species, having an average of 2.3973µg/g. The leaf samples from A. *mearsii* have uranium concentrations below the detection limit of the ICP-MS instrument and therefore the values of the concentration are not recorded. This shows that this species have extremely low accumulation capacity for the radionuclide in its leaves, while the E. *globulus* can accumulate the radionuclide very well within its leaves. *Hyparrhenia* spp. shows some accumulation of uranium, even though it is quite low. Figure 10 shows the concentration of uranium in the samples in the absence of E. *globulus* to show the concentration within the *Hyparrhenia spp*. These results show that the three species studied have different accumulation capacities in their leaves although the information cannot be used to draw a conclusion about the whole plant accumulation abilities. Different plants have different mechanisms that they employ to store and get rid of unwanted elements within their bodies. Some plants store these in their leaves, others in the stems, roots and in the bark. Therefore it is possible to get completely different results with the analysis of other compartments of the plants.

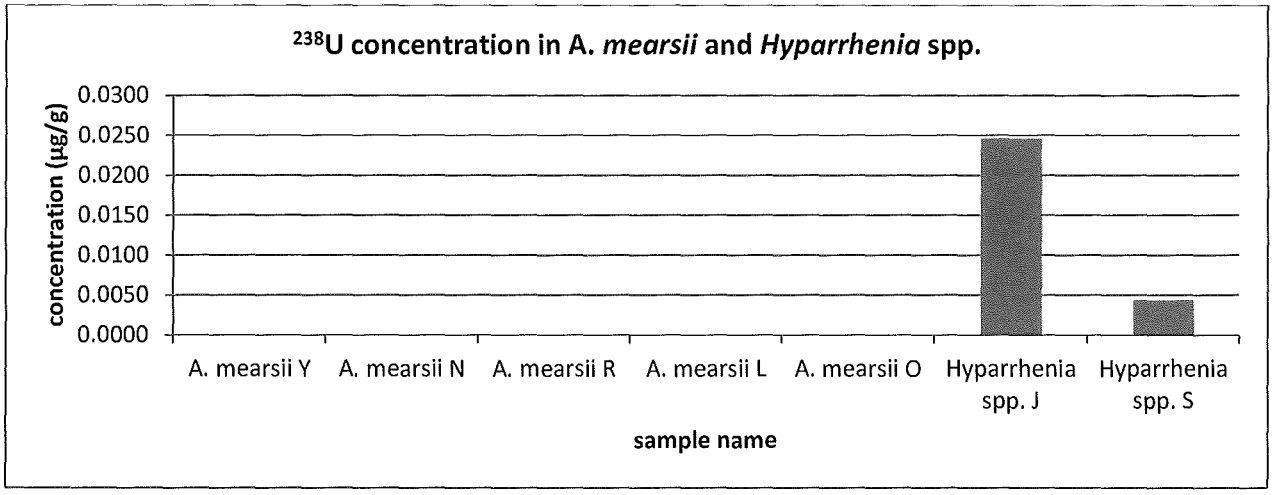

Figure 10 ^{238}U concentration in different species without the E. *globulus* data

4.1.2.1 Concentration of radiotoxic elements in soil substrate

Table 8 ICP-MS results for soils samples where the vegetation samples were collected, showing concentration of Thorium and Uranium (radionuclides) in µg/g dry weight

sample name	N	E	R	S	D	L	J	M	BG	O	G	Y	Mean
Th	0.705	1.0923	0.5127	0.6137	0.2537	0.585	1.0773	1.2173	2.5954	1.4362	0.2621	0.2687	0.88495
U	1.2385	3.7464	0.8403	0.9288	0.1858	0.3096	1.1075	1.1885	6.6858	0.7936	0.1238	0.4891	1.46981

Table 8 shows the concentrations of both uranium and thorium in the soil where the vegetation samples were taken. There is a slight variation in the concentration of thorium and a wide variation in the concentration of uranium. The concentration of thorium ranges from 0.2537-2.5954µg/g and that of uranium ranges between 0.1858µg/g and 6.6858µg/g. Uranium occurs in 4 valance states, namely, +3, +4, +5 and +6. In the soil the valences +4 and +6 are the most important and dominate the speciation of uranium (Environmental Protection Agency, 1999). Uranium +6 is quite immobile in the soil because it tends to form precipitates and bind strongly to organic matter. At pH below 5, this species is present in the form UO_2^{2+} and is quite immobile (Allard, B., Olofsson, U. and Torstenfelt, B., 1984). At pH ranges, 6-10, the uranyl ion is hydrolyzed and forms a number of aqueous hydroxide complexes. At this pH range the oxidized uranyl ion carbonate, sulphate and phosphate complexes are soluble and readily transported (Langmuir, D., 1978). This variability in sorption and solubility tendencies due to pH change goes to show how the pH of the soil determines the amount of uranium that the soil can hold

on to. Also different physico-chemical parameters have an effect. So the variability of the concentration of the uranium within the sampling area is due to the different chemical and physical parameters of the soil where the samples were collected. These parameters which govern the movement of the different radionuclides in the soil should vary from sampling one point to another.

The concentration and sorption of other radionuclides are affected by the physico-chemical parameters of the soil, just like uranium is and therefore their concentration in the soil will vary with these parameters. The effect of each parameter is not the same for each radionuclide and therefore it can be expected that the concentration of one radionuclide will not necessarily be related to the concentration of another in the soil. That explains why there is no particular trend in the concentration of the different elements at each sampling point

4.1.3 Transfer of radiotoxic elements from soil to plant leaves

Figure 11 shows the concentration of ^{232}Th in the soil and in the leaves of three different plant species. A small fraction of the radionuclide in the soil is transferred to the plant leaves. The difference in the concentration within the leaves and the soil is smaller for A. *pycnantha* than the other species. The variation within the species can be explained in terms of the variability in the soil properties which determine whether the element is in a complexed and un-available form or in a free form that can be absorbed by plants. The variation between the different species is mainly due to species specific properties.

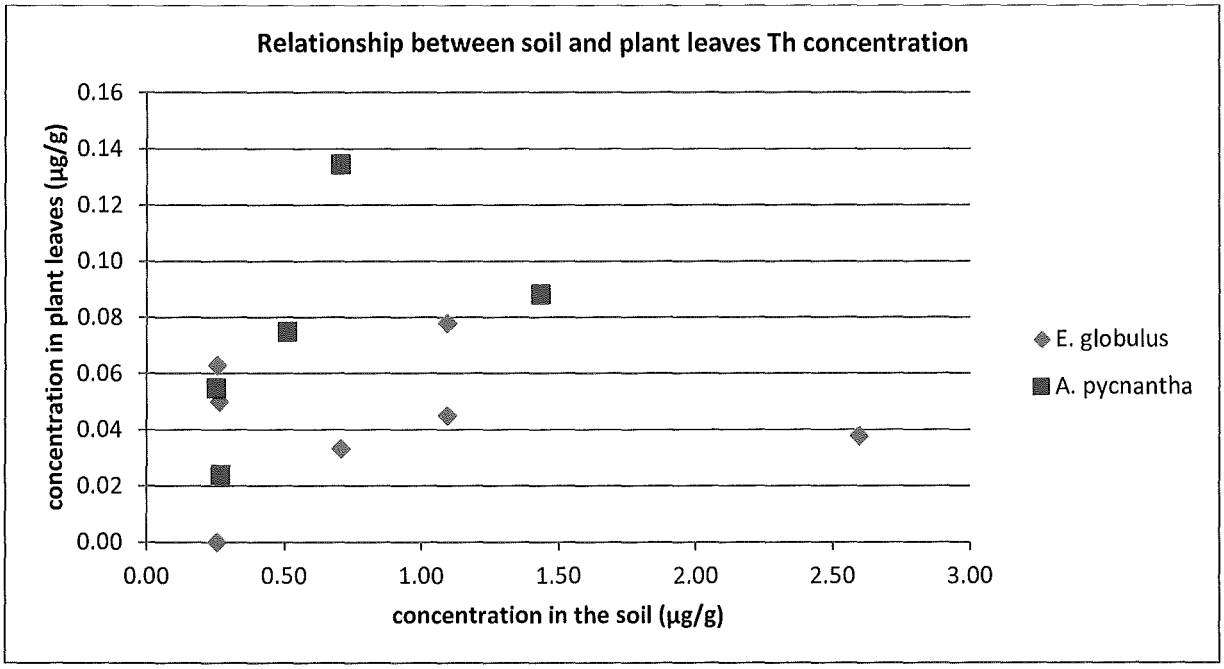

Figure 11 Comparison of ^{232}Th in plant leaves and in the soil where the plant is growing

There is a slightly positive linear correlation between the concentration of Thorium in the substrate (soil) and the plant leaves for E. *globulus*. The linear regression correlation co-efficient was calculated to be, R^2=0.2679. This means that 51.8% of the change in leaf concentration is due to change in soil concentration. However, there is a very poor linear correlation between the concentration of thorium within A. pycnantha leaves and the soil substrate. The linear regression coefficient was calculated to be R^2=0.008.

