Radiological Impact of the Height Extension of the Savuka 7A and 7B Tailings Storage Facilities

AQUISIM CONSULTING (PTY) LTD

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Revision Table

Revision 0

Section	Page	Changes Made in Revision

List of Acronyms

AADQ	Annual authorised discharged quantities
ACR	Authorisation Change Request
ALARA	As Low As Reasonably Achievable
Bq	Becquerel
CoR	Certificate of Registration
DoE	Department of Energy
EIA	Environmental Impact Assessment
ESHIA	Environmental, Social and Health Impact Assessment
GN	Government Notice
GSR	General Safety Requirement
HDPE	high-density polyethylene
IAEA	International Atomic Energy Agency
ICR	Congress of Radiology
ICRP	International Commission on Radiological Protection
ISAM	Improvement of Safety Assessment Methodologies
LLα	Long-Lived Radioactive Dust (Alpha)
LoM	Life of Mine
MAP	Mean Annual Precipitation
MR	Mining Right
mSv	millisievert
NEA	Nuclear Energy Act
Necsa	South African Nuclear Energy Corporation
NEMA	National Environmental Management Act
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act
NORM	Naturally Occurring Radioactive Materials
NRWMP	National Radioactive Waste Management Policy and Strategy
NUREG	US Nuclear Regulatory Commission
NWA	National Water Act
PAEC	Potential Alpha Energy Concentration
PM_{10}	Particulate matter less than 10 microns in size
RE	Remaining Extent
RG	Regulatory Guide
RGM	Radon Gas Monitors
RMP	Radiation Management Programme
RPM	Radiation Protection Monitor
RPO	Radiation Protection Officer
RPP	Radiation Protection Programme
RPS	Radiation Protection Specialist
RPSA	Radiological Public Safety Assessment
RWD	Return Water Dam
SPR	Source-Pathway-Receptor
TSF	Tailings Storage Facilities
TSP	Total Suspended Particles
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WMA	Water Management Area
WRD	Waste Rock Dump

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Credentials: Dr JJ van Blerk

Before joining AquiSim Consulting (Pty) Ltd (AquiSim) as Director 21 years ago, Dr Japie van Blerk worked at the South African Nuclear Energy Corporation (Necsa) for 11 years, with the post-closure safety assessment of the Vaalputs National Radioactive Waste Disposal Facility in South Africa as his main responsibility. During this period, he obtained a PhD in geohydrology from the University of the Free State in South Africa. He is registered as a Professional Natural Scientist (Pr.Sci.Nat.) in the field of Radiation Science and Earth Science (Reg. no 400239/05) through the South African Council for Natural Scientific Professions (SACNASP).

Through his responsibility for the post-closure safety assessment of Vaalputs, he obtained in-depth knowledge of the performance of near-surface radioactive waste disposal systems, especially under arid conditions. After joining AquiSim in 2000, he continued to provide consultancy services to Necsa in the field and radioactive waste management and post-closure safety assessment. The current Vaalputs post-closure safety assessment was prepared by him in collaboration with Dr Matt Kozak (Interra, USA). This assessment included an in-depth review of the national inventory of radioactive waste earmarked for disposal at Vaalputs.

Additional experience and knowledge of disposal in arid conditions were obtained in a project performed in collaboration with Facilia AB (Sweden) to evaluate the post-closure safety of a borehole-type facility for DSRS at Sandy Ridge in Western Australia, with Tellus Holding Ltd as the main client.

For the past 23 years, Dr. van Blerk has provided extensive consultancy and technical training services to the IAEA in the fields of post-closure safety assessment, safety case development, radioactive waste management (including NORM), development of disposal concepts for Disused Sealed Radioactive Sources (DSRS), as well as the cradle-to-grave management of DSRS.

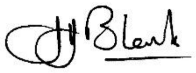
Through his involvement in these IAEA-related projects, he developed extensive knowledge and experience in the use and application of the *suite* of IAEA safety standards related to disposal and the management of radioactive waste in general. These include all stages in the radioactive waste management cycle such as site selection, site characterisation, disposal concept design, disposal, and final closure, as well as the use of post-closure safety assessment to inform the decision-making process through these different stages.

He has extensive experience in performing and managing radiological public safety assessment projects for mining and mineral processing facilities and operations involving NORM, both locally and abroad (e.g., uranium, gold, rare earth, copper, mineral sands, phosphate, etc.), for regulatory and ESIA purposes under operational and post-operational conditions. For the past 21 years, he has performed and managed more than 70 radiological public safety assessment-related projects for the NORM and nuclear industry. Many of these projects were in South Africa but also included countries such as Namibia, Mozambique, Madagascar, Ukraine, Kazakhstan, Mali, and Malawi.

His knowledge and experience in the nuclear industry are complemented by a very good working knowledge of a diversity of environmental processes and disciplines related to geology, geohydrology, geochemistry, hydrology, and meteorology. His understanding of these disciplines and knowledge of groundwater modelling principles for saturated and unsaturated conditions are well suited for reviewing waste disposal programmes and the impact and safety of these programmes on human health and the environment during the period following closure.

Certification

I, the undersigned, certify that to the best of my knowledge and belief, the above information is an accurate description of my experience and qualifications.



Jacobus Josia van Blerk (PhD)

Director: AquiSim Consulting (Pty) Ltd

1 Introduction

1.1 Background

Harmony Gold Mining Company Limited (Harmony) has an internationally diversified portfolio of gold mining projects in South Africa and Papua New Guinea. The company has nine underground mines, one open-pit mine and several surface tailings retreatment operations in South Africa. In Papua New Guinea, Harmony has several interests, including an open-pit gold and silver mine, the Wafi-Golpu project, and extensive exploration tenements.

Figure 1.2 shows that the South African interests of Harmony are divided into four discrete operations, namely: the Free State Operations, West Rand Operations, the Klerksdorp goldfields, and the Kraaipan Greenstone Belt (Kalgold Operations). Through these various operations, Harmony has made significant economic contributions to the provinces of South Africa where they are located, through job creation and stimulation of secondary services and industry.

Golden Core Trade and Invest Proprietary Limited, trading as the Mponeng Operations, is a wholly-owned subsidiary of Harmony, which acquired assets from the West Wits Operations of AngloGold Ashanti (AGA) in October 2020. The gold mining and processing assets cover a mine lease area of approximately 4,176 hectares. The assets acquired from AGA consist of two distinct but integrated mining entities known as the Mponeng and TauTona mines. Savuka mine was included in the TauTona operations in 2013. The Mponeng mine started producing in 1986.

Historically, each mine has extensive underground workings and surface production facilities, with associated infrastructure that is used to access and extract gold-bearing ore from the Ventersdorp Contact Reefs (VCR) and the Carbon Leader Reef (CLR) formations of the Witwatersrand Basin. The surface production facilities and associated infrastructure include gold processing plants, access and ventilation shafts, tailings storage facilities (TSF), marginally ore dumps (MOD), return water dams (RWD), transfer pipelines for water and tailings material, offices and living quarters.

The Savuka TSF comprises Compartments 5A, 5B, 7A and 7B. Final treated pulp residue from the Savuka processing plant is currently deposited onto Compartments 7A and 7B located at (26°26'11.85"S; 27°21'11.38"E). Water is decanted using the penstocks at the centre of the facility and is piped into the RWDs. The water in the RWDs is pumped back to the plant as process water. The delivery pipelines to the TSFs are open-end discharge, and the tipping area is controlled by manual operation of the discharge valves. Conventional hand packing and mechanical ditching methods construct the sidewalls.

The Savuka 7A and 7B TSFs are approaching their final and approved height. The current planned Life of Mine (LoM) for the West Wits region exceed the available deposition capacity of these TSFs. Accordingly, a feasibility assessment is undertaken to increase the height of the Savuka 7A and 7B TSFs by between 5m to 10m (hereafter referred to as the Project).

Geographically, the Mponeng Operations is situated approximately 75 Km (kilometres) west of Johannesburg within the Gauteng Province (see Figure 1.2). The site is approximately 7 km south of Carletonville (Merafong) and 12 km north of the closest neighbouring town, Fochville. The land occupied by the Mponeng Operations straddles the boundary between Gauteng and North West Provinces. The area falls within the Merafong City Local Municipality (LM) of the West Rand District Municipality of the Gauteng Province (see Figure 1.3).

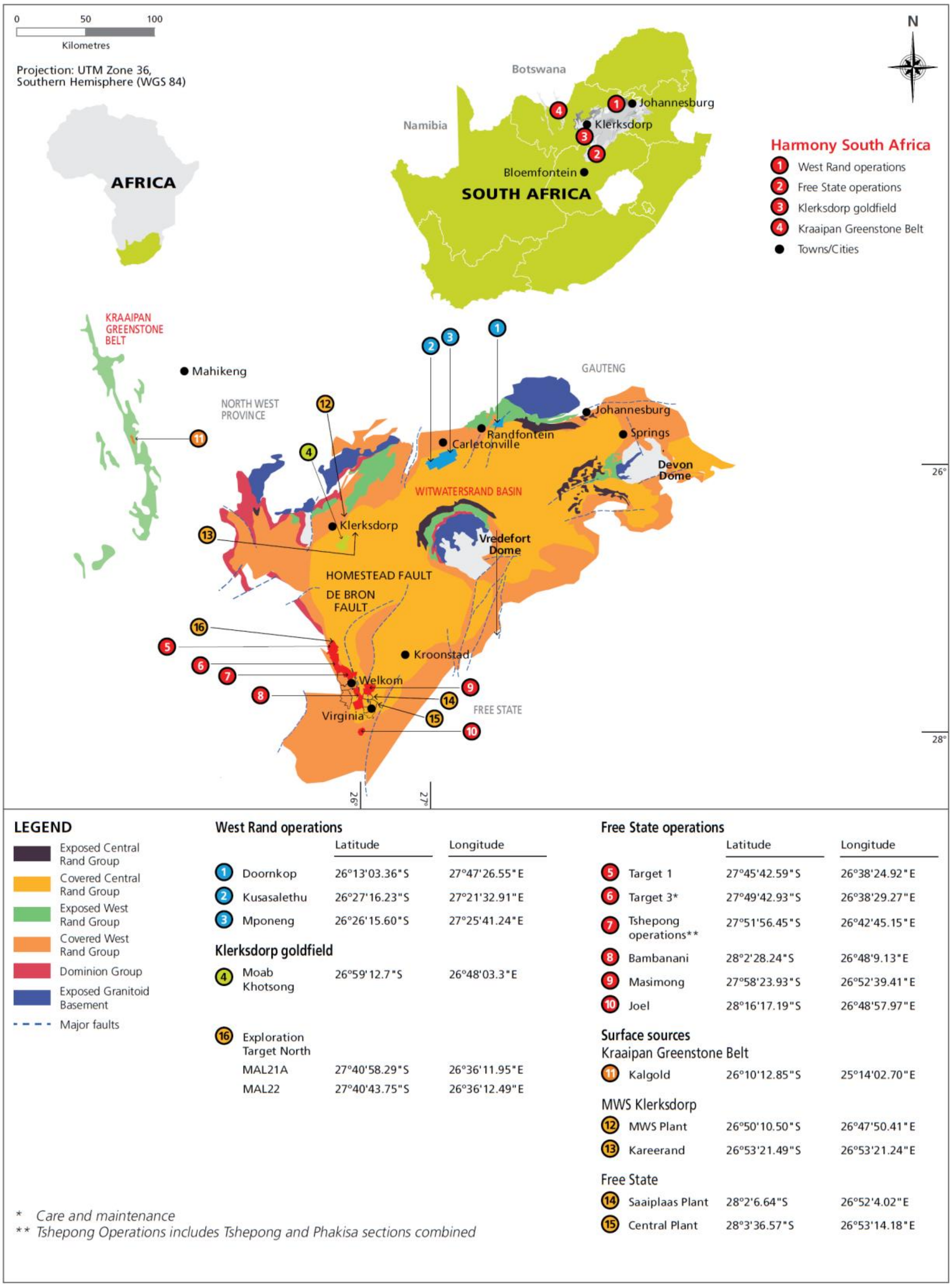


Figure 1.1 Locality map showing the distribution of the four discrete Harmony operations in South Africa.

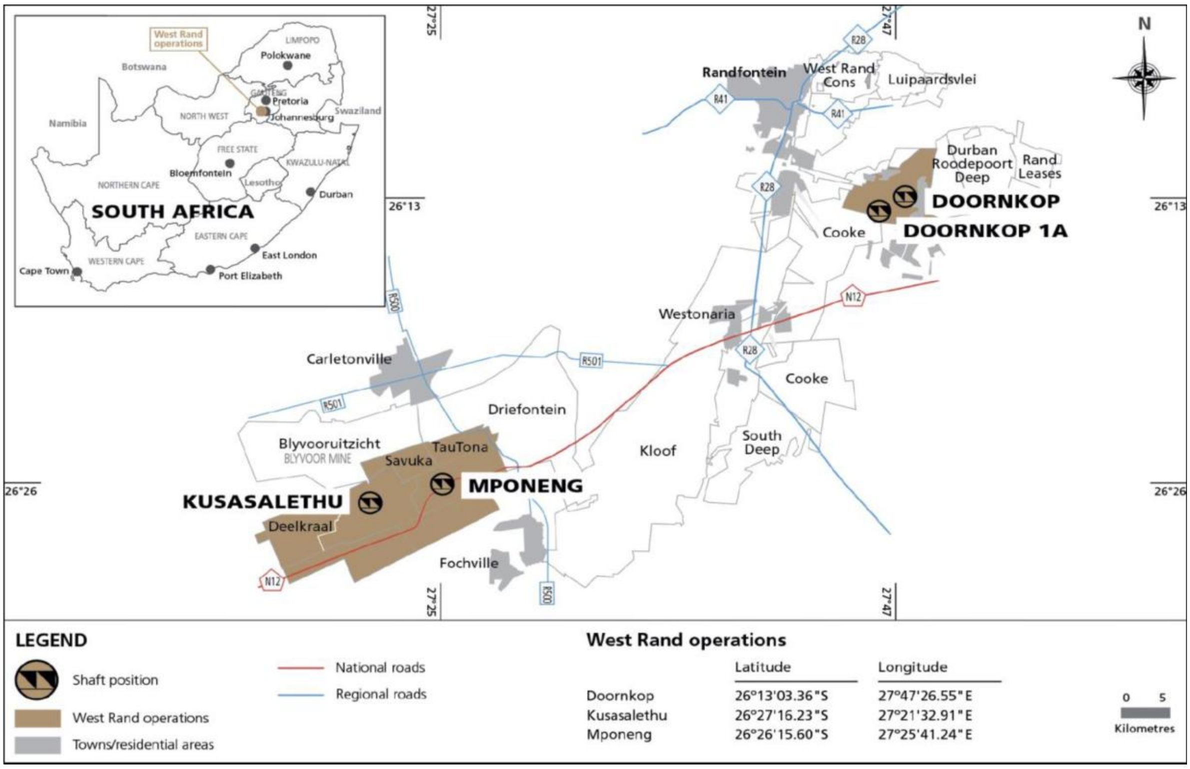


Figure 1.2 **Locality map showing the West Rand Operation of Harmony relative to other mining operations and towns.**

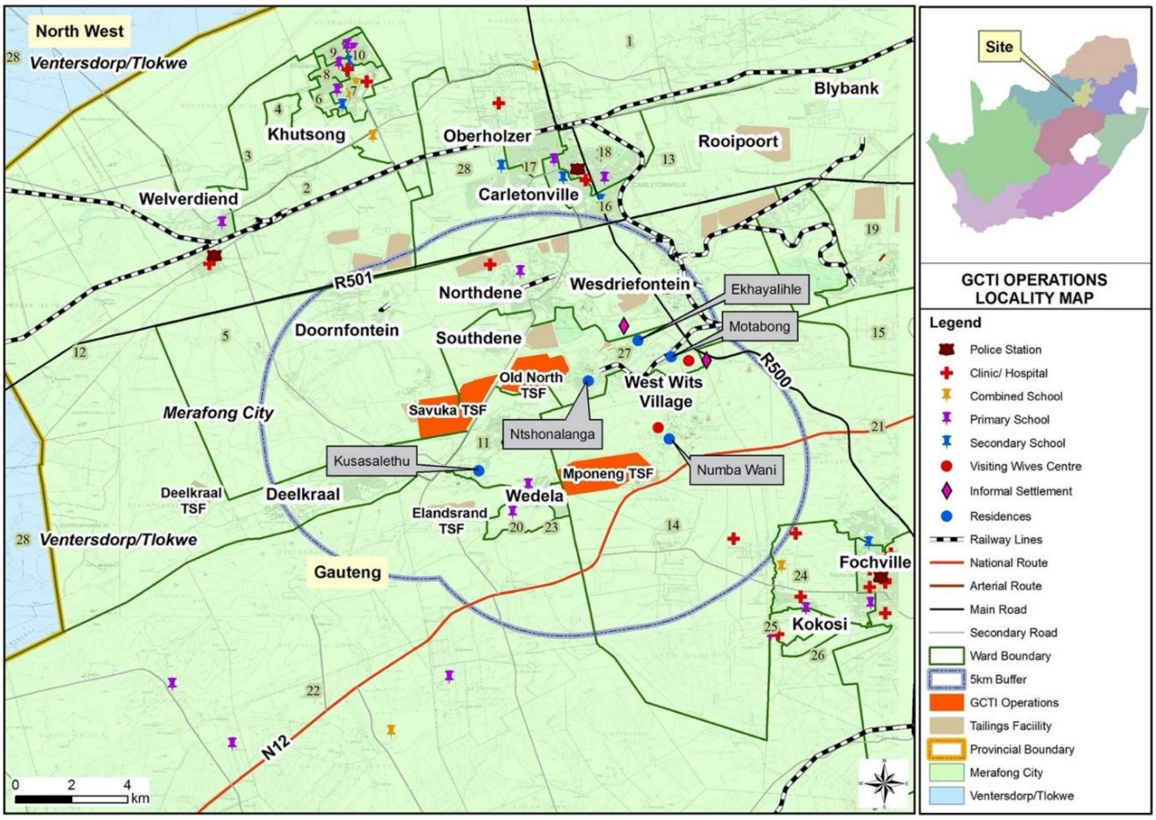


Figure 1.3 **Map showing the Mponeng Operations are located within the Merafong City Local Municipality of the West Rand District Municipality of the Gauteng Province of South Africa (Equispectives, 2020).**

1.2 Naturally Occurring Radionuclides and Background Radiation

Many radioactive isotopes (or radionuclides) occur naturally throughout the Earth's crust and are present in most rocks, soils, river water, as well as in seawater. Most of these naturally occurring radionuclides are members of four radioactive series identified as the uranium (U-238), actinium (U-235), thorium (Th-232), and neptunium (Np-237)[1] series, named according to the radionuclides that serve as progenitors (or parents) to the series products. Naturally occurring radionuclides that are of particular interest to radiation protection, which are not members of any of the four-decay series, include isotopes of potassium (K-40) and rubidium (Rb-87). These isotopes are of interest because of their presence in environmental media and their contribution to human exposure (Martin, 2006b).

In undisturbed environmental conditions, these naturally occurring radionuclides form part of the natural background radiation to which all humans are exposed daily through the air they breathe, the water they drink, the soil they live and work on, as well as the food they eat (Kathren, 1998).

The annual dose averaged over the population of the world is about 2.8 mSv in total. As indicated in Figure 1.4, over 85% of this total is from natural sources, with about half coming from radon decay products in the home (2.4 mSv). Medical exposure of patients accounts for 14% of the total (0.4 mSv), whereas all other artificial sources — fallout, consumer products, occupational exposure, and discharges from the nuclear industry — account for less than 1% of the total value. Other natural background radiation sources include cosmic radiation, gamma radiation, and internal radiation in our bodies (IAEA, 2004a).

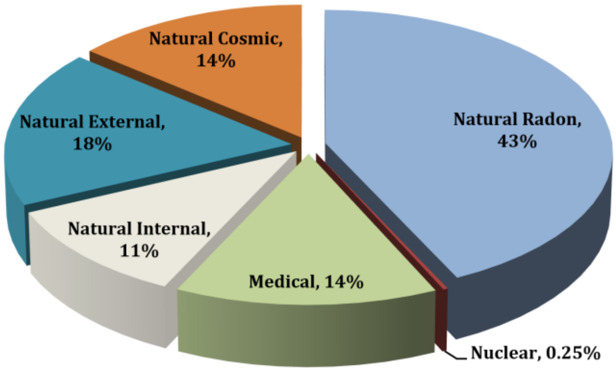


Figure 1.4 Distribution of the background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

In addition to the natural background radiation, anthropogenic activities that exploit the earth’s resources may enhance the potential for human exposure to naturally occurring radionuclides in their products, by-products, residues, and wastes. Industries such as mining and mineral processing operations and associated facilities and activities have the potential to alter the natural background radiation, and potentially increase radiation exposure, by:

- Moving naturally occurring radionuclides from inaccessible locations to locations where humans are present and can be exposed;
- Concentrating radionuclides in the accessible environment; or
- Changing the chemical or physical environment so that immobile radionuclides become more mobile in the natural environment (e.g., more soluble in water, or more transportable by the wind).

1 Primordial sources of Np-237 no longer exist because its half-life is only 2.1 million years (Martin, 2006), which means that natural sources of Np-237 decayed to insignificant levels since their creation some 4.5 billion years ago.

Nationally and internationally, the contribution of natural background radiation is not amenable to regulatory control. The focus is, therefore, on the contribution of a facility, activity, or operation to public ionizing radiation exposure conditions, *above natural background radiation* (i.e., complementary exposure).

Naturally occurring radionuclides associated with the uranium, thorium and actinium decay series are present within the Witwatersrand Basin gold-bearing reefs. These naturally occurring radionuclides are present in ore brought to the surface for processing and consequently have been and will continue to be carried through to the mining and mineral processing residues, such as waste rock or tailings materials. Materials and residues that contain naturally occurring radionuclides are generally referred to as Naturally Occurring Radioactive Materials (NORM) (IAEA, 2007). Due to the presence of naturally occurring radionuclides, NORM can negatively impact the health of humans exposed to these materials (Marsh *et al.*, 2010).

1.3 Regulatory Context

In South Africa, the protection of human health and the environment from adverse effects associated with exposure to ionising radiation is regulated in terms of the National Nuclear Regulator Act (NNRA) (Act 47 of 1999) and the Nuclear Energy Act (NEA) (Act No. 46 of 1999). The NNRA established the National Nuclear Regulator (NNR) as the statutory body responsible for regulating the nuclear industry, as well as regulating NORM associated with the mining and mineral processing industry. The legal limit for material to be classified as *radioactive* in terms of national standards (published in terms of the NNRA) is 0.5 $Bq.g^{-1}$ or 500 $Bq.kg^{-1}$ (radionuclide specific). Section 22 (1) of the NNRA states:

> "*Any person wishing to engage in any action which is capable of causing nuclear damage (Section 2(1)(c)) may apply in the prescribed format to the chief executive officer for a Certificate of Registration (CoR) and must furnish such information as the board requires*".

