Prospective Public Radiological Safety Assessment for the Proposed West Wits Mining Project

Assessing Radiological Impact on People & the Environment

Date: 13 May 2019

Prepared by: Dawid de Villiers, Ph.D. (Pr.Sci.Nat, Pr.Phys.)

Radiation Protection Specialist (NORM)

Document No: SR-REP-02/2019

SciRad Consulting (Pty) Ltd
Reg. No: 2012/210743/07

P.O. Box 843, Hartbeespoort, 0216, Tel: +27 12 253 1507, Cell: +27 82 339 0254, Email: dawid@sciradconsulting.com

DISCLAIMER

Although SciRAD Consulting (Pty) Ltd exercises due care and diligence in rendering services and preparing documents, SciRAD Consulting (Pty) Ltd accepts no liability. The Client, by receiving this document indemnifies SciRAD Consulting (Pty) Ltd, and its directors, agents, and employees, against all actions, claims, demands, losses, liabilities, costs, damages, and expenses arising from or in connection with services rendered, directly or indirectly by SciRAD Consulting (Pty) Ltd and using the information contained in this document.

DECLARATION

SciRAD Consulting (Pty) Ltd is an independent consulting firm with no interest in the project other than to fulfil the contract between the Environmental Assessment Practitioner and the Consultant for delivery of specialised services as stipulated in the project Terms of Reference.

AUTHORISATION

	NAME	SIGNATURE	DATE
COMPILED	Dr. Dawid de Villiers		13/05/2019
Radiation Protection Specialist			

DECLARATION OF INDEPENDENCE

I, Dr. Dawid de Villiers, in my capacity as a specialist consultant, hereby declare that I

* Act as an independent Radiation Specialist;

*Do not have any financial interest in the undertaking of the activity, other than remuneration for the work performed in terms of the National Environmental Management Act, 1998 (Act 107 of 1998);

* Undertake to disclose, to the competent authority, any material information that has or may have the potential to influence the decision of the competent authority or the objectivity of any report, plan or document required in terms of the National Environmental Management Act, 1998 (Act 107 of 1998);

* As a registered member of the South African Council for Natural Scientific Professions, will undertake my profession in accordance with the Code of Conduct of the Council, as well as any other societies to which I am a member; and

* Based on information provided to me by the project proponent, and in addition to information obtained during this study, have presented the results and conclusion within the associated document to the best of my professional judgement.

(Pr.Sci.Nat) Physical Science
SACNASP Reg. No. 400143/10

(Pr.Phys)
SAIP No: 2015002

(Radiation Protection Specialist)

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Definition
Becquerel	The unit for radioactive decay, equal to one decay per second
EIA	**E**nvironmental **I**mpact **A**ssessment
DME	South African **D**epartment **of** **E**nergy
DNA	**D**eoxyribo**n**ucleic **a**cid
IAEA	**I**nternational **A**tomic **E**nergy **A**gency
ICRP	**I**nternational **C**ommission on **R**adiation **P**rotection
MDA	**M**inimum **D**etectable **A**ctivity
Necsa	South African Nuclear Energy Corporation (Pty) Ltd
NNR	**N**ational **N**uclear **R**egulator
NORM	**N**aturally **O**ccurring **R**adioactive **M**aterial
PM$_{10}$	Inhalable **P**articulate **M**atter less than **10** micron (that is 0.01 mm) in size
ROM	**R**un **of** **M**ine
Sievert	The unit for effective and equivalent radiation dose
TSP	**T**otal **S**uspended **P**articles, the fraction of dust that deposits onto soil and surfaces
UNSCEAR	**U**nited **N**ations **S**cientific **C**ommittee on the **E**ffects of **A**tomic **R**adiation
WRD	**W**aste **R**ock **D**ump
%	Percentage
1/s	per second
Bq/g	Becquerel per gram
Bq/kg	Becquerel per kilogram
Bq/m^2	Becquerel per square metre
Bq/m^{2}s	Becquerel per square metre per second
Bq/m^3	Becquerel per cubic metre
e.g.	exempli gratia, which means “for example”
ha	hectare, equal to 10 000 square metres
h/a	hours per annum (or year)
i.e.	Id est, which means “that is” or “in other words”
kg/m^3	kilogram per cubic metre
km	kilometre
m	metre or milli, depending on the context
m/s	metre per second
m^2/s	square metre per second
m^3	cubic metre
m^3/h	cubic metre per hour
mg/m^{2}d	milligram per square metre per day

mJ/m3	milliJoule per cubic metre
mSv	milliSievert
mSv/a	milliSievert per annum (or year)
mSv/h	milliSievert per hour
ppm	parts-per-million
Sv/Bq	Sievert per Becquerel
µ	micro
µSv/a	microSievert per annum (or year)
µSv/h	microSievert per hour
µg/m^3	microgram per cubic metre
µg/m^{2}s	microgram per square metre per second

GLOSSARY

“E±##” is a form of scientific notation, often used in spreadsheets, to represent a very large (+) or very small (-) numbers. The number after the E is the exponent to the base ten e.g. 1.34 E-4 is equal to 1.34 x 10^{-4} (another form of scientific notation) or 0.000134;

“XX-###” is the abbreviation of an element’s name and the total number of protons and neutrons. For example, Lead-210 is Pb-210;

“Age group” is the division of the public according to ages. The following age groups are used:

- Adult represented by ‘Adult’
- 12 - 17 Years represented by ’15-Year’
- 7 - 12 Years represented by ’10-Year’
- 2 - 7 Years represented by ‘5-Year’
- 1 - 2 Years represented by ‘1-Year’
- 0 - 1 Years represented by ‘New-born’;

“**Cosmic ray interactions**” occur when high-energy charged particles and neutrons from the sun and outer space enter the earth’s atmosphere and collide with atoms therein to produce various forms of radiation;

“Dose constraint” is a prospective and source-related restriction on the individual dose arising from the predicted operation;

“**Dose conversion factor**” is a value specific to a particular radionuclide and exposure pathway that is used in the conversion of an activity concentration to dose;

“**DNA**” is mainly found within the nucleus of a cell and controls the structure and function of a cell;

“**Exposure pathway**” is a route by which a person can be subject to radiation from radioactive sources external and internal to the human body, the latter relating to inhaled or ingested radioactive material;

“**Insignificant dose**” is a radiation dose that is smaller than 1 µSv per year;

“Medical exposure” is the exposure to radiation due to a medical procedure or method, for example chest X-ray or a computed tomography (CT) scan;

"**Public exposure**" is exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure and the normal local natural background radiation but including exposure from authorised sources and practices and from intervention situations;

"**Radon flux density**" also called the Radon exhalation rate, refers to the rate at which radon is released from a material, e.g. rocks or soil;

“Re-suspension” is the freeing of a substance from the surface they deposited on;

"**Safety assessment**" is a review of the aspects of design and operation of a source which are relevant to the protection of persons or the safety of the source, including the analysis of risks associated with normal conditions and accident situations;

“**Trivial dose**” is a radiation dose that is less than 10 µSv per year (deduced from the NNR Regulations (DME, 2006);

“**Secular equilibrium**” is the situation where the activity concentration of a daughter radionuclide is equal to that of the parent radionuclide;

“**Source**” is anything that may cause radiation exposure or releasing radioactive substances or materials.

“**Tailings**” are a mixture of water and finely ground rock that is left over once mineral concentrate is removed;

“**Tailings Storage Facility (or abbreviated TSF)**” is a large area dedicated to the storage of tailings;

EXECUTIVE SUMMARY

West Wits MLI (Proprietary) Limited intends to establish an operation for the mining of uranium, gold, and silver (hereafter referred to as the "West Wits Mining Project") in an area located south of Roodepoort and to the north of Soweto in the City of Johannesburg Metropolitan Municipality, Gauteng. The area forms part of the "Witwatersrand basin", a geological formation that contains the largest repository of gold in South Africa.

The mining operation would involve the development of five open pit mining areas (Mona Lisa Bird Reef Pit, Roodepoort Main Reef Pit, Rugby Club Main Reef Pit, 11 Shaft Main Reef Pit and Kimberley Reef East Pit). Two existing infrastructure complexes (Bird Reef Central Infrastructure Complex and Kimberley Reef East Infrastructure Complex) will also be refurbished to access the existing underground mine workings.

The mining development would entail the establishment of run of mine (ROM) ore stockpiles, topsoil stockpiles, waste rock dumps (WRD) as well as supporting infrastructure. The operations will include on-site primary mineral processing where ore will be crushed prior to transportation to an existing off-site processing plant for mineral concentration. The expected life of mine for the open pit operations (inclusive of rehabilitation) is between 5 - 9 months for each pit, which includes rehabilitation. The total life of mine for the surface operations is therefore between 3-5 years. For the underground operations the life of mine is expected to be 20 years for the Kimberley Reef East underground workings, and 10 years for the Bird Reef Central underground workings. No tailings or tailings storage facilities will be constructed during surface or underground operations.

In the Witwatersrand basin Uranium exists alongside the gold. Besides being a heavy metal and chemically toxic, Uranium is also radioactive. People living and working in the areas surrounding the proposed West Wits operations may therefore be exposed to the radiation from the ore. This exposure stems from the dust, radon and effluents released from the mining operations.

Exposure to radiation has the potential to impact negatively on human health. To ensure the safety of the public (and the workers), mining operations are therefore obligated to assess the radiological impacts and risks to ensure that radioactive material is handled safely and responsibly.

This study, the *Prospective Public Radiological Safety Assessment,* is a specialist input to the Environmental Impact Assessment (EIA) for the proposed West Wits Mining Project. It considers the proposed operations of the West Wits Mining Project and to ensure the safety of the surrounding communities, aims to:

- determine the radiation doses and the associated radiological risks to which the public will be exposed, and
- if needed, provide recommendations on how to mitigate these risks.

The assessment of potential occupational radiation doses to workers has been assessed as part of a separate study.

The assessment methodology that was used is the source-pathway-receptor analysis in conjunction with an exposure scenario. In this analysis, the sources of radioactivity are related to the amount of radioactivity the public that stays near the proposed operations (the receptors) are exposed to through external and internal exposure. Furthermore, the different ways people are exposed to the radioactivity determines the exposure pathways that are investigated. An exposure scenario describes all the assumptions and parameters that are used to derive the radiation doses from the source-pathway-receptor analysis results. The doses assessed included external gamma radiation due to deposited dust, dust inhalation and radon inhalation. According to the Groundwater Specialist report, the leaching of contaminants and the development of acid mine drainage conditions from the waste rock dumps are unlikely. It is therefore not expected that the operations will have a radiological impact on the surface water or groundwater quality. For this reason, water ingestion and secondary ingestion doses were not considered. The assessed doses were compared with national guidelines and dose limits as to provide an opinion on the radiological risk the West Wits operations pose.

Radionuclide analysis results of the ore and waste rock indicated that all the individual radionuclides are below the regulatory limit of 0.5 Bq/g. This means that the proposed operations of the West Wits do not fall under the NNR Act, hence are not considered a radiological concern.

The above-mentioned was confirmed with the incremental individual pathway doses, without mitigation, at the different pits or underground operations as either trivial (i.e. less than 10 µSv/a) or insignificant (i.e. less than 1 µSv/a). The maximum total incremental dose, with the uncertainty considered, is not expected to exceed 11 µSv/a (that is 7 ± 4 µSv/a). This is much lower than the dose limit of 250 µSv/a. The Radon concentrations at public areas are also well below the action level of 300 Bq/m^3 with values less than 0.2 Bq/m^3. The associated risks are therefore very low. This translates to an EIA Impact Significance of Very Low. Given this, no mitigation measures are therefore deemed necessary.

It can be concluded that the proposed West Wits Mining operations do not warrant any concern regarding the radiological impacts to the public.

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION TO THE PROJECT

West Wits MLI (Proprietary) Limited intends to establish an operation for the mining of uranium, gold, and silver (hereafter referred to as the "West Wits Mining Project") in an area located south of Roodepoort and to the north of Soweto in the City of Johannesburg Metropolitan Municipality, Gauteng. The area forms part of the "Witwatersrand basin", a geological formation that contains the largest repository of gold in South Africa.

The mining operation would involve the development of five open pit mining areas (Mona Lisa Bird Reef Pit, Roodepoort Main Reef Pit, Rugby Club Main Reef Pit, 11 Shaft Main Reef Pit and Kimberley Reef East Pit). Two existing infrastructure complexes (Bird Reef Central Infrastructure Complex and Kimberley Reef East Infrastructure Complex) will also be refurbished to access the existing underground mine workings.

The mining development would entail the establishment of run of mine (ROM) ore stockpiles, topsoil stockpiles, waste rock dumps (WRD) as well as supporting infrastructure. The operations will include on-site primary mineral processing where ore will be crushed prior to transportation to an existing off-site processing plant for mineral concentration. The expected life of mine for the open pit operations (inclusive of rehabilitation) is between 6 - 16 months for each pit, which includes rehabilitation. The total life of mine for the surface operations is therefore between 3-5 years. For the underground operations the life of mine is expected to be 20 years for the Kimberley Reef East underground workings, and 10 years for the Bird Reef Central underground workings. No tailings or tailings storage facilities will be constructed during surface or underground operations (SLR, 2018).

1.2 PURPOSE OF THE REPORT

In the Witwatersrand basin Uranium exists alongside the gold. Besides being a heavy metal and chemically toxic, Uranium is also radioactive. People living and working in the areas surrounding the proposed West Wits operations may therefore be exposed to the radiation from the ore. This exposure stems from the dust, radon and effluents released from the mining operations.

Exposure to radiation has the potential to impact negatively on human health. To ensure the safety of the public (and the workers), mining operations are therefore obligated to assess the radiological impacts and risks to ensure that radioactive material is handled safely and responsibly.

This study, the *Prospective Public Radiological Safety Assessment,* is a specialist input to the Environmental Impact Assessment (EIA) for the proposed West Wits Mining Project. It considers the proposed operations of the West Wits Mining Project and to ensure the safety of the surrounding communities, aims to:

- determine the radiation doses and the associated radiological risks to which the public will be exposed, and
- if needed, provide recommendations on how to mitigate these risks.

1.3 SCOPE OF THE STUDY

In this assessment the radiation doses to the public resulting from the proposed operations of West Wits are calculated. The assessed doses will be compared with national guidelines and dose limits as to provide an opinion on the radiological risk the West Wits operations pose. Based on the radiological risk, recommendations, and mitigation measures (if applicable) will be discussed.

The assessment of potential occupational radiation doses to workers has been assessed as part of a separate study (de Villiers, 2019).[1]

1.4 OUTLINE OF THE REPORT

The report is structured as follows:

- In Chapter 2 the concepts and definitions that are used in this study are explained for the readers that are not familiar with radioactivity or radiation dose.
- Chapter 3 discusses the South African regulatory framework for Naturally Occurring Radioactive Material.
- Chapter 4 highlights the relevant site information, which includes the site description, summary of the mining operations, and the radiological data used to perform the radiological safety assessment.
- Chapter 5 discusses the Source-Pathway-Receptor assessment methodology that was followed to determine the radiation sources and the pathways of exposure for the members of the public that live in the surrounding areas. The Exposure Scenario that was used is also defined.
- Chapter 6 describes the assessment of the radiological impact in terms of radiation doses. The applicable mathematical models are explained and then used in the calculation of public doses for the relevant pathways as per the defined Exposure Scenario.
- Chapter 7 presents and discusses the assessed doses for the chosen Exposure Scenario. The radiological risks area also determined. Finally, the EIA Impact Significance Rating is deduced.
- Chapter 8 concludes the report with a summary of the findings and final conclusions.
- Chapter 9 contains all the referenced documents.
- Appendix A provides the radionuclide analysis results and Appendix B an abbreviated CV of the author of this report.

---

[1] The assessment of radiological risk to non-human species is not a requirement of the National Nuclear Regulator (NNR) yet, so this assessment will also exclude this aspect.

CHAPTER 2: CONCEPTS AND DEFINITIONS

This chapter provides explanations of the concepts and definitions that are used in this report relating to radioactivity and radiation dose. Readers with knowledge of this field can skip the following sections.

2.1 BRIEF OVERVIEW OF RADIOACTIVITY AND RADIATION DOSE

Everything around you are made up of matter, be it a chocolate cake, the chair you sit on, the air your breath or even you. The building blocks of matter are atoms. According to the Rutherford-Bohr model of an atom (Evans, 1955), it consists of **protons, neutrons** (these two forms the nucleus of the atom) and **electrons** (that surrounds the nucleus). An illustration of an atom is depicted in Figure 1.

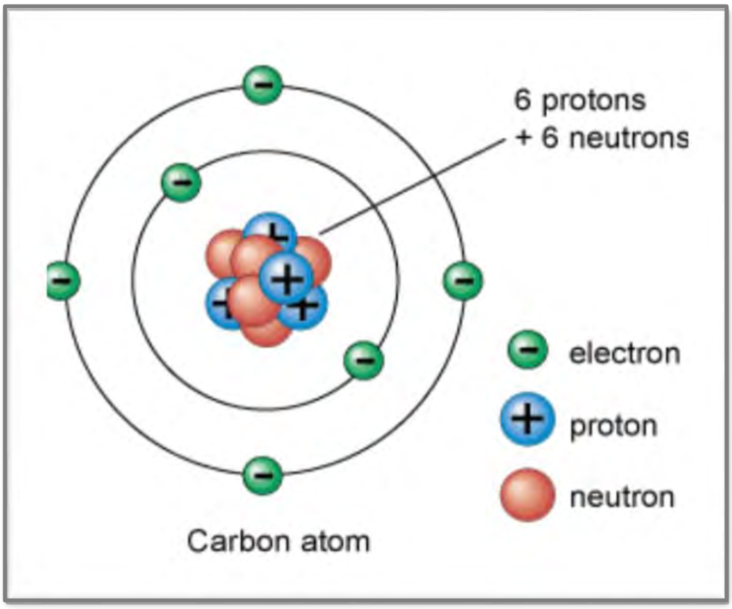

Figure 1: *An illustration (not to scale) of the Rutherford-Bohr model of an atom (i.e. the nucleus consisting of protons and neutrons at the centre with electrons around it (Universe Today, 2010).*

Atoms can be either electrically neutral or ionised. In a **neutral** atom, the number of electrons and protons are equal. **Ionised** atoms either gained or lost electrons (in other words, the number of protons and electrons are not equal).

The **number of protons** of a specific element is fixed. Therefore, the number of protons determines which chemical element on the periodic table the atom represents (e.g. Carbon has six protons and Uranium has ninety-two protons). The **number of neutrons** for that specific element can vary within a limited range. This means that there are substances that differ in the number of neutrons but they are all chemically still the same element. These variations are referred to as **isotopes** of that element. For example, Uranium has three isotopes naturally found in nature, namely Uranium-238 (146 neutrons), Uranium-235 (143 neutrons) and Uranium-234 (142 neutrons). When one refers to any element by its **name** and its **total number of protons and neutrons**, it identifies what is called a nuclide. Uranium-238 and Carbon-12 are both examples of nuclides.