Figure 12 shows the concentration of uranium in plant leaves and the corresponding concentration in the soil where the plants are growing. E. globulus is able to accumulate substantial amounts of uranium in the leaves and A. *pycnantha* cannot accumulate uranium in the leaves while *Hyparrhenia* spp. can accumulate just a little uranium. The variation is very wide between the species because of the different properties such as the reach of their roots and physiology of the individual plant species. There is a good linear correlation between the leaf uranium concentration and soil concentration for the E. globulus species, R^2=0.400. There is no correlation between the concentration of uranium in A. pycnantha leaves and the soil substrate.

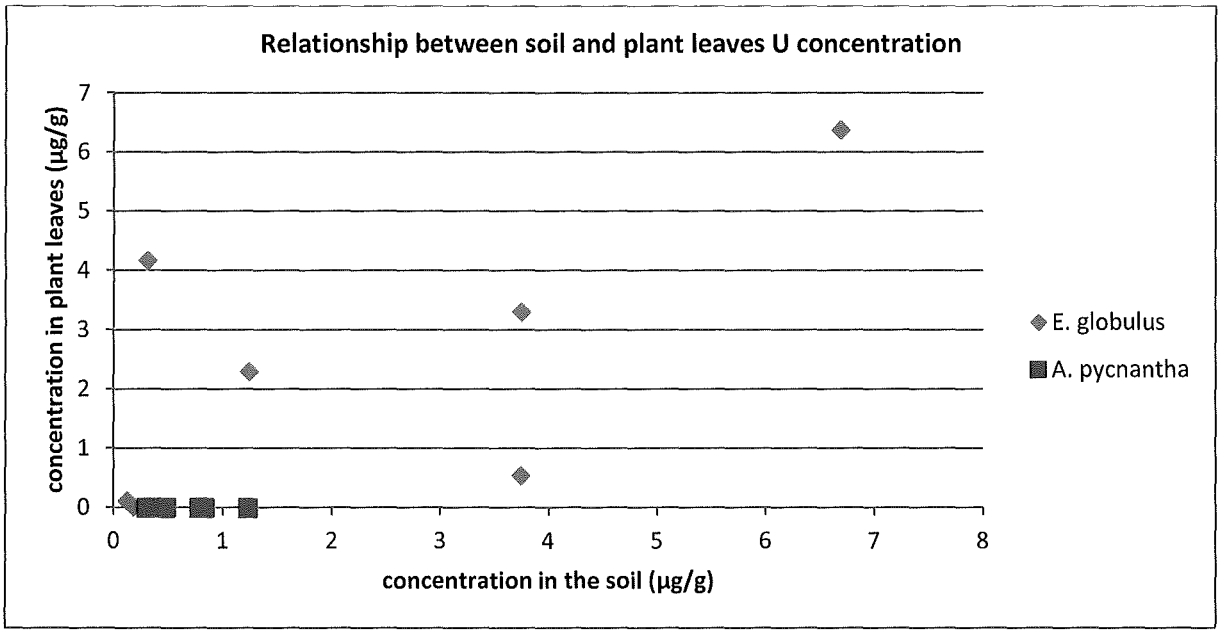

Figure 12 Uranium concentration in plant leaves and in the soil where plants are growing

The variability in soil-to-plant transfer factors is understood on the basis of the variability on both the concentration in the soil and the transfer of the radionuclides to plants. There are too many parameters that influence the transfer of the radionuclides from the soil to the plants and these parameters vary from sampling point to sampling point as well as between species.

4.1.4 Essential elements transfer from soil to plant leaves

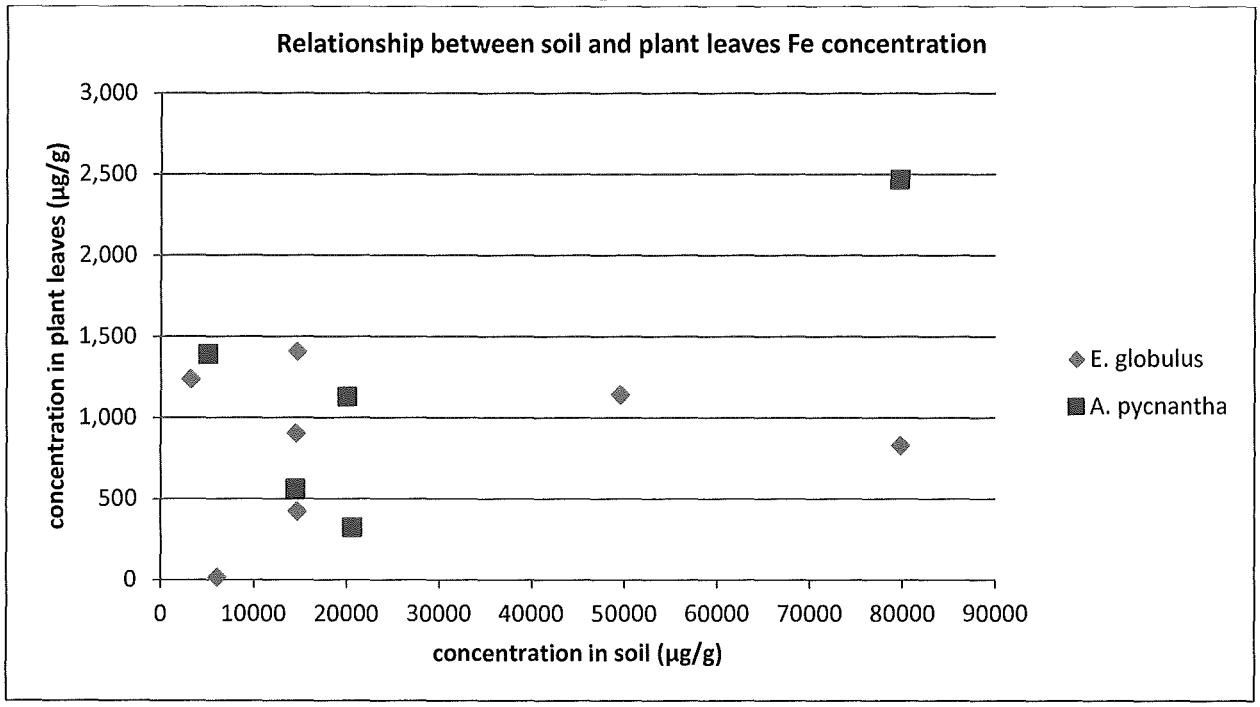

Figure 13 Relationship between soil and plant leaves Iron concentration

There is a significant transfer of Iron from the soil to the plants as shown in figure 13. There is a huge variation in the transfer of the elements between different species and within the species. There is no general trend in the concentration of iron in the leaves of A. pycnantha. The concentration in the leaves does not seem to be determined to a larger extent by the concentration in the soil substrate where the plant is growing. The linear regression coefficient is 0.02. On the other hand the concentration of iron in the leaves of E. globulus is determined to a larger extent by the concentration of the element in the soil. The linear regression coefficient (R^2) was calculated at 0.5983.