Harmony holds a Certificate of Registration (CoR-03) issued by the NNR to Harmony for their Mponeng Operations. Any changes to the scope of the CoR-03, such as the height extension of the Savuka 7A and 7B TSF compartments (hereafter referred to as the Project), require an Authorisation Change Request (ACR) to be prepared and submitted to the NNR. The ACR submitted to the NNR requires, amongst others, a quantification of the potential radiological impact of these changes or listed activities on members of the public.

The Project does not involve the upgrade of infrastructure, only continuing deposition for another 2 to 3 years. Currently, the approved height is 60, which will be extended by 5m to 10m up to a height of no higher than 70m. The only listed activity is 983, activity 34 and NEM:WA Category A: activity 13. This is a Basic Assessment process. Harmony has appointed Environmental Impact Management Services (Pty) Ltd (EIMS) as the Environmental Assessment Practitioner (EAP) to undertake the necessary environmental authorisation and associated consultation processes for the Project.

One of the key submissions as part of an ACR to the NNR is a Radiological Public Safety Assessment (RPSA), the purpose of which is to assess the potential radiological impact and safety of the proposed changes or listed activities on members of the public. AquiSim Consulting (Pty) Ltd (AquiSim) was consequently commissioned as a Radiation Protection Specialist (RPS) to perform the RPSA for the Project in a manner that is consistent with the provisions, requirements, and guidelines provided by the NNR, as well as the provisions and requirements of the Environmental, Social and Health Impact Assessment (ESHIA) process in terms of NEMA.

1.4 Purpose of the Report

The Project represent a scope change of CoR-03 and, therefore, requires the preparation and submission of an ACR to the NNR in terms of the NNRA. The purpose of this report is, consequently, to assess the potential radiological safety of the Project on members of the public. In addition, the RPSA serves as a basis to quantify the radiological impact of the Project as input into the ESHIA process prepared by EIMS in terms of NEMA.

1.5 Scope and Structure of the Report

The focus of the report is on the radiological safety of the Project as part of an ACR submission to the NNR. However, the report provides sufficient detail and includes the necessary impact rating to be included in the ESHIA process prepared by EIMS in terms of NEMA.

The report assumes a basic understanding of ionizing radiation and the effects of exposure to ionizing radiation on human health and the environment. If more information is needed on these subjects, the interested reader is referred to readily available literature resources, examples of which include documents entitled *Radiation, People and the Environment,* published by the International Atomic Energy Agency (IAEA, 2004a) or "*Radiation Effects and Sources*" published by the United Nations Environmental Programme (UNEP, 2016).

Figure 1.5 illustrates schematically the conceptual framework used to perform the RPSA of the Project. It resembles the International Atomic Energy Agency (IAEA) ISAM (Improvement of Safety Assessment Methodologies) methodology developed for the safety assessment of near-surface radioactive waste disposal facilities (IAEA, 2004b). It is inherently systematic and structured and allows for the continual improvement of the assessment or components of the assessment through successive iterations. The assessment framework consists of several interrelated elements that will be followed and presented in a different section of this report. The report has been structured as follows:

- Section 2 presents the overview of the assessment context that defines the high-level assumptions and constraints imposed on the assessment.
- Section 3 provides a more detailed description of the areas and activities of the Project and includes the regional and local setting and the associated operational components. An overview of the physical environment and the human receptors potentially affected is also presented as appropriate.
- Section 4 presents a discussion of the conditions of public exposure considered for the assessment. The section starts with a source-pathway-receptor analysis as derived from the Project and environmental system descriptions, followed by a definition of discrete sets of public exposure conditions.
- Section 5 is a discussion of the calculation approach used to estimate the total effective doses, calculate the doses for the public exposure conditions and discuss the results in terms of regulatory compliance criteria.
- Section 6 evaluates the sensitivity of the assessment results to variations in conditions and parameter values.
- Section 7 is devoted to the impact assessment rating for the operational and post-closure phases of the Project.
- Section 8 defines the radiation monitoring plan for the Project that includes the monitoring programme and the proposed monitoring locations.

- Section 9 presents some overall conclusions and recommendations for the improvement of public radiation safety, with the safety and impact assessment of the Project as a basis for the conclusions and recommendations.

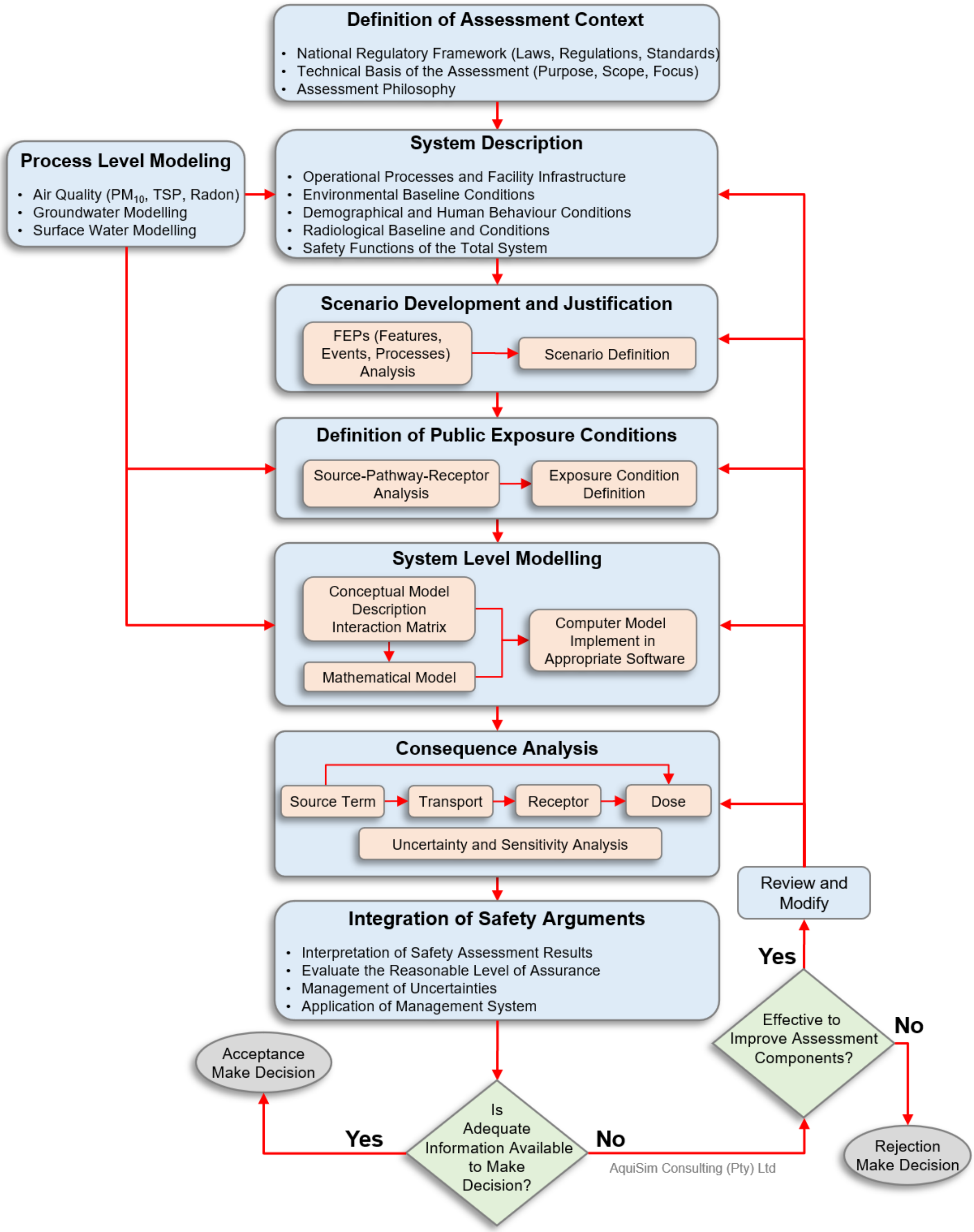


Figure 1.5 Schematic illustration of the conceptual safety assessment framework used to perform the RPSA of the Project.

2 Assessment Context

2.1 General

The first step in the assessment framework illustrated in Figure 1.5 is the definition of the *assessment context*, which in simple terms defines the *basis* or *context* within which the safety assessment is conducted. Once developed, it serves as a communication tool that provides how stakeholders or target audiences (see Section 2.3.2) are informed of what is included or excluded from the assessment, and justification for the choices made clearly and consistently.

Viewed from this perspective, the assessment context defines the boundary conditions within which the assessment will be performed. This includes the regulatory framework that applies to the assessment (see Section 2.2), and the technical basis of the assessment (e.g., purpose, scope and focus of the assessment) (see Section 2.3).

2.2 Regulatory Framework

2.2.1 General

The regulatory framework is defined by a combination of national legislation (see Section 1.3), and regulations, as well as guidance and requirements defined in terms of this legislation. The national framework is supplemented with principles, requirements, and guidance from international *organisations* concerned with radiation protection and the management of radioactive waste, including NORM.

Regulations regarding safety standards and regulatory practices in South Africa were Gazetted in 2006 (*Regulation* No. 388 dated 28 April 2006). Regulation No. 388 deals with Safety Standards and Regulatory Practices and defines the standards and principles that must be met to ensure safety at any nuclear installation (e.g., nuclear power plants, medical facilities, research centres and any other industrial applications of radiation sources), including mining and mineral processing facilities.

In 2013, the NNR published Regulatory Guide RG-002 entitled: "*Safety Assessment of Radiation Hazards to Members of the Public from NORM Activities*" (NNR, 2013) RG-002 is intended to provide guidelines to holders and prospective holders of NNR authorisations on how to conduct prior and operational public safety assessments for activities and operations involving NORM.

The international framework for radiation protection in the nuclear, medical, and mining industries is well-established and recognised. Organisations that play a key role in this regard include the *United Nations Scientific Committee on the Effects of Atomic Radiation* (UNSCEAR), the *International Commission on Radiological Protection* (ICRP), and the *International Atomic Energy Agency* (IAEA) (IAEA, 2004a).

The UNSCEAR mandate, established in 1955 by the General Assembly of the United Nations, is to assess and report the levels and effects of ionizing radiation exposure. Worldwide governments and organizations rely on the Committee's estimates as the scientific basis for evaluating radiation risk and for establishing protective measures. Consequently, UNSCEAR published informative documents. Some of these publications and reports may not be directly applicable to the mining and mineral processing industry but contribute to the overall framework for the protection of human health and the environment from exposure to ionizing radiation.

2.2.2 The ICRP System of Radiological Protection

The ICRP is a non-governmental, independent, scientific organization founded in 1928, following recommendations at the first International Congress of Radiology (ICR) held in London in 1925 to establish international protection standards (ICRP, 2009b). The ICRP has more than two hundred volunteer members from approximately thirty countries across six continents, who represent the world's leading scientists and policymakers in the field of radiological protection. The ICRP is a not-for-profit organisation registered as a charity in the United Kingdom and currently has its scientific secretariat in Ottawa, Canada. They publish recommendations for protection against ionizing radiation regularly (https://www.icrp.org/). The ICRP's authority derives from the scientific standing of its members and the merit of its recommendations.

Historically, the primary aim of the ICRP System of Radiological Protection is to provide an appropriate standard of protection for human beings without unduly limiting beneficial practices derived from radiological materials (ICRP, 1991). To achieve this objective, the ICRP system is intended to prevent the occurrence of deterministic effects by keeping doses below the relevant threshold. It also ensures that all reasonable steps are taken to reduce the induction of stochastic effects by keeping doses as low as reasonably achievable (ALARA), with economic and social factors being taken into account (ICRP, 2000).

The ICRP System of Radiological Protection is based on three principles. The first two principles are source-related and apply in all exposure situations, while the third principle is related to the exposure of an individual and applies in planned exposure situations (ICRP, 1991):

- *The Principle of Justification*: Any decision that alters the radiation exposure situation should do more good than harm. This means that by introducing a new radiation source, coupled with reducing existing exposure and reducing the risk of potential exposure, one should achieve sufficient individual or societal benefit to offset the detriment it causes.
- *The Principle of Optimisation of Protection*: The likelihood of incurring exposure, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable (ALARA), considering economic and societal factors.
- *The Principle of Application of Dose Limits*: The total dose to any individual from regulated sources in planned exposure situations (other than medical exposure of patients) should not exceed appropriate limits.

In its revised System of Protection, the ICRP recognises three types of exposure situations that are intended to cover the entire range of possible exposure situations (ICRP, 2007). These are:

- *Planned Exposure Situations*: Planned exposure situations involve the deliberate introduction and operation of sources. This may give rise to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur (potential exposures);
- *Emergency Exposure Situations*: Emergency exposure situations refer to unexpected situations that may occur during the operation of a planned situation, from a malicious act, or from any other unexpected situation that requires urgent action to avoid or reduce undesirable consequences.
- *Existing Exposure Situations*: Existing exposure situations refer to exposure situations that already exist when a control decision must be taken, including prolonged exposure situations after emergencies or those caused by natural background radiation.

The principles of *justification* and *optimisation* apply to all three exposure situations, whereas the principle of *application of dose limits* applies only to doses expected to be incurred with certainty because of planned exposure situations. The principle of *justification* requires that the net benefit of any action involving radiation be positive. The Harmony Operation is an existing operation, while the Project falls within the category of a *Planned Exposure Situation*.

2.2.3 International Basic Safety Standards (GSR Part 3) (IAEA, 2014)

The overall objective of the IAEA publication GSR Part 3"*Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*" (IAEA, 2014) in the General Safety Requirement series is to establish requirements (i.e. *shall* statements) for the protection of people and the environment from the harmful effects of ionizing radiation and the safety of radiation sources. Section 1 does not constitute requirements but explains the context, concepts and principles for the requirements presented in the remainder of the document. These include (amongst others) the following:

- The *System of Protection and Safety* that is based on the IAEA Fundamental Safety Principles outlined in IAEA (2006);
- The *Types of Exposure Situations* that, in their definition, are consistent with the ICRP exposure situations (ICRP, 2007) introduced in Section 2.2.2;
- An explanation of the concepts of *Dose Constraints and Reference Levels*. Both concepts are used for the optimization of protection and safety, the intended outcome of which is that all exposures are controlled to levels that are as low as reasonably achievable (ALARA), with economic, societal, and environmental factors being considered;
- *Protection of the Environment* that recognised the protection of the environment as an issue necessitating assessment, while allowing for flexibility in incorporating into decision-making processes the results of environmental assessments that are commensurate with the radiation risks; and
- *The Interface between Safety and Security*, both of which have in common the aim of protecting human life and health and the environment. Also, safety measures and security measures must be designed and implemented in an integrated manner so that security measures do not compromise safety and safety measures do not compromise security.

Requirements specified in Section 2 to Section 5 make a distinction between the three types of exposure situations, with a further distinction between occupational exposure, public exposure, and medical exposure.

2.2.4 Safety Standards for the Protection of the Public

To avoid severely inequitable outcomes of the optimisation procedure, restrictions should be imposed on the doses or risks to individuals from a source. The regulatory tools that can be used to achieve a reduction of risks are *dose or risk constraints* and *reference levels*. In planned exposure situations, the ICRP recommends that public exposure is controlled by the procedures of optimisation below the source-related constraint and using dose limits. In an emergency or existing exposure situation, the ICRP uses the term 'reference level' for the restriction on dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The ICRP recommends that any exposure caused by human activity above natural background radiation should be kept as low as reasonably achievable (ALARA), with economic and social factors being taken into account, but below the following individual dose limits (ICRP, 1991):

- The individual dose limit for public exposure in planned exposure situations is 1 mSv per year.
- In special circumstances, an effective dose of up to 5 mSv in a single year, provided that the average dose over five consecutive years does not exceed 1 mSv per year, can be applied.
- Also, the ICRP recommends equivalent dose limits of 15 mSv in a year to the lens of the eye and 50 mSv in a year to the skin.

The dose limits for public exposure presented in Schedule III of GSR Part 3 (IAEA, 2014) are consistent with the limits defined in ICRP (1991):

- An effective dose of 1 mSv in a year;
- In special circumstances (e.g., in authorized, justified, and planned operational circumstances that lead to transitory increases in exposures), a higher value of effective dose in a single year could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year;
- An equivalent dose to the lens of the eye of 15 mSv in a year; and
- An equivalent dose to the skin of 50 mSv in a year.

The ICRP further recommends that consideration must be given to the presence of other sources that may cause simultaneous radiation exposure to the same group of the public. Allowance for future sources must be kept in mind so that the total dose received by an individual member of the public does not exceed the dose limit. For this reason, *dose constraints* that are lower than the *dose limit* and typically around 0.1 to 0.3 mSv per year are proposed to ensure that 1 mSv per year is not exceeded. Dose constraints are thus set separately for each source under control, and they serve as boundary conditions in defining the range of options for optimization.

Note that a *dose constraint is not a dose limit*; *exceeding a dose constraint does not represent non-compliance with regulatory requirements*, but could result in follow-up actions as required by the regulatory body (IAEA, 2014). This means that the criteria of 1 mSv in a year adopted for the protection of the public in South Africa in Regulation No. 388 are consistent with the ICRP and IAEA recommendations for public exposure. The Regulation No. 388 dose constraint of 0.25 mSv in a year for public exposure per CoR holder is also within the range of 0.1 to 0.3 mSv per year proposed by the ICRP and IAEA.

2.2.5 National Radioactive Waste Management Policy and Strategy

The purpose of the National Radioactive Waste Management Policy and Strategy (NRWMP), published in 2005 (DME, 2005) is:

> *To ensure the establishment of a comprehensive radioactive waste governance framework by formulating, in addition to nuclear and other applicable legislation, a policy and implementation strategy in consultation with all stakeholders.*

Within the national framework, the NRWMP is viewed as the starting point for the definition and selection of an appropriate solution for the management of radioactive waste.

The NRWMP also addresses options for managing radioactive waste generated through the nuclear industry, as well as waste containing unconcentrated naturally occurring radioactive materials from the mining and minerals processing industries. In consideration of options for radioactive waste management, the document takes cognisance of the IAEA radioactive waste management principles (IAEA, 1995). In guiding the national strategy for radioactive waste management, several strategic points of reference in dealing with radioactive waste are defined. Two of the guiding principles that are of importance in terms of managing NORM are Principle No. 4 and Principle No. 13 (DME, 2005):

> *The aim (of a radioactive waste management strategy) shall be to achieve a maximum degree of passive safety in storage and disposal (Principle No. 4). The deliberate dilution of radioactive waste is not acceptable, however, in the case of NORM waste, the dilution of higher concentration material with lower concentration material will be considered if all relevant regulatory concerns are addressed (Principle No. 13).*

In implementing the NRWMP, South Africa followed the IAEA guidelines regarding the definition and classification of radioactive waste as presented in IAEA (1994b) (unless deviations therefrom can be justified). Table 2.1 summarises the waste classification scheme adopted for this purpose. Note that when the NRWMP was drafted in 2005, the waste classification scheme was in line with the IAEA waste classification scheme applicable at the time (IAEA, 1994b). The IAEA classification scheme has subsequently been revised and is presented in IAEA (2009b).

Table 2.1 Summary of the National Radioactive Waste Classification Scheme (DME, 2005).

Waste Class	Waste Description	Waste type / Origin	Waste Criteria	Generic waste treatment / conditioning requirements (1)	Disposal / Management Options
1 HLW	Heat generating radioactive waste with high long and short-lived radionuclide concentrations.	1 Used fuel declared as waste or used fuel recycling products 2 Sealed sources	1 Thermal power > 2 kW/m^3. **OR** 2 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels > levels specified for LILW-LL 3 **OR** Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) above 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 100 years). The waste form shall be solid with additional characteristics as prescribed for a specific repository.	1 (a) Regulated deep disposal (100's of metres). (b) Reprocessing, Conditioning and Recycling (c) Long Term Above Ground Storage
2 LILW-LL	Radioactive waste with low or intermediate short-lived radionuclide and intermediate long-lived radionuclide concentrations.	1 Irradiated uranium (isotope production). 2 Un-irradiated uranium (nuclear fuel production). 3 Fission and activation products (nuclear power generation and isotope production) 4 Sealed sources.	1 Thermal power (mainly due to short-lived radio nuclides (T ½ < 31 y) < 2 kW/m^3) **AND** 2 Long-lived radio nuclides (T ½ > 31 y) concentrations. ❖ Alpha: < 4000 Bq/g ❖ Beta and gamma: < 40000 Bq/g (Maximum per waste package up to 10x the concentration levels specified above). **OR** 3 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) between 10 and 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 50 years). The waste form shall be solid with additional characteristics as for a specific repository.	1 Regulated medium depth disposal (10's of metres). 2 Managed as NORM-E waste (un-irradiated uranium)
3 LILW-SL	Radioactive waste with low or intermediate short-lived radionuclide and / or low long-lived radionuclide concentrations.	1 Un-irradiated uranium (nuclear fuel production). 2 Fission and activation products (nuclear power generation and isotope production. 3 Sealed sources.	1 Thermal power (mainly due to short-lived radio nuclides (T ½ < 31 y) < 2 kW/m^3. **AND** 2 Long-lived radio nuclide (T ½ > 31 y) concentrations. ❖ Alpha: < 400 Bq/g ❖ Beta and gamma: < 4000 Bq/g (Maximum per waste package up to 10x the concentration levels specified above). 3 **OR** Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) below 10 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 10 years). The waste form shall be solid with additional characteristics as for a specific repository.	1 Regulated near surface disposal (< 10 metres). 2 Managed as NORM-E waste (un-irradiated uranium)
4 VLLW	Radioactive waste containing very low concentration of radioactivity.	1 Contaminated or slightly radioactive material originating from operation and decommissioning activities.	1 Clearance or authorised discharge or reuse criteria and levels approved by the relevant regulator.	Waste stream specific requirements and conditions.	1 Clearance. 2 Authorized disposal, discharge or reuse
5 NORM-L (low activity)	Potential Radioactive waste containing low concentrations of NORM.	1 Mining and minerals processing. 2 Fossil fuel electricity generation. 3 Bulk waste - un-irradiated uranium (Nuclear fuel production).	1 Long-lived radio nuclide concentration: < 100 Bq/g.	Unpackaged waste in a miscible waste form.	1 Re-use as underground backfill material in an underground area. 2 Extraction of any economically recoverable minerals, followed by disposal in any mine tailings dam or other sufficiently confined surface

Waste Class	Waste Description	Waste type / Origin	Waste Criteria	Generic waste treatment / conditioning requirements [(1)]	Disposal / Management Options
					impoundment 3 Authorised disposal 4 Clearance
6 NORM-E (enhanced activity)	Radioactive waste containing enhanced concentrations of NORM.	1 Scales 2 Soils contaminated with scales	1 Long-lived radio nuclide concentration: > 100 Bq/g.	Packaged or unpackaged waste in a miscible or solid form with additional characteristics for a specific repository.	1 Dilute and re-use as underground backfill material in an identified underground area. 2 Extraction of any economically recoverable minerals, followed by dilution and disposal in an identified mine tailings dam or other sufficiently confined surface impoundment 3 Regulated deep or medium depth disposal.