There are 103 elements and more than 2 000 known nuclides. Some nuclides are naturally occurring but the majority are artificially produced in accelerator laboratories and nuclear reactors. Of this total, only 266 are stable nuclides. The rest is **unstable** and referred to as **radionuclides** (or **radioisotopes** if the previously mentioned condition applies)**.**

All **radionuclides** will spontaneously and randomly transform (termed **decay**) to form a stable isotope or a radionuclide with a proton to neutron configuration that is closer to stability. In the case of the latter, the formed product, called the **daughter product**, will decay again. This is a referred to as a decay series (the three main decay series are illustrated in Figure 2). The process of reaching stability through decay is called **radioactivity** and the energy or particles emitted during the process are called **radiation.**

The most prominent radiation are **alpha** particles, **beta** particles and **gamma** rays. An alpha particle consists of two protons and two neutrons. It is a relatively massive charged particle, but has a short range in air (approximately 1-2 cm). Alpha particles do not penetrate the skin and can be stopped by clothing (or even paper). Alpha radiation can be hazardous if it enters the body by ingestion or inhalation as it can damage the internal organs e.g. lining of the stomach or lungs. Beta particles are negatively or positively charged electrons that can penetrate the skin, although normally not beyond the top layer. Beta radiation can also be hazardous if inhaled or ingested. Gamma rays are high-energy photons that are the most penetrating of the radiations. Only a substantial thickness of dense material (e.g. lead) can provide adequate shielding against gamma rays. Gamma radiation can therefore deliver high doses to the body without the need for ingestion or inhalation.

The **activity** of radioactive material is the number of decays that occurs per second. The unit of radioactivity is the Becquerel (Bq), with 1 Bq equal to 1 decay per second. To normalise activity values for different samples, the activity is divided by the mass (or volume or area etc.) of the sample. This is defined as the specific activity, also called the **activity concentration,** and has the unit of Bq/g (or Bq/m^3 or similar).

The **time** needed for a radionuclide to decay to half of its original quantity is called the **half-life** and can range from micro seconds to millions of years. The shorter the half-life of a radionuclide, the higher is its activity. This means that for the same number of initial unstable atoms, Radium-226 (with a half-life of 1600 years) has much more decays than Uranium-238 (with a half-life of ˜4 500 000 000 years).

Radiation is classified according to the effects it produces on biological material into **ionising and non-ionising radiation**. Radiation from radioactive materials and X-rays belongs to the former, while examples of the latter are ultraviolet light, radio waves, and microwaves. Ionising radiation has sufficient energy to interact with the atoms in matter, strip them of electrons and as a result produce positively charged particles called ions. These ions can create chemical changes in biological cells as well as DNA. In the case of DNA, these changes can either be repaired by the body or cause harmful biological effects leading to the development of cancers or inherited genetic defects. [*Side note*: *Keep in mind that radiation is not the only or main cause of cancer. According to the South African Cancer Institute, tobacco, certain viruses, and diet rank as the highest contributors to cancer in South Africa* (Stassen, 2015).]

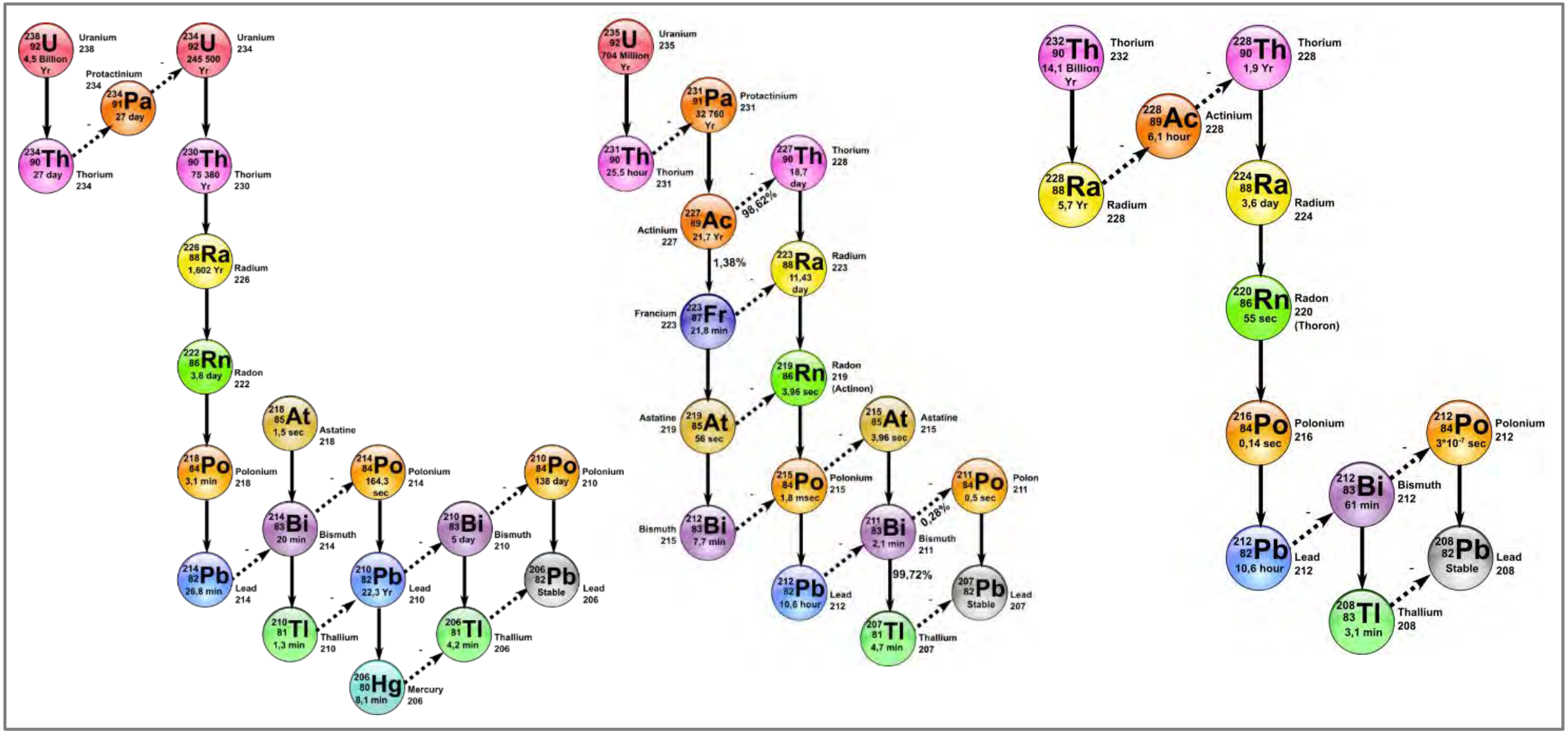

Figure 2: *An illustration of the Uranium-238, Uranium-235 and Thorium-232 decay series (the solid lines indicate alpha decay and the broken lines beta decay; gamma emissions are not indicated)(Clker Free Clipart, 2011).*

The likelihood of the **biological effects**, which may vary from damage to a few living cells to the death of a person, depends on the amount of radiation a person receives and to which part of the body. If a person were exposed to external or internal (through inhalation or ingestion) ionising radiation, the body would absorb a portion of the radiation. The amount of energy that is deposited in a unit mass of matter is called the **absorbed dose**, with the unit of gray. However, since ionising radiation differ in the way in which they interact with biological materials, equal absorbed doses from different types of radiation do not necessarily have equal biological effects. For example, one gray beta radiation is less harmful to the body than one gray alpha radiation since the beta particle is lighter and loses energy in smaller amounts as it traverses through the body. To equalise the different types of radiation, the absorbed dose is multiplied by a factor that accounts for the difference in energy distribution within tissue. The resulting quantity is called the **equivalent dose**, with the unit of Sievert (Sv). Furthermore, to account for organs or particular tissues differences in sensitivity to radiation, the equivalent dose is multiplied with tissue weighting factors. Adding all the tissue weighted equivalent doses together results in the quantity referred to as the **effective dose** (also with the unit of Sievert or smaller derivatives e.g. milliSievert (mSv) or microSievert (µSv)). In this report when the term “dose” is used it refers to “effective dose”.

2.2 RADIOLOGICAL RISK

Exposure to radiation may damage or kill living cells depending on the dose received. The biological effects may therefore vary from nothing to death. In general, **two types of effects** are observed in the human body. The first type is **chance effects** and are those effects that only have a possibility of appearing in the body due to cell changes. Examples of these chance effects are cancer and hereditary diseases. The second type are **threshold effects** that are only observed when one receives more than a threshold dose. Dose limits (discussed in Section 3.2) are set to ensure that the increase in the possibility i.e. risk of a chance effect is acceptable[2] and to prevent anyone from suffering any threshold effect.

The possibility of contracting a fatal cancer has been estimated by the International Commission on Radiological Protection (ICRP) by relying mainly on studies of the Japanese survivors of the atomic bombs and assessments by committees such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Their research indicated that for high doses the **relationship between risk and dose is linear** (meaning that if the dose increases by 50 % the risk would also increase with 50 %). This is accepted as the best practical approach for low doses[3] (ICRP, 2007) as well, and will therefore be applied in this assessment.

---

[2] In this sense radiation no different from other daily encountered hazards. It means that when the calculated risk from a radiation dose is the same as the risks one routinely takes and consider acceptable, then the radiation dose is also acceptable.

[3] This is referred to as the linear-no threshold theory. However, while some experiments have been used to create theories that low doses of radiation are more harmful than high doses, there are also experiments that suggest that low doses of radiation have no detrimental effect as the body can successfully repair all radiation related damage.

To this effect, the ICRP presents age-independent risk coefficients to express the possibility of contracting a fatal cancer and the possibility of heritable effects. These coefficients, 0.000055 per 1 mSv of exposure for fatal cancer and 0.000002 per 1 mSv of exposure for heritable effects (ICRP, 2007), will be used in Section 7.6 to determine the increase in risk from the highest calculated radiation dose.

2.3 RADIOACTIVITY IN NATURE

Radioactivity is found everywhere in nature and is categorised either as **artificial or naturally occurring**. **Artificial radionuclides** are produced by human activities. They do not belong in the environment and are found there due to nuclear power plant accidents or nuclear weapons testing. An example of artificial radioactivity is Strontium-90, which is a radionuclide created after the split of a Uranium-235 atom.

Naturally occurring radioactivity is either produced from cosmic ray interactions or naturally found in the sands, soils, and minerals in the earth's crust. Hydrogen-3 and Carbon-14 are examples of the former, with Potassium-40, Uranium-238, Uranium-235 and Thorium-232 are examples of the latter. Uranium-238/235 and Thorium-232 are the respective parents of a whole range of naturally occurring radionuclides, which are constantly produced through the decay of their parents (refer to Figure 2). The materials in which these radionuclides are found are called **Naturally Occurring Radioactive Materials or NORMs.**

Radon-222 (normally referred to as Radon) and its short-lived daughter products are continuously produced by the decay of Radium-226, a daughter product of Uranium-238. As an **odourless, tasteless noble gas**, it is inhaled and exhaled with normal air. However, its short-lived **daughter products** (e.g. Polonium-218 and Polonium-214) has the potential to deposit in the lungs. This leads to subsequent irradiation of lung tissue with alpha particles and **increase the risk** of lung cancer (ICRP, 1993).

2.4 BACKGROUND DOSE

Since **NORM is found everywhere on earth**, it means that all humans and other life on earth are continuously exposed to radiation through the air we breathe, the water we drink, the food we eat and the ground we walk, work, or play on. This **constant radiation** results in what is called a **background dose**. According to UNSCEAR (UNSCEAR, 2000), **NORM sources**, most notably Radon-222 and its daughter products, contributes on average more than **2.4 mSv** per year to this background dose (illustrated in Figure 3). Due to geological and meteorological differences between locations this value can vary substantially. For example, there are several places in Iran, India, and Europe where the natural environment gives rise to background doses that are more than 100 mSv (Web Ecoist, 2013). Nonetheless, the human body seems to be able to cope with this kind of doses as studies (ICRP, 2007) indicate that absorbed doses up to 100 milliGray do not show any clinically relevant functional impairment in tissue. The typical dose ranges for the contributors to the NORM background dose are presented in Table 1 (UNSCEAR, 2000).

Medical exposures of patients and **artificial sources** (e.g. releases from the nuclear industry, consumer products) also contributes to the background dose, although much less at approximately **0.4 mSv** per year.

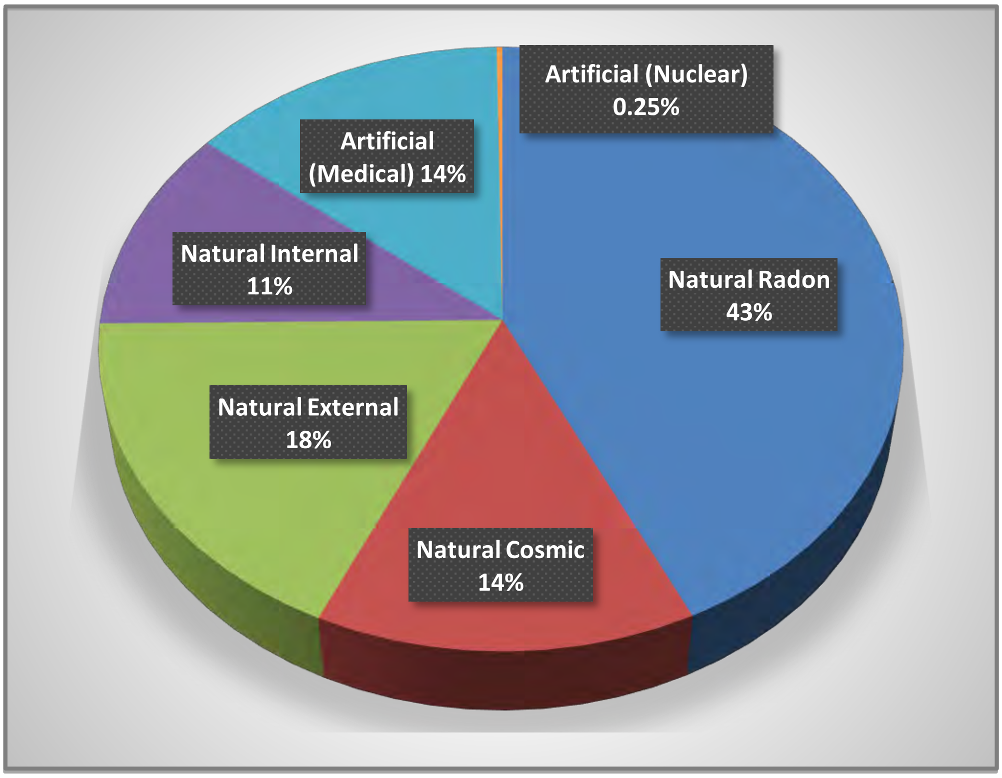

Figure 3: *The different contributions to the average annual background dose of ˜2.8 mSv.*

Table 1**:** *Typical dose ranges for the NORM sources of exposure contributing to the background dose.*

Source of Exposure	Annual Dose (mSv)	
	Typical Range	Average
Cosmic radiation	0.3 – 1.0	0.39
External terrestrial radiation	0.3 – 0.6	0.48
Inhalation exposure	0.2 – 10	1.26
Ingestion exposure	0.2 – 0.8	0.26
Total	**1 – 10**	**2.4**

CHAPTER 3: SOUTH AFRICAN REGULATORY FRAMEWORK RELATING TO NORM

In general, exposure to radiation from the natural background is not subject to regulatory control. On the other hand, human activities (for example current and historical mining and mineral processing) can cause an increase in the radiation dose that an individual receives. If this increase in dose exceeds certain limits, these activities need to be regulated or an area cleared from any radioactive material to ensure that people and the environment are protected.

In this chapter, the South African regulatory framework and the associated dose limits are described.

3.1 REGULATORY FRAMEWORK

To protect people and the environment from the risks of radiation, radiological protection standards were set up by the ICRP and International Atomic Energy Agency (IAEA) publications e.g. (ICRP, 1991), (ICRP, 1993), (IAEA, 1996). The NNR adopted these standards and promulgated the *National Nuclear Regulator Act* in 1999 (DME, 1999) to provide the regulatory framework for the Nuclear as well as the NORM industry in South Africa. In summary, the Act empowers the NNR to provide for the protection of persons, property, and the environment against nuclear damage through the establishment of safety standards and regulatory practices. The Act defines "*nuclear damage*" as

(a) "Any injury to or the death or any sickness or disease of a person; or
*(b) Other damage, including any damage to or any loss of use of property or damage to the environment, which arises out of or results from, or is attributable to the ionising radiation associated with a nuclear installation, nuclear vessel, or action (*where *"action"* is
  (a) the use, possession, production, storage, enrichment, processing, reprocessing, conveying or disposal of, or causing to be conveyed, radioactive material;
  (b) any action, the performance of which may result in persons accumulating a radiation dose resulting from exposure to ionising radiation; or
  (c) any other action involving radioactive material;)"

To provide elaboration of and implementation of the articles of the Act, the Regulations of the Act, the *National Safety Standards and Regulatory Practices* (DME, 2006), were published in 2006. The Regulations state that NORM containing materials (and operations handling them) do not fall under the NNR Act when:

"The level of radioactivity concentration of each radioactive nuclide in the materials is below -
(a) 0.5 Bq/g for naturally occurring radioactive nuclides of uranium and thorium and their progeny except for radon,
(b) 50 Bq/g for potassium-40 (10 Bq/g if the materials are used in building or disposed of), or
c) the level of total radioactivity content is below 1 000 Bq."

However, if the criteria above are exceeded, but it can be shown that the radiological impact due to the operations is low (based on the criteria as set out in the Regulations) an operation can still be indemnified from the NNR Act.

Over the years, the NNR provided more clarification on the use of the Act and Regulations by issuing Regulatory Documents, Guidance Documents and Licensing Guides. For example, Regulatory Guide RG-002 (NNR, 2014) describes the required content for a public safety assessment and provides default values for typically used parameters.

Although adequate, these documents do not provide, for instance any detail on the mathematical models that can be used to assess different exposure conditions. For this reason, the South African regulatory framework is complemented with the use of technical documents of ICRP and IAEA (amongst others) to provide additional guidance or assistance on radiation protection matters.

3.2 DOSE LIMITS

A practical outflow of the regulatory framework is the introduction of dose limits, dose constraints and a Radon action level. The individual dose limit places an upper limit to the dose from all controllable radiation sources to which an individual may be exposed (in other words an additional dose to the background dose). For a member of the public this dose limit is set at 1 000 µSv/a (or 1 mSv/a). To ensure that the dose limit is not exceeded, a dose constraint (a value lower than the limit) is introduced on individual sources of radiation.

For South Africa a dose constraint of 250 µSv/a (i.e. 0.25 mSv/a) is specified in the Regulations (DME, 2006), which also serves as a public dose limit for a single radiation source or operation (a person can therefore be exposed to more than one source/operation). For easy reference, Figure 4 depicts the dose limits in relation to possible doses from the sources of the natural background (ICRP, 1999). The total assessed doses for the West Wits Mining Project will be compared to the dose limit of 250 µSv/a.

Radon doses are normally not added to the total dose as the Regulations do not particularly address Radon exposure to members of the public. However, the calculated Radon concentration will be compared to the latest ICRP recommendation of 300 Bq/m^3 (ICRP, 2010). This criterion requires action to be taken when the level is exceeded.