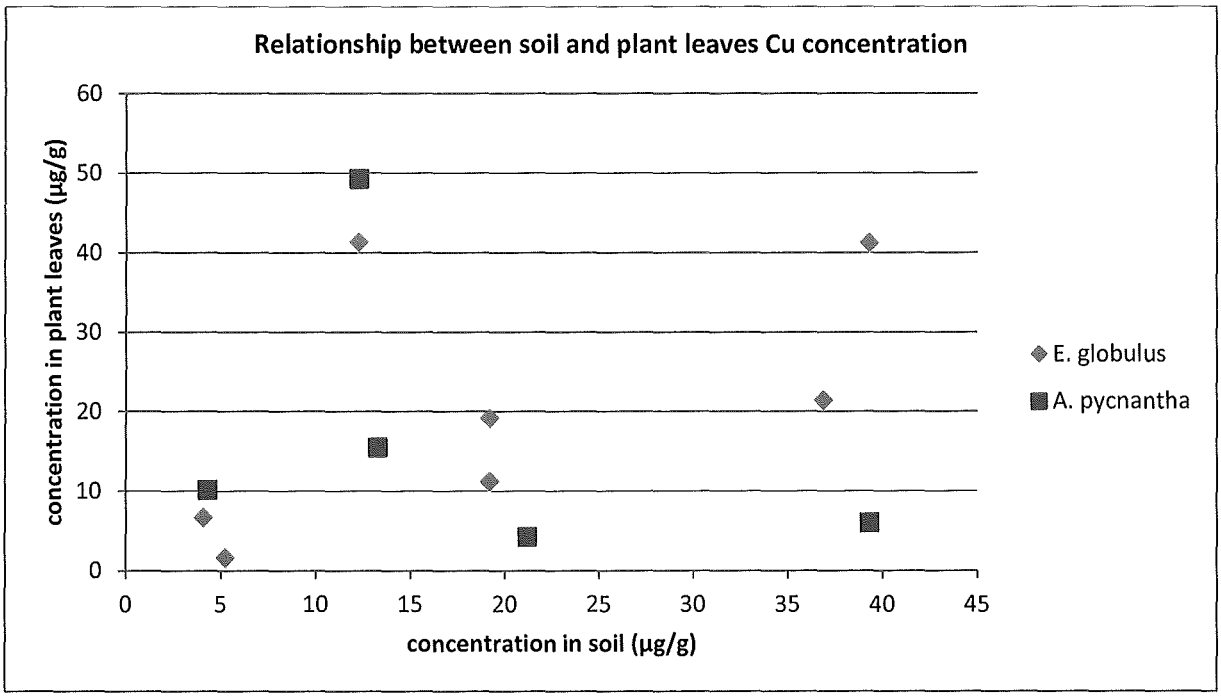

Figure 14 Relationship between soil and plant leaves Copper concentration

Figure 14 shows that the transfer of copper from the soil to the plants is high and like the transfer of all the other elements varies widely from species to species, sampling point to sampling point and within the same species. There is a very good positive linear correlation between the concentration copper in the soil and in the leaves of E. *globulus*. As the concentration of copper in the soil increases, the concentration within the leaves also increases. The linear regression coefficient is, R^2=0.3256. There is a poor correlation between the concentration of copper in the leaves of A. *pycnantha* and the soil substrate where the plants are growing. The concentration of copper in the plant hardly reflects the concentration in the soil.

4.1.5 Soil-to-plant transfer factors for Radionuclides

Table 9 shows the soil-to-plant transfer factors for thorium and uranium. The transfer factor for thorium is highest for the A. *pycnantha* and lowest for the *Hyparrhenia* spp samples. In all cases the concentration of the radionuclide in the soil is higher than that in the plant leaves. The uranium transfer factor is higher for the E. *globulus* than the other plant species; in some cases the concentration in the plant is actually higher than the concentration in the soil. The transfer

factor for the A. *pycnantha* could not be calculated since the levels of the radionuclide in the plant leaves were below the detection limit of the ICP-MS.

Table 9 Soil-to-plant Transfer factors of different radionuclides for different plant species and different sampling points

	E. *Globulus*							A. *pycnantha*					H. *filipendula*	
Elements	L	D	E	N	E	BG	G	L	R	N	Y	O	J	S
Th	1.08E-01	0.00E+00	7.14E-02	4.72E-02	4.13E-02	1.46E-02	1.90E-01	9.40E-02	1.46E-01	1.91E-01	8.98E-02	6.15E-02	1.90E-04	2.09E-02
U	1.34E+01	2.88E-02	8.80E-01	1.85E+00	1.44E-01	9.54E-01	8.92E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.23E-02	4.79E-03
Pb	7.58E-02	2.09E-01	2.64E-01	9.02E-02	1.39E-01	6.30E-01	8.06E-02	2.15E-01	4.79E-02	6.93E-02	6.81E-02	1.82E-01	9.39E-02	2.50E-02
Bi	5.96E-03	1.79E-02	3.87E-02	1.07E-02	2.42E-02	3.34E-02	2.02E-02	1.32E-02	9.41E-03	1.12E-02	1.08E-02	8.84E-03	7.26E-03	1.31E-03

4.2 Potential radiological impact

4.2.1 Exposure of people from consumption of milk and meat

There are different exposure pathways of radionuclides to man via the food-chain and they include; direct consumption of grains, fruits and vegetables, consumption of products from animals feeding on materials contaminated by the radionuclides. Here the exposure of the public through the consumption of meat and milk from animals grazing on pasture contaminated by material from the Princess mine dump is estimated. The evaluation of these parameters is based on procedures described in the publication RG-002 (National Nuclear Regulator, 2013). In this publication there is a description and presentation of default transfer parameters of radionuclides from the soil to pasture and from pasture to the animal and their products which are consumed by humans. Dose conversion factors presented in the same document converts the activity ingested from consumption of the animal products to dose received by the members of the public.

Transfer from soil, through pasture, to goat/cow milk and meat and the consequent default radiological exposure taking the default transfer factors provided in Licensing Guide RG-002 (National Nuclear Regulator, 2013) into consideration. The potential dose is calculated using the general formula:

$$\text{Dose} = \text{concentration in soil (mBq/g)} \times \text{soil} - \text{to} - \text{plant transfer factor} \times \text{feed} - \text{to} - \text{meat (milk) transfer factor} \times \text{consumption rate} \times \text{ingestion dose conversion factor} \quad (17)$$

Table 10 Average NORM-nuclide concentrations found in the Princess Dump measured by gamma spectroscopy (mBq/g) (National Nuclear Regulator, 2013)

Nuclide	Mean (x)	Std. dev. (σx)
^{238}U	1.60E+02	1.44E+01
^{226}Ra	2.11E+02	1.04E+01
^{210}Pb	5.08E+02	2.89E+01
^{228}Ra	1.83E+01	5.57E-01
^{228}Th	2.45E+01	9.81E-01

There is disequilibrium in the ^{238}U decay chain series. This is expected since the radionuclides in the environment are not kept tightly to where they were produced during decay. In nature the concentration of thorium in the soil is almost always higher than the concentration of uranium. In this study, the concentration of ^{238}U is almost 10 times the concentration of ^{232}Th. This shows that the uranium in this area is enhanced. This is obviously due to the mining of gold in the study area.

There is a high concentration of ^{210}Pb compared to the concentration of close parent ^{226}Ra. There are a number of explanations for this observation. Two reasons do seem more possible though, being the leaching rates that do differ due to different chemistries of the radionuclides. The other explanation is that one of the daughters of ^{226}Ra is ^{222}Rn, which is a gas. When radionuclides decay in deeper layers of the soil and the mine dump, this radioactive gas is produced and when its produced it will try to escape into the atmosphere. As it tries to escape it diffuses from the deeper layers to the surface layers which were sampled. As it moves though the soil, some of it decays and forms the ^{210}Pb. These two processes are the most likely cause for the disequilibrium in the decay chain

Table 11 Soil-to-Pasture transfer factors (mBq/g dry weight plant / mBq/g dry weight soil) (National Nuclear Regulator, 2013)

Element	Transfer factor
U	2.00E-01
Ra	4.00E-01
Pb	5.00E-01
Po	1.00E-01
Th	1.00E-01

Table 12 Uptake by goats and cows (mBq/g dry weight plant × default consumption per day) (National Nuclear Regulator, 2013)

Uptake by sheep	Uptake (mBq)	per day
Assuming intake	4	kg/day
Uptake by cows		
Assuming intake	25	kg/day

Table 13 Transfer factors to milk for goats and cows (mBq/day intake × transfer to milk) resulting in mBq/ℓ milk (National Nuclear Regulator, 2013)

Element	Transfer factor	Units
U	6.10E-04	day/litre
Ra	1.30E-03	day/litre
Pb	3.00E-04	day/litre
Po	3.00E-03	day/litre
Th	5.00E-06	day/litre

Table 14 Transfer factors to meat for goats and cows (mBq/day intake × transfer to meat) resulting in mBq/kg meat (National Nuclear Regulator, 2013)

Element	Transfer factor	Units
U	3.00E-02	day/kg
Ra	5.00E-03	day/kg
Pb	9.10E-04	day/kg
Po	5.00E-03	day/kg
Th	5.00E-03	day/kg

Table 15.1 Radiological exposure due to consumption of cow milk

Dose in mSv/a due to the consumption of Milk							
Age group	< 1 a	1 - 2 a	2 -7 a	7 - 12 a	12 - 17 a	> 17 a	Average Life-time Exposure
Litres/a	300	300	300	300	300	250	
Cow milk							
Total mSv/a	44	14	7.5	5.3	4.8	1.8	3.6
Uncertainty	2.4	0.8	0.42	0.29	0.26	0.10	0.20

Table 15.2 Radiological exposure due to consumption of beef in mSv/a

Age group	< 1 a	1 - 2 a	2 -7 a	7 - 12 a	12 - 17 a	> 17 a	Average Life-time Exposure
kg/a	10	20	50	75	100	100	mSv/a
Cow meat							
Total mSv/a	4.0	2.2	3.2	3.7	5.1	2.1	2.6
Uncertainty	0.24	0.13	0.19	0.22	0.29	0.13	0.16

Tables 15.1 and 15.2 show the potential radiological exposure of different age groups of members of the public due to the consumption of cow meat and milk.