(1) Treatment and conditioning requirements are mainly dependant on specific waste type in a waste class.

Note that at the time (in 2005) when the Policy and Strategy were drafted, the waste classification scheme was in line with the IAEA waste classification scheme (IAEA, 1994b). The IAEA classification scheme has subsequently been revised (IAEA, 2009b).

The NRWMP provides several options for NORM management. The options available depend on the classification of the NORM as either low activity (long-lived radionuclide concentration < 100 $Bq.g^{-1}$) or enhanced activity (long-lived radionuclide concentration > 100 $Bq.g^{-1}$). Table 2.2 summarises the available management options for each of these classes of NORM waste.

Table 2.2 Management options for low activity NORM and enhanced activity NORM as defined in DME (2005).

Low Activity NORM (less than 100 $Bq.g^{-1}$)	Enhanced Activity NORM (more than 100 $Bq.g^{-1}$)
Re-use NORM as underground backfill material in an underground area	
Extraction of any economically recoverable minerals from the NORM, followed by disposal in any mine tailings dam or another sufficiently confined surface impoundment	
Authorised disposal	Regulated deep or medium-depth disposal
Clearance	

2.2.6 Waste Categorisation for Mining and Mineral Processing Facilities

The waste categorisation scheme for mining and mineral processing facilities distinguishes between *non-process waste* (waste for which it is considered unlikely that any radioactive contamination of the waste could have occurred) and *process waste*. For *process waste*, the potential exists that the waste may have become radioactively contaminated, either directly through being involved in a process known for the presence of radioactivity, or indirectly by being near known or potentially radioactively contaminated waste. *Homogeneous Process Waste* refers to *process waste* that is in bulk or homogeneous form and may include materials such as tailings, pyrite, baddeleyite and calcine. Table 2.3 summarises the categorisation of homogenous process waste and associated management options.

Note that storage or disposal of Category I material with activity concentrations higher than 0.5 $Bq.g^{-1}$ may render the waste rock dump unsuitable for other uses (e.g., road construction). Also, note that the proposed management strategy of Category III waste (more than 1,000 $Bq.g^{-1}$) is still storage on a licensed site in an approved storage facility. This is because a long-term (permanent) solution for the management of this waste (i.e., high-level waste) is not available in South Africa at present.

Table 2.3 The categorisation of homogenous process waste and associated management options.

Category	Description	Disposal/Storage Option
Category I	Waste with a specific alpha activity (U-238, U-234, Th-230, Ra-226, Po-210, Th-232, and Th-228) not exceeding 100 $Bq.g^{-1}$	• Released to a licensed facility. • Stored on site. • Placed directly on TSFs or WRDs
Category II	Waste with a specific alpha activity (U-238, U-234, Th-230, Ra-226, Po-210, Th-232, and Th-228) exceeding 100 $Bq.g^{-1}$, but not exceeding 1,000 $Bq.g^{-1}$	• Released to a licensed facility. • Stored on site. • Placed directly on a TSFs or WRDs following a process of dilution of at least 1:10
Category III	Waste with a specific alpha activity (U-238, U-234, Th-230, Ra-226, Po-210, Th-232, and Th-228) exceeding 1,000 $Bq.g^{-1}$	• Stored on a licensed site in an approved storage facility until a final disposal option is available

2.3 Technical Basis of the Assessment

2.3.1 General

A radiological public safety and impact assessment can be used for different purposes as part of the overall management of an operation, facility, or activity. As the operation, facility or activity moves from a pre-operational to the post-closure phase, the purpose, scope and focus of these assessments may vary. Before operations commence, a pre-operational safety assessment is performed on a *prospective* basis to assess whether the proposed operations do not pose a radiological risk to workers and the public above the applicable regulatory compliance criteria. Once operational, the prospective assessment is updated with a facility and site-specific safety assessment, as appropriate. The purpose of this section is to define the technical basis of the assessment, which is largely defined by the purpose, scope and focus of the assessment, but *inter alia* the spatial and temporal boundary conditions and associated assessment endpoints.

2.3.2 Interested Parties to the Assessment

A radiological safety assessment is generally undertaken to provide confidence to interested parties that an operation, facility or activity does not pose a radiological risk to relevant exposure groups, notably workers or members of the public. As used here, interested parties are groups or individuals with an interest in the radiological safety of an existing or proposed operation, facility or activity. In some cases, these groups may have specific interests that may affect the purpose, scope and focus of the assessment. This may result in additional assessment endpoints to consider, or consideration as to how the assessment results are presented. For this reason, including the list of interested parties as part of the technical basis in the assessment context report is required.

Generally, the interested parties include management and technical staff responsible for the design, implementation and operation of facilities or activities, as well as regulatory authorities, workers, members of the public, as well as environmental interest and human rights groups. Viewed from this perspective the main stakeholders or target audience include the following:

- Regulatory authorities that include the NNR as a statutory body responsible for regulating NORM and that is responsible for monitoring the process to ensure that the operational activities are performed by following relevant regulatory guidance and requirements;
- EIMS as the Independent Environmental Practitioner responsible for the alignment of the Project with the NEMA and associated ESHIA Regulations;

- Workers at Harmony and more specifically the Mponeng Operations that are responsible and involved in the implementation of the Project;
- Members of the public living near the Mponeng Operations and more specifically near the Savuka 7A and 7B TSFs site, which may potentially be affected by the facilities and activities associated with the Project (e.g., ward councillors, labour unions, agriculture, and landowners);
- Mining and industry, particularly the mining and mineral processing operations near the Mponeng Operations; and
- Officials from the Local, Provincial and National Government Departments that will be responsible for evaluating the applications for environmental authorisation and have to ensure that the environmental investigations are performed by following relevant regulatory guidance and requirements; and
- Technical, scientific, and environmental groups that might have an interest in the approach followed for the assessment and the subsequent results.

2.3.3 Purpose of the Assessment

Any company endeavouring to develop a mining or mineral processing operation must undergo a rigorous permitting effort to convince regulators and public stakeholders that the mining, milling, and associated processing facilities can be developed, operated, decommissioned, and closed without threatening worker and public health, nearby communities, and the environment (Chambers *et al.*, 2012).

A key element in this process is the radiological public safety assessment, which can be defined as an analysis to evaluate the performance of the overall system (e.g. mining and mineral processing operation, facility or activity) and its impact, where the performance measure is the radiological safety in terms of a total effective dose criterion to workers and members of the public (IAEA, 2007).

The nuclear regulatory framework (see Section 2.2) is clear on the overall safety objective (IAEA, 2006) and the associated need to protect human health and the environment over the timescales of concern for all facilities and activities, including mining and mineral processing operations (IAEA, 2009a; ICRP, 2000). These assessments are required for all facilities and activities, including new or existing mining and mineral processing operations.

Viewed from this radiological perspective and complemented with the ESHIA requirements, the purpose of the radiological safety and impact assessment of the Project is twofold:

- To evaluate and demonstrate that members of the public living near the Tswelopele Beneficiation Operations and the Project area will not be exposed to levels of ionizing radiation released to the environment above the regulatory compliance criteria set for public exposure as defined in Section 2.2.3; and
- To assess the radiological impact on members of the public living near the Tswelopele Beneficiation Operations and the Project area as input into the ESHIA process. The basis for the impact assessment is the outcome of the radiological public safety assessment and is performed according to the criteria specified in Section 2.3.7.3.

2.3.4 Scope and Focus of the Assessment

2.3.4.1 Natural Background Radiation

The contribution of naturally occurring radionuclides to background radiation was introduced in Section 1.2. Nationally and internationally, the contribution of natural background radiation is not amenable to regulatory control. The focus of this assessment is thus on the radiation exposure contribution induced by Project, *above natural background radiation*. This means the background radiation is not included in the comparison of the total effective dose with the regulatory compliance criteria.

The approach that is followed for this purpose is to determine a source term (or source term release rate) of radioactivity from the facilities or activities to the environment, estimate the dispersion of released radioactivity into the environment and evaluate the subsequent interaction of members of the public with the affected environmental media in terms of a total effective dose. Where necessary and justified, this approach is complemented by actual environmental media measurements (e.g., soil, water, sediment, crops, etc.) and observations to quantify the actual dose contribution to members of the public.

2.3.4.2 Site-Specific Assessment

The radiological public safety assessment is based on site-specific data as far as practically possible and justified. Where appropriate and justified, the site-specific data and information are supplemented with values from the literature or analogue facilities such as those associated with the Project. All assumptions and conditions used in the assessment are documented and justified accordingly.

2.3.4.3 Ionising Radiation Exposure Assessment

Mining and mineral handling and processing activities may pose hazards to humans or the environment not only from the presence of naturally occurring radioactivity but also from toxic elements and compounds present in the products, by-products, residues, and wastes produced through these activities. The focus of the radiological public safety assessment is radiation exposure induced by ionising radiation and excludes any health risk considerations that may arise due to non-radioactive substances or any other health and safety aspect.

2.3.4.4 Contaminants of Concern

The contaminants of concern are those naturally occurring radionuclides associated with the uranium and thorium decay series. Table A 1 to Table A 3 list these series and their radiological properties, while Figure A 1 schematic illustration of the decay series (see Appendix A).

Uranium is a high-density metallic element that occurs naturally in the earth's crust at an average abundance of approximately 3 ppm. Naturally occurring uranium consists of three isotopes, all of which are radioactive, namely U-238, U-235 and U-234. U-238 and U-235 are the parent nuclides of two independent decay series, while U-234 is a decay product of the U-238 series. A third decay series, which is usually included as part of an assessment considering naturally occurring radionuclides, is that of the thorium (Th-232) isotope. Pure thorium is a soft and very ductile substance that readily combines with oxygen at ambient temperatures. It naturally occurs as black Thorium oxide and is almost three times as abundant as uranium.

Exposure to the isotopes of uranium, thorium and their progeny (i.e. daughter products), has been linked to detrimental health impacts in humans based on their properties of emitting ionizing radiation and the extensive weight of evidence provided by epidemiological studies of radiogenic health effects in humans

(Klaassen, 2001). However, not all the radionuclides in these decay series contribute equally to a total effective dose. Radionuclides that pose a significant risk to human health are identified from their dose conversion factors and reported half-lives. Only those radionuclides that can be shown to make a significant contribution to a total effective dose are considered. Table 2.4 lists the radionuclides explicitly considered in the RPSA of the Project.

Where applicable, radioactive decay and in-growth of daughter products are taken into consideration in the assessment. This serves the dual purpose of avoiding overly conservative results, in the case of slower transport processes, as well as accounting for impacts related to the radioactive decay products. Note that the radiological properties of some of the associated radioisotopes are such that they will remain a concern for periods of thousands of years.

Table 2.4 List of α and β emitting radionuclides explicitly considered in the radiological public safety and impact assessment of the Project.

Long-lived Alpha (α) Radiation Emitters	Beta (β) Radiation Emitters
U-238, U-234, Th-230, Ra-226, Po-210	Pb-210
U-235, Pa-231, Ra-223	Ac-227
Th-232, Th-228, Ra-224	Ra-228

Secular equilibrium is assumed between parent and daughter products in cases where analytical results of the progeny are not available. This implies that in the absence of analytical results, the following assumptions are applied:

- Po-210 = Pb-210 = Ra-226 = Th-230 = U-234 = U-238.
- Ra-224 = Th-228 = Ra-228 = Th-232.
- Ra-223 = Ac-227 = Pa-231 = U-235.

2.3.4.5 Cumulative Effect

The ICRP principles and IAEA safety standards set limits for the protection of human health and the environment from all radiation exposure situations or practices. This implies that limits set for the protection of members of the public are from all potential contributing operations near the Harmony Operations (i.e., CoRs) and associated Project area.

The focus of the assessment is on the contribution of the Project to the annual effective dose to members of the public. Other mining operations in the area belong to Harmony but with different CoRs. The scope of the assessment does not cater for a regional radiological safety assessment to include *all* potential operational activities and sources in the area. However, recognition is given to the potential contribution from these and other operations to a total effective dose through the application of the regulatory dose constraint.

2.3.4.6 Worker Safety Assessment

The NNRA and associated national safety standards make provision for the protection of both workers (occupational exposure) and members of the public from exposure to ionizing radiation. For this purpose, both worker and public safety assessments must be submitted to the NNR. The scope of the assessment is limited to the assessment of the radiological safety and impact on members of the public. A radiological assessment for worker exposures associated with the Project is documented and submitted to the NNR as a separate report.

2.3.4.7 Assessment of Non-Human Biota

The concept of establishing dose limits for non-human biota has been introduced by the ICRP in Publication 103 (ICRP, 2008) and Publication 108 (ICRP, 2009a). A radiation assessment for non-human biota focuses on evaluating the impact of radiation on ecosystems, including animals, plants, and microorganisms, rather than human populations. This assessment aims to understand how ionizing radiation affects different species by determining radiation dose rates, identifying exposure pathways (e.g., ingestion, inhalation, and direct radiation), and comparing these doses to established threshold levels for ecological protection. The goal is to ensure that radiation remains within safe limits to prevent adverse effects on biodiversity and ecosystem functions. Historically, it was assumed that protecting humans from radiation also protected non-human biota at the species level (ICRP, 1991).

One recognized method for assessing the impacts on non-human biota is the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA), which uses the ERICA software tool. This tool takes into account radionuclide concentrations in various media and species-specific concentration ratios to standardize the measurement of radiological impact on reference species.

While environmental protection is a key principle in IAEA safety standards, the scope of the current assessment excludes the consideration of non-human biota. Furthermore, the NNR regulatory framework does not require the assessment of non-human biota at this time.

2.3.4.8 Human Behavioural Conditions and Age Groups

The assessment considers site-specific human behavioural conditions observed near the Project area to the extent possible and justified through the definition of a discrete set of public exposure conditions (see Section 4.7), for all relevant age groups. Consistent with the guidance provided in RG-002 (NNR, 2013), the assessment considers the age groups and ranges of age groups listed in Table 2.5.

Table 2.5 Age group ranges applicable to age-dependent dose conversion factors as published in RG-002 (NNR, 2013).

Ages specified in RG-002	Applicable Age Range	Age Group Used in the Assessment
New-born	From 0 to 1 year of age	0 to 2 years
1 Year	From 1 year to 2 years	
5 Year	More than 2 years to 7 years	2 years to 7 years
10 Year	More than 7 years to 12 years	7 years to 12 years
15 Year	More than 12 years to 17 years	12 years to 17 years
Adult	More than 17 years	Adults

2.3.5 Spatial Domain of Concern

The spatial domain considered in the radiological public safety assessment is largely dictated by an understanding of the processes governing the movement of radionuclides and potential environmental exposure pathways for the potentially exposed groups. While physical boundaries cannot be applied rigorously to some of these processes, a 3 to 5 km radius around the environmental release points defines the area where environmental pathways need to be considered. If justified, a wider study area may be defined to accommodate processes governing the movement of radionuclides beyond these boundaries. Since the intent of the analysis is to evaluate critical groups, the exposure locations to be evaluated are likely to be near the sources, which means that the spatial scale is likely to be limited by the selected public exposure conditions.

2.3.6 Assessment Timescales

The lifecycle of a typical mining operation can be considered as three distinct periods, namely a pre-operational period (i.e., design and commissioning period), an operational period, and a post-operational (or post-closure) period. Of these, the operational and post-operational periods generally represent the periods during which conditions conducive to the dispersion of NORM into the environment and public exposure are most likely to exist.

Assessment of the potential radiological impact during the operational phase can be performed with a greater level of certainty since the conditions at present or in the near future are known or can be more reliably predicted than conditions during the post-operational period. Conditions during the post-operational period are more uncertain, in which case provision must be made to address these uncertainties in the assessment. Consequently, the radiological public safety assessment primarily addresses the radiological impact associated with the operational period, while an attempt is made to address the radiological impacts that may occur in the distant future to the extent possible and justified.

2.3.7 Assessment Endpoint

2.3.7.1 General

Assessment (or calculation) endpoints for a radiological public safety assessment are determined by the regulatory framework but also by the purpose, scope, and focus of the assessment. In some cases, the target audience or stakeholders may determine additional assessment endpoints to consider. While quantitative endpoints are most common for a safety assessment, in some cases qualitative endpoints may also be required.

2.3.7.2 Radiological Public Safety Assessment Endpoints

The focus of the radiological public safety assessment is the radiological impact on members of the public near the Project area (see Section 2.3.4). More specifically, the objective is to quantify the release and subsequent distribution of radioactivity into and through the environment and the subsequent interaction of members of the public with the environmental media.

Consistent with the ICRP System of Protection defined in Section 2.2.3, the primary assessment endpoint for this purpose is the annual individual effective dose rate. Unless otherwise stated, the term dose refers to the annual individual effective radiation dose to members of the public, calculated using the method described in ICRP (1991). This is consistent with the NNR requirements for the radiological protection of members of the public and adopted in the Safety Standards and Regulatory Practices presented in Regulation No. 388.

2.3.7.3 ESHIA Criteria

The following EIMS methodology and rationale are used to assess the significance of the potential impacts of the final site layout plan on the surrounding biophysical and socio-economic environment. The impact assessment methodology is guided by the requirements of the NEMA ESHIA Regulations. The broad approach to the significance rating methodology is to determine the environmental risk (ER) by considering the consequence (C) of each impact (comprising Nature, Extent, Duration, Magnitude, and Reversibility) and relate this to the probability/likelihood (P) of the impact occurring. This determines the environmental risk. In addition, other factors, including cumulative impacts, public concern, and potential for irreplaceable loss of resources, are used to determine a prioritisation factor (PF) which is applied to the ER to determine the overall significance (S).

The significance (S) of an impact is determined by applying a prioritisation factor (PF) to the environmental risk (ER). The environmental risk is dependent on the consequence (C) of the particular impact and the probability (P) of the impact occurring. Consequence is determined through the consideration of the Nature (N), Extent (E), Duration (D), Magnitude (M), and Reversibility (R) applicable to the specific impact.

For this methodology, the consequence of the impact is represented by:

$$C = \frac{(E + D + M + R) \cdot N}{4}$$

Each individual aspect in the determination of the consequence is represented by a rating scale as defined in Table 2.6. Once the consequence has been determined, the ER is determined following the standard risk assessment relationship by multiplying the C and the P. Probability is rated/scored as per Table 2.7.

The result is a qualitative representation of the relative ER associated with the impact. ER is therefore calculated as follows (see Table 2.8):

$$ER = C \cdot P$$

The outcome of the environmental risk assessment will result in a range of scores, ranging from 1 to 25. These ER scores are then grouped into respective classes as described in Table 2.9. The impact ER will be determined for each impact without relevant management and mitigation measures (pre-mitigation), as well as post-implementation of relevant management and mitigation measures (post-mitigation). This allows for a prediction of the degree to which the impact can be managed/mitigated.

Table 2.6 Criteria used to determine the impact consequence.

Aspect	Score	Definition
Nature	- 1	Likely to result in a negative/ detrimental impact
	+1	Likely to result in a positive/ beneficial impact
Extent	1	Activity (i.e., limited to the area applicable to the specific activity)
	2	Site (i.e., within the development property boundary),
	3	Local (i.e., the area within 5 km of the site),
	4	Regional (i.e., extends between 5 and 50 km from the site)
	5	Provincial / National (i.e., extends beyond 50 km from the site)
Duration	1	Immediate (<1 year)
	2	Short-term (1-5 years),
	3	Medium-term (6-15 years),
	4	Long-term (the impact will cease after the operational life span of the project),
	5	Permanent (no mitigation measure or natural process will reduce the impact after construction).
Magnitude/ Intensity	1	Minor (where the impact affects the environment in such a way that natural, cultural, and social functions and processes are not affected),
	2	Low (where the impact affects the environment in such a way that natural, cultural, and social functions and processes are slightly affected),
	3	Moderate (where the affected environment is altered but natural, cultural, and social functions and processes continue albeit in a modified way),
	4	High (where natural, cultural, or social functions or processes are altered to the extent that they will temporarily cease), or
	5	Very high / do not know (where natural, cultural, or social functions or processes are altered to the extent that it will permanently cease).
Reversibility	1	The impact is reversible without any time and cost.
	2	The impact is reversible without incurring significant time and cost.
	3	The impact is reversible only by incurring significant time and cost.
	4	The impact is reversible only by incurring prohibitively high time and cost.
	5	Irreversible Impact

Table 2.7 Probability scoring.

Aspect	Score	Definition
Probability	1	Improbable (the possibility of the impact materializing is very low as a result of design, historic experience, or implementation of adequate corrective actions; <25%),
	2	Low probability (there is a possibility that the impact will occur; >25% and <50%),
	3	Medium probability (the impact may occur; >50% and <75%),
	4	High probability (it is most likely that the impact will occur- > 75% probability), or
	5	Definite (the impact will occur).

Following the requirements of Appendix 3(3)(j) of the NEMA 2014 EIA Regulations (GN R. 982), and further to the assessment criteria presented above, it is necessary to assess each potentially significant impact in terms of:

- Cumulative impacts; and
- The degree to which the impact may cause irreplaceable loss of resources.

Table 2.8 Determination of environmental risk.

Consequence	5	5	10	15	20	25
	4	4	8	12	16	20
	3	3	6	9	12	15
	2	2	4	6	8	10
	1	1	2	3	4	5
		1	2	3	4	5
	Probability					

Table 2.9 Significance classes.

Environmental Risk Score	
Value	Description
< 9	Low (i.e., where this impact is unlikely to be a significant environmental risk),
≥9; <17	Medium (i.e., where the impact could have a significant environmental risk),
≥ 17	High (i.e., where the impact will have a significant environmental risk).

In addition, public opinion and sentiment regarding a prospective development and consequent potential impacts must be considered in the decision-making process.

To ensure that these factors are considered, an impact prioritisation factor (PF) will be applied to each impact ER (post-mitigation) (see Table 2.10). This prioritisation factor does not aim to detract from the risk ratings but rather to focus the attention of the decision-making authority on the higher priority/significance issues and impacts. The PF will be applied to the ER score based on the assumption that relevant suggested management/mitigation impacts are implemented.