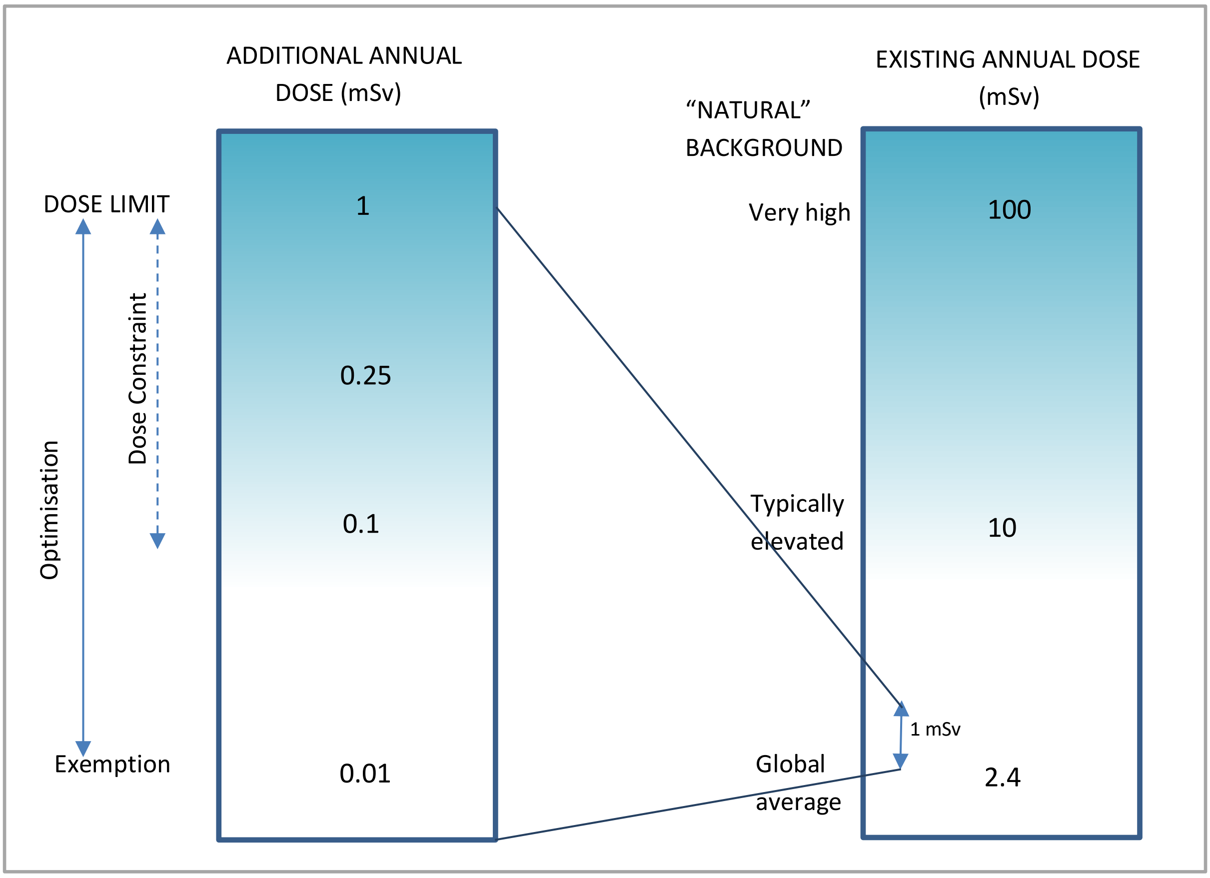

Figure 4: *A schematic representation of the individual public dose limits in relation to the annual dose from natural background sources. Note that the 1 mSv is in addition to the dose a person receives from background sources.*

CHAPTER 4: SITE INFORMATION

This chapter describes the relevant details of the site and provides the radiological data to be used later in the assessment.

4.1 SITE DESCRIPTION

The proposed West Wits Mining Project will be in an area south of Roodepoort and to the north of Soweto in the City of Johannesburg Metropolitan Municipality, Gauteng. The following farm portions will be affected by the operations: Glen Lea 228 IQ, Perdekraal 226 IQ, Rand Glen 229 IQ, Dobsonville 386 IQ, Doornkop 239 IQ, Fleurhof Township, Roodepoort 236 IQ, Roodepoort 237 IQ, Uitval 677 IQ, Vlakfontein 233 IQ, Vlakfontein 238 IQ, Witpoortjie 245 IQ, Vogelstruisfontein 231 IQ, Vogelstruisfontein 233 IQ, Soweto 387 IQ, Klipspruit 298 IQ, Klipriviersoog 299 IQ, Durban Roodepoort Deep 641 IQ, Bram Fischerville 663 IQ, Bram Fischerville 649 IQ and Tshekisho 710 IQ. This mining right application area is illustrated in Figure 5 (Mercury, 2019).

Figure 5: *The proposed West Wits mining right area south of Roodepoort and north of Soweto, Johannesburg* (*Mercury*, 2019).

The following paragraphs are a brief overview of the site characteristics. Further detail can be found in the Scoping Report (SLR, 2018), EIA Report (SLR, 2019) and other relevant specialist reports (Grobler, 2019), (Mercury, 2019), (Meyer & Smith, 2019).

The dominant geological formations found within the project area are those of the Central Rand Group within the Witwatersrand Supergroup and the Klipriviersberg Group within the Ventersdorp Supergroup. These supergroups are dominated by quartzite, shale, and mining conglomerates. The gold ore within the Witwatersrand Supergroup occurs in reefs (thin bands) with thickness between 20 to 540 m. Other minerals, such as silver, are recovered during the gold refining process. The northern perimeter of the project area follows the outcrop of the Johannesburg Subgroup which is overlain towards the south by strata of the Turffontein Subgroup. Volcanic rocks of the Ventersdorp Supergroup are observed in the southwestern portion of the project area, while a circular outcrop of Transvaal Supergroup sedimentary rocks is found in the central southern portion of the project area. These Transvaal Supergroup rocks predominantly consist of dolomite, with the Black Reef present at its base.

The project area consists of plains with interspersed hills, with a dominant hill crest in the north where previous mining activities have impacted on the outcrop. The general elevation across the project area varies from 1 600 to 1 780 m above mean sea level, with a generally slope to the south-west. Historical mining activities have altered the natural topography with the presence of various old tailings dams scattered throughout the project area.

The soils surrounding the proposed mining areas are characterised as sub-dominant sandy soils. These soils have been significantly disturbed due to historic mining activities. As such, the chemical pollution, soil compaction and the unavailability of essential soil microorganisms to mediate and facilitate the uptake of essential plant nutrients from soil, result in a soil quality that is not regarded as important for agricultural production. Furthermore, these soils have almost no clay content and therefore it is expected that the soils will be vulnerable to wind erosion when the vegetation cover is removed.

The project area is characterised by a Highveld climate. The average annual rainfall is 600 mm to 750 mm, which falls in the summer months. The annual average evaporation is expected to be double this value. Winds are generally from the north, north-west and north east, with an average speed of 3.2 m/s. Temperatures are warm-temperate with severe frost occurring in winter.

The proposed project area is in the upper reaches of the Upper Vaal Water Management Area, approximately 60 km downstream of the Vaal Barrage. The Klip River is the major river within this catchment area. However, this river has been significantly affected by the extensive historical and ongoing gold mining activities, industrial, sewage treatment and urban areas upstream and surrounding the project area. The aquatic macro-invertebrate community has significantly declined from the natural conditions in the system, while an abundance of fish species is expected.

Land uses associated with the project area include a combination of informal settlements, low-cost and high-cost residential areas, community and municipal facilities, agricultural areas, recreational areas, industrial areas, manufacturing and distribution facilities, commercial businesses, historical mine housing and historical mine infrastructure, illegal informal mining activities, mining activities, open land, substations and powerlines, gas and petrol pipelines, service and road infrastructure. Within the proposed open pit mining areas and infrastructure complexes, the existing land uses are a mixture of historical mine infrastructure, illegal informal mining activities, illegal dumping of waste, open land and in some instances service infrastructure.

4.2 PROJECT DESCRIPTION

The proposed mining operation would involve the development of five open pit mining areas:

- Mona Lisa Bird Reef Pit,
- Roodepoort Main Reef Pit,
- Rugby Club Main Reef Pit,
- 11 Shaft Main Reef Pit and
- Kimberley Reef East Pit.

Two existing infrastructure complexes will also be refurbished to access the existing underground mine workings:

- Bird Reef Central Infrastructure Complex and
- Kimberley Reef East Infrastructure Complex.

The location of the open pit areas and infrastructure complexes within the mining right application area are illustrated in Figure 6 (Mercury, 2019). Although the mining right application area is 2 072.2 ha, the open pit areas are ~ 73 ha and the infrastructure complexes ~ 6 ha.

The mining development would entail the establishment of ROM ore stockpiles, topsoil stockpiles and waste rock dumps as well as supporting infrastructure. The infrastructure would include material storage and handling facilities (for fuel, lubricants, general and hazardous substances), general and hazardous waste management facilities, sewage management facilities, water management infrastructure, communication and lighting facilities, centralised and satellite offices, workshops, wash bays, stores, change houses, lamp rooms, vent fans and security facilities. Refer to Figures 7 -10 for the detail on each of the respective open pit and infrastructure areas.

Initially, near surface resources will be targeted for mining through means of open pit methods. The open pit activities would include primary mineral processing that involves a conventional excavate, load and haul mining cycle. Once the topsoil and waste rock have been removed and stockpiled, an Xcentric Ripper would be used to break the ground instead of the commonly used blasting methods. Ore would then be excavated and hauled to an ore stockpile for crushing before transportation to an existing off-site processing plant for mineral concentration.

The five proposed open pit mining areas would be developed in a phased approach. Once an open pit area has been mined, backfilled using waste rock and rehabilitated, the next pit would be targeted. Following final rehabilitation and adequate stabilisation, each of the areas would be made available in line with post-closure land use objectives. No waste rock dumps would remain, nor would any tailings or tailings storage facilities be constructed. It is anticipated that up to 180 000 tonnes of ore would be mined per annum from the open pit resources. The expected life of mine for the open pit operations (inclusive of rehabilitation) is between 5 - 9 months for each pit. The total life-of-mine for the surface operations is therefore between 3-5 years. A summary of the open pit operations is presented in Table 2 (SLR, 2019).

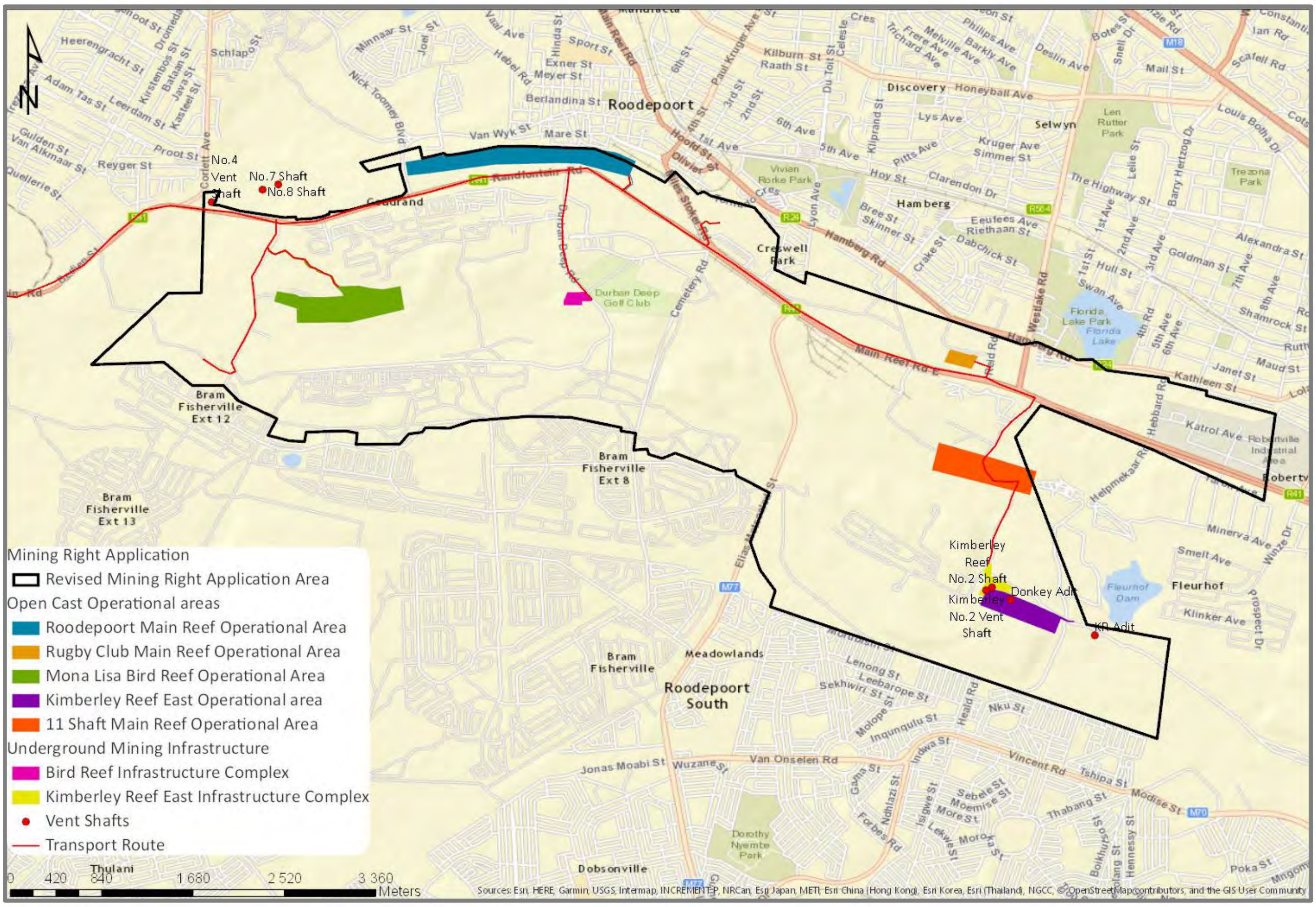

Figure 6: *The proposed open pit areas and existing infrastructure complexes within the West Wits mining right area (Mercury, 2019).*

Table 2: *Summary of the open pit operations.*

	Kimberley East	11 Shaft	Rugby Club	Mona Lisa	Roodepoort
Size of mining area	~ 9.2 ha	~ 15 ha	~ 2.6 ha	~ 20 ha	~ 26.5 ha
Mining rate (per month)	15 000 tonnes	15 000 tonnes	15 000 tonnes	15 000 tonnes	15 000 tonnes
Pit depth	20 - 30 m	20 - 30 m	7 - 10 m	20 - 30 m	7 - 10 m
Mineable resource (tonnes)	62 917	117 631	30 212	34 351	179 290
Mining duration (including concurrent rehabilitation, season dependent)	~ 5 months	~ 6 months	~ 6 months	~ 3 months	~ 6 months
Final rehabilitation duration	~ 2 months	~ 2 months	~ 3 months	~ 2 months	~ 2 months
Temporary waste rock dump volume	503 336 m^3	1 013 436 m^3	260 288 m^3	295 947 m^3	1 103 323 m^3
Temporary waste rock dump height	20 - 30 m	20 - 30 m	10 m	20 - 30 m	10 m

When the resources at the open pits near depletion, the underground mining operations will commence with the re-establishment of existing incline, circular and vertical shafts, and related infrastructure. Existing workings will also be rehabilitated. Conventional drill and blast breast mining methods will be used for the underground mining. The incline shafts, equipped with a winder house, would provide means for movement of men, material, and rock to and from the underground workings. Ore drives would be developed on reef with raises developed from the drives. Loading boxes would be constructed and winches would be installed on the down-dip side of the raise to remove the broken rock from the stopes. Ore would be transported to the incline shafts by means of conventional track bound equipment. Ore would be stored for initial crushing before transportation off-site. No tailings or tailings storage facilities will be constructed. Any waste rock produced by the underground mining operations would remain underground. It is anticipated that up to 360 000 tonnes of ore would be mined per annum from the underground resources. The life-of-mine for the underground operations is expected to be 20 years for the Kimberley Reef East underground workings, and 10 years for the Bird Reef Central underground workings (SLR, 2019). A summary of the underground operations is presented in Table 3.

Table 3: *Summary of the underground operations.*

	Bird Reef Central	Kimberley Reef East
Infrastructure complex size	~ 2.19 ha	~ 3.5 ha
Size of mining area	~ 52 ha	~ 100 ha
Mining rate (per month)	15 000 tonnes	15 000 tonnes
Workings depth	100 m to interception of reef (up 3 km below surface)	100 m to interception of reef (up 3 km below surface)
Waste rock	All waste rock will remain in the underground workings.	All waste rock will remain in the underground workings.