The results show that there is a high annual dose received by members of the public from the consumption of milk and beef, assuming that the products are from cattle that are consuming pasture growing on soil that is contaminated by the mine dump. The average life-time exposure from consumption of milk is 3.6 ± 0.2 mSv/a, which is high compared to a dose constraint of 250 μSv/a set by the South African National Nuclear Regulator (National Nuclear Regulator, 2013) and that received from the consumption of beef is 2.6 ± 0.16 mSv/a.

4.2.2 Dose from consumption of garden leafy vegetables

Annexure E shows the dose conversion factors for ingestion for members of the public. These are parameters that have been calculated through extensive experimentation all-over the world by different scientists and have been compiled by the IAEA for use in modeling the dose to members of the public from ingestion of contaminated material. To calculate the dose to members of the public, three key parameters are needed and these are; the radionuclides concentration in the ingested material, the amount of the material consumed over a specific period also called the consumption rate and lastly the dose conversion factors to covert the activity in the ingested material into dose within the body. The general method shown in equation 18 is used to evaluate the dose to humans.

$$\text{Dose} = \text{yearly consumption rate} \times \text{dose conversion factor} \times \text{activity concentration} \qquad (18)$$

The total yearly dose from consumption of leafy vegetables usually grown in small home gardens varied among the different age groups with children below the age of 1 getting the most dose which is 0.278 mSv/a and the other age groups getting insignificant amounts of dose from the consumption of such vegetables.

CHAPTER 5: CONCLUSIONS AND RECOMENDATIONS

There is a transfer of radionuclides and toxic elements from the mine dump to the vegetation at and around the Princess Gold mine dump in Roodepoort South Africa. The transfer of essential elements is normal and the concentrations of the essential elements, even though slightly elevated than average plant concentration, are quite normal. There is a variation in the relationship between concentration in the plant and the corresponding concentration of the essential elements in the soil. In this study the relationship between copper and iron concentration in the soil and their respective concentration in the leaves of plants was evaluated even though all other elements were considered and measured. The relationship is dependent on both the species of plant involved and the sampling point where the sample was collected. This result proves that soil factors and plant species specific factors influence the transfer of essential elements from the soil to plants.

The transfer of toxic elements from the soil to plant leaves was also species and sampling point dependent. Uranium concentration in the soil and plant leaves of two species was greatly enhanced and was linearly correlated with the concentration in the leaves for both E. *globulus* and *Hyparrhenia* spp. A. *pycnantha* species had a very low ability to take up uranium such that the concentration of the element inside the leaves was below the detection limit of the ICP-MS instrument. There was a very poor linear correlation between the concentration of thorium in the soil and in plant leaves. The transfer was both plant species dependent and sampling point dependent. The concentration of thorium, unlike uranium was not enhanced during the mining activity.

The potential transfer of both essential and toxic elements to vegetables and other food plants can present a toxicity danger to humans. Essential elements when in extremely high concentration in food become toxic and when toxic elements have concentrations above their tolerable limit, they are also hazardous to humans. In this study, the transfer of 5 major essential elements to leafy vegetables was evaluated and the concentrations of the elements within the vegetables was calculated to be below the highest tolerable concentrations and

therefore there is minimal danger, if any, posed by the transfer of essential elements to leafy vegetables grown in small home gardens. On the other hand the transfer of toxic elements, uranium and lead, present a danger because when their transfer to leafy vegetables from the soil was modelled, they exceed the highest tolerable limits by as much as 10 times. Therefore, growing vegetables from small home gardens is not recommended for the community living close to the Princess dump.

Through modeling, the transfer of radionuclides from the soil to pasture and then to cattle and sheep, a potential radiological impact assessment was made. If meat and milk from cattle feeding on contaminated pasture are consumed by members of the community, the dose levels will be very high and will exceed the limits set for annual dose for members of the public. Also the potential transfer of the radionuclides from the soil to leafy vegetables was evaluated and the corresponding radiological impact was then estimated. The dose from consumption of these vegetables to members of the public above the age of 1 year is insignificant but for children below that age, the yearly dose exceeds the dose constraint from a single source to members of the public, which is 250 μSv/a.

It is recommended that residents avoid grazing their sheep and cattle in the vicinity of the mine dump and if they have animals grazing there, avoid consuming any products from those animals. Growing of leafy vegetables has no real danger from a radiological point of view except to children under the age of 1 year, although there is real danger to members of the community from toxicity of lead and uranium. Therefore, it is recommended that leafy vegetables from small home gardens around the princess dump should not be consumed or even grown.

Further studies to evaluate the real consumption rates by the members of the community living in the area and real-time radionuclide and toxic elements concentrations in the food that the members of the community consume should be done. These studies will produce the exact radiological and toxicological impact to the residents.

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Annexure A

Trace element	Uses and health benefits	Negative effects or symptoms caused by trace element deficient.	Negative effects or symptoms caused by trace element abundance.
Aluminium	Bone formation.	Depressed growth, decreased life expectancy and an increased number of spontaneous abortions.	Reduce bone formation and *osteomalacia*.
Arsenic	Proper growth, development and reproduction.	Carcinogenic.	Death.
Boron	Promotes healthy bone metabolism, proper function of the endocrine system (ovaries, testes and adrenals).	Decreased bone density, greater risk for prostate cancer, decreased mental alertness in men and women past age of 45.	Skeletal abnormalities, diarrhoea, nausea, vomiting, anaemia, *enema*, *seizures*, gastrointestinal disturbances, fatigue and cold-like symptoms.
Cadmium	Maximize growth.	Gastrointestinal irritation, vomiting, abdominal pain and diarrhoea.	Kidney, skeletal and *pulmonary* damage.
Calcium	Formation and maintenance of bones, muscular growth and normal *blood clotting*.	*Hypertension*, *osteoporosis*, prostate cancer, kidney stones, miscarriage, menstrual problems, bone diseases, menstrual problems, sleep disturbances, cardiovascular and depressive disorders.	Joint degeneration, stroke, gastrointestinal disturbances, chronic *fatigue* and it inhibit the Vitamin D's cancer protective effect.
Chlorine	Constituent of stomach acid and as an electrolyte for controlled regulation of acid-alkaline balance.	*Metabolic alkalosis*, apathy, slowed growth and delayed speech.	Enema, high blood pressure, greater risk of some cancers, choking, chest pains, nausea and vomiting.
Chromium	*Anti-inflammatory* properties, normal blood sugar and fat metabolism.	Glucose intolerance, elevated total *cholesterol*, inflammatory joint disease and nerve degeneration.	Spinal/ joint degeneration, depressed immune system and lymphatic swelling.
Cobalt	Myelin formation to support the manufacture of red blood cells, metabolism of fats, carbohydrates and synthesis of proteins.	*Demyelination* of large nerve trunk and the spinal cord, reduced white blood cells, shortness of breath, headaches and dizziness.	Asthma, anxiety and cardiac symptoms.
Copper	Wound healing, formation of oxygen-carrying molecule *haemoglobin*, formation red blood cells and bones.	*Anaemia*, increased susceptibility for infections, *osteoporosis*, weakened immune system, irregular heart beat and nerve degeneration.	*Anaemia*, nausea, vomiting, abdominal pain, *arthritis*, joint/spinal degeneration, higher risk of some cancers, heart disease and stroke.
Fluorine	Bones and teeth, preventing dental caries.	Weakened bone and dental caries.	Increased bone fractures, fluorosis, osteosclerosis, hearing loss, stomach ulcers and greater risk of some cancers.
Iodine	Production of hormones (thyroxin) by the thyroid gland.	*Goitre*, fatigue, depression, low cardiac output, enema, hair loss, *hypothyroid*, asthma, infertility and weight gain.	Palpitations, *insomnia*, skin rash, sweating, goitre, weight loss and *hyperthyroid*.
Iron	Production of haemoglobin and *myoglobin*, energy production, oxygenation of red blood cells and healthy immune system.	Fatigue, anaemia, depression, dizziness, asthma, gastrointestinal disorders, migraine-headaches and weak immune system.	Arthritis, high blood pressure, heart disease, liver disease, nausea, higher risk for several cancers and constipation.