The value for the final impact priority is represented as a single consolidated priority, determined as the sum of each individual criterion represented in Table 2.11. The impact priority is therefore determined as follows:

$$\boldsymbol{Priority = PR + CI + LR}$$

The result is a priority score which ranges from 3 to 9 and a consequent PF ranging from 1 to 2 (see Table 2.11).

To determine the final impact significance, the PF is multiplied by the ER of the post-mitigation scoring (see Table 2.12). The ultimate aim of the PF is to be able to increase the post-mitigation environmental risk rating by a full ranking class if all the priority attributes are high (i.e., if an impact comes out with a medium environmental risk after the conventional impact rating, but there is significant cumulative impact potential, significant public response, and significant potential for irreplaceable loss of resources, then the net result would be to upscale the impact to a high significance).

Table 2.10 The criteria used to determine the prioritisation.

Public response (PR)	Low (1)	Issue not raised in the public response.
	Medium (2)	The issue has received a meaningful and justifiable public response.
	High (3)	The issue has received an intense, meaningful and justifiable public response.
Cumulative Impact (CI)	Low (1)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikely that the impact will result in spatial and temporal cumulative change.
	Medium (2)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cumulative change.
	High (3)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is highly probable/definite that the impact will result in spatial and temporal cumulative change.
The irreplaceable loss of resources (LR)	Low (1)	Where the impact is unlikely to result in irreplaceable loss of resources.
	Medium (2)	Where the impact may result in the irreplaceable loss (cannot be replaced or substituted) of resources but the value (services and/or functions) of these resources is limited.
	High (3)	Where the impact may result in the irreplaceable loss of resources of high value (services and/or functions).

Table 2.11 Determination of prioritisation factor

Priority	Ranking	Prioritization Factor
3	Low	**1**
4	Medium	**1.17**
5	Medium	**1.33**
6	Medium	**1.5**
7	Medium	**1.67**
8	Medium	**1.83**
9	High	**2**

Table 2.12 Final environmental significance rating

Environmental Significance Rating	
Value	Description
< -9	Low negative (i.e., where this impact would not have a direct influence on the decision to develop in the area).
≥ -9 < -17	Medium negative (i.e., where the impact could influence the decision to develop in the area).
≥ -17	High negative (i.e., where the impact must influence the decision process to develop in the area).
0	No impact
< 9	Low positive (i.e., where this impact would not have a direct influence on the decision to develop in the area).
≥ 9 < 17	Medium positive (i.e., where the impact could influence the decision to develop in the area).
≥ 17	High positive (i.e., where the impact must influence the decision process to develop in the area).

3 System Description

3.1 Introduction

Within the conceptual framework presented in Figure 1.5, the purpose of the system description is first to provide a summary overview of the Project with specific reference to the facilities, activities, and associated infrastructure. This information is normally complemented with a description of the prevailing site characteristics and potentially affected human populations located near the Project area, as well as the associated radiological conditions.

The level of detail to include in the system description is proportionate to the information needed for a radiological public safety assessment. That means the system description is intended to provide a clear representation of the features of the system relevant to the potential impacts under evaluation and, therefore, does not necessarily require a comprehensive and detailed description of all aspects of the system.

The section is structured as follows. Section 3.2 presents the regional and local setting of the Project. Section 3.3 describes the Project, processes and associated infrastructure as well as the waste or by-products generated as part of these processes, highlighting the areas and activities that may contribute to the release and dispersion of naturally occurring radionuclides into the environment. With the various specialist studies prepared as part of the ESHIA process for the Project as the primary reference, Section 3.4 summarises the baseline environmental conditions and the population characteristics observed near the Project area. Section 3.5 summarises the available radiological data and information available for the Project at present.

3.2 Project Location

Figure 1.2 and Figure 1.3 present the regional location of the Project area. Figure 3.1 presents a more local locality map showing the location of the Savuka TSF Complex within the Mponeng Operations Mining Right. The Savuka TSF Complex is located at 26°26'11.85"S; 27°21'11.38"E.

3.3 Project Description

The Project was briefly introduced in Section 1.1. Presented here is a more detailed description of the Project and the associated activities and surface infrastructure.

The Savuka TSF Complex is located in the north-western corner of the surface operations area (see Figure 3.1). This TSF was used to serve the Savuka gold plant and contains residues of ore mined at both the Savuka and TauTona shafts. The Savuka TSF consists of four compartments. Construction of the northern two compartments (No. 5a & 5b) commenced in 1971, followed by commissioning of the southern compartments (No. 7A and 7B TSF) in 1979. The No. 7 RWD is situated on the western side of the Savuka TSF complex and comprises two RWDs and an emergency pollution control dam, with a combined capacity of 279,400 m^3. A trench on the southern side of the Savuka TSF gravitates water that drains from the Savuka TSF against the topographical gradient to the No. 7 RWD.

The Savuka TSF comprises Compartments 5A, 5B, 7A and 7B and covers an area of about 325 ha, with a height of about 30 m. Final treated pulp residue from the Savuka processing plant is currently deposited onto Compartments 7A and 7B. Water is decanted using the penstocks at the centre of the facility and is piped into the RWDs. The water in the RWDs is pumped back to the plant as process water. The delivery pipelines to the TSFs are open-end discharge and the tipping area is controlled by manual operation of the discharge valves. Conventional hand packing and mechanical ditching methods construct the sidewalls.

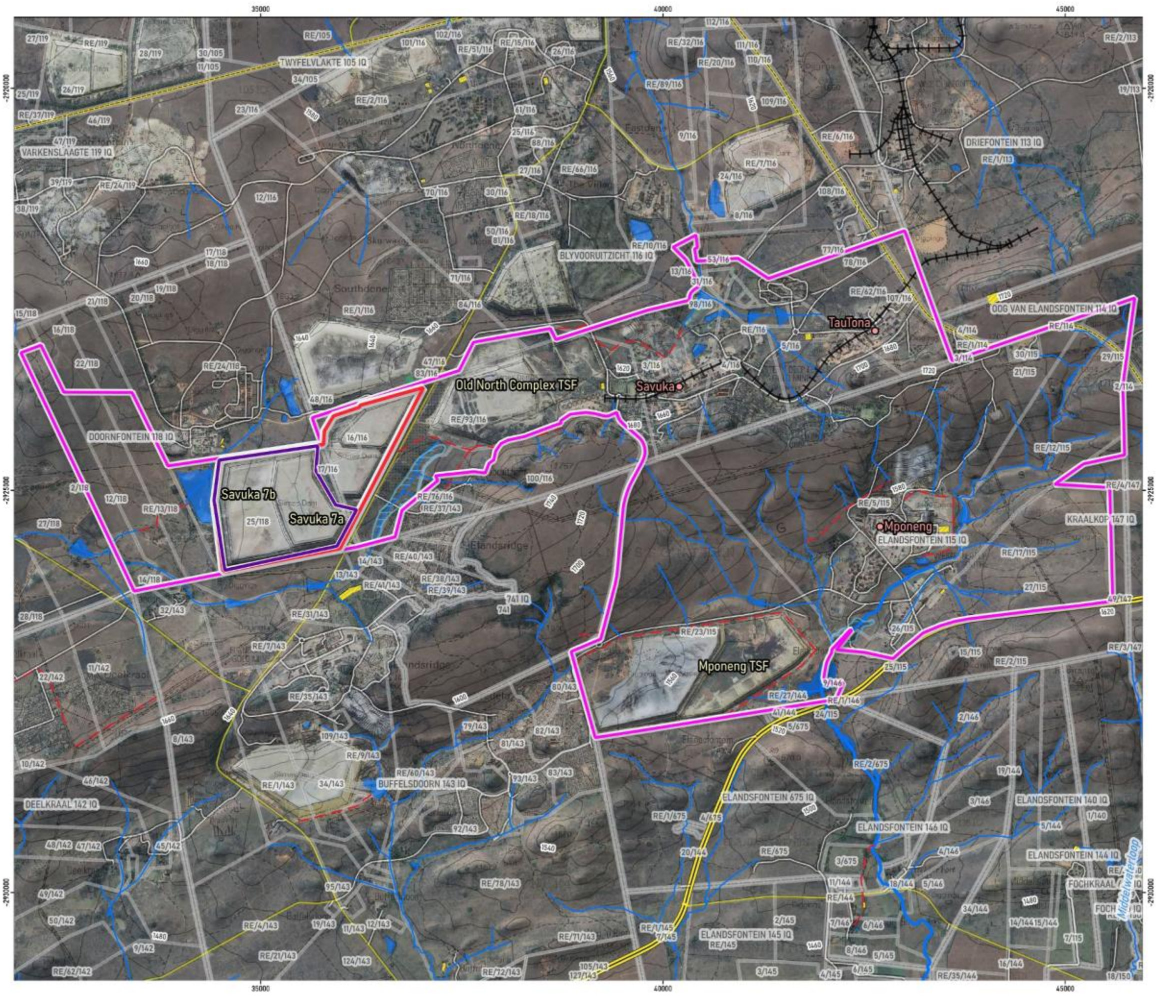


Figure 3.1 The location of the Savuka TSF Complex relative to the Mining Right of the Mponeng Operations (HydroLogic, 2025).

The Savuka 7A and 7B TSFs are approaching their final and approved height. The current planned Life of Mine (LoM) for the West Wits region exceed the available deposition capacity of these TSFs. Accordingly, a feasibility assessment is undertaken to increase the height of the Savuka 7A and 7B TSFs by between 5m to 10m.

The TSFs are constructed and operated through a drywall paddock system. However, it is proposed to change the deposition method to cycloning. This will lengthen the deposition timeframe up to the currently approved height, with cyclone deposition continuing into the height extension. No additional infrastructure is proposed as part of the height extension over and above the conversion to cyclone deposition.

3.4 Description of the Baseline Environment

3.4.1 General

The purpose of this section is to provide a summary description of the environmental baseline conditions associated with the Project area. Within the conceptual assessment framework presented in Figure 1.5, this information would provide input into understanding the potential distribution of radioactivity released from the Project into the environment (e.g., atmosphere, groundwater, and surface water), the accumulation of radioactivity in the associated environmental media and the subsequent interaction of members of the public with the impacted environmental media.

The environmental baseline conditions observed near the Project area are described in a series of specialist studies that serve as a basis and input into the radiological public safety and impact assessment process for the Project (Airshed, 2025; Equispectives, 2020; HydroLogic, 2025; MvB Consulting, 2025). These reports were used and referenced for information on the topography and drainage, geology and hydrogeology, soils, meteorological conditions, as well as the human behavioural and social conditions as appropriate and justified.

3.4.2 Topography

The area is part of the Highveld region and has an average elevation of about 1,600 metres above mean sea level (mamsl). Figure 3.2 shows that the topography changes from 1,740 mamsl on the hill, referred to as the Gatsrant, and slopes towards the Wonderfontein Spruit at 1,465 m above sea level.

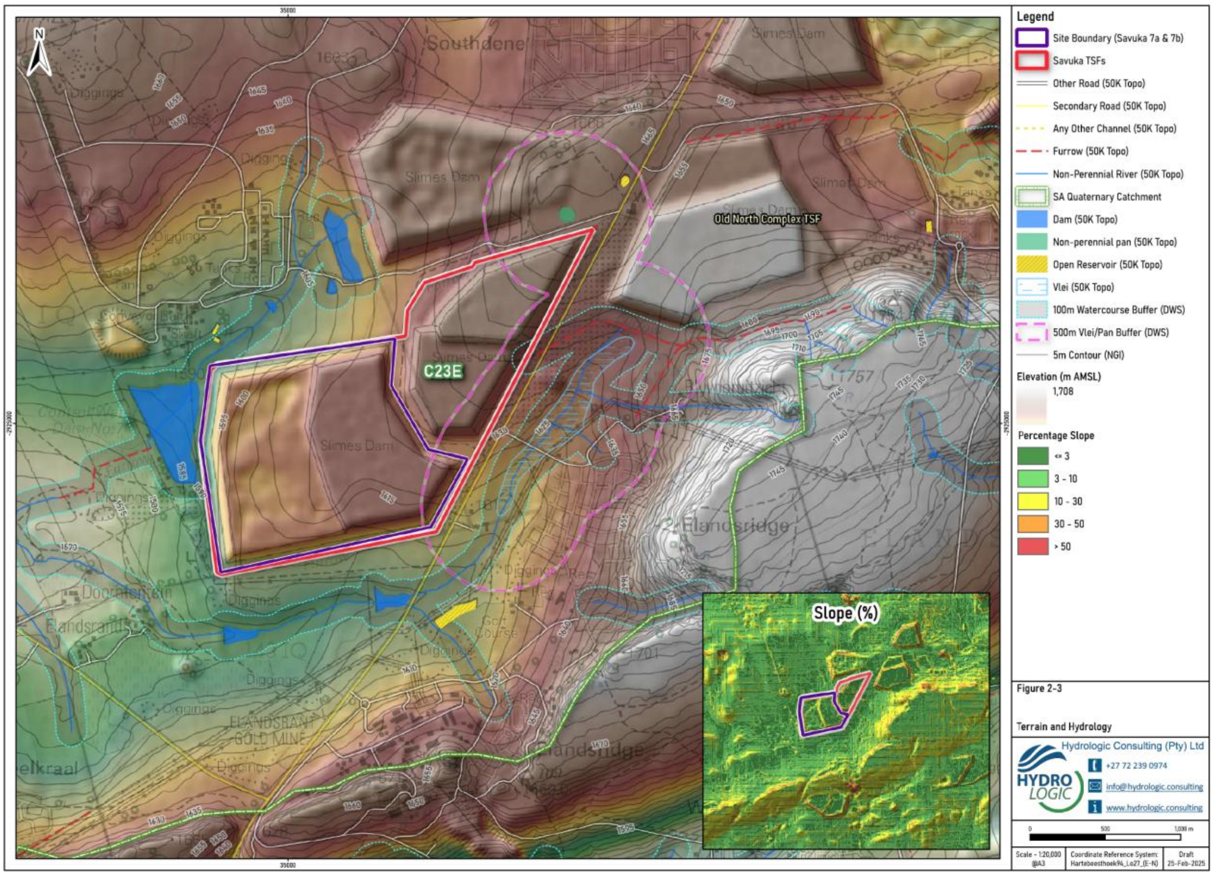


Figure 3.2 Locality map showing the local topography and drainage of the Project area (HydroLogic, 2025).

3.4.3 Drainage and Catchment

Figure 3.3 presents the regional surface water network, while Figure 3.2 also illustrates the local hydrological setting of the Project area. Figure 3.2 and Figure 3.3 show that the Savuka TSF falls within quaternary catchment C23E and is drained by an unnamed tributary of the Wonderfontein Spruit (also referred to as the Mooirivierloop). The drainage area forms part of the Vaal Water Management Area. The surface water flow from the TSF is to the west and southwest.

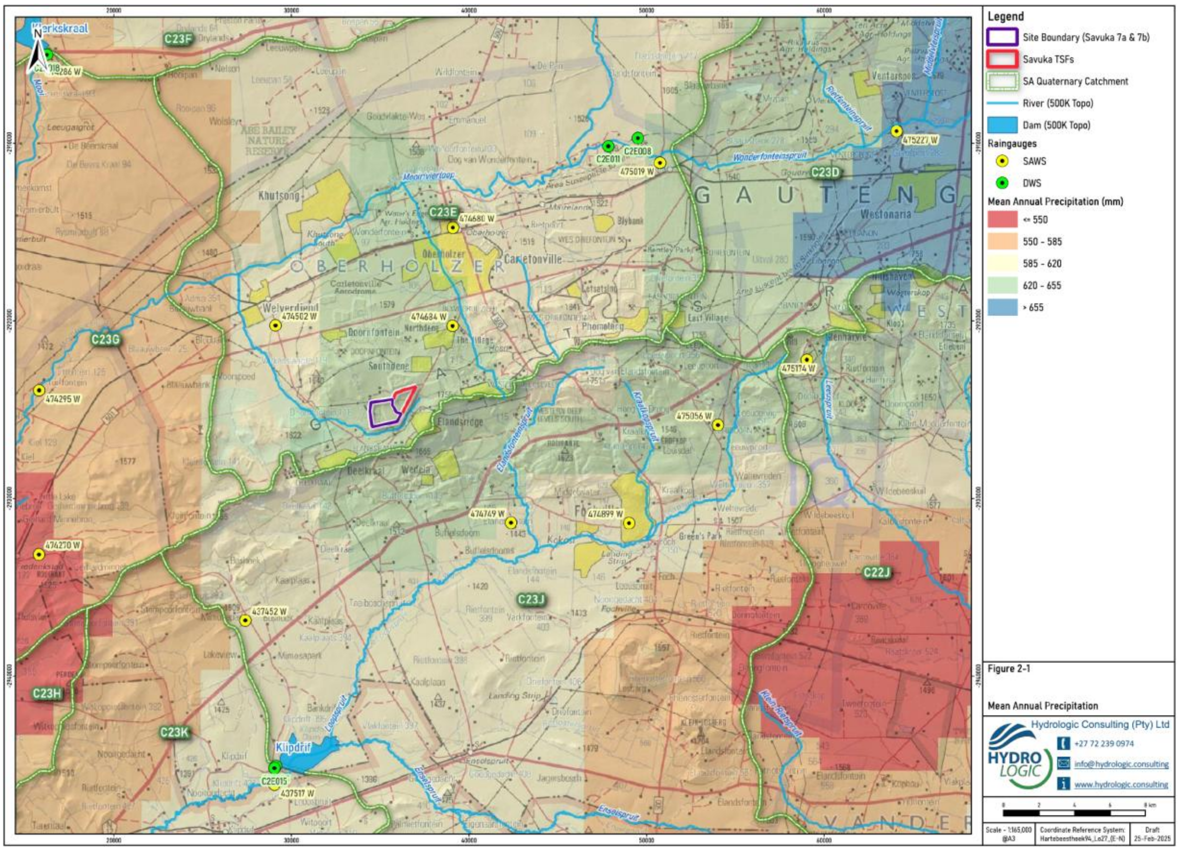


Figure 3.3 Locality map showing the regional surface water network and features of the Project area (HydroLogic, 2025).

The river and streams near the site are unnamed, with the 1:50,000 topographical map data illustrating two non-perennial river systems to the north and south, both of which converge to the west of the site. The southern system is larger than the northern system. However, neither area is sufficiently sized to enable perennial flows.

The southern system is associated with a vlei and has upstream furrows directing runoff from part of the greater Mponeng Operation (south of the Old North Complex TSF). Two small dams are noted. The northern system is characterised by two larger dams, both of which appear to be return water dams when reviewing Google Earth imagery. A single non-perennial pan is noted to the northeast of the site.

3.4.4 Geological Setting

3.4.4.1 General

According to MvB Consulting (2025), the regional surface geology includes the following (in chronological order):

- Witwatersrand Supergroup.
- Ventersdorp Supergroup.
- Transvaal Supergroup.
- Karoo Supergroup.

Figure 3.4 presents the stratigraphy, while the regional surface geology is presented in Figure 3.5. Presented here is an overview of the regional geology as presented in MvB Consulting (2025).

3.4.4.2 Witwatersrand Supergroup

The Witwatersrand Basin is a thick sequence of shale, quartzite and conglomerate. There are two main divisions, a lower predominantly argillaceous unit, known as the West Rand Group and an upper unit, composed almost entirely of quartzite and conglomerates, known as the Central Rand Group.

The West Rand Group is divided into three subgroups, namely the Hospital Hill, Government Reef and Jeppestown. These rocks comprise mainly shale, but quartzite, banded ironstones, tillite and intercalated lava flows are also present. The rocks were subjected to low-grade metamorphism, causing the shale to become more indurated and slaty. The original sandstone was recrystallised to quartzite.

The Central Rand Group is divided into the Johannesburg and Turffontein Subgroups and is composed largely of quartzite, within which there are numerous conglomerate zones. The conglomerate zones may contain any number of conglomerate bands, with individual bands interbedded with quartzite. The upper conglomerates are usually thicker with coarser fragments. An argillaceous zone known as the Booysens Shale (also known as the Kimberley Shale) separates the Johannesburg and Turffontein Subgroups.

The economic gold placers (reefs) are restricted to the Central Rand Group of the Witwatersrand Supergroup. A primary economic horizon that is mined in all the mines in the region is the Ventersdorp Contact Reef (VCR), at the base of the Ventersdorp lava. The Carbon Leader is also mined extensively in the region.

3.4.4.3 Ventersdorp Supergroup

The younger Ventersdorp Supergroup overlies the Witwatersrand rocks. Although acid lavas and sedimentary intercalations occur, the Ventersdorp is composed largely of andesitic lavas and related pyroclastics. The Ventersdorp Supergroup consists of the Platberg Group and the Klipriviersberg Group. The Klipriviersberg Group consists of the Alberton and Westonaria Formations.

3.4.4.4 Transvaal Supergroup

Overlying the Ventersdorp Lavas are the Black Reef quartzite and dolomite of the Transvaal Supergroup. The Black Reef quartzite comprises coarse to gritty quartzite with occasional economically exploitable conglomerates (reefs). The entire area was peneplained in post-Ventersdorp time, and it was on this surface that the Transvaal Supergroup was deposited, some 2200 million years ago. The deposition commenced with the Kromdraai Member with the Black Reef at its base. The Black Reef has eroded the Witwatersrand outcrop areas and, as a result, contains zones (reefs) in which gold is present. The occurrence of the gold is not as widespread as in the Witwatersrand and is mainly restricted to north-south trending channels. The Black Reef is overlain by a dark, siliceous quartzite with occasional grits or small pebble bands. The quartzite grades into black carbonaceous shale. The shale then grades into the overlying dolomite through a transition zone approximately 10 m thick.

Overlying the Kromdraai Member is the dolomite of the Malmani Subgroup of the Chuniespoort Group. The dolomites vary between 200 m and 1,500 m in thickness. Only the two lower formations of the Malmani Subgroup are present in the study area. The lowermost is the Oaktree Formation, which is succeeded southward by the Monte Christo Formation.