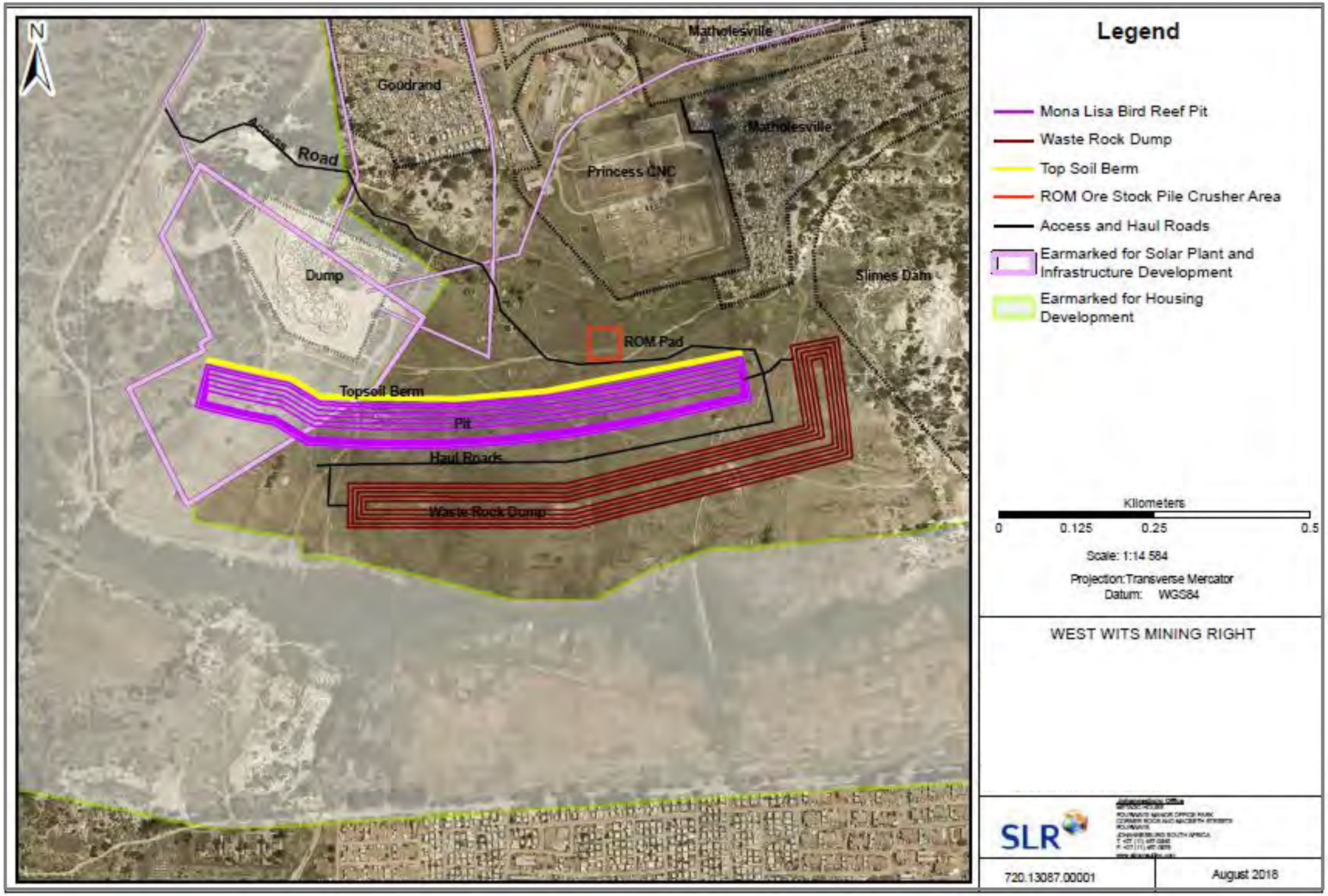

__Figure 7:__ Conceptual design layout of the proposed Mona Lisa Bird Reef Pit (SLR, 2018).

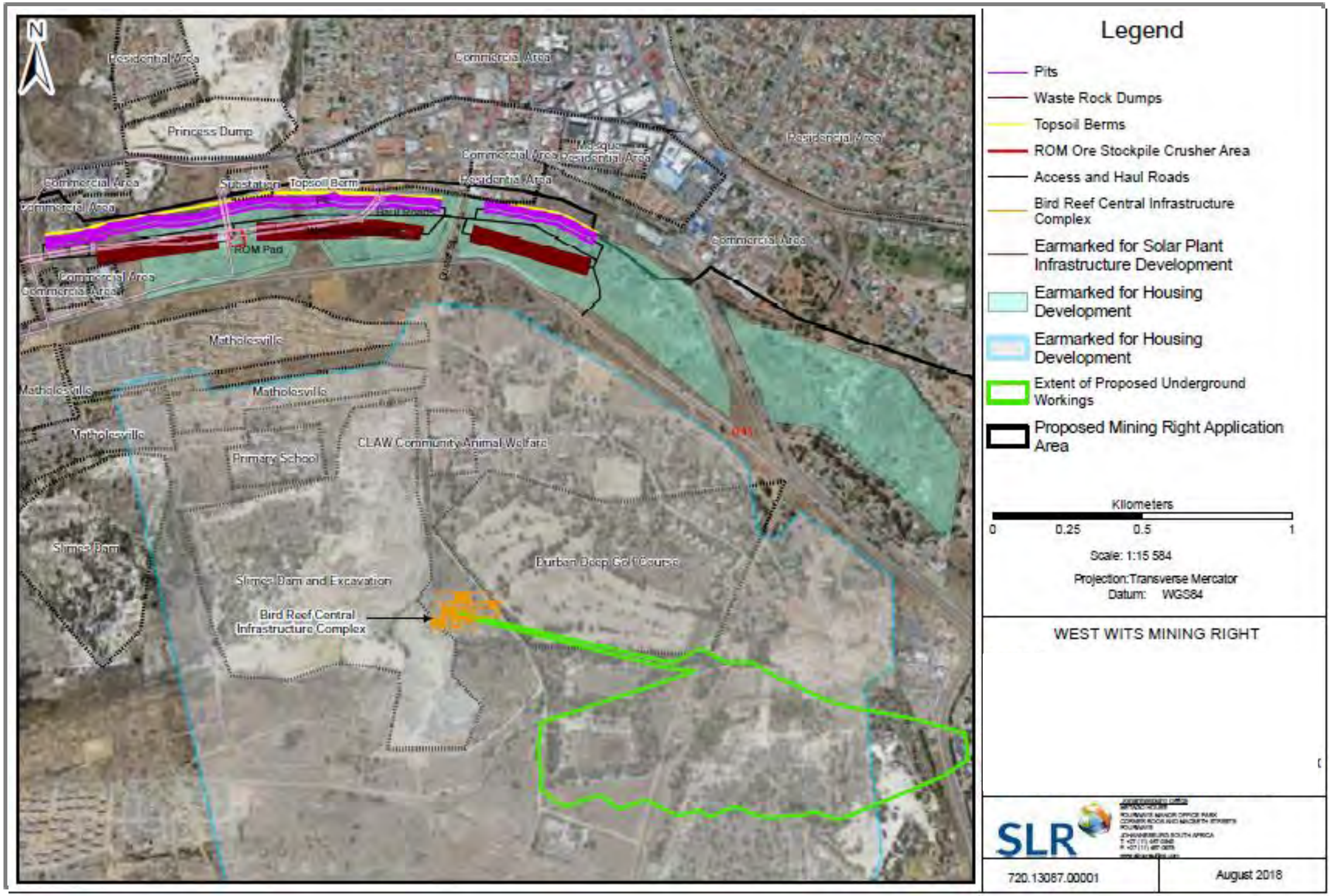

Figure 8: *Conceptual design layout of the proposed Roodepoort Pit, Main Reef Pit and Bird Reef Central Infrastructure Complex (SLR, 2018).*

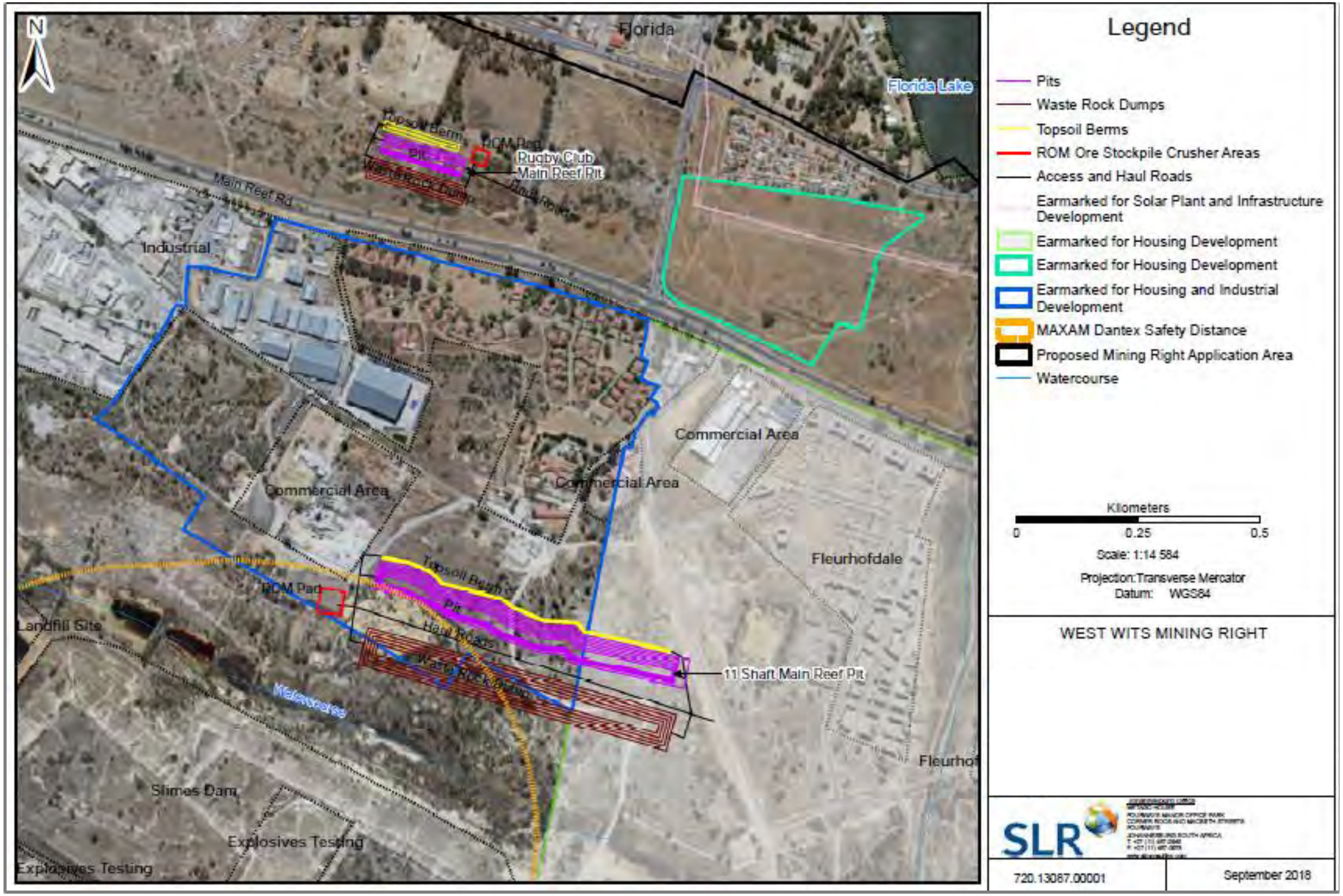

***Figure 9:** Conceptual design layout of the proposed Rugby Club Main Reef Pit and 11 Shaft Main Reef Pit (SLR, 2018).*

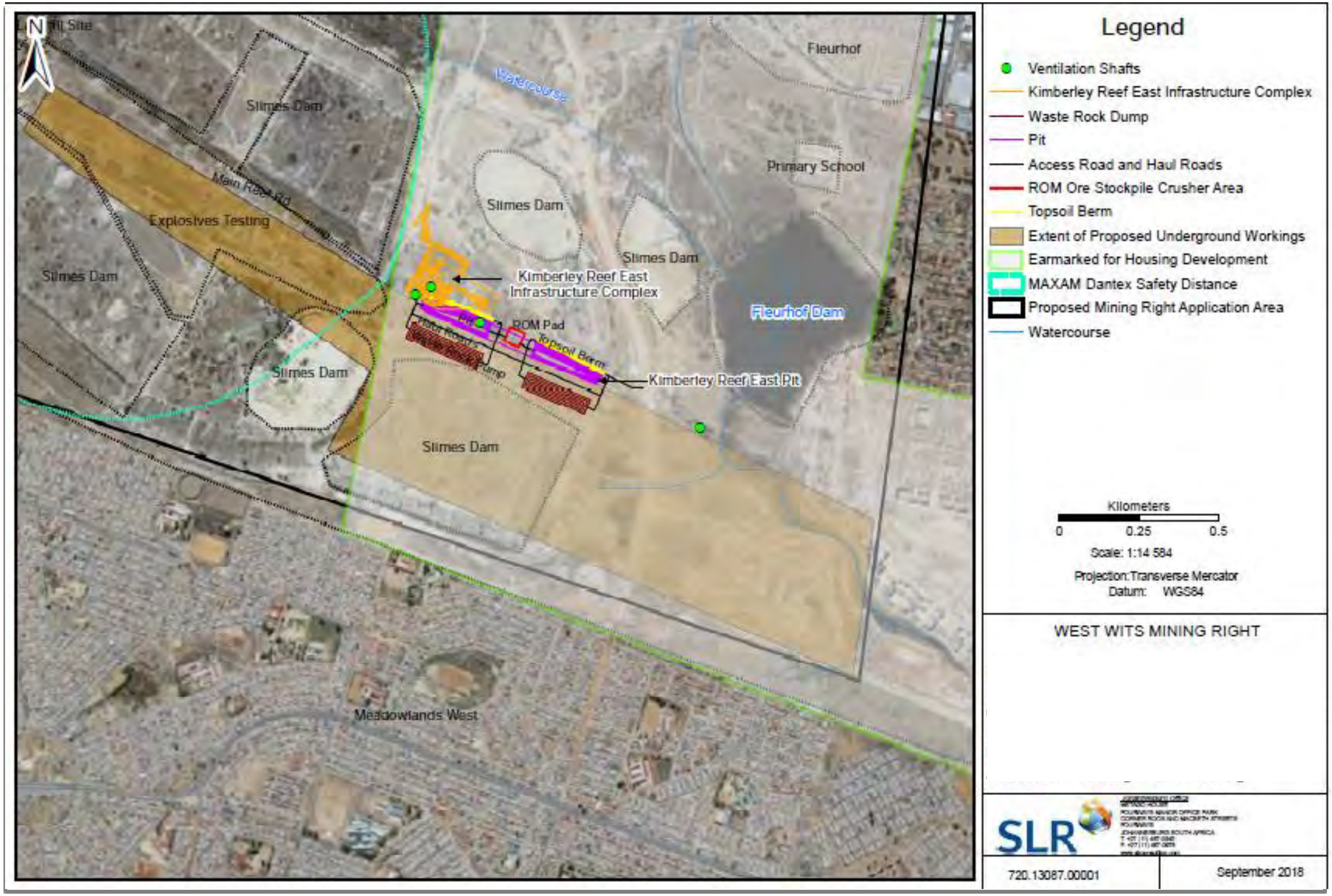

Figure 10: *Conceptual design layout of the proposed Kimberley Reef East Pit and Kimberley Reef East Infrastructure Complex (SLR, 2018).*

4.3 RADIOLOGICAL DATA

Composite samples were collected from the current operations at Sol Plaatjies (ore samples), the Kimberley Reef Pit (ore sample and waste rock sample) as well as a background soil sample obtained some distance away from the proposed operations. These samples are assumed to be representative of all the ore pits and were sent to RadioAnalysis, Necsa for analysis of all the relevant radionuclides. These results (NECSA, 2018) are tabulated in Table 4 and attached as Appendix A.

Table 4: *Measured radionuclide activity concentrations (Bq/kg) for ore, waste rock and background soil samples collected from the proposed West Wits mining area (italics font indicates derived values based on the assumption of secular equilibrium).*

Radionuclide	Activity Concentration (Bq/kg)			
	WW-04 = Waste Rock	WW-05 = Kimberley Reef Ore	WW-06 = Sol Plaatjies Pit 3 Ore	WW-07 = Background Soil
U-238	37.4 ± 0.9	38.5 ± 0.9	34.9 ± 0.8	23.8 ± 0.7
U-234	37.7 ± 0.9	38.8 ± 0.9	35.2 ± 0.9	24.0 ± 0.7
Th-230	*37.7 ± 0.9*	*38.8 ± 0.9*	*35.2 ± 0.9*	*24.0 ± 0.7*
Ra-226	31.1 ± 4.7	43.2 ± 4.1	38.7 ± 4.3	30.4 ± 3.7
Pb-210	92 ± 38	67.6 ± 21.2	90.6 ± 23.3	72.2 ± 22.3
Po-210	*92 ± 38*	*67.6 ± 21.2*	*90.6 ± 23.3*	*72.2 ± 22.3*
U-235	1.72 ± 0.04	1.77 ± 0.04	1.61 ± 0.04	1.1 ± 0.03
Th-232	24.3 ± 0.8	14.2 ± 0.6	12.2 ± 0.4	16.2 ± 0.4
Ra-228	18 ± 6.5	16.5 ± 4.9	24 (< MDA)	19.3 ± 5.8
Th-228	20 ± 4.8	11 ± 2.9	17 ± 3.4	15 ± 3.4
Ra-224	*20 ± 4.8*	*11 ± 2.9*	*17 ± 3.4*	*15 ± 3.4*

In the Geochemical Specialist reports (Hansen, 2019a), (Hansen, 2019b), (Hansen, 2019c), (Hansen, 2019d), (Hansen, 2019e) the uranium and thorium concentrations in waste rock were determined by elemental analysis. These results are presented in Table 5.

Table 5: *Elemental analysis results of waste rock samples from the five open pit areas.*

Element	Concentration (ppm)			
	Roodepoort	Rugby Club	Mona Lisa/11 Shaft	Kimberley East
Uranium	< 1	1	7	1
Thorium	<1	1	3	3

Two surface water samples (WW-01: West Dam Float and WW-03: Fleurhof Dam) and one borehole water sample (WW-02: WitBH1) were collected and sent for radionuclide analysis. Since the water is not fit for human consumption (refer to Section 5.2.4) and they represent baseline activity concentrations they are not used in this assessment (refer to Section 1.3). However, the results (NECSA, 2019) are attached as part of Appendix A.

Observations on the radionuclide analysis results:

Using the conversions factors of 1 ppm U = 12.35 Bq/kg U-238 and 1 ppm Th = 4.06 Bq/kg Th-232 (IAEA, 2003), the uranium and thorium concentrations of sample WW-04 (U ~ 3 ppm and Th ~ 6 ppm) are higher than most pits measured by elemental analysis. Only in the case of the Mona Lisa/11 Shaft pits is the uranium concentration lower. There is however good correlation between the radionuclide results and the average elemental analysis values. This indicates that although not all the pits were sampled for radionuclide analysis, the samples can be regarded as an adequate representation of the activity concentrations of the materials in the proposed pits.

All the individual radionuclide activity concentrations for all the samples are well below the regulatory limit of 500 Bg/kg (or 0.5 Bq/g). This means that **the proposed operations of the West Wits Mining Project do not fall under the NNR Act.** It is expected that the doses from all pathways will be far less than the dose limit and hence are not considered a radiological concern. This radiological assessment is therefore not needed. Nevertheless, it was decided to complete the assessment to offer the public peace of mind that their concerns were adequately addressed.

Furthermore, the low values for the sample of the current operations (i.e. the Sol Plaatjies ore sample) are indicative that the current operations also have a very low radiological impact on the public.

CHAPTER 5: SOURCE-PATHWAY-RECEPTOR ANALYSIS

In this chapter the source-pathway-receptor assessment methodology is described. Thereafter the different radiation sources, pathways and receptors are identified and the associated Exposure Scenario created.

5.1 ASSESSMENT METHODOLOGY

The radiological public safety assessment is an iterative (meaning that it is a repeated) process. It is performed within the knowledge of radiation protection principles, and South African regulatory requirements. The assessment process starts with a screening assessment which uses default values for all radiological variables or constants and worst-case assumptions for the exposure conditions. If the dose limit of 250 µSv/a is not exceeded, no further assessment would be required (NNR, 2014). However, if the dose limit is exceeded, the assessment can be repeated several times, ever increasing in the complexity of the exposure models and with more realistic or site-specific values and exposure conditions. This approach ensures that one does not conclude an exceedance of the dose limit on too conservative parameters, which may cost the client unnecessary mitigation options or in the worst case the “no-go” option without proper scientific evidence.

The assessment methodology that will be used is the source-pathway-receptor analysis in combination with an exposure scenario. In this analysis, the sources of radioactivity are related to the amount of radioactivity the public that stays near the operations (the receptors) are exposed to through external and internal exposure. For example, the radionuclide data from the sample analysis are used together with the gravimetric dust concentrations from the Air Quality Impact Assessment to determine the amount of radioactivity that is dispersed in the environment. Furthermore, the different ways people are exposed to the radioactivity determines the exposure pathways that are investigated e.g. inhalation or ingestion. An exposure scenario describes all the assumptions and parameters that are used to derive the radiation doses from the source-pathway-receptor analysis results. For example, the relevant age groups and their assumed indoor and outdoor exposure periods form part of an exposure scenario.

5.2 SOURCES OF RADIOACTIVITY

5.2.1 Dust Sources

The Air Quality Impact Assessment (Grobler, 2019) identified the various dust sources applicable to this study as:

- Open pit and underground materials handling (i.e. rock-breaking, crushing, loading, unloading) of:
    - ROM,
    - waste rock in the pit and
    - waste rock at the WRD,
- Vehicle activity on unpaved roads,
- Windblown dust due to wind erosion from

  - ROM stockpiles and
  - WRD stockpiles, and
- Ventilation shaft emissions from the underground operations.

These sources include inhalable dust (the PM_{10} fraction) as well as the dust fallout – dust that deposits on the ground or surfaces in the area (the TSP fraction).

Note that the recommended mitigation options described in the Air Quality Impact Assessment, e.g. wet suppression, do not change the dust sources, only the amount of dust emissions. Furthermore, the amount of dust from each of these sources will vary across the study area mainly due to different emission rates and source-receptor distances.

5.2.2 Radon Sources

Since NORM is found everywhere in the environment, Radon is also ever present. When mining operations involve materials with enhanced concentrations of Radium-226, additional sources of Radon are created. In the case of the West Wits operations these include the open and underground pits, the ROM stockpiles and to a lesser degree the waste rock dumps.