Lead	Functioning of the nervous system and the kidneys.	Liver and kidney damage, mental retardation as well as abnormalities in fertility and pregnancy.	Neurological, neurobehavioral and development effects in children, haematological effects, renal effects and increased blood pressure.
Lithium	Mood stabilizing agent, produce positive effects regarding mental health and immune function.	Gastrointestinal disorders, low stomach acid and heartburn.	Nausea, vomiting, weight gain, *goitre*, liver disease, kidney disease, frequent urination, diarrhoea, enema and death.
Magnesium	Formation of bones and teeth, relax muscles, synthesis of protein, important co-factor in most enzymatic reactions, production of energy and for cardiovascular functions.	Kidney stones, high blood pressure, heart problems, insomnia, anxieties, chronic constipation and menstrual cramps.	Neuromuscular problems, gastrointestinal problems, low blood pressure, depression, dizziness, cardiovascular disease, osteoporosis, dry skin and management of premature labour.
Manganese	Protein metabolism, bone formation, carbohydrate (glucose) metabolism, blood clotting, activates enzyme responsible for formation of urea, breast milk in females, DNA and *RNA* synthesis.	*Fatigue*, depression, low blood sugar, joint dislocations, high cholesterol, asthma, migraine-headaches, infrequent menstrual cycles, gastrointestinal disorders, osteoporosis, enema and nausea.	Migraine-headaches, frequent menstrual cycles, dizziness, depression, mental illness, higher risk for several cancers, insomnia, enema and nausea.
Mercury	Nervous and renal system functioning.	*Hypothyroidism* and *anaemia.*	Neurological effects, renal disturbances and *hyperthyroidism.*
Molybdenum	Normal *uric acid* levels, anti-cancer properties anti-oxidative properties and protect cells from free radicals.	Spinal degeneration, higher risk for several cancers, insufficient uric acid.	Skin eruptions, itchy skin, inflammatory spinal/ joint disease and decreased growth.
Nickel	Interacts with nucleic acids (*RDA and DNA*), activation of enzymes, constituent of circulating proteins *nickeloplasmin* and *albumin.*	Liver and kidney diseases, thyroid disease, gastrointestinal irritation.	Asthma, cardiac symptoms, potential to cause cancer of the sinuses, throat and lungs.
Phosphorus	Bone and teeth formation, kidney functioning, cell growth and the contraction of the heart.	Osteoporosis, joint/bone pain, arthritis, weakness, weight loss, higher risk for several cancers, dehydration and *kidney stones.*	Arthritis, bone loss, gout, dental problems, skin eruptions, higher risk for several cancers and kidney stones.
Potassium	Normal blood pressure, building muscles, transmission of nerve impulses and heart activity.	Irregular heartbeat, *hypertension*, stroke, asthma, muscle spasms, muscle weakness, frequent menstrual cycles, liver disease, kidney disease, and weight gain.	Low blood pressure, kidney disease, bladder infections, higher risk of several types of cancer, infrequent menstrual cycles, ovarian cysts, joint/back pains, weakened immune system, anxiety and *insomnia.*
Selenium	Anti-aging properties, prevent cancer, stimulates anti-body response to infections, fight cold sores and shingles.	Cardiomyopathy, cardiovascular disease, stroke, nerve degeneration, higher risk for some cancers, arthritis and anaemia.	Nerve degeneration, osteoporosis, shingles, loss of hair, abnormal nails, tooth decay, garlic breath and death.
Silicon	Promotes the union of bone after fracture and keeping blood vessel walls healthy.	Cartilage/ joint degeneration, osteoporosis, headaches, cardiovascular disease, vascular degeneration, dry/ brittle nails and hair.	Bruising, stomach irritations, skin rashes and irritations.

Sodium	Acts as an electrolyte, required in the manufacture of hydrochloric acid in the stomach and for normal kidney functioning.	Fatigue, depression, low blood pressure, headaches, dehydration, dizziness, arthritis, kidney stones and seizures.	Enema, hypertension, stroke, dizziness, gout, headaches, kidney damage, stomach problems, nausea and vomiting.
Sulphur	Detoxify the body, cartilage regeneration, assist in immune system and fights the effect of aging.	*Alzheimer's disease*, nerve degeneration, memory loss, arthritis/ cartilage degeneration, reduced insulin production, collagen diseases affecting hair, skin and nails.	Inflammatory disease of the gut, nerve degeneration, asthma, inflammatory vascular/ joint degeneration.
Thorium	No data available.	Lung disease, cancer of the bone, lung or pancreas, liver disease,	Death.
Tin	Supporting adrenals and cardiac functions.	*Fatigue*, depression, low cardiac output, shortness of breath, asthma, headaches and *insomnia*.	Skin rash, stomach problems, palpitations, vomiting, diarrhoea, abdominal pains, nausea and headaches.
Uranium	No data available.	Kidney and lung problems.	Reproductive, developmental, mutagenic and carcinogenic consequences.
Vanadium	Stabilize blood sugar levels, formation of bones and teeth.	Spinal degeneration, reduced growth and reproductive and elevated *cholesterol*.	Arthritis, aching bones, weakened immune system chronic colds and gastrointestinal problems.
Zinc	Immune system, synthesis of the nucleic acids RNA and DNA, protect cells from free radicals, normal growth and reproductive development.	Decreased growth, loss of taste and smell, sterility, decreased wound healing, skin rash, heart disease, kidney disease, muscle weakness, several types of cancer, depression and high blood pressure.	Nausea, vomiting, dehydration, gastrointestinal problems, stomach ulcers, higher risk of several types of cancer, *anaemia*, hair loss, muscles cramps, weakened immune system and *insomnia*.

Annexure B.1 Concentration of different elements in the soil samples at different sampling points

			Soil ICP-MS Results (µg/g)									
Element	J	BG	O	M	N	E	R	S	D	L	G1	Y1
Na	3.9E+02	3.2E+02	4.6E+02	5.1E+02	1.0E+03	1.2E+03	5.9E+02	6.7E+02	6.4E+02	1.4E+03	5.3E+02	1.7E+03
Mg	1.0E+02	1.2E+02	1.3E+02	1.5E+02	6.5E+03	7.5E+02	2.1E+02	3.9E+02	2.1E+02	2.6E+02	1.4E+02	1.7E+03
Al	5.6E+02	s	4.4E+02	5.2E+02	2.1E+03	9.3E+02	6.6E+02	7.6E+02	1.6E+02	4.3E+02	1.4E+02	5.9E+02
Si	4.8E+02	2.6E+02	3.9E+02	4.3E+02	5.0E+02	4.0E+02	2.9E+02	4.3E+02	1.5E+02	3.5E+02	1.5E+02	6.5E+02
P	1.2E+02	1.4E+02	1.1E+02	9.8E+01	9.5E+01	1.6E+01	1.9E+01	2.4E+01	1.2E+01	1.9E+01	6.0E+00	3.0E+03
S	5.1E+03	5.2E+03	5.6E+03	5.6E+03	4.4E+03	8.6E+03	2.4E+03	6.9E+03	5.8E+03	9.1E+03	0.0E+00	1.0E+04
K	6.6E+02	3.5E+02	9.2E+02	5.3E+02	1.4E+03	7.3E+02	5.0E+02	5.9E+02	5.6E+02	7.2E+02	4.9E+02	s
Ca	1.7E+03	2.3E+03	1.3E+03	1.9E+03	3.8E+03	4.0E+03	6.9E+02	1.0E+04	7.0E+02	7.7E+02	4.9E+02	9.7E+03
Ti	3.9E+01	5.4E+01	1.1E+01	1.3E+01	8.4E+02	3.3E+01	1.3E+02	1.1E+02	2.9E+01	7.2E+01	4.6E+01	2.4E+02
V	2.4E+01	5.1E+01	2.1E+01	2.7E+01	1.5E+02	9.3E+01	1.2E+02	1.1E+02	1.0E+02	1.1E+02	1.0E+02	1.2E+02
Cr	2.7E+01	1.9E+02	9.5E+00	1.9E+01	1.1E+03	3.6E+01	8.3E+01	2.2E+02	2.2E+01	3.8E+01	1.7E+01	8.7E+01
Mn	7.3E+00	6.3E+01	5.9E+00	5.3E+00	1.1E+02	1.7E+01	1.7E+01	8.0E+01	4.8E+00	9.4E+00	2.2E+00	6.0E+01
Fe	7.8E+03	5.0E+04	5.1E+03	7.8E+03	8.0E+04	1.5E+04	2.0E+04	2.4E+04	6.0E+03	1.4E+04	3.2E+03	2.1E+04
Co	6.4E-01	7.6E+00	5.2E-01	4.9E-01	1.1E+01	1.9E+01	1.4E+00	4.3E+00	1.6E+00	7.2E-01	3.5E-01	1.5E+00
Ni	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.0E+00	2.1E+01	0.0E+00	7.2E+01	1.8E+00	1.5E+01	5.1E+00	3.1E+01
Cu	7.3E+00	3.7E+01	4.3E+00	7.7E+00	3.9E+01	1.9E+01	1.3E+01	1.8E+01	5.2E+00	1.2E+01	4.1E+00	2.1E+01
Zn	5.5E+00	1.8E+01	1.3E+01	4.4E+00	2.5E+01	1.5E+02	1.1E+01	1.2E+02	8.9E+00	6.4E+01	3.0E+01	8.9E+01
Ga	3.7E-01	4.6E+00	2.4E-01	3.6E-01	7.6E-01	2.3E-01	3.5E-01	4.0E-01	1.0E-01	2.4E-01	1.0E-01	3.5E-01
Ge	8.7E-02	4.6E-02	1.0E-01	1.2E-01	9.5E-02	5.5E-02	7.3E-02	6.5E-02	6.1E-02	9.3E-02	9.5E-02	1.3E-01
As	3.9E+01	9.3E+01	2.5E+01	6.0E+01	5.9E+01	3.5E+01	5.3E+01	8.2E+01	1.5E+01	5.1E+01	1.3E+01	7.1E+01
Se	6.4E-01	1.2E+00	9.1E-01	6.9E-01	4.4E-01	3.2E-01	6.1E-01	6.8E-01	3.0E-01	8.3E-01	4.5E-01	1.1E+00