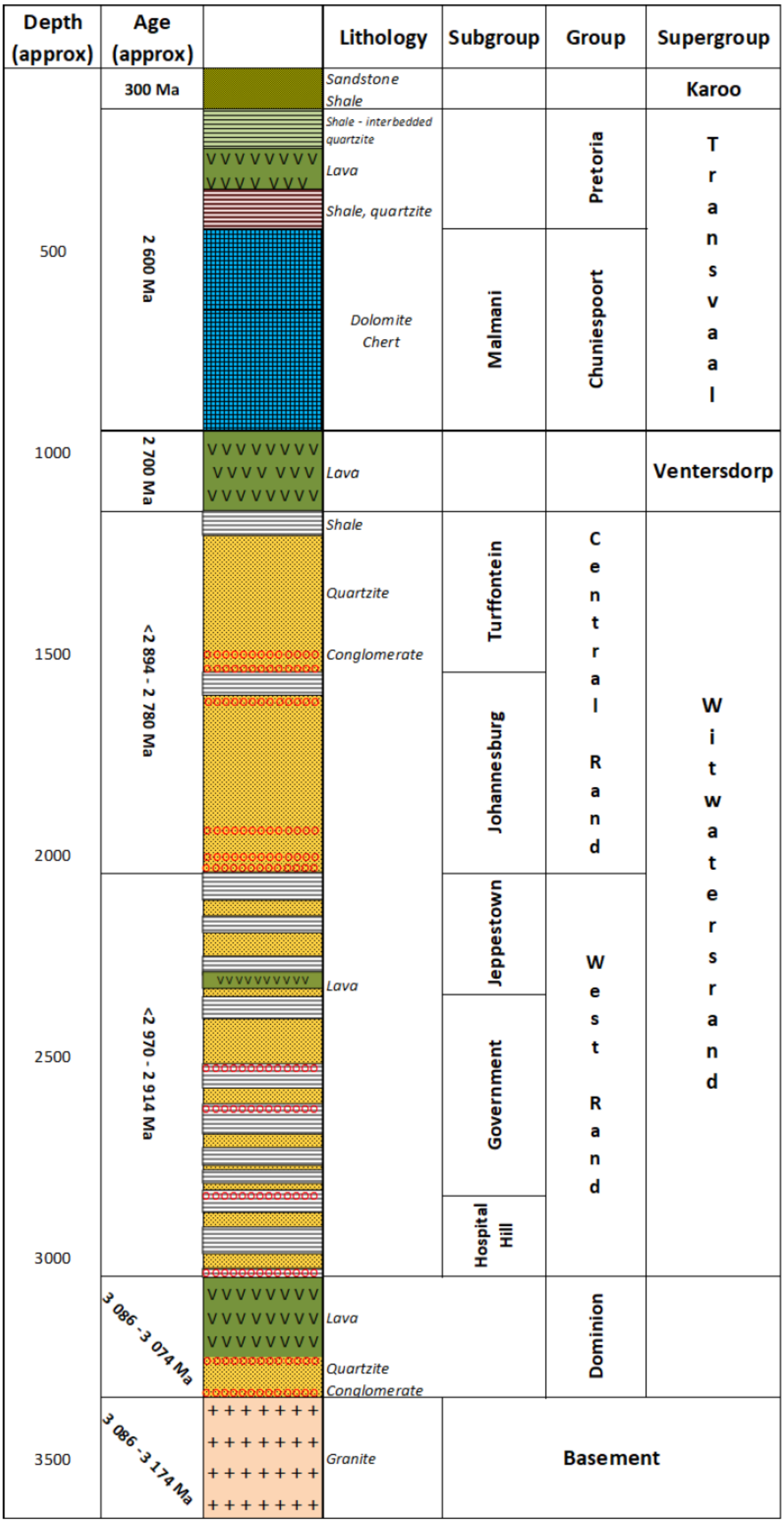


Figure 3.4 The stratigraphy of the Project area (MvB Consulting, 2025).

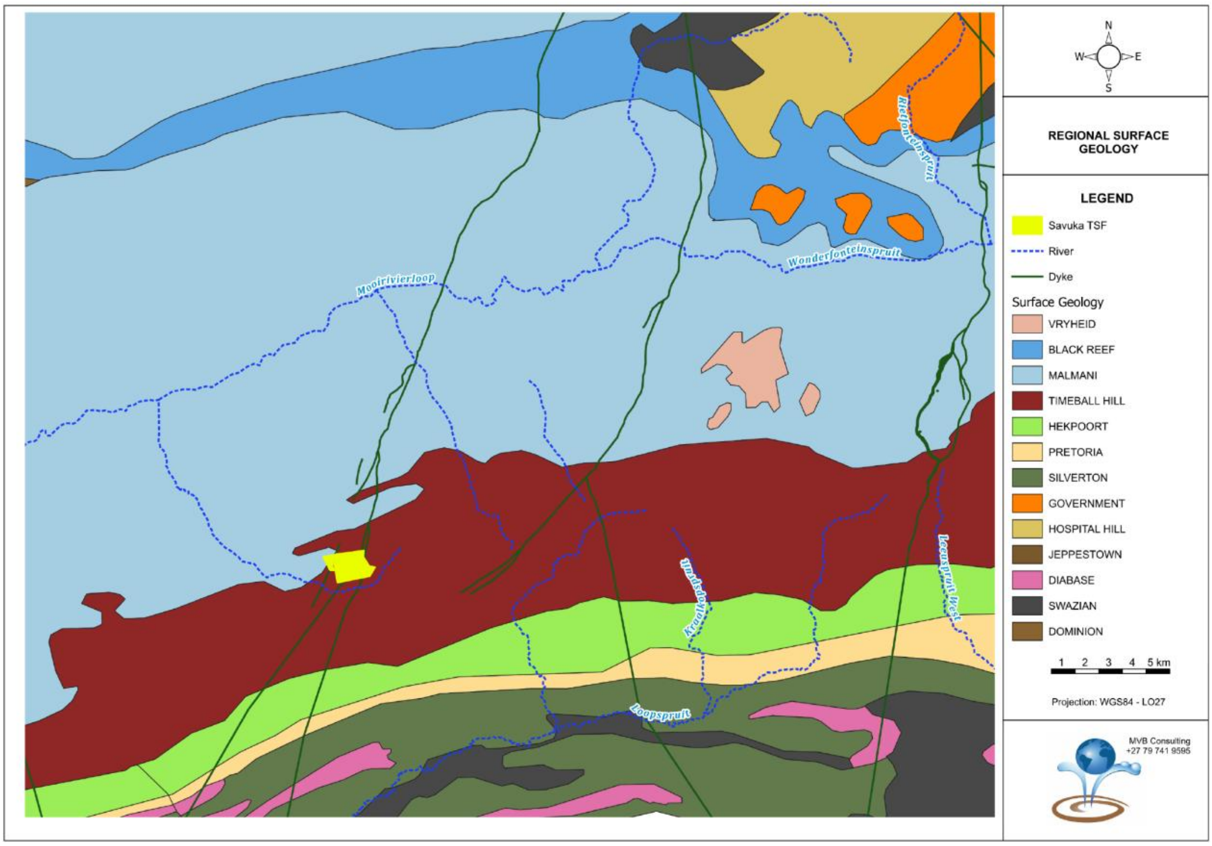


Figure 3.5 **The regional surface geology near the Project area (MvB Consulting, 2025).**

The Oaktree Formation consists of chert-poor, homogenous, dark-grey dolomite containing interbeds of carbonaceous shale, which decrease in frequency and thickness from the base of the formation upwards. Columnar stromatolites are numerous within this sequence, and the formation follows conformably on the Black Reef Formation with a transitional mixed zone consisting of carbonaceous and calcareous, argillaceous and arenaceous sediments.

The Monte Christo Formation conforms to the Oaktree Formation. The Monte Christo Formation consists of alternating chert-rich and chert-poor, dark to light-grey dolomite and has an estimated thickness of 700 m. A 1.5 m thick chert layer, consisting of 10 cm to 15 cm thick layers of chert separated by manganese-rich bands, is present towards the base of the formation. Layers of crystalline, coarse-grained dark dolomite, laminated calcareous shale, shaley dolomite and fine-grained white dolomite occur in the sequence, parts of which are chert-rich, containing numerous chert layers, 10 cm to 20 cm in thickness.

The dolomite hosts the primary and most significant aquifer in the study area. The Pretoria Group rocks overlie the dolomite aquifer and is also the surface geology at Mponeng mine. The Rooihoogte Formation forms the basal member of the Pretoria Group, consisting of the Bevets conglomerate, shale and quartzite. The Bevets conglomerate varies in thickness between 3 m and 60 m.

Overlying the Bevets conglomerate is shale and sporadically developed quartzite, referred to as the Pologround quartzite. Where developed the Pologround quartzite is overlain by 150 m – 200 m of pink to purple shales, forming the basis of the Timeball Hill Formation. The shale is overlain by quartzite, which forms the linear northwesterly trending ridges in the central portion of the study area.

Further south are the Hekpoort and Strubenkop Formations. These formations consist predominantly of andesite lava (Hekpoort Formation) and ferruginous shale (Strubenskop Formation). The weathering of the shale and the lava results in grey to dark grey silty sand and clay.

The Hekpoort Andesite Formation is visible through several scattered lava outcrops, giving it an uneven landscape. The quicker erosion of the softer tuffaceous sediments, interbedded between the amygdaloidal lava flows, is believed to be the cause of the topographical features. The weathering of the Hekpoort Andesite results in dark to reddish–brown silty sand. These can contain fragments of lava and quartz ranging from pebble to cobble size.

The Strubenkop Formation achieves a maximum thickness of 130 m and consists predominantly of ferruginous shale. The contact between the Hekpoort and Strubenkop Formations is difficult to identify in the field, especially since localised intrusions of younger dolerite occur.

Most of these rocks, especially in the lower-lying areas, are concealed beneath a cover of younger sedimentary rocks, residual soils and alluvium. There is also a significant accumulation of hillwash and transported sediments. The floodplains of the Loopspruit and Leeuspruit tributaries contain grey, silty clayey soils.

3.4.4.5 Transvaal Supergroup

The Karoo Supergroup was deposited approximately 345 million years ago. It commenced with the glacial period, during which most of South Africa was covered by a thick sheet of ice. This ice cap slowly moved towards the south, causing extensive erosion as a result of accumulated debris at the base. This debris was eventually deposited as the Dwyka tillite. The Dwyka, which generally forms an impermeable barrier to the downward percolation of groundwater, is absent in most parts of the study area. Younger superficial deposits cover the Karoo in places. The Karoo strata filled the extremely rugged paleo-topography of the underlying karst dolomite to form a relatively even topography that is visible today.

3.4.5 Geohydrological Setting

3.4.5.1 General

The geohydrological setting of the Project area is described in MvB Consulting (2025) and includes aspects such as borehole information, aquifer types, groundwater use, aquifer parameters and recharge, groundwater gradients and flow, groundwater quality and aquifer classification. Groundwater occurrences in the study area are predominantly restricted to the following types of terrains.

- Weathered and fractured rock aquifer in the Ventersdorp and Transvaal Formations.
- Dolomitic and Karst Aquifers.

Although the dolomite aquifer is the most prominent aquifer in the region, it does not play any role in the activities at the Savuka TSFs.

3.4.5.2 Weathered and Fractured Aquifer

Groundwater occurs in the near-surface geology in the weathered and fractured sedimentary deposits (quartzite and shale) of the Transvaal strata. The lava of the Hekpoort Formation has similar weathering characteristics to those of the shale and is therefore deemed as the same aquifer. These formations are not considered to contain economic and sustainable aquifers, but localised high-yielding boreholes may, however, exist where significant fractures are intersected.

Groundwater occurrences are mainly restricted to the weathered formations, although fracturing in the underlying “fresh” bedrock may also contain water. Experience has shown that these open fractures seldom occur deeper than 60m. The base of the aquifer is the impermeable quartzite, shale and lava formations, whereas the top of the aquifer would be the surface topography. The groundwater table is affected by seasonal and atmospheric variations and generally mimics the topography. These aquifers are classified as semi-confined. The two aquifers (weathered and fractured) are mostly hydraulically connected, but confining layers such as clay and shale often separate the two. In the latter instance, the fractured aquifer is classified as confined. The aquifer parameters, which include transmissivity and storativity, are generally low, and groundwater movement through this aquifer is, therefore, also slow.

3.4.5.3 Dolimite Aquifer

Dolomite aquifers in the region are known to contain large quantities of groundwater and are commonly associated with sustainable groundwater abstraction. The water that plagues the underground mining is primarily derived from the dolomite aquifer overlying the workings.

The depth of groundwater in the region ranges from 4 m to 41 m below the surface in the non-dewatered groundwater compartments (Zuurbekom and Boskop/Turffontein). This is in contrast to the groundwater levels above 200 m in the dewatered compartments (Gemsbokfontein West, Venterspost, Bank and Oberholzer). The unsaturated zone in the dolomite aquifer ranges from weathered wad material and Karoo sediments within deep solution cavities or grykes (deeply weathered paleo valley within the dolomite) to relatively fresh fractured dolomite between major solution cavities and at depth.

The shallow weathered dolomite aquifer has been formed because of the karstification, which has taken place before the deposition of the Karoo sediments on top of the dolomites. There is general agreement that this aquifer is a significant source of water within the dolomite. The base of the weathered dolomite (aquifer) is irregular, and there are zones of deep weathering (grykes). The maximum depth to the base of this aquifer is in the order of 200 m below the surface.

The non-weathered dolomite approximates a traditional fractured rock aquifer at the depth where dissolution has been less pronounced. It is extremely unlikely that any significant groundwater flow occurs below these depths except along intersecting structural conduits to the underlying mine workings.

3.4.5.4 Relationship between the Weathered / Fractured Aquifer and the Dolomitic Aquifer

Evidence has shown that there is very little connectivity between the weathered/fractured aquifer and the underlying dolomite aquifer. Even in compartments where the dolomite aquifer is dewatered, the groundwater levels in the weathered/fractured aquifer remain unaffected.

Figure 3.6 illustrates the relationship between the fractured and dolomite aquifers and also shows the degree of karstification. Based on the exploration borehole information, it appears that the dolomite that is covered by Transvaal strata is less karstified, and the dolomite aquifer is therefore not as well developed. The mines situated south of the “Gatsrant” are generally dry mines with limited groundwater inflow, whereas the mines north of the “Gatsrant” are plagued by high groundwater inflow volumes. This is, in part, attributed to the well-defined karstification in the northern dolomites.

3.4.5.5 Groundwater Use

According to MvB Consulting (2025), there are no groundwater users downstream from the Savuka TSF complex.

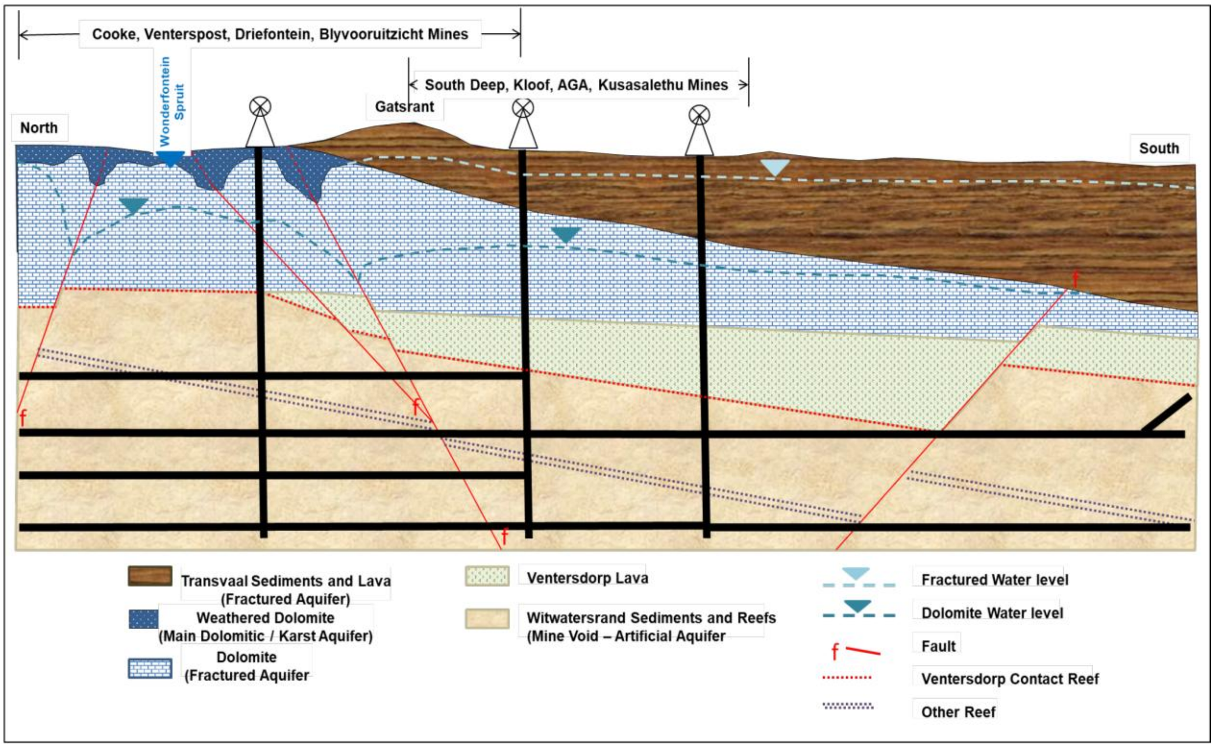


Figure 3.6 Schematic geological section showing the relationship between the aquifers in the study area (MvB Consulting, 2025).

3.4.5.6 Aquifer Parameters

Table 3.1 summarises the aquifer parameters in the weathered and fractured aquifer as derived from pump testing that was undertaken in the region.

Table 3.1 Transmissivity and hydraulic conductivity values in the weathered and fractured aquifers.

Borehole	Transmissivity	Hydraulic Conductivity	Aquifer
	$m^2.day^{-1}$	$m.day^{-1}$	
RGC01	0.75	0.02	Dyke contact - fractured aquifer
RGC02	1.12	0.12	Weathered sandstone, overlying dolerite
RGC02d	0.39	0.02	Fractured dolerite
RGC03	0.42	0.01	Dyke contact - fractured aquifer
RGC04	0.63	0.06	Weathered sandstone, overlying dolerite
RGC04d	0.43	0.02	Fractured dolerite
BH 0	0.49	0.01	Fractured shale, quartzite
SD1	1.35	0.0604	Weathered shale
SD4	0.65	0.0078	Weathered shale
SD6	0.04	0.0015	Weathered shale
SD7	0.38	0.0216	Weathered shale
SD11	0.1	0.0068	Weathered shale
SD12	3.39	0.2827	Weathered shale
Geometric Mean	**0.50**	**0.02**	

3.4.5.7 Aquifer Recharge

Groundwater recharge (R) for the study area was calculated using the chloride method (Bredenkamp *et al.*, 1995) and is expressed as a percentage of the Mean Annual Precipitation (MAP). The average rainfall in the area is approximately 646 mm per annum. The average chloride in rainfall for areas inland is approximately 1.0 $mg.L^{-1}$ and the harmonic mean of the chloride concentration values in groundwater samples obtained from the mining area is 25.88 $mg.L^{-1}$. Using the chloride method, the recharge was calculated to be in the order of 3.9% of the MAP.

3.4.5.8 Groundwater Flow and Gradients

In most geological terrains, the groundwater mimics the topography, and to test if this is the case within the study area, the available groundwater levels were plotted against the topography (represented by the borehole collar elevations). The result of this assessment is presented in Figure 3.7. This graph indicates a very good correlation (96%) between the topography and the groundwater level, which suggests that groundwater flow will follow the topographical gradient.

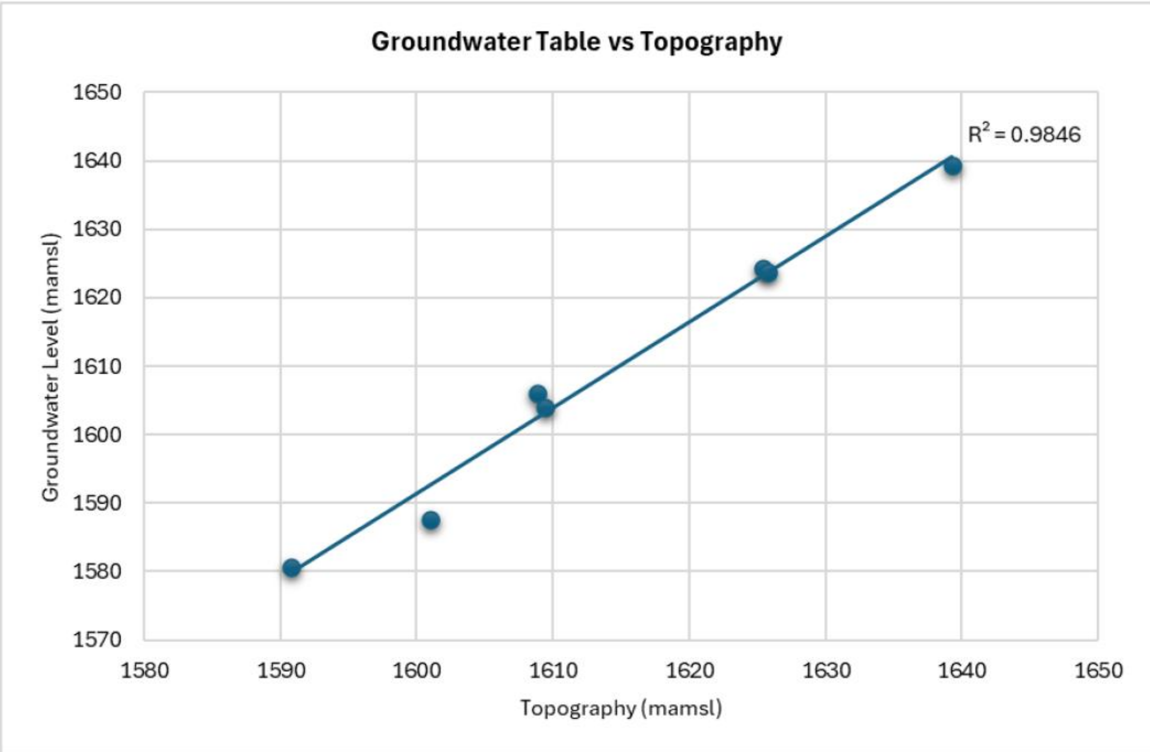


Figure 3.7 Correlation between the topography and the groundwater level near the Project area (MvB Consulting, 2025).

Figure 3.8 depicts the groundwater level elevations, which, as expected, mimic the surface contours. Groundwater flow is perpendicular to the groundwater contours and flows predominantly towards the southwest. The groundwater gradient averages about 0.64% in the area. The porosity of the aquifer material is estimated to be between 3% to 7%. A value of 5% was used.

3.4.5.9 Mass Transport Modelling

Mass transport modelling was performed assuming a source term concentration of 2,500 $mg.L^{-1}$ SO_4 for the tailings seepage and the RWD. Figure 3.9 shows the current simulated SO_4 plume compared to the current SO_4 concentrations.