5.2.3 External Radiation Sources

Experience at other mines indicates that direct external exposure to radiation from mine sources (such as the open pits and stockpiles) only become important when members of the public are living on areas containing mine ore or residues. While this pathway should be further investigated for post-closure conditions, it is not considered in this prospective assessment as members of the public will not have access to such areas during mine operation.

5.2.4 Water Sources

Groundwater (e.g. water from boreholes) and surface water (e.g. water from dams in the area) can be contaminated from mining operations. The radioactively contaminated water then becomes a source of exposure that needs to be considered and assessed. However, the Hydrogeological Specialist Report (Meyer & Smith, 2019) states that historical and present activities in the area created baseline groundwater and surface water with concentrations of dissolved uranium and other elements that exceed the chronic/acute health limits. This means that the existing water, if not treated, is unfit for human consumption.

The same report also states that the leaching of contaminants and the development of acid mine drainage conditions are unlikely. It is therefore not expected that the operations will have a radiological impact on the surface water or groundwater quality. Hence, the water is not regarded as a possible source of exposure to radioactivity.

5.3 EXPOSURE PATHWAYS

5.3.1 External Exposure Pathway

While the public will not work or live on areas containing mine ore or residues, the deposition of airborne radioactivity in the form of dust that settled on surfaces is considered a pathway for external gamma radiation.

5.3.2 Atmospheric Pathway

Dust from the mining operations and wind erosion from the stockpiles can be inhaled and as a result, people are exposed to the radioactivity within the dust. Additional Radon is also released from these stockpiles and operations. The meteorological and mechanical processes (e.g. wind speed, wind direction and dispersion) that cause this environmental transfer are described in the Air Quality Impact Assessment (Grobler, 2019) and will not be repeated here. The atmospheric pathway will therefore consider the inhalation of the PM_{10} dust fraction and Radon.

5.3.3 Ingestion Pathways

Since water is not considered to be a source of radioactivity, as it is either unfit for human consumption or no additional radioactive contaminants are added to the water (refer to Section 5.2.4), the water ingestion pathway is excluded from the assessment. The same applies to the secondary ingestion pathways i.e. ingestion of vegetables irrigated with the water or food derived from animals that consumed the water (e.g. eggs, milk, or meat).

If home-grown vegetables or fruit contain deposited dust it would be washed or, as in the case of maize, the outer leaves that contain the dust removed before consumption. The ingestion pathway due to transfer of deposited dust to food are therefore also excluded.

5.4 RECEPTORS

The Air Quality Impact Assessment (Grobler, 2019) identified the residences around the various open pits as sensitive receptor areas in regards to air quality. These areas also house the receptors for radiation exposure, although the focus of this assessment will be on the Representative Person (ICRP, 2006). The Representative Person is the most exposed individual, in other words the person with the highest dose irrespective of age. Since exposure is higher the closer one is to the source, the Representative Person will most probably be living near the pit operations. Specific locations for the Representative Person were not chosen beforehand, but are identified after the calculation of the doses.

5.5 EXPOSURE SCENARIOS

The following exposure scenario describes the radiation exposure conditions assumed, based on expected human actions and behaviour, for the public around the respective West Wits Mining open pits or infrastructure.

5.5.1 Exposure Scenario 1: Residential

This Exposure Scenario assumes that the residents of the respective areas near the West Wits operations are of all ages and spent time outdoors and indoors. Houses are assumed to provide a shielding factor of 0.6 (NNR, 2014) from outside dust concentrations. The default values for exposure periods and breathing rates are chosen and taken from RG-002 (NNR, 2014). These are tabulated in Table 6. The people will be internally exposed from the inhalation of radioactive dust and Radon. They will also be externally exposed to gamma radiation from the deposited dust. While various environmental factors reduce the amount of deposited dust that is available, and therefore also the exposure, these factors will be ignored for this screening assessment in order to provide a worst case.

Other assumptions that relate to the mathematical models, will be mentioned in their respective sections in Chapter 6.

Table 6: *Average breathing rates and default exposure periods for the different age groups (NNR, 2014).*

Age Group	Breathing Rate (m^3/h)	Exposure Period	
		Outdoors (h/a)	Indoors (h/a)
New-born	0.12	0	8 760
1-Year	0.22	846	7 914
5-Year	0.37	985	7 775
10-Year	0.64	**1 192**	7 568
15-Year	0.84	1 095	7 665
Adult	0.92	1 710*	7 050*
Worker	1.2	2 000	0

* For Radon exposure these values will change to 1 760 h/a outdoors and 7 000 h/a indoors to use the default dose conversion factors (refer to Section 6.3).

CHAPTER 6: RADIOLOGICAL ASSESSMENT

This chapter presents the relevant mathematical models, radiological parameters and additional assumptions used to assess the radiation doses applicable to the proposed West Wits Mining Project.

6.1 EXTERNAL EXPOSURE DOSES FROM DUST DEPOSITION

The daily dust fallout rates from all fugitive dust sources at the proposed West Wits operations were determined through dispersion modelling (Grobler, 2019). Assuming no re-suspension of the dust, these rates were changed to annual dust fallout rates by multiplying with the number of days in a year, i.e. 365.25. Thereafter the annual dust fallout rates were converted to a surface dust activity concentration for each individual radionuclide by multiplying with the respective radionuclide concentration of either the waste rock or the ore (from Table 4). For the pits, the higher Sol Plaatjies Pit values were chosen. Mathematically this can be expressed by:

$$C_{TSP,j} = (365.25).k.F_{TSP}.R_j \qquad \text{Eq. 1}$$

where

$C_{TSP,j}$ = Surface dust activity concentration of radionuclide *j* [Bq/m^2]
F_{TSP} = Daily dust fallout rate [mg/m^{2}d]
R_j = Activity concentration of radionuclide *j* [Bq/kg]
k = Unit correction (0.001/1000) [-]

Since dust deposition creates a thin layer of radioactivity, it is assumed that it can be modelled with an infinite large surface source. The surface activity concentration for each individual radionuclide is converted to a dose rate using the applicable dose conversion factor and the results summed. The dose conversion factors mostly apply to gamma rays as the contribution of alpha and beta radiation is insignificant in comparison. Finally, the dose rate is multiplied with the chosen exposure periods (Table 6) and house shielding factor to obtain the dose. The mathematical expression is:

$$D_{ext\ dep} = \left(\sum_j C_{TSP,j}.DCF_{ext,j}\right).\left(T_o + T_{i.}(1 - SF)\right) \qquad \text{Eq. 2}$$

where

$D_{ext\ dep}$ = Dose from external exposure due to deposition [μSv/a]
$C_{dust,j}$ = Surface dust activity concentration of radionuclide *j* [Bq/m^2]
DCF_{ext} = External exposure dose conversion factor for radionuclide *j* [μSv/h per Bq/m^2]
T_O = Annual outdoor exposure period [h/a]
T_i = Annual indoor exposure period [h/a]
SF = Indoor shielding factor (i.e. 0.6) [-]

Dose conversion factors for external exposure were obtained from RG-002 (NNR, 2014) and are tabulated in Table 7.

Table 7: *Age-independent dose conversion factors for external exposure from deposited dust (NNR, 2014).*

Radionuclide	Dose Conversion Factor (μSv/h per Bq/m^2)
U-238+	6.71E-06
U-234	2.69E-09
Th-230	2.7E-09
Ra-226+	5.98E-06
Pb-210+	1.34E-07
Po-210	2.98E-11
U-235+	5.99E-07
Pa-231	1.47E-07
Ac-227+	3.75E-07
Ra-223+	1.01E-06
Th-232	1.98E-09
Ra-228+	3.34E-06
Th-228	8.46E-09
Ra-224+	6.10E-04
K-40	7.34E-07

* The + sign indicates that daughter radionuclides up to the next radionuclide were included in the value.

6.2 DUST INHALATION DOSES

The annual airborne dust concentrations from all fugitive dust sources at the proposed West Wits operations were determined through dispersion modelling (Grobler, 2019). These dust concentrations were converted to airborne dust activity concentrations for each individual radionuclide by multiplying with the respective radionuclide concentration of either the waste rock or the ore (from Table 4). For the pits, the higher Sol Plaatjies Pit values were chosen. Mathematically this can be expressed by:

$$C_{PM10,j} = 0.001. F_{PM10}. R_j \qquad \text{Eq. 3}$$

where

$C_{PM10,j}$	= Airborne dust activity concentration of radionuclide *j*	[μBq/m^3]
F_{PM10}	= Annual airborne (PM_{10}) dust concentration	[μg/m^3]
R_j	= Activity concentration of radionuclide *j*	[Bq/kg]

The annual dose from the exposure to inhaled airborne radioactive dust is calculated by multiplication of the average breathing rate for the different age groups (Table 6), exposure periods (Table 6), shielding factor (i.e. 0.6) and the sum of each radionuclide's dust activity concentration times the appropriate age-dependent dose conversion factor (Table 8) (NNR, 2014). This calculation is expressed by the following:

$$D_{inh} = \left(\sum_j C_{PM10,j}. DCF_{inh,j}\right). \left(T_o + (T_{i.}SF)\right). BR \qquad \text{Eq. 4}$$

where

D_{inh} = Inhalation dose from radioactive airborne dust [μSv/a]
$C_{PM10,j}$ = Dust activity concentration of radionuclide *j* [μBq/m^3]
$DCF_{inh,j}$ = Dust inhalation dose conversion factor for radionuclide *r* [Sv/Bq]
T_o = Annual outdoor exposure period [h/a]
T_i = Annual indoor exposure period [h/a]
SF = Indoor shielding factor [-]
BR = Breathing rate [m^3/h]

Dose conversion factors for inhalation were obtained from RG-002 (NNR, 2014) and are tabulated in Table 8.

Table 8: *Dose conversion factors for dust inhalation for all age groups.*

Radionuclide	Dose Conversion Factors (Sv/Bq)					
	Adult	15-Year	10-Year	5-Year	1-Year	New-born
U-238+	8.0E-06	8.7E-06	1.0E-05	1.6E-05	2.5E-05	2.90E-05
U-234	9.4E-06	1.0E-05	1.2E-05	1.9E-05	2.9E-05	3.30E-05
Th-230	1.4E-05	1.5E-05	1.6E-05	2.4E-05	3.5E-05	4.00E-05
Ra-226+	9.5E-06	1.0E-05	1.2E-05	1.9E-05	2.9E-05	3.40E-05
Pb-210+	5.7E-06	6.0E-06	7.3E-06	1.1E-05	1.8E-05	1.80E-05
Po-210	4.3E-06	5.1E-06	5.9E-06	8.6E-06	1.4E-05	1.80E-05
U-235+	8.5E-06	9.2E-06	1.1E-05	1.7E-05	2.6E-05	3.00E-05
Pa-231	3.4E-05	3.6E-05	3.9E-05	5.2E-05	6.9E-05	7.40E-05
Ac-227+	8.2E-05	8.9E-05	1.0E-04	1.5E-04	2.3E-04	2.20E-04
Ra-223	8.7E-06	1.1E-05	1.1E-05	1.5E-05	2.4E-05	3.20E-05
Th-232	2.5E-05	2.5E-05	2.6E-05	3.7E-05	5.0E-05	5.40E-05
Ra-228+	1.6E-05	1.6E-05	2.0E-05	3.2E-05	4.8E-05	4.90E-05
Th-228	4.0E-05	4.7E-05	5.5E-05	8.2E-05	1.3E-04	1.60E-04
Ra-224+	3.6E-06	4.5E-06	4.7E-06	6.3E-06	9.8E-06	1.20E-05

* The + sign indicates that daughter radionuclides up to the next radionuclide were included in the value.

6.3 RADON INHALATION DOSES

Radon flux densities and Radon concentrations were not measured at part of the study. However, the Air Quality Specialist calculated gas concentrations for each source, using a dispersion model with an emission rate of 1 μg/m^{2}s. These gas concentrations were converted to Radon concentrations by dividing by the emission rate and multiplying with the calculated Radon flux density applicable to the specific source. Since the total areas of the Radon sources were already multiplied in the dispersion calculations, it was not needed to repeat this step.

The Radon flux density is calculated using the following mathematical expression (IAEA, 2013):

$$f = C_{Ra}.\rho.E.\sqrt{\lambda.D_t} \qquad \text{Eq. 5}$$

where

F	= Radon flux density	[Bq/m^{2}s]
C_{Ra}	= Radium-226 concentration	[Bq/kg]
P	= Bulk density	[kg/m^3]
E	= Emanation coefficient	[-]
Λ	= Decay constant of Radon-222	[1/s]
D_t	= Diffusion coefficient	[m^2/s]

The Radium-226 values were taken from Table 4. For the pits, the Kimberley East pit value was chosen as it is slightly higher than that of the Sol Plaatjies pit. The other values were taken from RG-002 (NNR, 2014): 0.25 for the emanation coefficient, 4.2E-06 m^2/s for the diffusion coefficient and a decay constant equal to 2.06E-06/s. The material bulk density was assumed to be 1 500 kg/m^3.

The doses from the exposure to inhaled Radon daughters were calculated by multiplication of the Radon concentrations (indoor and outdoor concentrations were taken as equal), exposure periods, equilibrium factors and dose conversion factor according to the following mathematical expression

$$D_{Rn} = C_{Rn}.(E_i.T_i + E_o.T_o).DCF_{Rn} \qquad \text{Eq. 6}$$

where

D_{Rn}	= Radon inhalation dose	[μSv/a]
C_{Rn}	= Radon concentration	[Bq/m^3]
E_i	= Indoor equilibrium factor	[-]
T_i	= Indoor exposure period	[h/a]
E_o	= Outdoor equilibrium factor	[-]
T_o	= Outdoor exposure period	[h/a]
DCF_{Rn}	= Dose conversion factor for Radon exposure	[mSv/h per mJ/m^3]

The default exposure period values were used for the indoor exposure (i.e. 7 000 h/a) and outdoor exposure (i.e. 1 760 h/a) (ICRP, 1993), indoor and outdoor equilibrium factors were taken as 0.4 (ICRP, 1993) and 0.6 (UNSCEAR, 2000) respectively. The dose conversion factor was taken as 6.2E-06 (ICRP, 1993). This value is lower than the latest recommended value of 1.4E-05 (ICRP, 2010), but the higher value is not yet accepted by the NNR and therefore not used.

6.4 UNCERTAINTY ANALYSIS

Uncertainties exist in the calculations performed for this assessment. As far as air dispersion modelling is concerned, the uncertainty (σ_{Air}) may be responsible for a ± 50 % deviation from the measured value. Nevertheless, dispersion models are still the best-case approximation of a very complex physical process. Uncertainties associated with the radionuclide concentrations (σ_{Rad}) in the sample material can be as much as ± 10 %. Dose conversion factors, inhalation rates and other parameters are regarded as internationally accepted fixed values. Therefore, they do not have an uncertainty association. The propagation of the uncertainty in a specific calculation is complex, but an estimate of this total uncertainty is given by the following expression:

$$\sigma_{Total} = \sqrt{\sigma_{Air}^2 + \sigma_{Rad}^2} \ . \qquad \text{Eq. 7}$$

The estimated total uncertainty (σ_{Total}) can therefore be in the order of ± 51 % for the calculations.

CHAPTER 7: RESULTS & DISCUSSION

The mathematical expressions, as detailed in the previous Chapter, were developed as interconnecting worksheets on a Microsoft Excel spreadsheet file. Using the mentioned best estimates of published parameter values, doses were assessed for all the exposure pathways associated with the public living and working in the areas near the proposed West Wits Mining Project. These doses are presented and discussed in this chapter.

7.1 OVERVIEW OF THE ASSESSED DOSES FOR THE RESIDENTIAL EXPOSURE SCENARIO

The following doses represent the increase in the dose to the public due to the proposed unmitigated operations of the West Wits Mining Project. As such, no background subtraction was done. Furthermore, most of the pit operations will be in operation for approximately a year, where after mining will seize and rehabilitation actions commence. The reduction of radioactivity in the environment due to various environmental processes and the build-up of radioactivity, due to years of operation, were therefore not included in the calculations. This means that the assessed doses can be considered to be a worst case of what the public can receive. Also note that since no data was available on other, existing or legacy, operations in the area, a cumulative dose for all the operations in the area cannot be provided. For the same reason the baseline air dispersion data cannot be converted and hence no baseline doses calculated.

7.2 EXTERNAL EXPOSURE DOSES

Contour plots of the calculated external exposure doses from deposited dust, applicable to an adult (as all other age groups have doses that are less), are depicted in Figures 11 and 12 for the pits and the underground operations respectively. Using the satellite imagery in the figures as reference, the receptors nearest to the sources were identified. Their doses are tabulated in Table 9. All the external exposure doses at residential areas are below 10 µSv/a, with a maximum of 5.0 µSv/a and therefore not considered a concern.

Table 9: *Calculated doses (µSv/a) for external exposure from deposited dust for all age groups of the receptors nearest to the pit/underground operations.*

Operation	Dose (µSv/a)					
	Adult	15-Year	10-Year	5-Year	1-Year	New-born
Mona Lisa Bird Reef Pit	1.1	1.0	1.0	1.0	1.0	< 1
Roodepoort Main Reef Pit	2.4	2.3	2.3	2.3	2.3	2.1
Rugby Club Main Reef Pit	5.0	4.8	4.8	4.8	4.7	4.4
11 Shaft Main Reef Pit	4.2	4.0	4.1	4.0	4.0	3.7
Kimberley Reef East Pit	<1	<1	<1	<1	<1	<1
Bird Reef Underground (No. 4 Shaft)	<1	<1	<1	<1	<1	<1
Kimberley East Underground (No.2 Shaft)	<1	<1	<1	<1	<1	<1

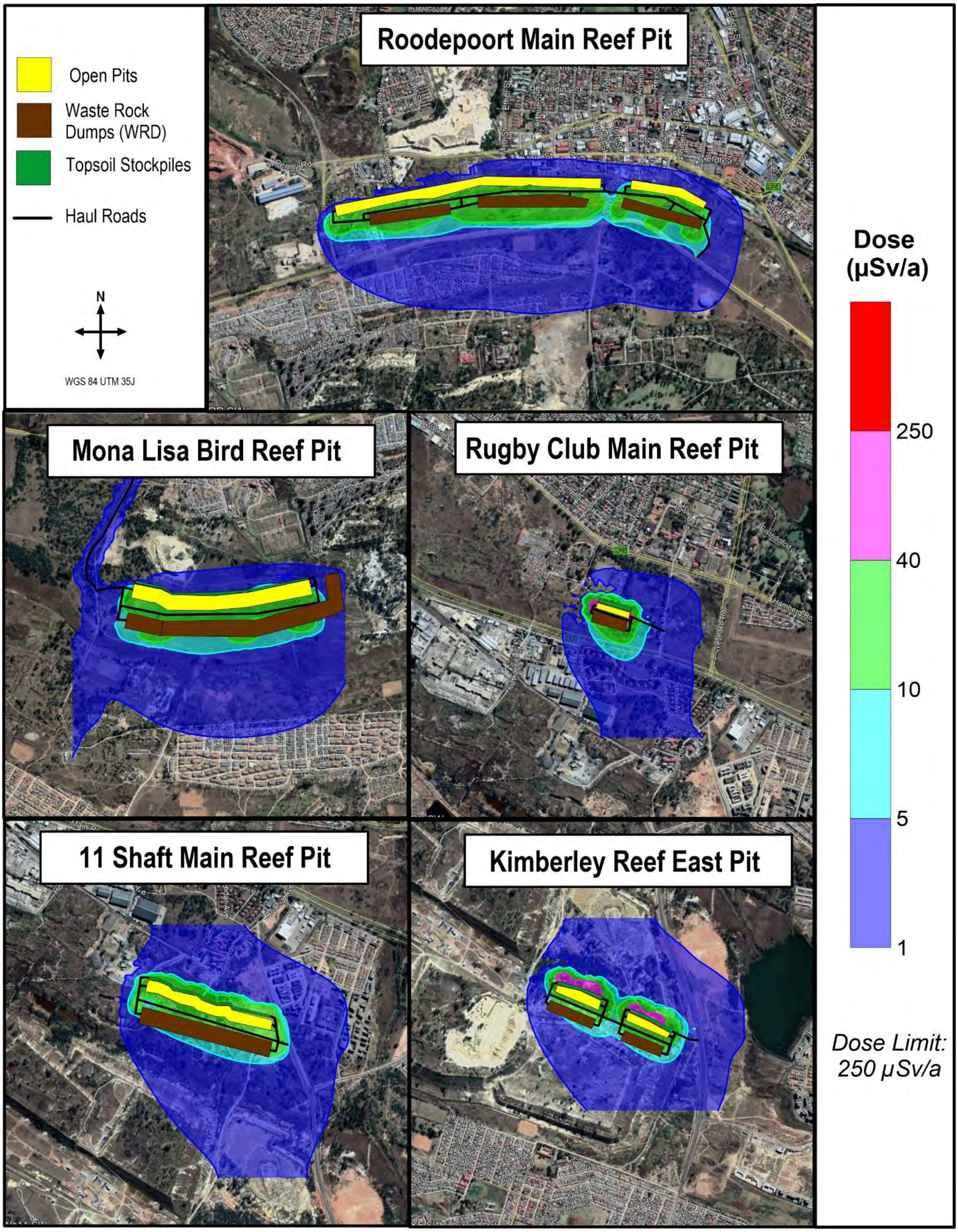

Figure 11: *Calculated adult doses (µSv/a) for external exposure from deposited dust from the pit operations.*