Rb	2.3E-01	9.1E-01	4.4E-01	2.5E-01	8.0E-01	2.7E-01	2.1E-01	2.4E-01	1.9E-01	3.0E-01	1.7E-01	1.1E+01
Sr	1.6E+00	1.6E+00	1.9E+00	1.5E+00	5.2E+00	1.1E+00	5.9E-01	9.9E-01	4.7E-01	1.4E+00	4.5E-01	9.1E+00
Y	2.7E-01	2.0E+00	3.4E-01	2.8E-01	1.5E-01	3.0E-01	7.3E-02	1.6E-01	5.0E-03	1.2E-01	4.7E-02	1.0E-01
Zr	1.6E+00	2.3E+00	1.8E+00	2.1E+00	9.9E-01	2.1E+00	1.2E+00	1.7E+00	8.5E-01	1.6E+00	2.3E+00	2.5E+00
Nb	7.6E-02	5.4E-02	5.4E-02	2.2E-02	4.0E-02	5.8E-03	1.5E-02	1.4E-02	5.8E-03	1.4E-02	6.7E-03	3.2E-02
Mo	5.2E-01	8.0E-01	9.8E-01	5.7E-01	6.2E-01	3.2E-01	4.0E-01	8.2E-01	4.4E-01	5.6E-01	2.3E-01	6.5E-01
Ru	4.0E-04	8.0E-04	0.0E+00	1.0E-04	1.6E-03	0.0E+00	2.0E-04	3.0E-04	2.0E-04	5.0E-04	2.0E-04	5.0E-04
Rh	1.3E-03	1.8E-03	1.3E-03	1.1E-03	1.8E-03	1.0E-03	1.0E-03	1.3E-03	9.0E-04	1.3E-03	8.0E-04	3.3E-03
Pd	1.4E-02	3.6E-02	1.3E-02	1.3E-02	9.8E-03	1.6E-02	9.9E-03	1.4E-02	3.7E-03	1.1E-02	7.8E-03	3.0E-02
Ag	1.5E-02	4.4E-02	3.7E-02	2.0E-02	1.2E-01	6.3E-02	1.7E-02	3.1E-02	3.7E-02	4.8E-02	6.2E-02	1.3E+00
Cd	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Yb	3.2E-02	2.6E-01	3.9E-02	3.3E-02	4.2E-02	5.8E-02	2.7E-02	4.1E-03	1.2E-02	2.4E-02	1.5E-02	2.4E-02
Lu	4.6E-03	4.1E-02	5.3E-03	5.5E-03	6.5E-03	8.9E-03	3.4E-03	5.7E-03	1.1E-03	3.0E-03	2.3E-03	3.1E-03
Hf	4.4E-02	3.0E-02	5.5E-02	6.7E-02	2.3E-02	9.0E-02	5.3E-02	6.9E-02	3.1E-02	4.5E-02	9.4E-02	7.2E-02
W	1.4E-01	2.4E-02	1.8E-01	1.9E-01	1.9E+00	9.3E-02	1.3E-01	2.0E-01	5.9E-02	1.7E-01	1.5E-01	1.9E-01
Re	1.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04	3.0E-04	1.0E-04	4.0E-04	1.0E-04	1.0E-04	1.0E-04	3.0E-04
Os	5.0E-04	9.0E-04	3.0E-04	4.0E-04	5.0E-04	1.0E-04	0.0E+00	1.0E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Pt	6.8E-03	9.5E-03	6.8E-03	6.1E-03	1.7E-02	5.4E-03	5.4E-03	5.3E-03	5.6E-03	5.5E-03	4.5E-03	2.1E-02
Au	1.3E-01	6.4E-02	1.7E-01	3.6E-01	1.3E-01	5.5E-02	1.4E-01	3.1E-01	6.4E-01	2.7E-01	1.9E-01	4.4E-01
Hg	8.9E-02	6.6E-02	5.6E-01	2.7E-01	2.0E+00	3.0E-01	3.4E-01	7.8E-01	4.8E-01	4.1E-01	1.9E-01	4.2E-01
Tl	4.3E-03	9.0E-03	1.2E-02	5.1E-03	3.1E-02	9.0E-03	7.7E-03	8.7E-03	9.1E-03	7.4E-03	9.7E-03	7.2E-03
Pb	1.1E+01	4.1E+00	6.1E+00	9.7E+00	1.5E+01	7.0E+00	2.2E+01	3.9E+01	5.1E+00	1.3E+01	1.0E+01	1.3E+01
Bi	3.1E-01	1.9E-01	7.2E-01	2.9E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Th	1.1E+00	2.6E+00	1.4E+00	1.2E+00	7.1E-01	1.1E+00	5.1E-01	6.1E-01	2.5E-01	5.9E-01	2.6E-01	2.7E-01
U	1.1E+00	6.7E+00	7.9E-01	1.2E+00	1.2E+00	3.7E+00	8.4E-01	9.3E-01	1.9E-01	3.1E-01	1.2E-01	4.9E-01

Annexure B.2 Concentration of different elements in the leaves of different plant species at different sampling points

	E. globulus							A. pycnantha					H. filipendula	
Point	L	D	E	N	E	BG	G	L	R	N	Y	O	J	S
Elements														
Na	2.3E+03	3.9E+02	7.7E+02	1.1E+03	4.8E+02	3.7E+02	3.5E+02	7.3E+02	5.0E+02	1.4E+02	5.7E+01	3.4E+02	3.9E+02	8.5E+01
Mg	2.0E+03	9.4E+01	4.4E+03	3.4E+03	1.5E+03	5.2E+03	4.3E+03	3.1E+03	5.4E+03	4.8E+03	2.9E+03	5.6E+03	9.4E+01	5.5E+01
Al	1.8E+03	2.1E+01	1.5E+03	1.6E+03	1.2E+03	1.0E+03	4.9E+02	4.0E+02	8.9E+02	8.9E+02	1.9E+02	1.2E+03	2.4E+01	2.4E+01
Si	7.6E+03	5.4E+02	4.1E+03	5.9E+03	3.2E+03	2.7E+03	1.3E+03	2.3E+03	2.8E+03	1.9E+03	4.9E+02	3.0E+03	5.5E+02	7.7E+01
P	1.9E+03	6.5E+02	2.6E+03	1.9E+03	1.8E+03	1.4E+03	8.9E+02	6.1E+02	1.3E+03	7.4E+02	4.7E+02	1.3E+03	6.3E+02	3.9E+01
S	4.4E+04	4.5E+04	4.0E+04	3.5E+04	4.0E+04	3.0E+04	1.7E+04	1.7E+04	1.6E+04	1.7E+04	1.9E+04	1.4E+04	4.2E+04	2.7E+04
K	2.3E+04	1.6E+04	1.3E+04	4.0E+03	2.0E+04	2.1E+03	4.5E+03	1.4E+04	3.3E+03	1.9E+03	3.6E+02	3.6E+03	1.6E+04	1.8E+03
Ca	1.9E+05	5.8E+03	4.7E+05	2.3E+05	5.1E+04	1.5E+05	2.6E+04	8.8E+04	6.2E+04	4.7E+04	3.0E+04	6.0E+04	5.9E+03	7.3E+02
Ti	2.7E+01	2.5E+00	2.5E+01	2.2E+01	3.3E+01	2.7E+01	1.2E+01	1.1E+01	2.3E+01	2.4E+01	8.2E+00	3.0E+01	2.6E+00	2.0E+00
V	6.6E+01	7.1E+01	4.5E+01	5.4E+01	5.6E+01	8.1E+01	5.1E+01	4.4E+01	5.8E+01	5.5E+01	5.3E+01	4.3E+01	6.6E+01	9.6E+01
Cr	1.8E+01	5.1E+00	1.0E+01	1.0E+01	9.1E+00	1.8E+01	8.1E+00	8.7E+00	1.5E+01	1.8E+01	1.4E+01	1.6E+01	4.9E+00	3.5E+00
Mn	3.6E+03	3.7E+00	1.7E+03	1.6E+03	1.3E+03	1.9E+03	3.8E+02	3.3E+03	6.7E+02	3.8E+02	7.1E+02	6.3E+02	7.9E+00	2.6E+00
Fe	9.1E+02	1.6E+01	1.4E+03	8.3E+02	4.3E+02	1.1E+03	1.2E+03	5.6E+02	1.1E+03	2.5E+03	3.3E+02	1.4E+03	2.0E+01	5.3E+01
Co	4.3E+00	6.9E-02	2.1E+00	1.6E+00	1.7E+00	2.9E+00	8.5E-01	1.3E+00	2.5E+00	3.7E+00	2.2E+00	2.0E+00	7.2E-02	2.0E-02
Ni	6.6E+01	2.6E+00	5.0E+01	3.2E+01	1.1E+01	6.6E+01	7.7E+00	2.9E+01	1.5E+01	1.5E+01	1.2E+01	1.1E+01	2.6E+00	4.7E-01
Cu	4.1E+01	1.5E+00	1.9E+01	4.1E+01	1.1E+01	2.1E+01	6.6E+00	4.9E+01	1.5E+01	6.0E+00	4.2E+00	1.0E+01	1.6E+00	1.8E+00
Zn	3.6E+01	4.2E+00	3.4E+01	2.9E+01	2.3E+01	7.3E+01	1.5E+01	9.9E+01	4.9E+01	1.2E+01	3.2E+01	4.4E+01	4.2E+00	7.3E+00
Ga	2.6E-01	3.8E-01	3.8E-01	4.2E-01	2.4E-01	5.0E-01	2.8E-01	4.0E-01	6.1E-01	5.4E-01	1.6E-01	6.0E-01	3.5E-01	2.1E-01
Ge	5.0E-01	5.5E-01	3.5E-01	4.4E-01	4.4E-01	8.1E-01	4.4E-01	3.9E-01	5.5E-01	5.0E-01	5.5E-01	3.9E-01	5.1E-01	9.3E-01
As	5.4E+01	4.6E+01	5.2E+01	5.0E+01	4.1E+01	7.8E+01	4.5E+01	4.4E+01	5.3E+01	5.2E+01	4.6E+01	3.9E+01	4.3E+01	7.5E+01
Se	8.6E-01	5.6E-01	6.8E-01	9.4E-01	4.9E-01	1.2E+00	4.8E-01	8.2E-01	9.3E-01	5.6E-01	7.7E-01	5.4E-01	5.2E-01	1.3E+00
Rb	2.3E+00	1.3E+00	2.0E+00	4.7E-01	3.9E+00	7.8E-01	1.7E+00	2.5E+00	1.6E+00	9.7E-01	9.1E-02	2.0E+00	1.3E+00	3.0E-01
Sr	1.1E+01	8.8E-01	4.5E+01	1.9E+01	1.5E+01	1.7E+01	5.0E+00	1.3E+01	2.9E+01	1.1E+01	2.5E+01	2.7E+01	8.7E-01	2.9E-01