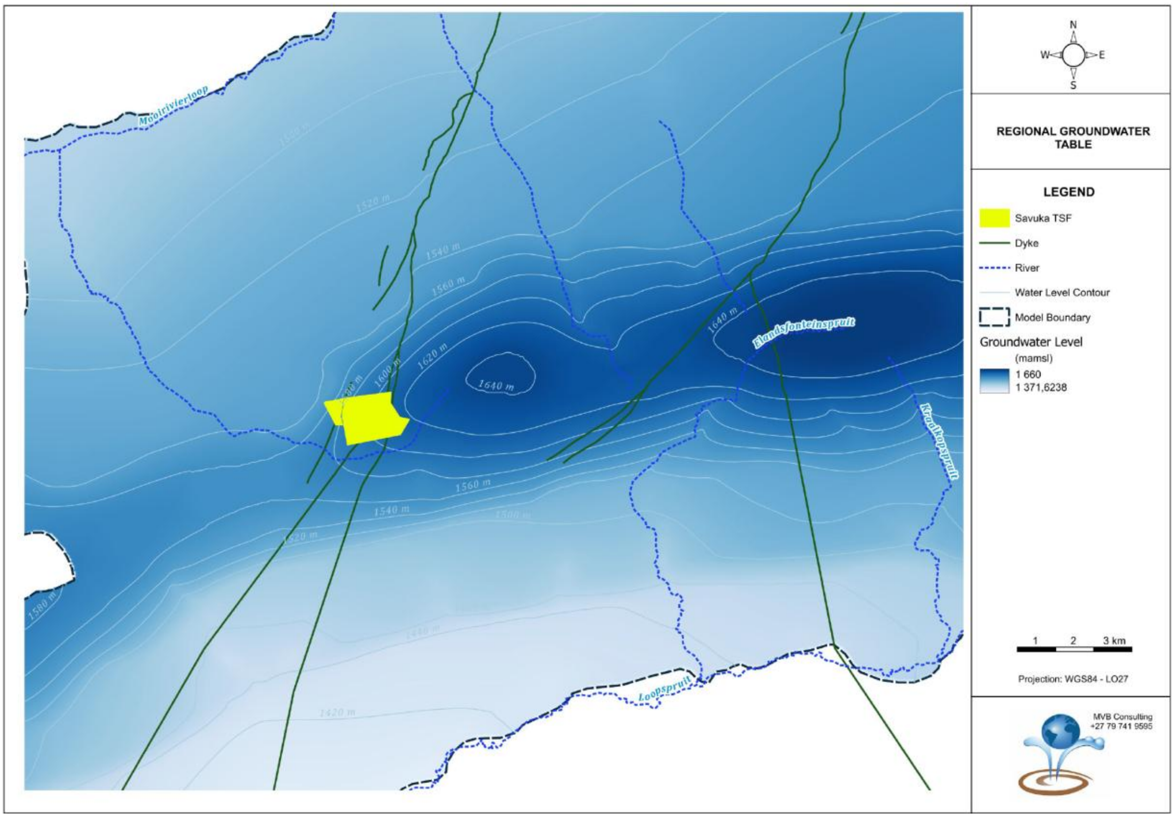


Figure 3.8 **The regional interpolated groundwater gradient near the Project area (MvB Consulting, 2025).**

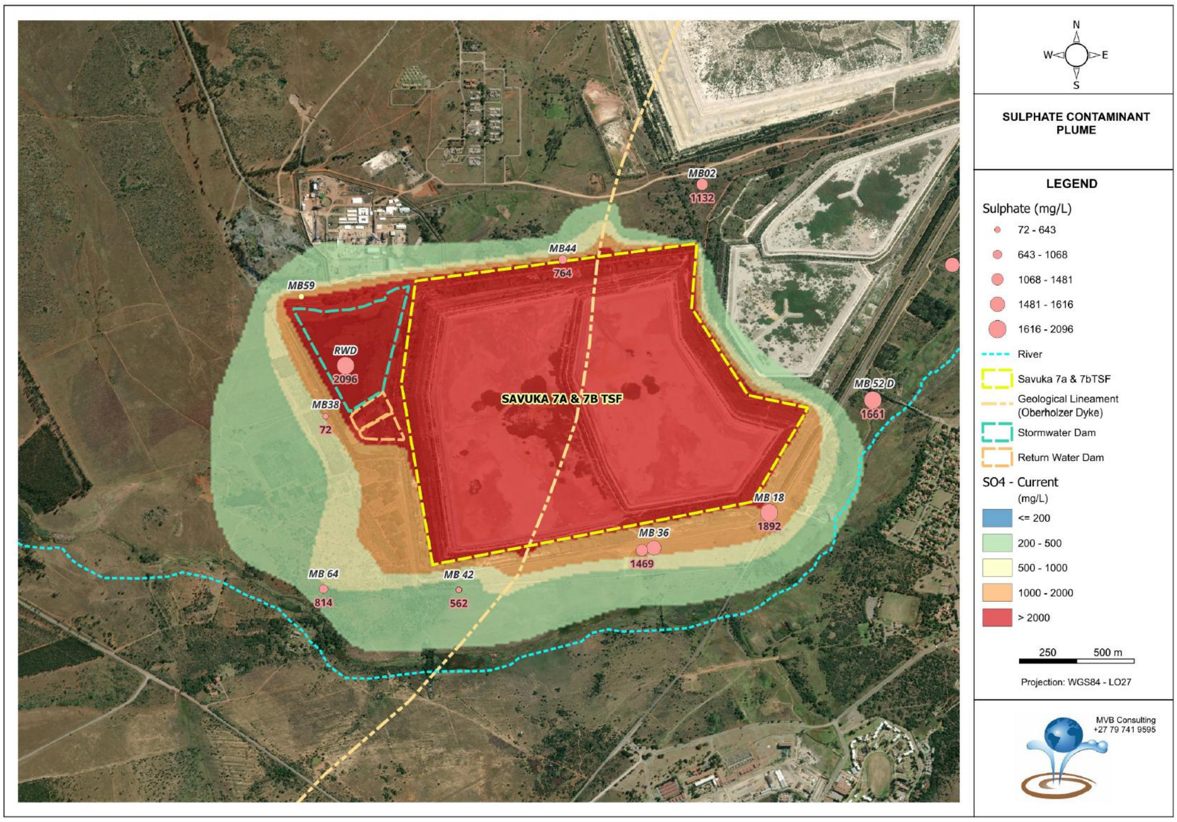


Figure 3.9 **The Current simulated plume compared to the measured SO_4 concentrations (MvB Consulting, 2025).**

For the geohydrological impact assessment, MvB Consulting (2025) performed a series of Scenarios to evaluate the SO_4 plume migration over 50 and 100-year periods. Figure 3.10 depicts the simulated SO_4 plume after 50 years for a do-nothing scenario, while the same results after 100 years are depicted in Figure 3.11.

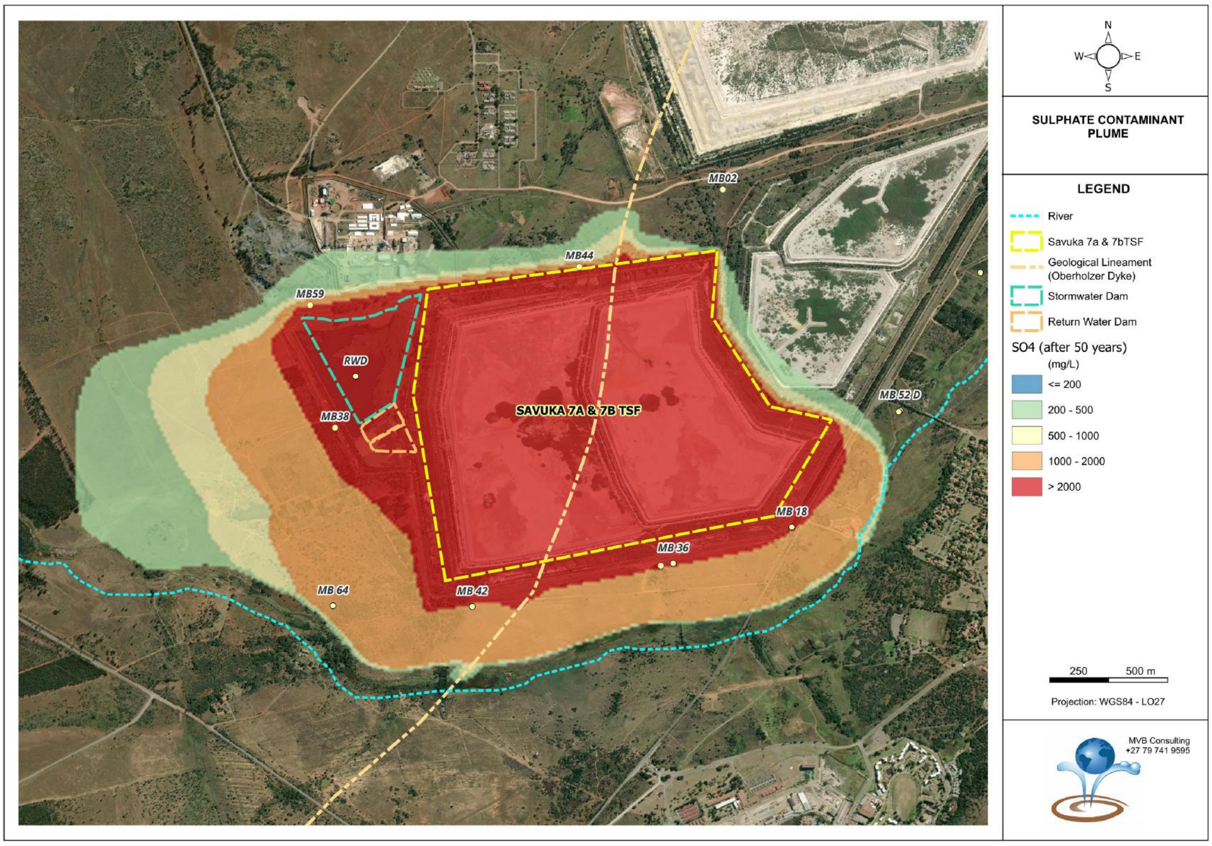


Figure 3.10 The simulated sulphate plume after 50 years (MvB Consulting, 2025).

Figure 3.12 to Figure 3.14 present the SO_4 plume migration results for three mitigation measures: assuming a liner for the RWD (see Figure 3.12), the implementation of phyto-remediation (see Figure 3.13) and assuming the installation of seepage-capturing boreholes (see Figure 3.14). Both options show a reduction in plume migration from the TSF complex towards the west after 50 years.

3.4.6 Meteorological Conditions

3.4.6.1 General

The Project area is located within the Merafong City Local Municipality (LM) of the West Rand District Municipality of the Gauteng Province. The meteorological characteristics of the area presented and used in the Air Quality Impact Assessment (Airshed, 2025) are based on modelled Weather Research and Forecasting Model (WRF) meteorological data for an on-site location for the period 1 January 2022 to 31 December 2024. This data was used to construct wind roses, and general climatic information such as diurnal temperature variations, atmospheric stability estimates and dispersion modelling.

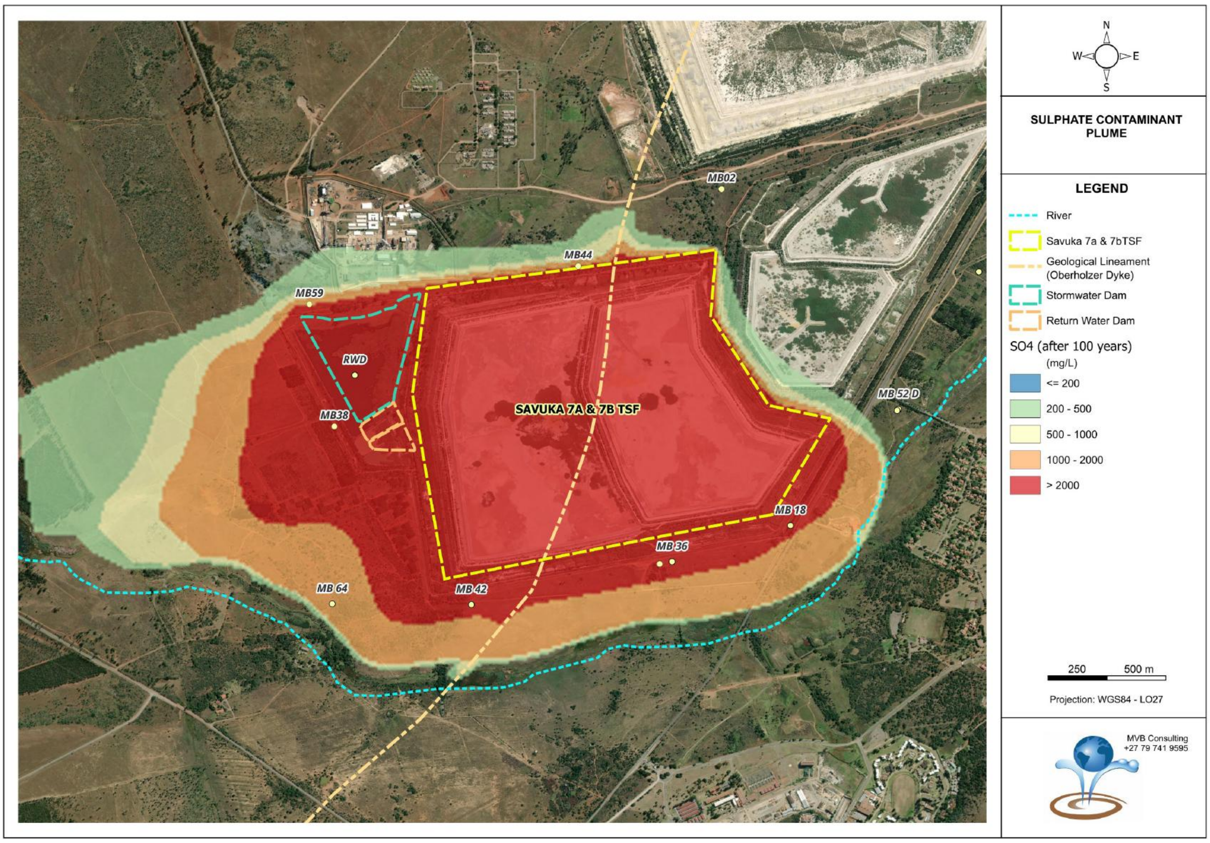


Figure 3.11 **The simulated sulphate plume after 100 years (MvB Consulting, 2025).**

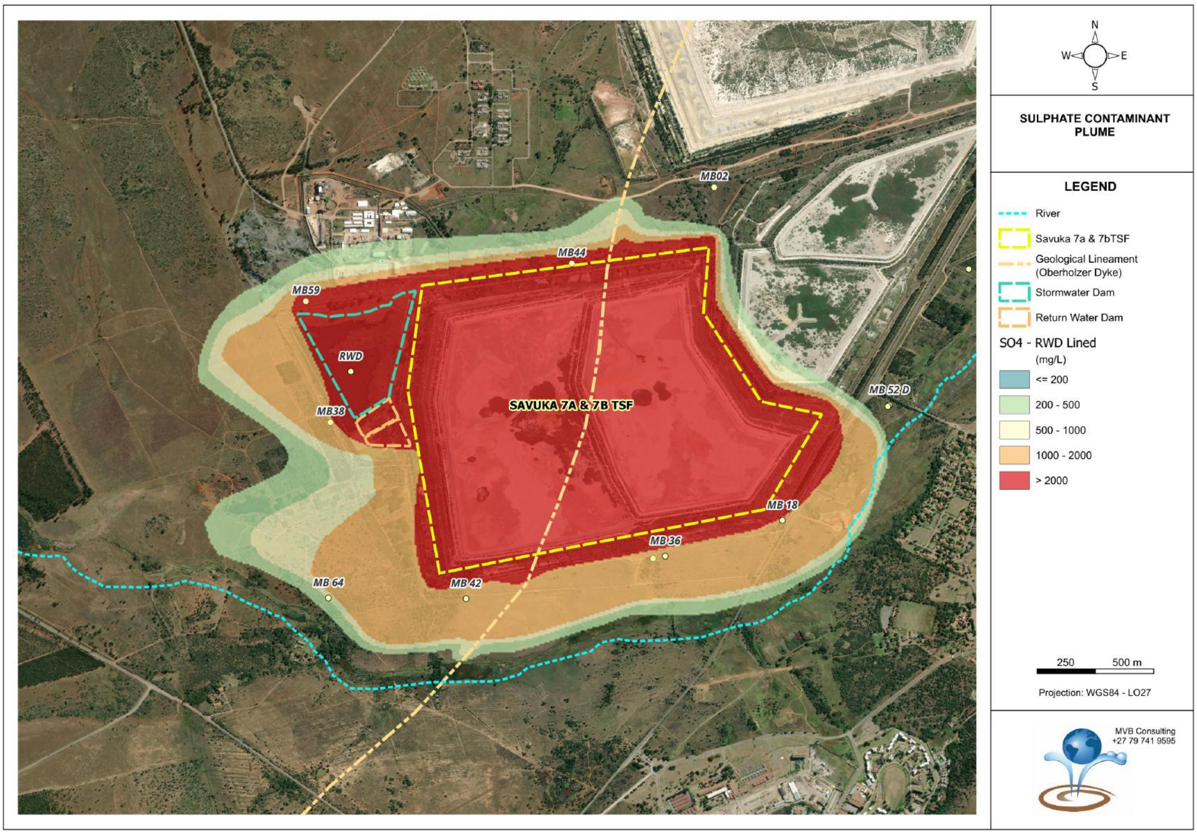


Figure 3.12 **The simulated sulphate plume after 50 years with a liner in the RWD (MvB Consulting, 2025).**

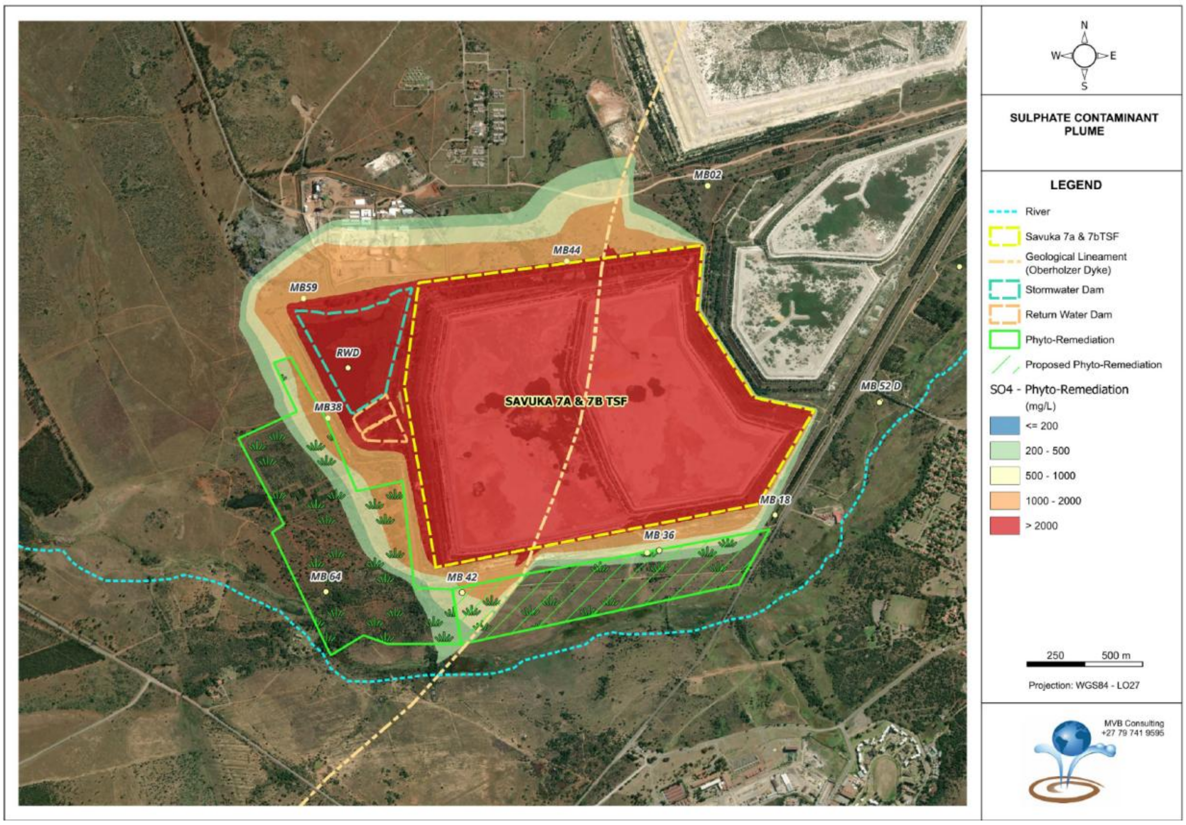


Figure 3.13 **The simulated sulphate plume after 50 years with phyto-remediation fully functional (MvB Consulting, 2025).**

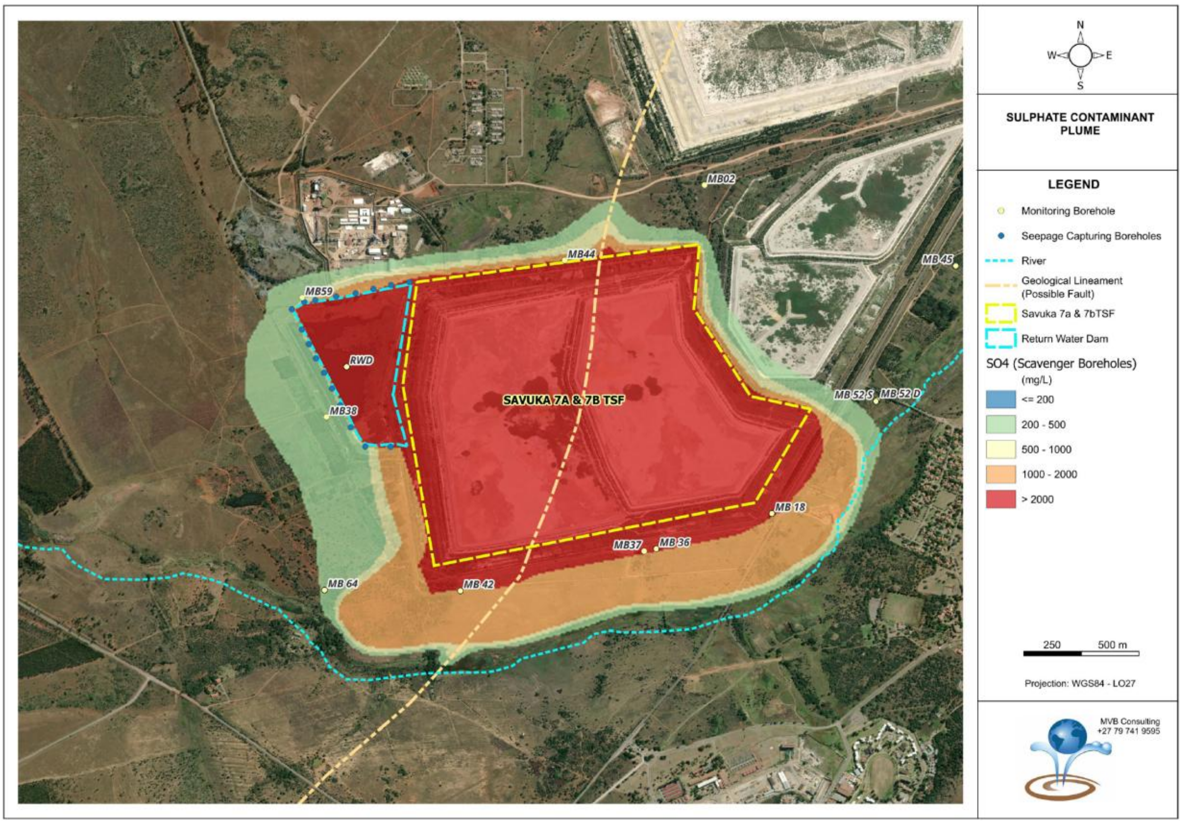


Figure 3.14 **The simulated sulphate plume after 50 years assuming seepage capturing boreholes (MvB Consulting, 2025).**

3.4.6.2 Wind Field

Wind roses comprise 16 spokes, which represent the directions from which winds blew during a specific period. The colours used in the wind roses below reflect the different categories of wind speeds; for example, red represents winds greater than 10 $m.s^{-1}$.