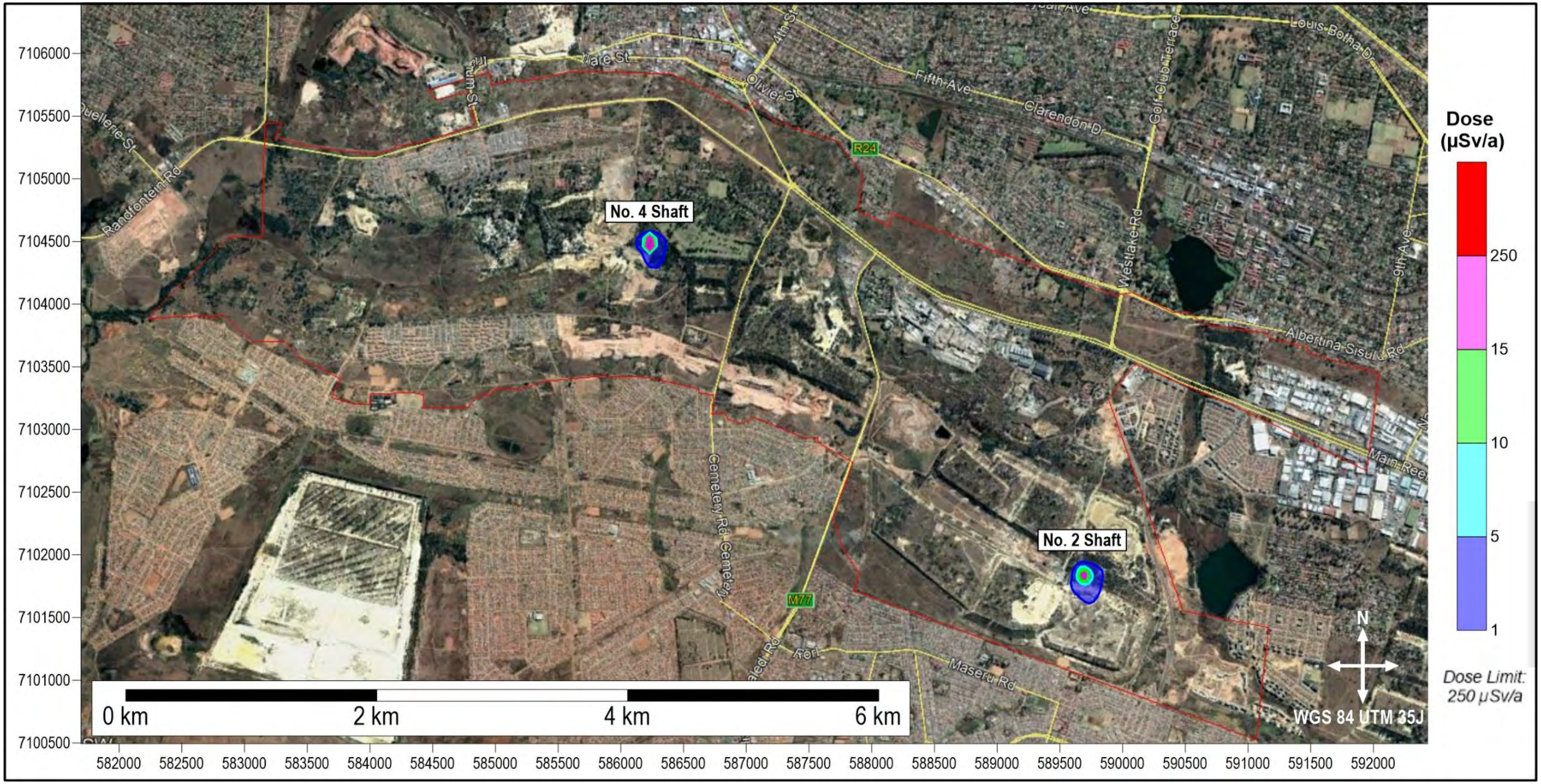

***Figure 12**: Calculated adult doses (μSv/a) for external exposure from deposited dust from the underground operations.*

7.3 DUST INHALATION DOSES

Contour plots of the calculated doses from inhalation of dust, applicable to an adult (as all other age groups have doses that are less), are depicted in Figures 11 and 12 for the pits and the underground operations respectively. Doses (tabulated in Table 10) to all receptors are below 1 µSv/a and therefore considered a concern.

***Table 10:** Calculated doses (µSv/a) from inhalation of dust for all age groups of the receptors nearest to the pit/underground operations.*

Operation	Dose (µSv/a)					
	Adult	15-Year	10-Year	5-Year	1-Year	New-born
Mona Lisa Bird Reef Pit	<1	<1	<1	<1	<1	<1
Roodepoort Main Reef Pit	<1	<1	<1	<1	<1	<1
Rugby Club Main Reef Pit	<1	<1	<1	<1	<1	<1
11 Shaft Main Reef Pit	<1	<1	<1	<1	<1	<1
Kimberley Reef East Pit	<1	<1	<1	<1	<1	<1
Bird Reef Underground (No. 4 Shaft)	<1	<1	<1	<1	<1	<1
Kimberley East Underground (No.2 Shaft)	<1	<1	<1	<1	<1	<1

7.4 RADON CONCENTRATIONS & RADON INHALATION DOSES

Contour plots of the calculated Radon concentrations are depicted in Figures 13 and 14 for the pits and the underground operations respectively. The concentrations are all well below the action level with values of less than 0.2 Bq/m^3 for all receptor locations.

The resulting Radon inhalation doses, applicable to an adult (as all other age groups have doses that are less), are depicted in Figures 15 for the pit operations and Figure 16 for the underground operations. Using the satellite imagery in the figures as reference, the receptors nearest to the sources were identified. Their doses are tabulated in Table 11. All the Radon inhalation doses at residential areas are below 1 µSv/a, therefore not considered a concern.

***Table 11:** Calculated doses (µSv/a) from inhalation of Radon for all age groups of the receptors nearest to the pit/underground operations.*

Operation	Dose (µSv/a)					
	Adult	15-Year	10-Year	5-Year	1-Year	New-born
Mona Lisa Bird Reef Pit	<1	<1	<1	<1	<1	<1
Roodepoort Main Reef Pit	<1	<1	<1	<1	<1	<1
Rugby Club Main Reef Pit	<1	<1	<1	<1	<1	<1
11 Shaft Main Reef Pit	<1	<1	<1	<1	<1	<1
Kimberley Reef East Pit	<1	<1	<1	<1	<1	<1
Bird Reef Underground (No. 4 Shaft)	<1	<1	<1	<1	<1	<1
Kimberley East Underground (No.2 Shaft)	<1	<1	<1	<1	<1	<1