Y	9.2E-01	0.0E+00	6.5E-01	3.6E-01	1.7E-01	6.1E-01	2.5E-01	2.7E-01	4.2E+00	2.8E-01	5.6E-01	3.5E+00	3.3E-03	5.5E-03
Zr	1.2E+00	3.3E-01	2.5E+00	4.7E-01	7.4E-01	6.3E-01	3.8E-01	6.3E-01	7.0E-01	9.0E-01	6.1E-01	6.2E-01	3.6E-01	2.7E-01
Nb	7.4E-02	0.0E+00	4.5E-02	2.8E-02	8.6E-02	1.1E-01	2.1E-02	1.0E-01	7.5E-02	5.0E-02	2.0E-02	6.7E-02	1.0E-03	5.4E-03
Mo	2.7E-01	5.6E-01	2.7E-01	1.7E-01	1.8E-01	3.4E-01	2.4E-01	2.6E-01	3.6E-01	4.4E-01	2.4E-01	3.4E-01	5.6E-01	1.8E-01
Ru	6.3E-04	0.0E+00	1.2E-03	1.0E-03	1.2E-04	2.9E-03	6.2E-04	0.0E+00	0.0E+00	1.1E-03	6.3E-04	1.5E-03	0.0E+00	4.0E-04
Rh	2.1E-03	1.6E-03	3.2E-03	2.6E-03	1.9E-03	4.0E-03	1.5E-03	2.2E-03	2.6E-03	2.4E-03	2.7E-03	3.0E-03	1.6E-03	2.7E-04
Pd	2.1E-02	1.2E-02	2.5E-02	6.4E-03	1.8E-02	1.4E-02	6.4E-03	1.6E-02	7.5E-03	2.1E-02	1.2E-02	7.0E-03	1.2E-02	4.6E-03
Ag	1.4E-02	6.7E-03	1.5E-02	1.0E-02	5.6E-03	1.3E-02	6.6E-03	3.6E-02	2.4E-01	1.1E-02	3.3E-02	4.0E-02	7.1E-03	3.5E-03
Cd	2.2E-03	1.6E-03	1.0E-02	2.9E-03	3.7E-03	1.4E-02	1.5E-02	2.1E-02	3.0E-03	8.1E-03	7.0E-03	6.1E-03	1.2E-03	1.1E-03
Yb	3.2E-02	3.2E-04	2.5E-02	1.6E-02	9.8E-03	2.5E-02	1.1E-02	1.0E-02	1.5E-01	1.3E-03	1.4E-02	1.2E-01	4.1E-04	0.0E+00
Lu	4.8E-03	0.0E+00	4.1E-03	2.5E-03	1.6E-03	9.0E-03	1.3E-03	1.9E-03	2.1E-02	2.1E-03	2.1E-03	1.9E-02	0.0E+00	0.0E+00
Hf	2.0E-02	4.6E-03	3.8E-02	7.9E-03	1.1E-02	9.3E-03	3.5E-03	9.2E-03	1.3E-02	1.4E-02	8.3E-03	1.3E-02	4.0E-03	2.3E-03
W	2.5E-02	1.1E-02	3.1E-02	3.2E-02	2.4E-02	3.1E-02	3.2E-02	2.8E-02	4.4E-02	5.6E-02	1.8E-02	5.7E-02	1.4E-02	8.2E-03
Re	6.3E-03	0.0E+00	1.2E-02	1.1E-02	1.2E-04	1.4E-02	1.5E-02	4.9E-03	3.1E-03	2.1E-03	1.5E-03	3.6E-03	0.0E+00	1.3E-04
Os	6.3E-04	0.0E+00	1.0E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.0E-03	3.1E-04	0.0E+00	0.0E+00	2.1E-04	0.0E+00	0.0E+00
Pt	8.7E-03	8.4E-03	8.4E-03	7.6E-03	6.9E-03	1.4E-02	4.9E-03	5.8E-03	8.3E-03	8.8E-03	7.6E-03	8.5E-03	7.3E-03	0.0E+00
Au	1.4E-02	2.3E-03	2.7E-02	1.8E-02	3.9E-03	7.1E-03	1.3E-03	4.7E-03	9.5E-03	2.7E-03	1.6E-03	4.7E-03	3.7E-03	0.0E+00
Hg	1.1E-02	8.3E-03	1.4E-02	1.2E-02	1.1E-02	2.2E-02	6.3E-03	8.4E-03	1.0E-02	8.3E-03	1.1E-02	1.2E-02	1.2E-02	0.0E+00
Tl	2.1E-04	0.0E+00	6.2E-04	1.7E-03	1.2E-04	2.4E-04	0.0E+00	0.0E+00	1.0E-04	0.0E+00	1.0E-04	0.0E+00	0.0E+00	0.0E+00
Pb	9.9E-01	1.1E+00	1.9E+00	1.4E+00	9.8E-01	2.6E+00	8.2E-01	2.8E+00	1.0E+00	1.1E+00	9.2E-01	1.1E+00	1.0E+00	9.8E-01
Bi	2.5E-03	2.2E-03	7.3E-03	3.7E-03	4.5E-03	6.4E-03	5.2E-03	5.6E-03	3.8E-03	3.8E-03	2.2E-03	6.3E-03	2.3E-03	5.4E-04
Th	6.3E-02	0.0E+00	7.8E-02	3.3E-02	4.5E-02	3.8E-02	5.0E-02	5.5E-02	7.5E-02	1.3E-01	2.4E-02	8.8E-02	2.0E-04	1.3E-02
U	4.2E+00	5.4E-03	3.3E+00	2.3E+00	5.4E-01	6.4E+00	1.1E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.5E-02	4.4E-03