The dotted circles provide information regarding the frequency of occurrence of wind speed and direction categories. The frequency with which calms occurred, i.e. periods during which the wind speed was below 1 $m.s^{-1}$ is also indicated.

The period wind field and diurnal variability in the wind field are shown in Figure 3.15, while the seasonal variations are shown in Figure 3.16.

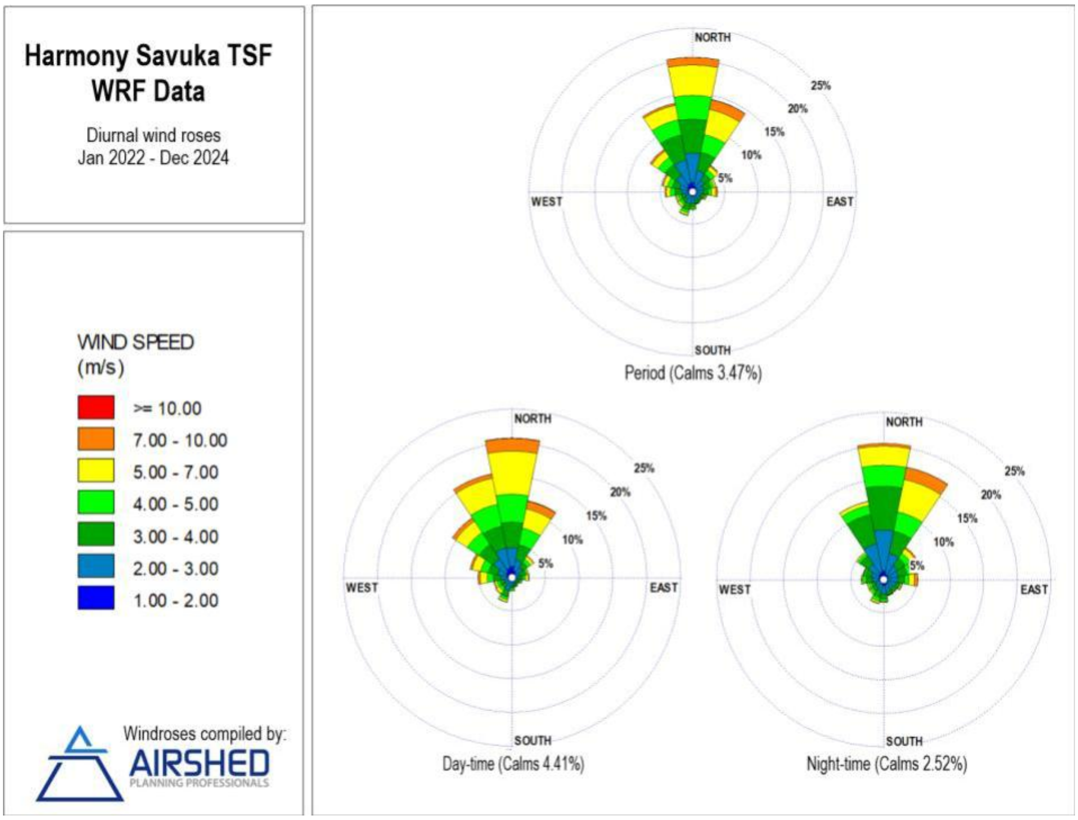


Figure 3.15 Period, day- and night-time wind roses for the Project area (WRF data, January 2022 to December 2024) (Airshed, 2025).

The wind field is dominated by winds from the northerly sector. The strongest winds (>6 m/s) occurred mostly from the north-northeastern sector. Calm conditions occurred 3.5% of the time, with the average wind speed over the period of 3.63 $m.s^{-1}$. Both daytime and night-time show dominant northerly wind fields, with calm conditions 4.4% during the day, and 2.52% during the night. The dominant northerly winds prevail throughout the seasons, with an increase in wind speeds during the spring months in Figure 3.16.

3.4.6.3 Ambient Temperature

Air temperature is important, both for determining the effect of plume buoyancy (the larger the temperature difference between the emissions plume and the ambient air, the higher the plume can rise), and for determining the development of the mixing and inversion layers.

Diurnal and average monthly temperature trends are presented in Figure 3.17. The monthly average and hourly maximum and minimum temperatures are given in Figure 3.18. Temperatures ranged between -4°C and 37°C. The highest temperature occurred in January and the lowest in July. During the day, temperatures increase to reach a maximum at around 14:00. Ambient air temperature decreases to reach a minimum at around 06:00, i.e. just before sunrise.

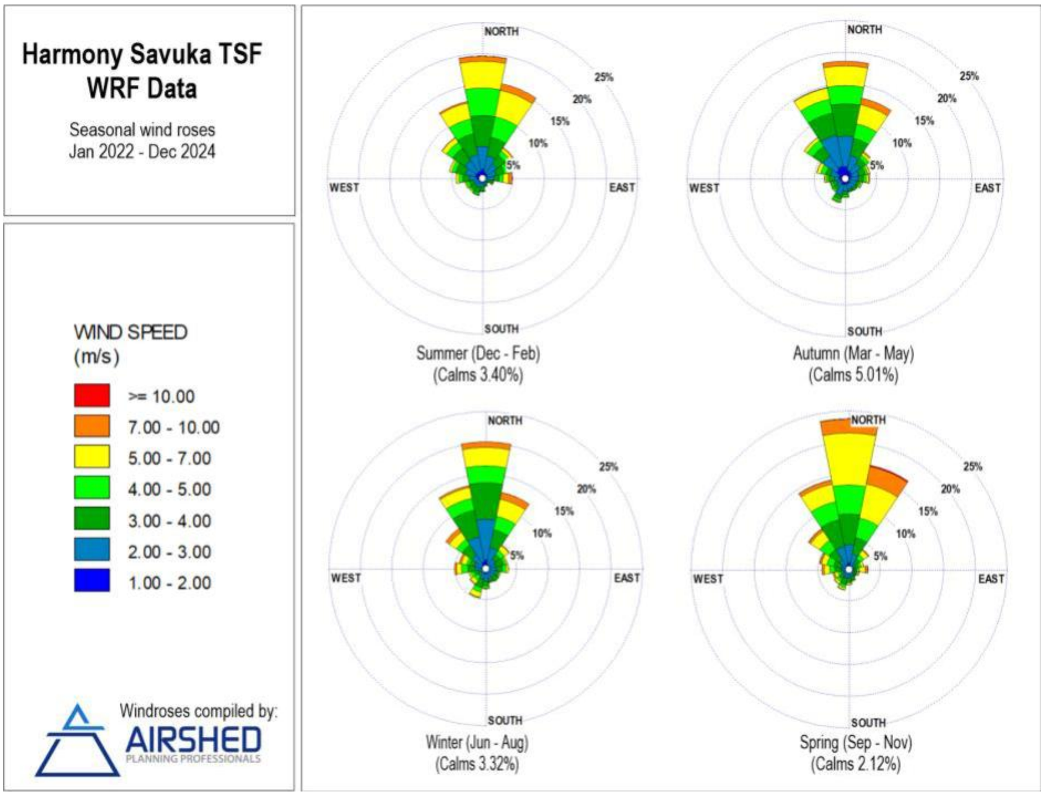


Figure 3.16 Seasonal wind roses for the Project area (WRF data, January 2022 to December 2024) (Airshed, 2025).

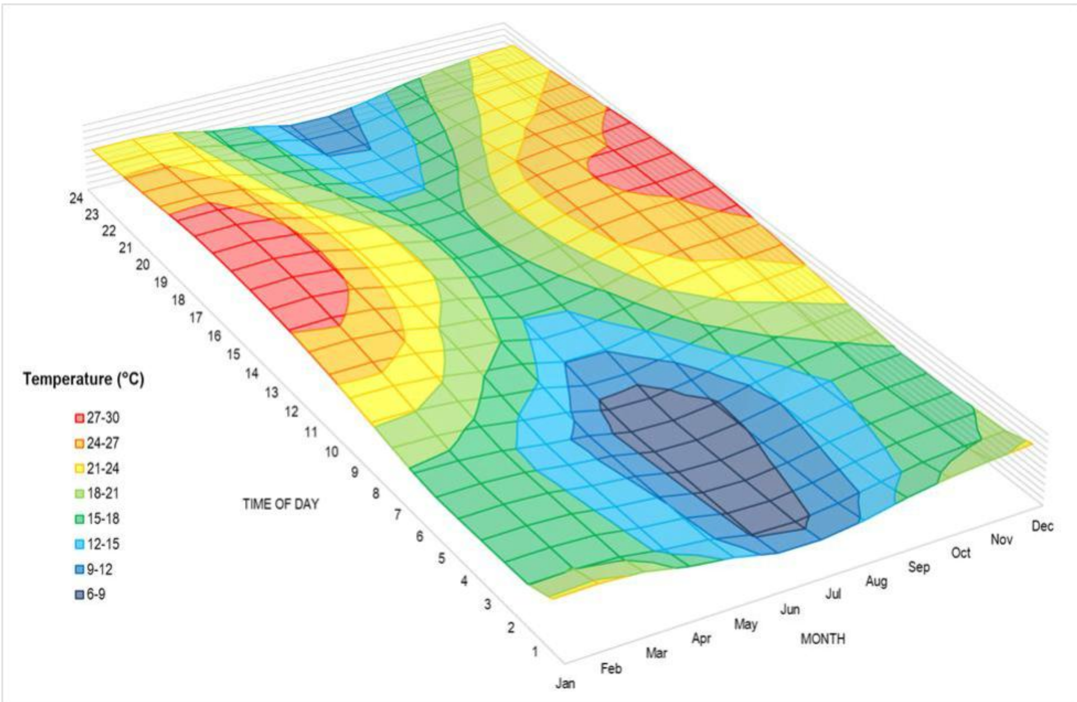


Figure 3.17 Diurnal temperature profile (WRF data, January 2022 to December 2024) (Airshed, 2025).

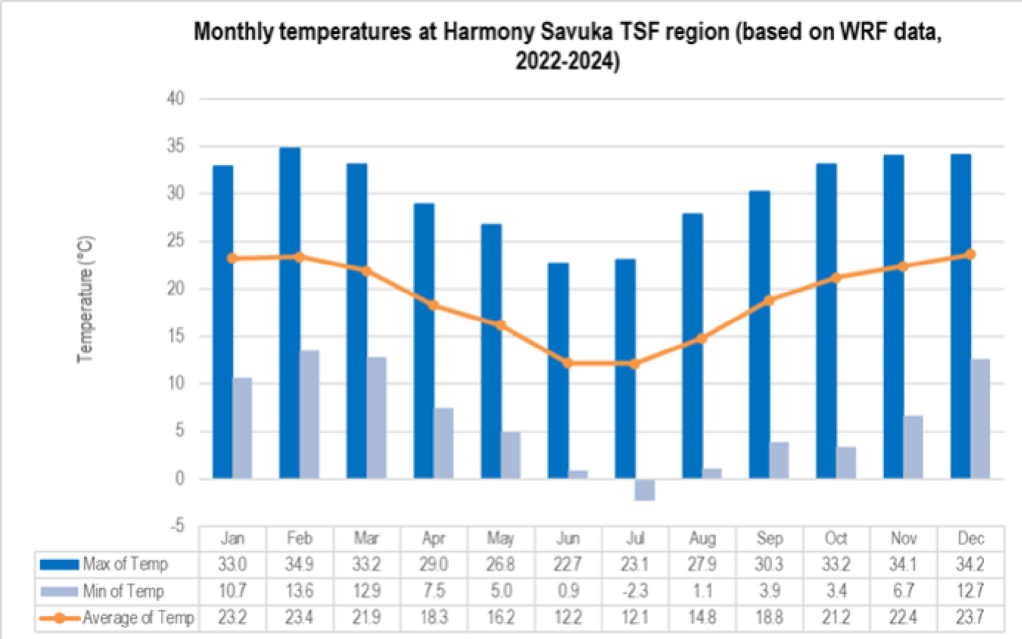


Figure 3.18 Monthly average and hourly minimum and maximum temperatures (°C) (Airshed, 2025).

3.4.6.4 Precipitation

Rainfall is important to air pollution studies since it represents an effective removal mechanism of atmospheric pollutants. The monthly rainfall obtained from the on-site data did not appear to be accurate. Rainfall in this area occurs mostly during the summer months, although it also rains during spring and autumn, while the winter months are dry, even though the relative humidity is greater during the winter period than in other seasons. Colder air can hold less moisture than warmer air, and thus the percentage saturation is higher at a lower moisture quantity, resulting in higher relative humidity during colder periods than warmer periods.

3.4.7 Socio-Economic Baseline Conditions

3.4.7.1 General

The socio-economic baseline conditions relevant to the Project area are described in Equispectives (2015; 2020). Presented here is a summary of the conditions that serve as a basis for human behavioural conditions and their interaction with the environment. Within the conceptual assessment framework presented in Figure 1.5, this information provides input into the definition of receptor groups and their behaviour within the public exposure conditions (see Section 4.7). The location of the Project area is described in Section 3.2 and will not be repeated here.

3.4.7.2 Community Types

Communities can be classified as belonging to one of the following groups (Equispectives, 2024):

- Formal Residential Structure Communities
  A formal dwelling can be described as "*A structure built according to approved plans, i.e., house on a separate stand, flat or apartment, townhouse, a room in a backyard or rooms or flatlet elsewhere*" (Statistics South Africa, 2012). In some areas, there may be a formal as well as an informal dwelling on a stand, creating a community with *mixed dwelling types*.

- Informal Residential Structure Communities

  An informal dwelling can be described as “*A makeshift structure not approved by a local authority and not intended as a permanent dwelling. Typically built with found materials (corrugated iron, cardboard, plastic, etc.), and is contrasted with formal dwelling and traditional dwelling*” (Statistics South Africa, 2012).

- Commercial Agricultural Communities

  Commercial agriculture includes farms where the farmer earns a livelihood from agriculture, such as crop, livestock, or game farming. Areas with smallholdings are categorised according to their character. If the residents of the smallholdings practise agriculture, they are grouped with commercial agriculture; if they just reside in the area or have a business on the smallholding not related to agriculture, the area is classified as formal residential.

- Small-scale Subsistence Farming

  Small-scale subsistence farming can be described as food gardening taking place on a large scale on a piece of land that is not in someone’s backyard. The land is usually cultivated by different members of the community, and they may belong to a formalised group. Food gardens in the backyard of an organisation, like a school or crèche, would also be grouped in this category. Keeping livestock in the community or on the outskirts of the community would form part of this group.

  Agricultural projects conducted as part of a Social and Labour Plan of a mine can contain characteristics of both commercial agriculture and subsistence farming. To classify these projects, the following guideline is used: if the projects have reached a stage where it is sustainable and function with minimal to no input from the mine, they are classified as commercial agriculture. However, if the mine is still heavily involved, it is classified as small-scale subsistence farming, as the Project has not yet proved its sustainability.

Figure 3.19 shows a 5 km radius around the Project surface infrastructure, as well as the potentially sensitive receptors within a 5 km radius. The following residential areas were identified in 2015 near the Project:

- AngloGold Ashanti residences (now part of GCTI operations)

  The West Wits (GCTI) Operations had four residences for employees in 2015, namely Ntshonalanga, Matabong, Ekhayalihle and Numba Wani, which were converted to single rooms or family quarters. The family quarters were at Ekhayalihle and could host up to 25 people who became paraplegic after injuries on duty. Matabong housed employees from the TauTona mine, while Ntshonalanga housed employees who worked at the Savuka mine, which was integrated with the TauTona mine. Numba Wani hosted employees from the Mponeng mine. The operations also had facilities for visiting wives.

  The TauTona and Savuka mines were placed in orderly closure in 2017, and as such, the only residence where the activity is expected is the Numba Wani residence. The Merafong City LM (2019/2020) has indicated that Mponeng has a good locality relative to the N12 that could be exploited once mine closure looms, and that there is possibly good potential for non-residential uses.

- West Wits Village

  In 2015, the West Wits Village housed employees of AngloGold Ashanti. The 2019/2020 IDP of the Merafong City LM indicates that township establishment is underway. The municipality is looking into the feasibility of a Mining Industrial Park as part of the second phase of Mining Phakisa implementation. The re-use potential of the area is considered good, with the possibility of developing into a significant node.

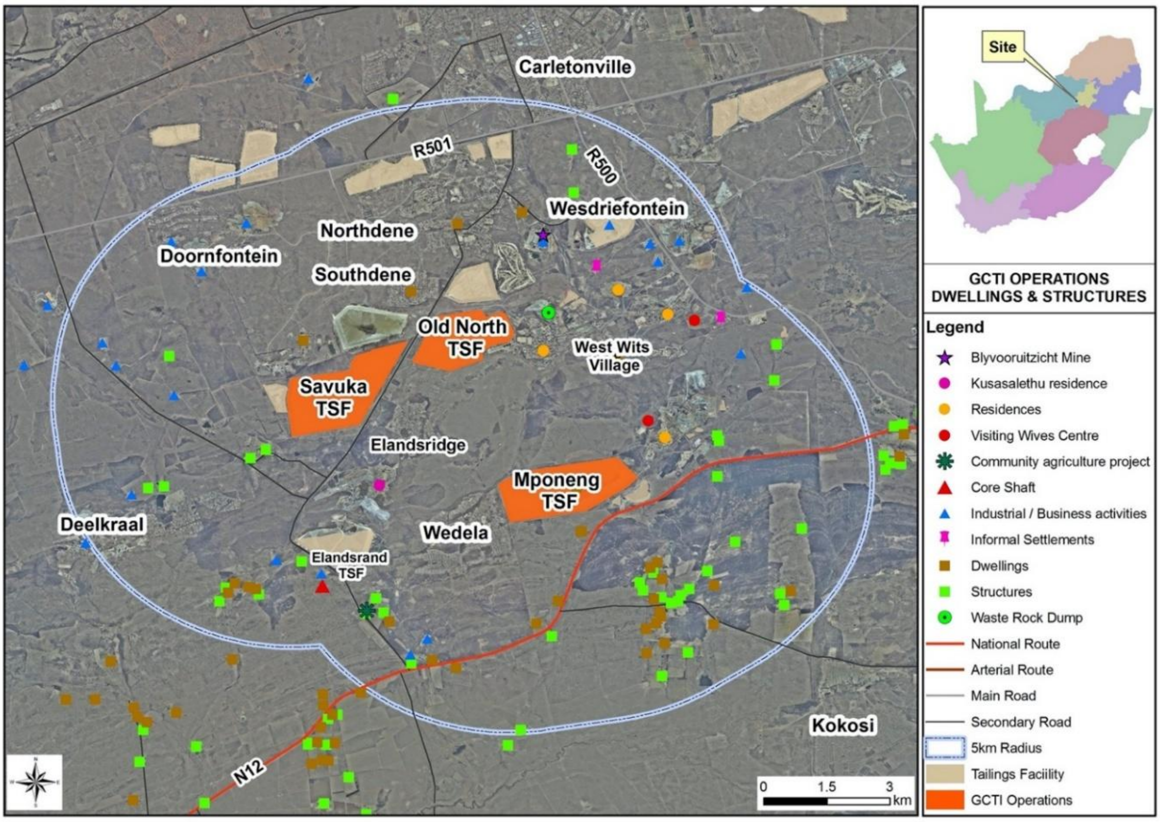


Figure 3.19 Map indicating the study area used for the Project Baseline Social and Land Use Assessment (Equispectives, 2020).

- Deelkraal Estate

  Deelkraal Estate used to be a mining village, but was in private ownership in 2015, with the owners being in the process of having the estate declared as a township. In the 2019/2020 IDP document of the Merafong City LM, Deelkraal is still indicated as a mining village with limited supportive land uses and limited economic potential. Although most residences are in fair condition, the municipality anticipates that the market for rental or buying in Deelkraal to collapse within the next few years due to new rental options in Carletonville and Fochville, as well as the mineshaft closure at Kusasalethu mine. The municipality will not take over services in the area and anticipates that Deelkraal will be demolished and that the area will be rehabilitated.

- Elandsridge

  Elandsridge/Elandsrand is a mining village where employees of Harmony's Kusasalethu mine reside. The Merafong City LM (2019/2020 IDP) has indicated that the Kusasalethu mine is expected to close within a few years, and if it does open again, it would be operated through mechanisation and automation. The municipality would not take over services, and the residential viability is regarded as low due to the lack of a new economic foundation, few facilities and the isolated location. It is anticipated that the area will be demolished and rehabilitated, possibly for agriculture or renewable energy.

- Wedela

  Wedela is situated between Harmony's Kusasalethu Operations and the Mponeng tailings storage facility. It was established in 1978 and granted municipal status in January 1990. Wedela is mostly a formal settlement, but there is an informal settlement on the edge of Wedela, and many houses have backyard shacks. It is currently located close to mining operations that will not be sustained indefinitely.

- Mohaleshoek Informal Settlement

  This informal settlement is located on private land adjacent to the R500, between the TauTona and Mponeng mines. Many residents are rumoured to be illegal immigrants. The Merafong City LM (IDP 2019/2020) has indicated that the informal settlements located at Blyvooruitzicht and Western Deep Levels can be accommodated at the West Wits township, either through subsidised housing or a CRU (Community Residential Units) project. The CRU programme aims to facilitate the provision of secure, stable rental tenure for lower-income individuals (www.gov.za).

- Farming Community

  The farming community consists of farms and smallholdings that are located in the Deelkraal area as well as adjacent to the Mponeng mine. Farming activities consist of crop farming, livestock, game breeding and hunting. Some of the farms offer tourist activities. Some farms have workers residing on the farm, while the workers from other farms do not reside on the farm, but somewhere else in the vicinity.