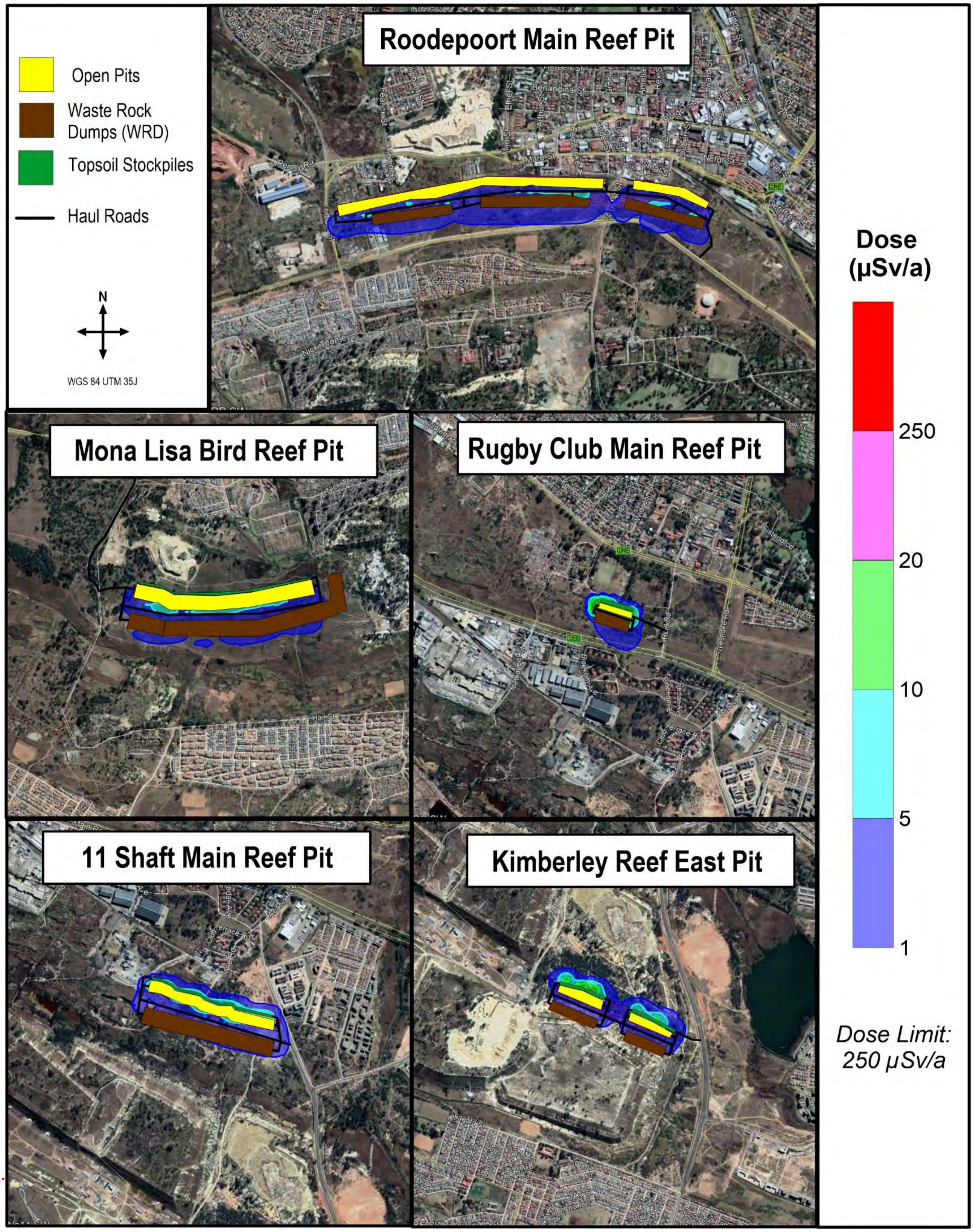

***Figure 13**: Calculated adult doses (µSv/a) for inhalation of dust from the pit operations.*

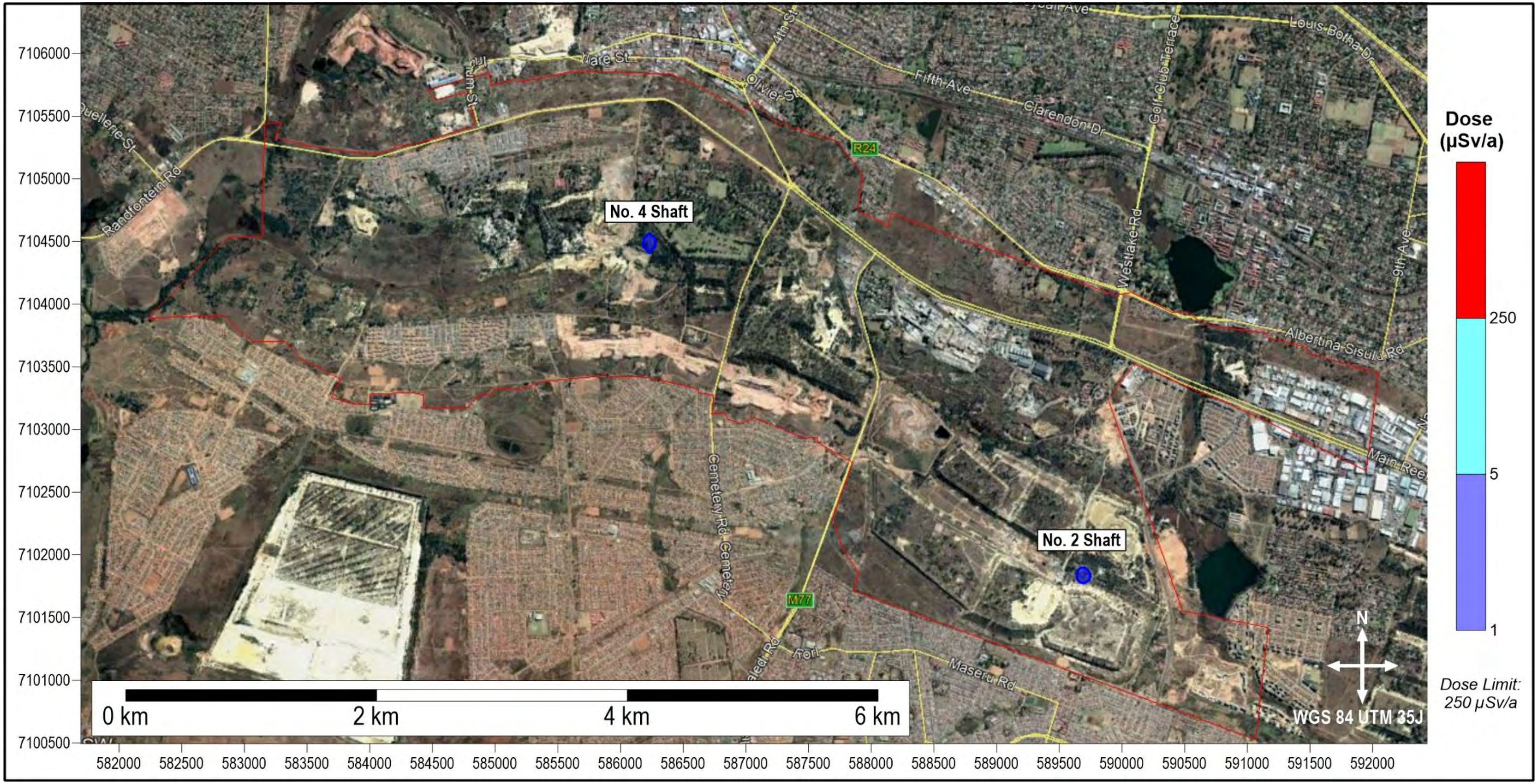

***Figure 14**: Calculated adult doses (µSv/a) for dust inhalation from the underground operations.*

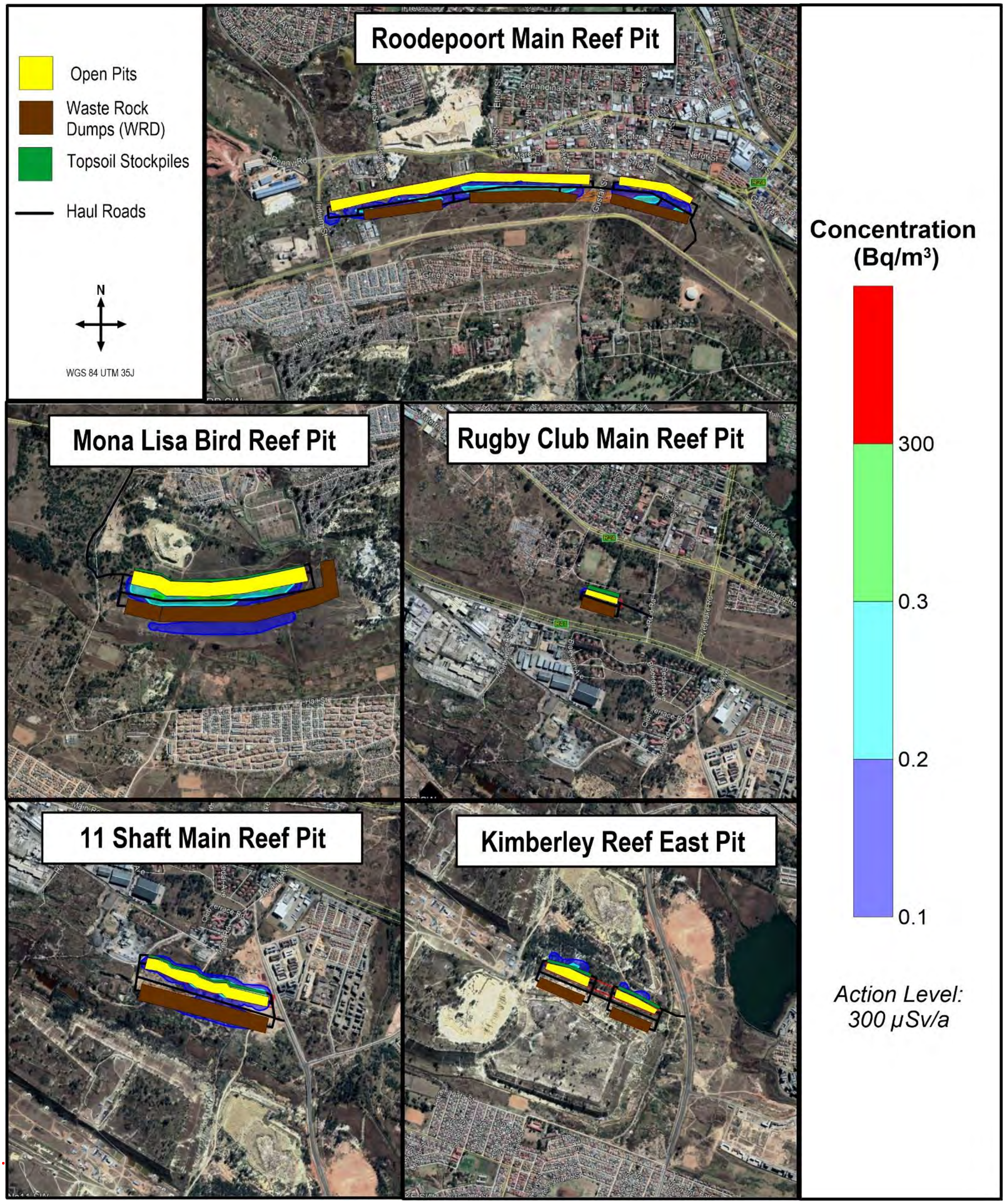

***Figure 15**: Calculated Radon concentrations (Bq/m^3) from the pit operations.*

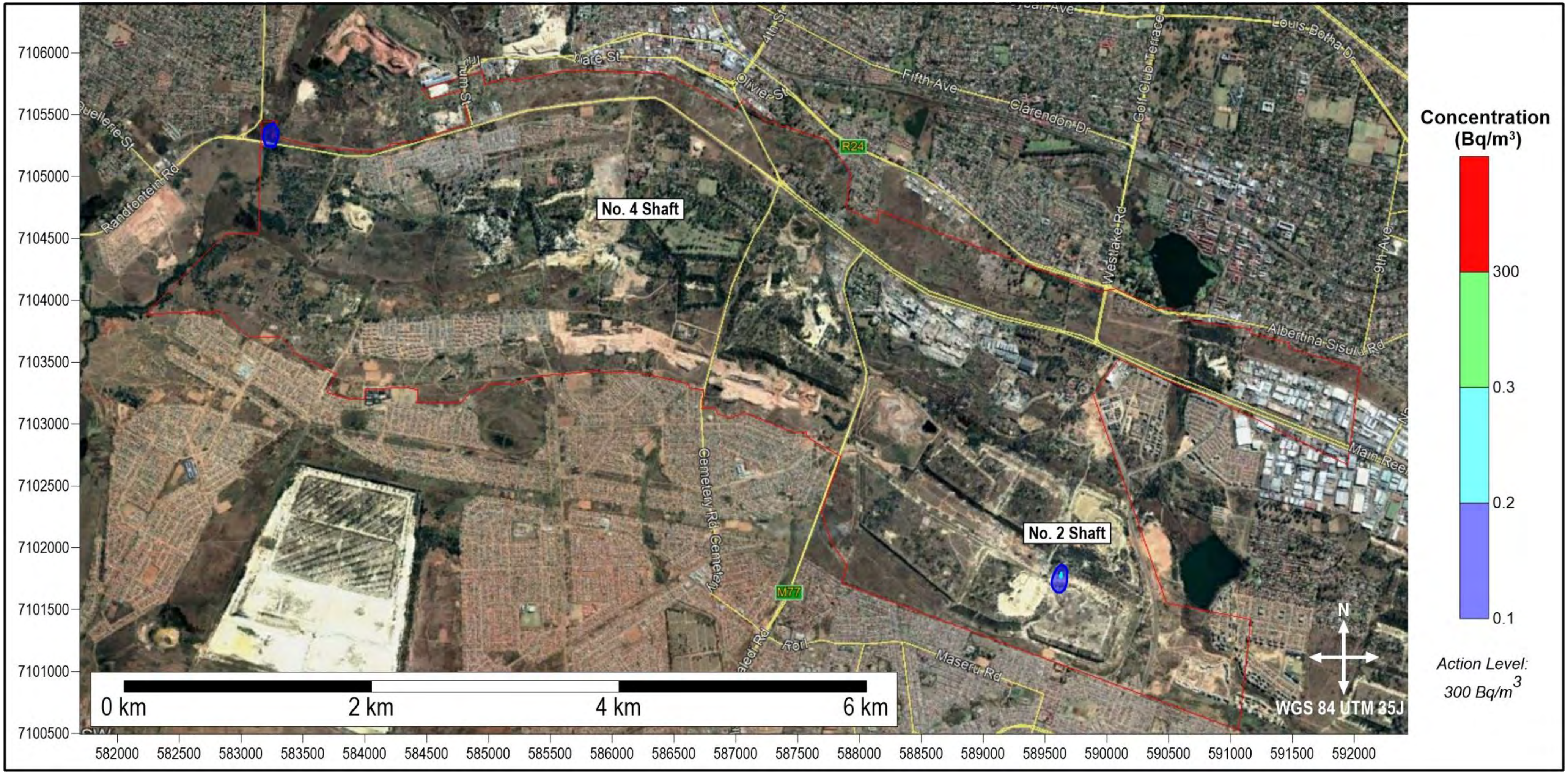

***Figure 16**: Calculated Radon concentrations (Bq/m^3) from the underground operations.*

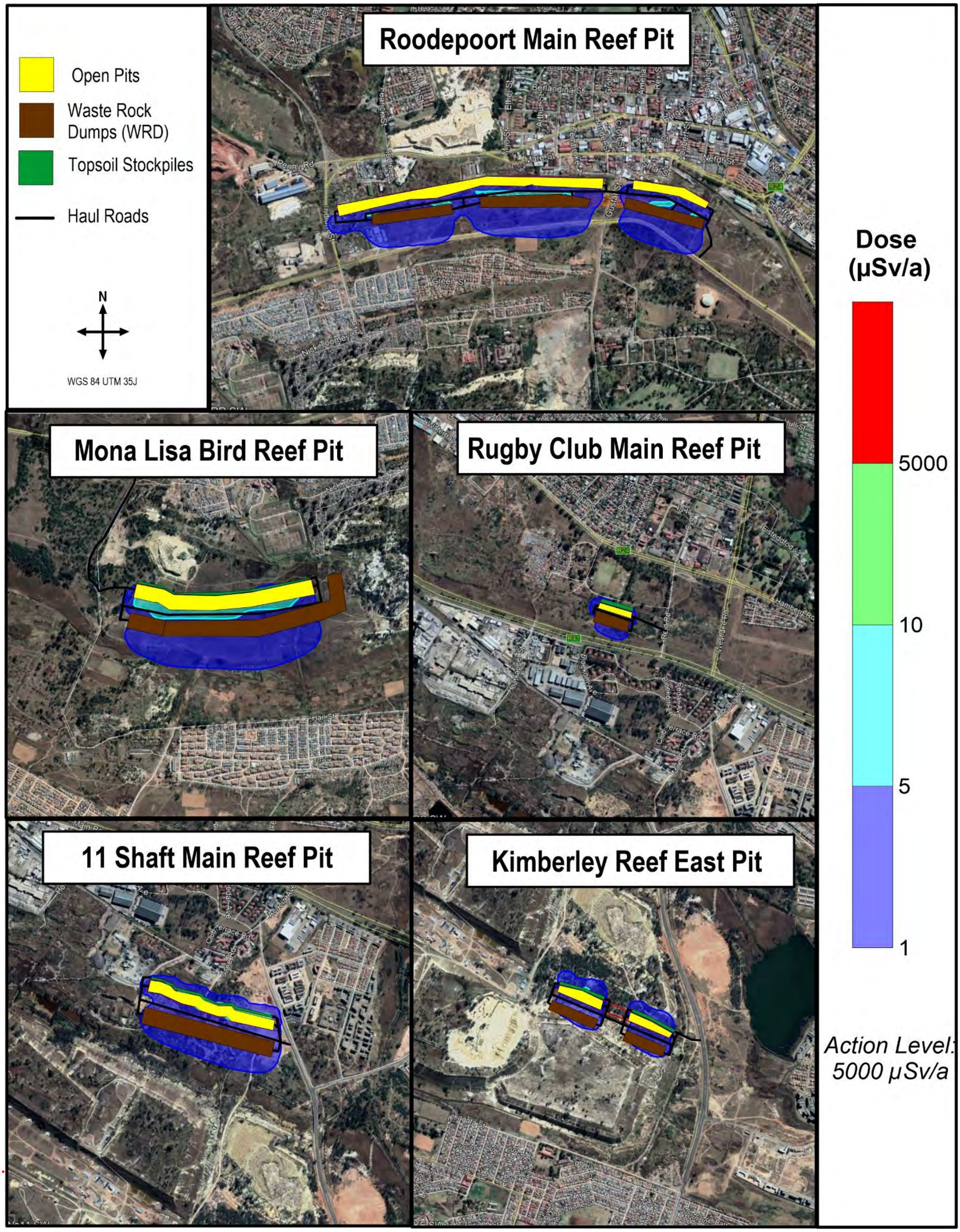

Figure 17: *Calculated adult doses (µSv/a) for Radon inhalation from the pit operations.*

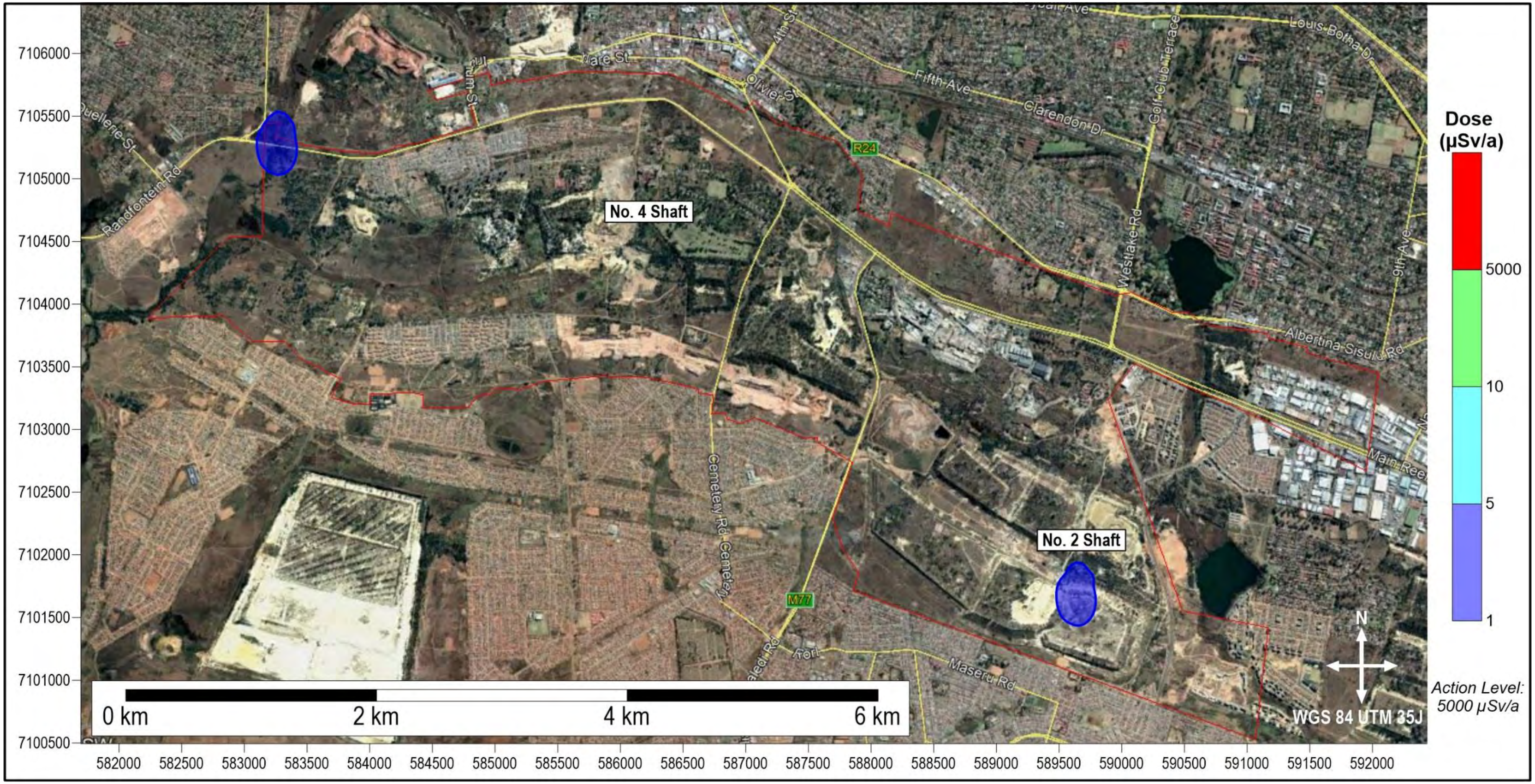

***Figure 18**: Calculated adult doses (µSv/a) for Radon inhalation from the underground operations.*

7.5 Total Doses

The total doses are the sum of the external exposure and inhalation doses. For all the age groups in the public areas around the various pits and underground operations the total doses are trivial, with a maximum of ~7 µSv/a for the Representative Person, who in this case is an adult. If the uncertainty in the value is considered the possible maximum total dose is very close to 11 µSv/a, which is much lower than the dose limit of 250 µSv/a. Mitigation options, as described in the Air Quality Impact Assessment (Grobler, 2019) would reduce all the doses even further.

7.6 Radiological Risk

The ICRP presents in its latest publication (ICRP, 2007) risk coefficients as 0.000055 per 1 mSv of exposure for cancer and 0.000002 per 1 mSv of exposure for heritable effects (refer to Section 2.2). This value is for a whole population, meaning an average for males and females and a typical age distribution of 18 to 65. Using these risk coefficients, the estimated increase in cancer risk to an individual that receives the maximum assessed dose of 7 µSv/a is ~3.9E-05 %. For heritable effects, the risk increase is ~1.4E-06 %. These increases in health risk are considered very low. In comparison, in 2009 the overall cancer risk for South Africans was 11% for women and 13% for men. The increase in risk will not significantly change these values.

7.7 EIA Impact Significance Rating

The Scoping Report (SLR, 2018) presented the general EIA criteria for the evaluation of the environmental impacts in a format involving the ranking of various aspects of the impacts. These are presented in Table 12.

***Table 12:** EIA criteria for impact evaluation*

PART A: DEFINITION AND CRITERIA*		
Definition of SIGNIFICANCE		**Significance = consequence x probability**
Definition of CONSEQUENCE		**Consequence is a function of severity, spatial extent, and duration**
Criteria for ranking of the SEVERITY of environmental impacts	**H**	Substantial deterioration (death, illness, or injury). Recommended level will often be violated. Vigorous community action.
	M	Moderate/ measurable deterioration (discomfort). Recommended level will occasionally be violated. Widespread complaints.
	L	Minor deterioration (nuisance or minor deterioration). Change not measurable/ will remain in the current range. Recommended level will never be violated. Sporadic complaints.
	L+	Minor improvement. Change not measurable/ will remain in the current range. Recommended level will never be violated. Sporadic complaints.
	M+	Moderate improvement. Will be within or better than the recommended level. No observed reaction.
	H+	Substantial improvement. Will be within or better than the recommended level. Favourable publicity.
Criteria for ranking the DURATION of impacts	**L**	Quickly reversible. Less than the project life. Short term
	M	Reversible over time. Life of the project. Medium term
	H	Permanent. Beyond closure. Long term.

Criteria for ranking the SPATIAL SCALE of impacts	**L**	Localised - Within the site boundary.
	M	Fairly widespread – Beyond the site boundary. Local
	H	Widespread – Far beyond site boundary. Regional/ national

PART B: DETERMINING CONSEQUENCE					
SEVERITY = L					
DURATION	Long term	**H**	**Medium**	**Medium**	**Medium**
	Medium term	**M**	**Low**	**Low**	**Medium**
	Short term	**L**	**Low**	**Low**	**Medium**
SEVERITY = M					
DURATION	Long term	**H**	**Medium**	**High**	**High**
	Medium term	**M**	**Medium**	**Medium**	**High**
	Short term	**L**	**Low**	**Medium**	**Medium**
SEVERITY = H					
DURATION	Long term	**H**	**High**	**High**	**High**
	Medium term	**M**	**Medium**	**Medium**	**High**
	Short term	**L**	**Medium**	**Medium**	**High**
			L	**M**	**H**
			Localised Within site boundary Site	Fairly widespread Beyond site boundary Local	Widespread Far beyond site boundary Regional/ national
			SPATIAL SCALE		

PART C: DETERMINING SIGNIFICANCE					
PROBABILITY (of exposure to impacts)	Definite/ Continuous	**H**	**Medium**	**Medium**	**High**
	Possible/ frequent	**M**	**Medium**	**Medium**	**High**
	Unlikely/ seldom	**L**	**Low**	**Low**	**Medium**
			L	**M**	**H**
			CONSEQUENCE		

PART D: INTERPRETATION OF SIGNIFICANCE	
Significance	**Decision guideline**
High	It would influence the decision regardless of any possible mitigation.
Medium	It should have an influence on the decision unless it is mitigated.
Low	It will not have an influence on the decision.

The Criteria for ranking the SEVERITY of impacts and PROBABILITY (of exposure to impacts) are based on the ICRP proposed data. Should a person contract cancer the SEVERITY is high as it can lead to fatality. However, the probability of obtaining fatal cancer is linked to the dose risk coefficient and the dose received. In this case the doses are very low (in the order of 10 µSv/a). For this reason, the SEVERITY and PROBABILITY is taken as **L**. The DURATION is taken as **H** as cancer is long-term and could remain post-closure. The SPATIAL SCALE is taken as **M** because the impact could go beyond the site boundary.

Using the above-mentioned indicators, the significance of the risk for the public is determined as **Low.** However, although the criteria results in a rating of Low, the potential impact and associated risks are considered to be **Very Low**. This evaluation applies to both the unmitigated and mitigated operations.

CHAPTER 8: CONCLUSION AND RECOMMENDATION

This report describes how the source-pathway-receptor analysis, in conjunction with a specific Exposure Scenario, was used to assess radiation doses to the public who are living near the proposed West Wits operations. The doses assessed included external gamma radiation due to deposited dust, dust inhalation and radon inhalation. According to the Groundwater Specialist report, the leaching of contaminants and the development of acid mine drainage conditions from the waste rock dumps is unlikely. It is therefore not expected that the operations will have a radiological impact on the surface water or groundwater quality. For this reason, water ingestion and secondary ingestion doses were not considered.

Radionuclide analysis results of the ore and waste rock indicated that all the individual radionuclides are below the regulatory limit of 0.5 Bq/g. This means that the proposed operations of the West Wits do not fall under the NNR Act, hence are not considered a radiological concern.

The above-mentioned was confirmed with the incremental individual pathway doses, without mitigation, at the different pits or underground operations as either trivial (i.e. less than 10 µSv/a) or insignificant (i.e. less than 1 µSv/a). The maximum total incremental dose, with the uncertainty considered, is not expected to exceed 11 µSv/a (that is 7 ± 4 µSv/a). This dose is much lower than the dose limit of 250 µSv/a. The Radon concentrations at public areas are also well below the action level of 300 Bq/m^3 with values less than 0.2 Bq/m^3. The associated risks are therefore very low. This translate to an EIA Impact Significance of Very Low. Given this, no mitigation measures are therefore deemed necessary.

It can be concluded that the proposed West Wits Mining operations do not warrant any concern regarding the radiological impacts to the public.

CHAPTER 9: REFERENCES

Clker Free Clipart, 2011. *Radioactive Series by Juhele Clip Art.* [Online]
Available at: http://www.clker.com/clipart-90240.html
[Accessed 7 July 2017].

de Villiers, D., 2019. *Formal Safety Assessment Report on the Proposed Operations at West Wits, in order to obtain Exemption,* Report No: SR-REP-03-2019: SciRAD Consulting (Pty) Ltd, May.

DME, 1999. *National Nuclear Regulator Act, No. 47 of 1999.,* Government Gazette No. 20760: Cape Town, 23 December.

DME, 2006. *National Safety Standards and Regulatory Practices,* Regulation 388, Revision 0, Government Gazette No. 28755, Vol. 490: Department of Minerals and Energy, Pretoria, 28 April.

Evans, R., 1955. *The Atomic Nucleus.* 1st ed. McGraw-Hill Book Company: New York.