Annexure C

Transfer of different radionuclides from soil to plants

Elem	Plant Part	N	Mean	GSD/SD	Minimum	Maximum
Pd	Leaves All	31	8.0×10–2	1.3×101	3.2×10–3	2.5×101
Po	Leaves All	12	7.4×10–3	6.9	2.5×10–4	5.0×10–2
Ra	Leaves All	77	9.1×10–2	6.7	1.8×10–3	1.3×102
Th	Leaves All	24	1.2×10–3	6.0	9.4×10–5	2.1×10–1
U	Leaves All	108	2.0×10–2	7.3	7.8×10–5	8.8

Nuclide	**Transfer Factor**	**soil activity (Bq/kg)**	**Plant activity (Bq/kg)**
U-238	2.00E-02	1.63E+02	3.26E+00
Th-234	1.20E-03	1.63E+02	1.95E-01
Pa-234m	NA	1.63E+02	
U-234	2.00E-02	1.63E+02	3.26E+00
Th-230	1.20E-03	1.63E+02	1.95E-01
Ra-226	9.10E-02	2.14E+02	1.95E+01
Rn-222	NA	2.14E+02	
Po-218	7.40E-03	2.14E+02	1.59E+00
Pb-214	8.00E-02	2.14E+02	1.72E+01
Bi-214	NA	2.14E+02	
Po-214	7.40E-03	2.14E+02	1.59E+00
Pb-210	8.00E-02	6.40E+02	5.12E+01
Bi-210	NA	6.40E+02	
Po-210	7.40E-03	6.40E+02	4.74E+00
Th-232	1.20E-03	2.18E+01	2.61E-02
Ra-228	9.10E-02	2.18E+01	1.98E+00
Ac-228	NA	2.18E+01	
Th-228	1.20E-03	2.18E+01	2.61E-02
Ra-224	9.10E-02	2.18E+01	1.98E+00
Rn-220	NA	2.18E+01	
Po-216	7.40E-03	2.18E+01	1.61E-01
Pb-212	8.00E-02	2.18E+01	1.74E+00
Bi-212	NA	2.18E+01	
Po-212	7.40E-03	2.18E+01	1.61E-01
Tl-208	NA	2.18E+01	

Annexure D

Transfer of essential elements from soil to plant

	Eucalyptus globulus							Acacia pycnantha					Hyparrhenia spp.	
Sample name	L	D	E	N	E	BG	G	Y	N	R	L	O	I	S
plants Fe	906.1	15.8	425.1	832.2	1407.7	1142.1	1236.3	326.6	2471.2	1131.4	565.0	1394.3	19.7	53.4
soil Fe	14478.2	6014.8	14647.7	79711.6	14647.7	49538.3	3154.0	20616.3	79711.6	20091.5	14478.2	5089.6	7783.8	23710.7
Transfer factor	0.063	0.003	0.029	0.010	0.096	0.023	0.392	0.016	0.031	0.056	0.039	0.274	0.003	0.002
plants Cu	41.2	1.5	11.1	41.2	19.1	21.3	6.6	4.2	6.0	15.5	49.3	10.1	1.6	1.8
soil Cu	12.2	5.2	19.2	39.3	19.2	36.9	4.1	21.2	39.3	13.3	12.2	4.3	7.3	18.0
Transfer factor	3.369	0.291	0.579	1.048	0.998	0.579	1.614	0.199	0.153	1.168	4.027	2.365	0.223	0.103

Annexure E: Dose conversion factors for ingestion by members of the public

Nuclide	Activity in plant	< 1a	1-2a	2-7a	7-12 a	12-17 a	>17 a
U-238	3.26E+00	3.4E-07	1.2E-07	8E-08	6.8E-08	6.7E-08	4.5E-08
Th-234	1.95E-01	4E-08	2.5E-08	1.3E-08	7.4E-09	4.2E-09	3.4E-09
Pa-234m	0.00E+00	NA	NA	NA	NA	NA	NA
U-234	3.26E+00	3.7E-07	1.3E-07	8.8E-08	7.4E-08	7.4E-08	4.9E-08
Th-230	1.95E-01	4.1E-06	4.1E-07	3.1E-07	2.4E-07	2.2E-07	2.1E-07
Ra-226	1.95E+01	4.7E-06	9.6E-07	6.2E-07	8E-07	1.5E-06	2.8E-07
Rn-222	0.00E+00	NA	NA	NA	NA	NA	NA
Po-218	1.59E+00	NA	NA	NA	NA	NA	NA
Pb-214	1.72E+01	2.7E-09	1E-09	5.2E-10	3.1E-10	2E-10	1.4E-10
Bi-214	0.00E+00	1.4E-09	7.4E-10	3.6E-10	2.1E-10	1.4E-10	1.1E-10
Po-214	1.59E+00	NA	NA	NA	NA	NA	NA
Pb-210	5.12E+01	8.4E-06	3.6E-06	2.2E-06	1.9E-06	1.9E-06	5.9E-07
Bi-210	0.00E+00	1.5E-08	9.7E-09	4.8E-09	2.9E-09	1.6E-09	1.3E-09
Po-210	4.74E+00	0.000026	8.8E-06	4.4E-06	2.6E-06	1.6E-06	1.2E-06
Th-232	2.61E-02	4.6E-06	4.5E-07	3.5E-07	2.9E-07	2.5E-07	2.3E-07
Ra-228	1.98E+00	0.00003	5.7E-06	3.4E-06	3.9E-06	5.3E-06	6.9E-07
Ac-228	0.00E+00	7.4E-09	2.8E-09	1.4E-09	8.7E-10	5.3E-10	4.3E-10
Th-228	2.61E-02	3.7E-06	3.7E-07	2.2E-07	1.5E-07	9.4E-08	7.2E-08
Ra-224	1.98E+00	2.7E-06	6.6E-07	3.5E-07	2.6E-07	2E-07	6.5E-08
Rn-220	0.00E+00	NA	NA	NA	NA	NA	NA
Po-216	1.61E-01	NA	NA	NA	NA	NA	NA
Pb-212	1.74E+00	1.5E-07	6.3E-07	3.3E-08	2E-08	1.3E-08	6E-09
Bi-212	0.00E+00	3.2E-09	1.8E-09	8.7E-10	5E-10	3.3E-10	2.6E-10
Po-212	1.61E-01	NA	NA	NA	NA	NA	NA
Tl-208	0.00E+00	NA	NA	NA	NA	NA	NA

Annexure F

Effective Dose to members of the public via ingestion of contaminated leafy vegetables

Dose to man via ingestion of leafy vegetables						
Age	< 1a	1-2a	2-7a	7-12 a	12-17 a	>17 a
Yearly consumption	39	52	65	78	111	130
U-238	4.32E-05	2.12E-12	6.24E-13	4.24E-13	5.06E-13	3.92E-13
Th-234	3.05E-07	5.20E-14	2.11E-14	7.50E-15	3.45E-15	1.86E-15
Pa-234m						
U-234	4.70E-05	2.50E-12	7.44E-13	5.08E-13	6.08E-13	4.71E-13
Th-230	3.12E-05	8.74E-11	8.26E-12	5.80E-12	5.86E-12	6.01E-12
Ra-226	3.58E-03	2.35E-10	3.87E-11	3.87E-11	1.33E-10	5.46E-11
Rn-222						
Po-218						
Pb-214	1.81E-06	1.40E-16	3.38E-17	1.26E-17	6.88E-18	3.64E-18
Bi-214	0.00E+00	5.39E-17	1.73E-17	5.90E-18	3.26E-18	2.00E-18
Po-214						
Pb-210	1.68E-02	1.57E-09	5.15E-10	3.26E-10	4.01E-10	1.46E-10
Bi-210	0.00E+00	7.57E-15	3.03E-15	1.09E-15	5.15E-16	2.70E-16
Po-210	4.80E-03	1.19E-08	2.52E-09	8.92E-10	4.62E-10	2.50E-10
Th-232	4.68E-06	1.08E-10	1.02E-11	7.92E-12	8.05E-12	7.48E-12
Ra-228	2.32E-03	8.89E-09	1.26E-09	1.03E-09	2.29E-09	4.75E-10
Ac-228	0.00E+00	1.08E-15	2.55E-16	9.50E-17	5.12E-17	2.96E-17
Ra-224	3.77E-06	7.12E-11	5.29E-12	2.57E-12	1.57E-12	8.80E-13
Th-228	2.08E-04	9.27E-11	1.50E-11	7.10E-12	5.77E-12	1.69E-12
Rn-220						
Po-216						
Pb-212	1.02E-05	4.91E-12	1.35E-12	5.15E-14	2.89E-14	1.01E-14
Bi-212	0.00E+00	3.00E-16	1.02E-16	3.39E-17	1.83E-17	1.12E-17
Po-212						
Tl-208						
Yearly dose (mSv)	2.78E-02	2.30E-08	4.37E-09	2.32E-09	3.31E-09	9.42E-10
Yearly dose (µSv)	2.78E+03	2.30E-03	4.37E-04	2.32E-04	3.31E-04	9.42E-05