Grobler, N., 2019. *Air Quality Impact Assessment for the West Wits Mining Project,* Report No: 17SLR20: Airshed Planning Professionals (Pty) Ltd, May.

Hansen, R., 2019a. *West Wits MLI (Pty) Ltd 11 Shaft Gold Mine Mining Right Application - Geochemical Specialist Assessment,* Report No: 20190303: GeoDyn Systems, March.

Hansen, R., 2019b. *West Wits MLI (Pty) Ltd Kimberley East Gold Mine Mining Right Application - Geochemical Specialist Assessment,* Report No: 20100302: GeoDyn Systems, March.

Hansen, R., 2019c. *West Wits MLI (Pty) Ltd Mona LIza Gold Mine Mining Right Application - Geochemical Specialist Assessment,* Report No: 20190304: GeoDyn Systems, March.

Hansen, R., 2019d. *West Wits MLI (Pty) Ltd Roodepoort Gold Mine Mining Right Application - Geochemical Specialist Assessment,* Report No: 20190305: GeoDyn Systems, March.

Hansen, R., 2019e. *West Wits MLI (Pty) Ltd Rugby Club Gold Mine Mining Right Application - Geochemical Specialist Assessment,* Report No: 20190306: GeoDyn Systems, March.

IAEA, 1996. *International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources,* IAEA Safety Series No. 115: International Atomic Energy Agency, Vienna.

IAEA, 2003. *Guidelines for Radioelement Mapping using Gamma Ray Spectrometry Data,* IAEA-TECDOC-1363: International Atomic Energy Agency, Vienna.

IAEA, 2013. *Measurement and Calculation of Radon Releases from NORM Residues,* Technical Report Series No. 474: International Atomic Energy Agency.

ICRP, 1991. *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 60: International Commission on Radiological Protection.

ICRP, 1993. *Protection Against Radon-222 at Home and at Work,* ICRP Publication 65, Annals of the ICRP, Volume 23, No. 2: International Commission on Radiological Protection.

ICRP, 1999. *Protection of the Public in Situations of Prolonged Radiation Exposure,* ICRP Publication 82: International Commission on Radiological Protection.

ICRP, 2006. *Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public,* Publication 1101a, Ann. ICRP 36(1): International Commission on Radiological Protection.

ICRP, 2007. *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 103: International Commission on Radiological Protection.

ICRP, 2007. *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 103: International Commission on Radiological Protection.

ICRP, 2010. *Lung Cancer Risk from Radon and Progeny and Statement on Radon,* Publication 115, Ann. ICRP 40(1): International Commission on Radiological Protection.

Mercury, 2019. *Social Impact Assessment Report,* Mercury Financial Consultants: May.

Meyer, S. & Smith, L., 2019. *Hydrogeological Specialist Investigation for the Proposed West Wits Mining Project,* Report Version 1.1: Noa Agencies (Pty) Ltd, May.

NECSA, 2018. *Analysis Report: Radioactivity Analysis of Solids,* RS2018-2403-02: Necsa (RadioAnalysis), 05 November.

NECSA, 2019. *Analysis Report: Radioactivity Analysis of Water,* RS2018-2045-01: Necsa (RadioAnalysis), 29 January.

NNR, 2014. *Safety Assessment of Radiation Hazards to Members of the Public from NORM Activities,* Regulatory Guide, RG-002, Rev. 0.: National Nuclear Regulator.

SLR, 2018. *Scoping Report for the Proposed West Wits Mining Project,* SLR Project No: 720.13087.00001: SLR Consulting (South Africa) (Pty) Ltd, December.

SLR, 2019. *Proposed West Wits Mining Project: Environmental Impact Assessment and Environmental Management Programme,* SLR Project No: 720.13087.00001: SLR Consulting (South Africa) (Pty) Ltd, May.

Stassen, W., 2015. *What's driving cancer in South Africa.* [Online]
Available at: http://www.health-e.org.za/2015/02/04/cut-cancer-risk/
[Accessed 5 February 2015].

Universe Today, 2010. *Atom Diagram.* [Online]
Available at: https://www.universetoday.com/56469/atom-diagram/
[Accessed 15 March 2011].

UNSCEAR, 2000. *Source, Effects and Risks of Ionising Radiation,* United Nation Scientific Committee on the Effects of Atomic Radiation: New York.

Web Ecoist, 2013. *Hot Spots: Earth's 5 Most Naturally Radioactive Places.* [Online] Available at: http://webecoist.momtastic.com/2013/01/22/hot-spots-earths-5-most-naturally-radioactive-places/
[Accessed November 17 2013].

APPENDIX A: RADIONUCLIDE ANALYSIS REPORTS

RadioAnalysis
Building 1600
P O Box 582
Pretoria 0001

Telephone: + 27 12 305 5527
Facsimile: + 27 12 305 5944

necsa
We're in your world
South African Nuclear Energy
Corporation SOC Limited

Contact: ***Dr D de Villiers***
Company: ***SciRad Consulting***
Address: ***P O Box 843***
Hartbeespoort
0216

Date: ***2018-11-05***
Report number: ***RS2018-2403-02***
Pages: ***3***
Order no.: ***08-2018***

Analysis Report

This report replaces RS2018-2403-01

Radioactivity analysis of solids

Compiled by: A Sathekge Sathekge

Checker: N Seaga Seaga

1. SERVICE

The analysis of solid samples for gross alpha and beta activities and for selected radionuclides in the uranium and thorium decay series.

Number of sample(s) received: 4

The sample(s) were received on: 2018-05-24

2. SAMPLE PREPARATION AND ANALYSIS

Method	Description	Completed	Assayer	Verified by
WIN-121	**Mill sample material**	2018-06-21	E Motlhabane	O Mathekga
WIN-138	**Gross alpha/beta analysis**	2018-08-17	S Zhou	E Nhlapo
WIN-167	**U and Th by neutron activation analysis**	2018-10-31	A Sathekge	N Seaga
WIN-101	^{226}Ra, ^{228}Ra, ^{228}Th, ^{40}K by gamma analysis	2018-09-10	R Gaven	A Sathekge
WIN-158	**^{210}Pb by low energy gamma analysis**	2018-08-01	M Rapetsoa	N Seaga

Results indicated in* ***bold* *in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory*

3. RESULTS

3.1 Results are attached as an appendix to this report.

3.2 Results reported are related only to sample portions tested.

3.3 The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities. Errors associated with unavoidable differences between particle energies of the calibration standards and samples, are not accounted for in the reported uncertainty which is mainly based on counting statistics. The reported uncertainty may therefore be an underestimation of the true uncertainty.

3.4 Uranium-234 is derived from the measured uranium results by calculation using natural isotopic ratios.

4. QUALITY ASSURANCE

4.1 RadioAnalysis is a SANAS accredited laboratory (Testing Laboratory T0111) based on ISO/IEC Standard 17025. All analytical methods are documented in the RadioAnalysis Quality System.

4.2 Results in this report were obtained from one or more individual test reports produced by accredited or non-accredit methods.

- Test reports containing results obtained from methods included in the SANAS Schedule of Accreditation, are verified and signed by SANAS Technical Signatories for those methods.
- Test reports containing results obtained from methods not included in the SANAS Schedule of Accreditation, are verified and signed by qualified competent analysts for those methods.
- The individual test reports are available upon request

4.3 The compiled report is checked by a person other than the compiler for accuracy of data transcription.

4.4 The RadioAnalysis Laboratory keeps the original signed hard copy of this report on record for three years.

APPENDIX 1: ANALYTICAL RESULTS

Activity concentration

Unit: Bq/kg

Field Code	**WW-04**			**WW-05**			**WW-06**			**WW-07**		
Lab Code	**RS2018-2403X001**			**RS2018-2403X002**			**RS2018-2403X003**			**RS2018-2403X004**		
Nuclide	**Value**	**Unc.**	**MDA**	**Value**	**Unc.**	**MDA**	**Value**	**Unc.**	**MDA**	**Value**	**Unc.**	**MDA**
^{238}U	**37.4**	**0.9**	**0.42**	**38.5**	**0.9**	**0.46**	**34.9**	**0.8**	**0.45**	**23.8**	**0.7**	**0.43**
^{234}U	**37.7**	**0.9**	**0.42**	**38.8**	**0.9**	**0.47**	**35.2**	**0.9**	**0.45**	**24.0**	**0.7**	**0.43**
^{226}Ra	31.1	4.7	13	43.2	4.1	9.6	38.7	4.3	11	30.4	3.7	9.3
^{210}Pb	**92**	**38**	**92**	**67.6**	**21.2**	**62**	**90.6**	**23.3**	**65**	**72.2**	**22.3**	**65**
^{235}U	**1.72**	**0.04**	**0.019**	**1.77**	**0.04**	**0.021**	**1.61**	**0.04**	**0.021**	**1.10**	**0.03**	**0.020**
^{232}Th	**24.3**	**0.8**	**1.4**	**14.2**	**0.6**	**1.6**	**12.2**	**0.4**	**1.6**	**16.2**	**0.4**	**1.6**
^{228}Ra	18	6.5	20	16.5	4.9	14	< MDA		24	19.3	5.8	17
^{228}Th	20	4.8	40	11	2.9	30	17	3.4	30	15	3.4	32
^{40}K	< MDA		110	< MDA		88	70.4	2.2	67	154	26	67
Gross alpha	**210**	**170**	**550**	**635**	**190**	**560**	**554**	**185**	**550**	**735**	**196**	**560**
Gross beta	**194**	**21**	**59**	**263**	**23**	**61**	**208**	**22**	**61**	**307**	**24**	**62**

*Results indicated in **bold** in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory*

Notes:

1. If a measured value (**Value** column) was recorded, it is reported regardless if the value is less than the minimum detectable activity concentration (**MDA** column) or even if the value is negative. In the case where a value could not be obtained, a less than MDA ("< MDA") will be indicated.
2. The reported uncertainty (**Unc.** column) is quoted at 1 sigma (or coverage factor k = 1). The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements. No uncertainty value is reported of a less than MDA ("< MDA") is indicated in the **Value** column.
3. The minimum detectable activity concentration (**MDA** column) is calculated with a 95% confidence level.
4. A value is reported with 3 significant digits if it is greater than the MDA value and the associated uncertainty will be reported the same precision. If a value is less than the MDA, the value and its associated uncertainty are reported with 2 significant digits regardless of their respective magnitudes. A MDA value is always reported with 2 significant digits.

RadioAnalysis
Building 1600
P O Box 582
Pretoria 0001

Telephone: + 27 12 305 5527
Facsimile: + 27 12 305 5944

necsa
We're in your world
South African Nuclear Energy
Corporation SOC Limited

Contact: ***Dr D de Villiers***
Company: ***SciRad Consulting (Pty) Ltd***
Address: ***PO Box 843***
Hartbeespoort
0216

Date: ***2019-01-29***
Report number: ***RS2018-2405-01***
Pages: ***3***
Order no.: ***10-2018***

Final Analysis Report

Radioactivity analysis of water

Compiled by: ***A Rasutha***

Checked by: ***A Mokgalane***

This report is for Pb-210 results. Refer to RS2018-2404-01 for other nuclides results.

1. SERVICE

Analysis of water samples for gross alpha/beta-activity and for selected radionuclides in the uranium and thorium decay series.

Number of samples received: 3

Date samples received: 2018-05-24

2. SAMPLE PREPARATION AND ANALYSIS

Method	Description	Completed	Assayer	Technical Signatory
WIN-121	Filtration of suspended solids	2018-06-05	L Seshoka	O Mathekga
WIN-161	Gross alpha/beta-analysis	2018-07-26	Q Daniels	E Nhlapo
WIN-124	Radium by alpha spectrometry	2018-06-20	A Mokgalane	C Zwane
WIN-145	Uranium by alpha spectrometry	2018-07-31	C Zwane	A Rasutha
WIN-142	Thorium by alpha spectrometry	2018-07-18	N Sono	A Rasutha
WIN-129	Polonium-210 by alpha spectrometry	2018-06-28	N Yawa	A Rasutha
WIN-129	Lead-210 by alpha spectrometry	2019-01-29	B Zulu	A Rasutha

Results indicated in* ***bold* *in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory.*

3. RESULTS

3.1 Results are attached as an appendix to this report.

3.2 Reported results relate only to the sample portions tested.

3.3 The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities. Errors associated with unavoidable differences between particle energies of the calibration standards and samples, are not accounted for in the reported uncertainty which is mainly based on counting statistics. The reported uncertainty may therefore be an underestimation of the true uncertainty.

4. QUALITY ASSURANCE

4.1 RadioAnalysis is a SANAS accredited laboratory (Testing Laboratory T0111) based on ISO/IEC Standard 17025. All analytical methods are documented in the RadioAnalysis Quality System.

4.2 Results in this report were obtained from one or more individual test reports produced by accredited or non-accredited methods.

- Test reports containing results obtained from methods included in the SANAS Schedule of Accreditation, are verified and signed by SANAS Technical Signatories for those methods.
- Test reports containing results obtained from methods not included in the SANAS Schedule of Accreditation, are verified and signed by qualified competent analysts for those methods. Results reported for non-accredited methods are indicated in bold.

4.3 The compiled report is checked by a person other than the compiler for accuracy of data transcription.

4.4 The RadioAnalysis Laboratory keeps the original signed hard copy of this report on record for three years.

Activity concentrations of nuclides in filtered samples

Unit: mBq/L

Field Code	**WW-01**			**WW-02**			**WW-03**		
Lab Code	**RS2018-2404X001**			**RS2018-2404X002**			**RS2018-2404X003**		
Nuclide	**Value**	**Unc.**	**MDA**	**Value**	**Unc.**	**MDA**	**Value**	**Unc.**	**MDA**
^{238}**U**	17700	200	3.9	7450	80	2.2	52.6	5.9	1.8
^{234}**U**	14200	100	3.9	16200	200	2.2	53.5	6.1	1.8
^{230}**Th**	590	90	11	148	23	9.0	16.1	3.3	9.3
^{226}**Ra**	133	8	8.4	706	16	3.9	6.03	1.38	0.86
^{210}**Pb**	43.3	11.0	9.5	312	23	2.2	25.1	8.9	6.4
^{210}**Po**	15.9	5.2	10	2.2	5.5	9.3	1.8	3.8	13
^{235}**U**	815	8	0.18	343	4	0.10	2.42	0.27	0.083
^{227}**Th**	98.3	6.5	1.1	116	7	5.0	2.4	1.6	5.1
^{223}**Ra**	37.8	7.2	3.5	32.9	12.7	4.7	-2.2	1.6	5.9
^{232}**Th**	46.6	4.4	3.7	5.04	1.26	0.85	2.0	0.92	2.4
^{228}**Th**	25.8	3.2	2.9	73.0	4.8	3.3	2.90	1.07	2.4
^{224}**Ra**	32.0	5.3	2.4	56.6	6.7	7.0	22.6	4.1	6.1
Gross alpha	16500	600	250	17600	600	180	96.6	24.7	63
Gross beta	15200	700	370	9080	370	370	389	74	220

Results indicated in **bold in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory*

Notes:

1. If a measured value (**Value** column) was recorded, it is reported regardless if the value is less than the minimum detectable activity concentration (**MDA** column) or even if the value is negative. In the case where a value could not be obtained, a less than MDA ("< MDA") will be indicated.
2. The reported uncertainty (**Unc.** column) is quoted at 1 sigma (or coverage factor k = 1). The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements. No uncertainty value is reported if a less than MDA ("< MDA") is indicated in the **Value** column.
3. The minimum detectable activity concentration (**MDA** column) is calculated with a 95% confidence level.
4. A value is reported with 3 significant digits if it is greater than the MDA value and the associated uncertainty will be reported the same precision. If a value is less than the MDA, the value and its associated uncertainty are reported with 2 significant digits regardless of their respective magnitudes. A MDA value is always reported with 2 significant digits.

APPENDIX B: SHORTENED CV OF THE AUTHOR

SHORTENED CURRICULUM VITAE

P.O. BOX 843
HARTBEESPOORT
+27 12 253 1507
+27 82 339 0254
dawid@sciradconsulting.com

DR. DAWID DE VILLIERS (PR.SCI.NAT, PR.PHYS, RPS)

DATE OF BIRTH	14 June 1973
NATIONALITY	South African
LANGUAGES	English & Afrikaans
PROFESSION	Nuclear Physicist
SPECIALISATION	Radiation Protection
YEARS EXPERIENCE	20+ Years
PUBLICATIONS	125+ (International & National)
PRESENTATIONS	15 International, 26 National
SOFTWARE	7

SUMMARY I hold a Doctorate and Master degree in Nuclear Physics and an Honours Degree in Medical Physics from Stellenbosch University. I am certified as a Professional Natural Scientist, Professional Physicist and Radiation Protection Specialist (other countries Radiation Expert) with more than 20 years of experience, published more than 125 client reports and publications, and spoken at various national & international conferences and courses. I also have experience in software development, business management, project management, teaching and supervision of Ph.D. and M.Sc. students.

Before I started my own company, I worked at various departments within iThemba LABS & Necsa and gained experience in a wide variety of applied fields (i.e. medical and industrial).

As Specialist Scientist and Managing Director for SciRAD Consulting (Pty) Ltd, I mostly provide radiation protection and nuclear physics specialist services to mining, mineral processing, petrochemical & nuclear industries, government departments and private clients (for a more comprehensive list see *Services* below.).

QUALIFICATIONS

Ph.D. (Nuclear Physics) – Stellenbosch University – March 2011
Project Management – Damelin College – February 2009
M.Sc. (Nuclear Physics) – Stellenbosch University – March 2000
Hons. B.Sc. (Medical Physics) – Stellenbosch University – December 1997
B.Sc. (Theoretical Physics) – Stellenbosch University – December 1996

EMPLOYMENT RECORD

January 2013 – present : Specialist Scientist & MD – SciRAD Consulting (Pty) Ltd
Oct 2005 – Dec 2012 : Senior Scientist – NECSA
Mar 2004 – Sept 2005 : Research Physicist - Stellenbosch University (part-time)
Jan 1998 – Feb 2004 : Radiation Physicist - iThemba LABS

PROFESSIONAL AFFILIATIONS

International Health Physics Society,
International Radiation Physics Society,
South African Council for Natural Scientific Professions (No. 400143/10),
South African Institute of Physics (No. 2015002),
Southern African Radiation Protection Association.

SERVICES

Radiological Safety Assessments (i.e. Worker, Public, Environmental),
Development & Review of Radiation Protection, Waste Management and other Regulatory Programmes and Procedures for nuclear authorisation or compliance with regulatory requirements (e.g. Certificate of Registration, Certificate of Exemption, Nuclear License, Nuclear Vessel License, Dept. of Health Documentation),
Decommissioning of Mining and Mineral Processing Plants,
Environmental Monitoring (e.g. radon, dust-fallout measurements, sampling),
Land Clearance of mine or other radioactive contaminated land,
Radiological Characterisation,
Radiation Protection Training,
Mathematical Modelling (with the use of e.g. MCNPX, MicroShield, ERICA, RESRAD),
Software Development (radiation protection applications),
Provision of Expert Opinions for Court Cases,
Research and Development,
Supervision of Ph.D. students and
Ad-Hoc Specialist Studies involving radiation or physics that does not fall under the mentioned categories.

REFERENCE

MR. GERT LIEBENBERG
International Atomic Energy Agency
Tel: +43 676 3900 452
Email: g.liebenberg@iaea.org

DR. GERT DE BEER
Radiation Protection Specialist, Retired
Tel: 012 259 8253
Email: gpmdebeer@xanaduecopark.co.za