- Residential areas around the Blyvooruitzicht mine

  In 2015 people living in the area around the Blyvooruitzicht mine that was put in provisional liquidation in August 2013 lived in dire socio-economic conditions. The Merafong City LM (2019/2020 IDP) has indicated that the mine's gold mining component has been revived recently. According to the municipality, the village has significant potential to be integrated into Carletonville although buildings and infrastructure have been stripped and vandalised. The lawlessness that marked the area in 2015, seems to have been resolved by the new mine owner. There are dolomitic constraints in the area and the Housing Development Agency is conducting a feasibility study on the potential of reviving the village.

Figure 3.19 also shows the location of dwellings and structures relative to the Project that are not located in a town or a village. The number of dwelling groups has remained more or less the same, as observed through aerial photography. At some of the dwelling clusters, new buildings have been observed. Table 3.2 presents the breakdown for households according to geo types as per Census 2011.

Table 3.2 Breakdown of households according to geo types (source: Census 2011) (Equispectives, 2020).

Geo Type	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Urban area	68,199	2,431	3,586	4,575	3,827	1,475	3,234	2,040	2,402
Traditional Area	0	0	0	0	0	0	0	0	0
Farm area	2,207	0	0	75	0	68	0	374	0
Total	70,406	2,431	3,586	4,650	3,827	1,543	3,234	2,414	2,402

From Figure 3.19 it can be concluded that the land use near the Project is dominated by open grassland, agricultural (cultivated cropland), mining and residential land use conditions. Equispectives (2020) divided communities into those living in formal structures, communities living in informal structures, commercial agricultural communities, and small-scale subsistence farming communities.

3.4.7.3 Demographic and Socio-economic Characteristics

Population and Household Size

The population in the Merafong City LM showed a decrease in population of 4.39% and an increase of 19.83% in households between 2011 and 2016. As shown in Table 3.3, this is much lower than on the provincial level, while average household sizes have decreased. This suggests an increased demand for housing and infrastructure, as well as open space that can be converted to residential areas. More people moved out of the area than moved into the area. According to the Merafong City LM IDP (2019/2020), this is due to the low quality of life and low economic growth in the area.

Table 3.3 Change in population and number of households between 2011 and 2016 (source: Census 2011 and Community Survey 2016) (Equispectives, 2020).

	Census 2011	Community Survey 2016	Difference
Merafong City Local Municipality			
Population	197,520	188,843	-4.39%
Households	66,624	79,834	19.83%
Average household size	2.96	2.37	

Table 3.4 shows that in most Wards, the majority of the population belongs to the Black population group. In Ward 12 more than half of the population belonged to the White population group, while in Ward 14 just over a third of the population belonged to the White population group. Ward 12 includes Deelkraal as well as Welverdiend (which is located outside the 5 km radius). Ward 14 includes West Wits Village, a portion of Fochville, the Numba Wani Residence and the Mohaleshoek Informal Settlement. Between 2011 and 2016, the proportion of residents belonging to the Black population group decreased in the Merafong City LM from 86.52% to 83.43% while the proportion for the White population increased from 11.79% to 15.07%.

Socio-economic Conditions

Census 2011 data summarised in Table 3.5 shows that in 2011 the employment levels for the economically active part of the population (aged 15 to 64 years) varied. Ward 11, Ward 14 and Ward 27 (all three are mining wards) have the highest levels of employed people, higher than on local, district and provincial levels. It must be noted that large-scale retrenchments have taken place in the gold mining industry since 2012. Given the decline in employment in the gold mining industry over the past decade it is anticipated that the proportion of unemployed people in the area has increased since 2016.

Table 3.4 Breakdown of the population distribution in the different areas (source: Census 2011) (Equispectives, 2020).

Population	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Black African	170,897	4,902	6,610	4,880	5,964	2,107	8,652	7,449	6,699
Coloured	2,130	14	27	84	30	30	2	107	20
Indian or Asian	564	2	2	28	4	14	9	9	6
White	23,291	425	336	2,730	257	2,576	5	427	4
Other	639	11	23	18	22	29	23	34	49
Total	197,520	5,354	6,997	7,739	6,276	4,757	8,691	8,026	6,777

Population Composition, Age, and Gender

Census 2011 data summarised in Table 3.6 shows that in 2011, more than half of the households on provincial, regional, local and ward levels consisted of 1 to 2 people, except in Ward 12 and Ward 22, where the incidence was just under half. Ward 5 (64.85%), Ward 11 (68.34%), Ward 14 (71.55%) and Ward 27 (75.89%) had the highest incidence of households consisting of only one person. All these areas contain mining residences or mining villages. The proportion of single-person households decreased at all levels between 2011 and 2016. In Merafong City LM, it decreased from 40.11% to 30.72%. This can be indicative of people trying to cut their living expenses by sharing a dwelling, given the shrinking number of employment opportunities in the area. Average household sizes decreased between 2011 and 2016.

Table 3.5 Employment status (persons aged 15 to 64 years in age, source: Census 2011, shown in percentage) (Equispectives, 2020).

Employment Status	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Employed	46.51	53.99	70.61	74.99	74.61	45.15	44.36	34.24	46.83
Unemployed	17.37	10.61	8.54	6.14	5.00	8.05	28.95	15.93	19.26
Discouraged work-seeker	3.47	1.03	1.20	1.15	1.82	2.12	2.99	5.06	4.75
Other[1]	32.66	34.37	19.65	17.72	18.56	44.68	23.70	44.77	29.16
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

([1]) Not economically active

Census 2011 data summarised in Table 3.7 shows that more than two-thirds of households in Merafong City LM were headed by males. On a ward level, this proportion varied between two-thirds and more than 90%. Community Survey 2016 shows that between 2011 and 2016, the proportion of female-headed households remained more or less the same. Female-headed households are often financially less well-off than similar male-headed households and can be considered more vulnerable.

Census 2011 data summarised in Table 3.8 shows a bias towards males on a district, local and ward level, except in Ward 12, Ward 20, Ward 22 and Ward 23, where the split between males and females was more or less equal. These are the wards that do not mainly consist of mining residences and villages and include Wedela, Deelkraal and farming areas. The split between males and females remained more or less the same between 2011 and 2016, with a slight increase in the proportion of females.

Table 3.6 Household sizes (source: Census 2011) (Equispectives, 2020).

Household Size	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
1	28,238	1,577	2,451	3,327	2,904	379	1,182	681	903
2	13,387	383	333	600	358	381	685	443	467
3	9,677	209	261	322	247	266	460	394	334
4	8,207	117	223	257	156	249	407	333	249
5	4,651	67	141	92	76	141	205	229	171
6	2,737	29	82	35	44	63	134	135	110
7	1,555	17	40	7	20	35	81	87	78
8	904	17	35	4	11	8	43	55	41
9	422	5	6	0	2	8	16	23	19
10+	627	11	15	5	9	10	23	33	30
Total	70,406	2,431	3,586	4,650	3,827	1,543	3,234	2,414	2,402
Average	2.81	2.20	1.95	1.66	1.64	3.08	2.69	3.33	2.82

Table 3.7 Gender of the head of household (source: Census 2011) (Equispectives, 2020).

Sex of Head of Household	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Male	49,583	2,089	3,172	4,227	3,585	1,121	2,182	1,501	1,633
Female	20,752	334	413	420	235	421	1,052	912	769
Total	70,335	2,423	3,585	4,647	3,821	1,543	3,234	2,414	2,402

Table 3.8 Gender distribution (source: Census 2011) (Equispectives, 2020).

Sex Distribution	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Male	107,157	3,918	4,592	5,298	4,634	2,417	4,435	3,967	3,431
Female	90,363	1,436	2,405	2,441	1,643	2,340	4,256	4,059	3,347
Total	197,520	5,354	6,997	7,739	6,276	4,757	8,691	8,026	6,777

Census 2011 data presented in Figure 3.20 shows that Ward 5, Ward 14 and Ward 27 had the highest proportion of people older than 17 years of age, while Ward 22 had the lowest. Between 2011 and 2016, the proportion of people older than 17 years of age in Merafong City LM increased slightly, while the proportion of people under 2 years decreased slightly.

Child-headed households are considered extremely vulnerable as there is usually no adult who can provide them with food and other necessities, and often these households need to rely on the kindness of neighbours and other family members for survival. A child who heads a household often does not have the experience and maturity required to raise his or her siblings and often has to drop out of school to do this.

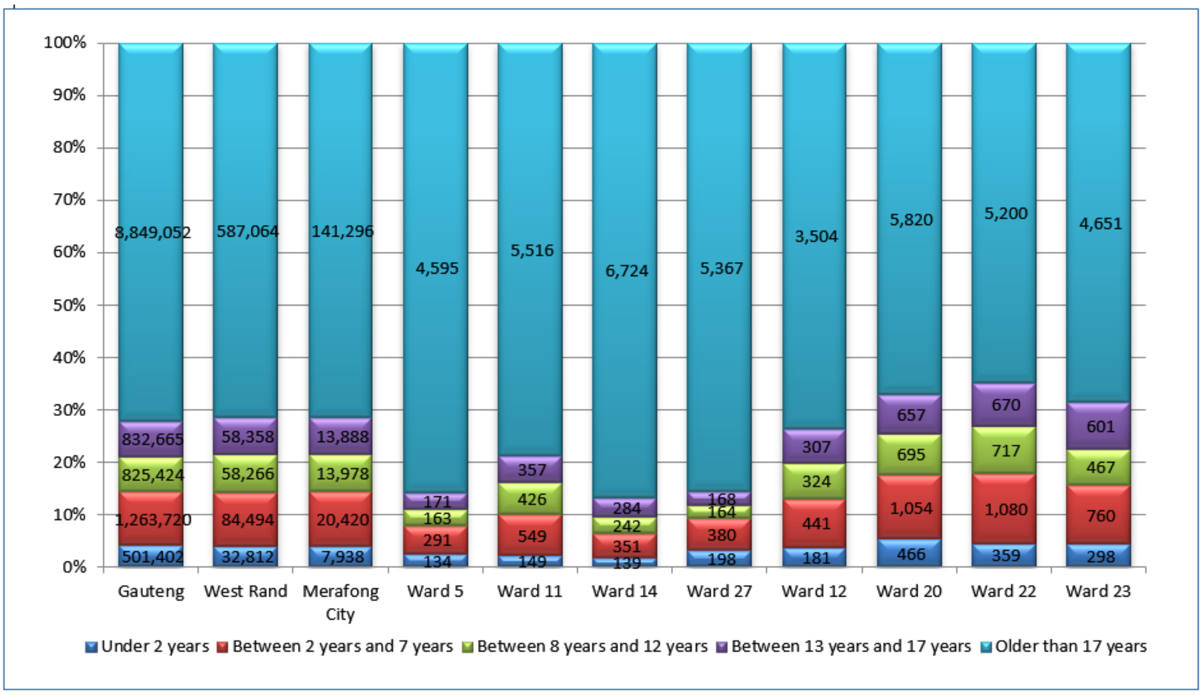


Figure 3.20 Age distribution of the population (shown in percentage; source: Census 2011) (Equispectives, 2020).

Census 2011 data summarised in Table 3.9 shows that Ward 20 (1.1%), 22 (1.4%) and Ward 23 (1.2%) had the highest incidence of child-headed households with the age of the heads of household between 10 and 19 years. This was still slightly above the incidence on the municipal level for Merafong City LM (1%). The area with the highest incidence of heads of household that have reached retirement age was Ward 12 (9.7%) and Ward 22 (8.9%). Between 2011 and 2016, the incidence of heads of households that are 19 years or younger increased marginally, but the proportion of household heads that have reached retirement age (65+ years) in Merafong City LM increased from 6.4% to 7.9%. This suggests that many people stay in the area after they have retired.

Table 3.9 Gender distribution (source: Census 2011) (Equispectives, 2020).

Gender Distribution	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
10-19 years	694	11	14	17	18	5	34	33	29
20-34 years	22,139	798	910	1,251	1,064	348	1,256	724	825
35-64 years	43,016	1,590	2,622	3,116	2,721	1,040	1,886	1,441	1,485
65+ years	4,485	24	39	262	17	150	58	215	63
Total	70,335	2,423	3,585	4,647	3,821	1,543	3,234	2,414	2,402

3.4.7.4 Household Structures

The different residential areas in the area can be grouped according to the settlement types and the housing structures present in each area. Table 3.10 summarises the settlement types and representative residential areas that are included in the discussions.

Table 3.10 A summary of community types and representative residential areas inside the study are identified for the Project.

Settlement Type	Representative Area
Formal Residential	Deelkraal, Elandsridge and Wedela
Informal Residential	Mohaleshoek informal settlement, Wedela
Mine Workers Residences	Anglo Gold Ashanti residences and West Wits village
Agricultural areas	The surrounding farming community and the Matlosana agricultural project

Table 3.11 shows that Ward 12 (90.1%) and Ward 20 (79.4%) had the highest incidence of households living in dwellings that are brick or concrete structures, such as a dwelling in a separate yard, a block of flats, a cluster house or townhouse in a complex, or a semi-detached house. Ward 22 (30.4%) and Ward 5 (11.3%) had the highest incidence of informal dwellings that were not in someone's backyard, while Ward 23 (21.0%) had the highest incidence of households living in informal dwellings in someone's backyard. Ward 11, Ward 14 and Ward 27 had the highest incidence of households living in a flat or apartment in a block of flats or a dwelling that could be described as 'Other'. Given the high incidence of mining activities in these wards, these refer most likely to households living in mine residences.

Community Survey 2016 shows that the number of households living in formal dwellings or houses on a separate stand has increased in Merafong City LM from 59.7% in 2011 to 64.5% in 2016. The proportion of households living in any type of informal dwelling decreased between 2011 and 2016. In 2016, about a quarter (24.8%) of households in Merafong City LM indicated that they lived in RDP or government-subsidized dwellings. Almost two-thirds (61.3%) of those living in RDP or government-subsidized dwellings have rated the overall quality of the dwellings as good. According to the Merafong City LM IDP (2019/2020), the following urban developments are in the pipeline:

Table 3.11 Main dwelling types (households, source: Census 2011) (Equispectives, 2020).

Dwelling Type	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
House or brick/concrete block structure on a separate stand or yard or a farm	39,776	1,114	1,494	2,002	1,406	1,363	2,563	1,241	1,406
Traditional dwelling/hut/structure made of traditional materials	137	6	13	15	10	3	4	7	7
Flat or apartment in a block of flats	4,634	158	19	1,801	1,554	55	87	6	147
Cluster house in a complex	846	38	4	43	621	1	1	2	4
Townhouse (semi-detached house in a complex)	204	0	0	59	4	0	1	0	9
Semi-detached house	174	26	10	2	6	12	4	7	7
House/flat/room in the backyard	2,867	104	175	25	60	43	202	78	274
Informal dwelling (shack; in backyard)	3,576	56	9	99	7	7	306	163	501
Informal dwelling (shack; not in a backyard; e.g. in an informal/squatter settlement or on a farm)	10,600	270	7	330	89	11	9	664	22
Room/flatlet on a property or larger dwelling/servants quarters/granny flat	1,292	611	4	50	7	8	41	3	3
Caravan/tent	36	1	4	1	0	3	1	0	0
Other	2,482	3	1,813	3	7	8	7	13	10
Unspecified	352	6	13	32	9	21	4	23	5
Not applicable	3,430	38	23	188	47	8	4	207	8
Total	70,406	2,431	3,586	4,650	3,827	1,543	3,234	2,414	2,402

- Ward 12: Elija Barayi Village – west of Carletonville, next to Welverdiend. This development is planned to consist of about 8,150 RDP (Reconstruction and Development Programme)/BNG (Breaking New Ground) houses and 2,900 Gap houses.
- Ward 12: Khutsong South – expansions in the current Khutsong South area.
- Ward 14: Fochville Extension 7 – an undeveloped township area next to Fochville that is located on a hilltop and is regarded as more suited for high-income development.
- Ward 22, Ward 23: Wedela Extension 4 – undeveloped area next to Wedela (furthest away from mining infrastructure and located in the area where currently agricultural activities are taking place). This development will consider the need for additional business and institutional activities. A strip of multi-use business is envisioned, and the design and layout will focus on an 'Agri village' type of theme.
- Ward 27: West Wits Village Extension – forms part of the formalisation of West Wits Village and is intended to provide housing to informal dwellers within the area. Approximately 279 low-income (RDP/BNG) units are planned.

3.4.7.5 Social Infrastructure and Services

Activities that take place in a community differ from community to community. Based on similar studies over time in other areas, people who live in areas where there are high levels of unemployment tend to spend more time outside. They socialise outside, children tend to play outside for most of the day, as many households in these areas cannot afford to send their children to daycare. Informal housing tends to be very cold in winter and hot in summer, and is usually quite small inside; as such, these residents prefer to be outside. In many lower-income areas, there are usually make-shift sports fields where residents can play soccer or other sports. Incidents of food gardens in areas with high levels of poverty and unemployment are usually higher than in other areas, as many residents do not have the means to buy all their food, and a higher proportion of people have time available to tend to a food garden.

In 2015, Equispectives (2015) stated that the residents of West Wits Village and the then AngloGold Ashanti residences were employed and would spend time outside when off duty. Those living in the residences would socialise or do chores like washing, while those in West Wits Village most likely spent more time outside over weekends for recreational purposes. In Deelkraal, people were observed outside, and there were some recreational facilities.

In Wedela, time spent outside depended to a great extent on individual circumstances. Some women spent the whole day outside with chores, while many small children were playing outside. Some people hunted in the fields around the township, where some religious activities also took place. Given the high levels of unemployment, many people in Mohaleshoek were outside during the day, some just sat outside and socialised. On the farms, the farmers and their workers would spend most of the day outside, while their family members either farmed with them or spent less time outside. Community Survey 2016 shows that 14.85% of Merafong City LM have indicated that they walk to their place of education. As a result of the downscaling activities in the gold mining industry, it is anticipated that in certain residential areas, the number of people spending time outside would have increased, as they are no longer employed.

Census 2011 data summarized in Table 3.12 shows that more than 90% of households in the area have access to water from a regional or local water scheme that is operated by the municipality or other water services providers, except in Ward 22, where only 77% of households have access to water from a local or regional water scheme. Ward 22, which consists mostly of farms and smallholdings, has the highest incidence (13.5%) of households that access water through boreholes. Ward 5 (4.4%) and Ward 14 (2.7%) have the highest incidence of households getting their water from water tankers.

Table 3.12 Sources of water for households (source: Census 2011) (Equispectives, 2020).

Source of Water	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Regional/local water scheme (operated by municipality or other water services provider)	64,953	2,287	3,537	4,205	3,660	1,466	3,155	1,855	2,381
Borehole	1,530	4	11	84	31	24	8	326	1
Spring	53	0	0	6	1	0	1	3	1
Rainwater tank	307	12	0	1	96	3	2	7	0
Dam/pool/stagnant water	51	0	0	12	0	1	0	1	0
River/stream	23	0	1	1	0	0	0	6	1
Water vendor	170	2	10	5	8	3	5	8	6
Water tanker	1,570	108	5	126	11	13	2	20	0
Other	1,749	18	21	208	19	33	61	188	10
Total	70,406	2,431	3,586	4,650	3,827	1,543	3,234	2,414	2,402

Table 3.13 shows that more than half of households had access to piped water inside their dwellings in 2011, except in Ward 14 (30.7%), Ward 22 (33.3%) and Ward 27 (28.0%). Ward 14 (3.4%) and Ward 22 (2.5%) had the highest incidence of households that did not have access to piped water. Community Survey 2016 2016 shows that the incidence of households with access to piped water inside the dwelling in Merafong City LM has increased from 51.0% to 62.1%.

Table 3.13 Households that have access to piped water (source: Census 2011) (Equispectives, 2020).

Piped Water	Merafong City LM	Mining Wards				Mixed Wards			
		Ward 5	Ward 11	Ward 14	Ward 27	Ward 12	Ward 20	Ward 22	Ward 23
Piped (tap) water inside the dwelling	35,905	1,352	1,828	1,428	1,073	1,381	1,824	804	1,466
Piped (tap) water inside the yard	21,110	718	1,471	2,422	2,637	110	1,351	1,488	921
Piped (tap) water on community stand: distance less than 200m from dwelling	7,775	185	267	316	7	5	46	88	3
Piped (tap) water to community stand: distance less than 200m and 500m from dwelling	2,558	104	0	176	2	0	4	1	1
Piped (tap) water to community stand: distance less than 500m and 1000m from dwelling	1,423	49	3	44	1	2	0	1	1
Piped (tap) water on community stand: distance greater than 1000m (1 km) from dwelling	390	7	0	73	0	2	0	1	0
No access to piped (tap) water	893	10	5	159	97	20	6	8	5
Unspecified	352	6	13	32	9	21	4	23	5
Total	70,406	2,431	3,586	4,650	3,827	1,543	3,234	2,414	2,402

In the Community Survey 2016, approximately 6.7% of households in Merafong City LM have indicated that they do not have access to safe drinking water, while about 12.6% of people rate the overall quality of water services as poor. Approximately 22.2% of households have indicated that they have experienced municipal water interruptions in the past three months, while 15.0% of households have indicated that they had water interruptions that lasted for longer than two days. In Merafong City, LM 40.8% of the households that experienced water interruptions have indicated that they used water from a water tanker, 22.6% an 'other' water source (it is not specified what the alternative sources are), and about 28% used no other alternative water source during interruptions. The majority of people (80.9%) who do not have access to piped water inside their dwellings or yards have access to a source of water within less than 200 m.

3.5 Radiological Conditions

3.5.1 General

The purpose of this section is to provide a summary overview of the currently available radiological information relevant to the Project. Radionuclide concentrations in the relevant residue material (i.e., tailings materials) are presented in Section 3.5.2, while the radon exhalation rates for the existing TSFs, WRDs and ventilation shafts are presented in 3.5.3. The data presented here were sourced from the 2020 Golden Core Trade and Invest RPSA, which was submitted and approved by the NNR for the Mponeng Operations (AquiSim, 2018).

3.5.2 Tailings Material

Of the three TSF complexes associated with the Mponeng Operations, only the Savuka TSF is operational at present. The Old North Complex TSF has been dormant for several years and has been rehabilitated with the establishment of vegetation on the surface and side slopes. A section of this TSF is being reclaimed at present. Table 3.14 summarises the full-spectrum radioanalysis results of tailings samples collected in 2009 at the three TSFs as presented in the 2020 Golden Core Trade and Invest RPSA. Table 3.15 summarises the most recent full-spectrum radioanalysis results of tailings samples submitted to the Necsa Laboratories in May 2014.

Table 3.14 Summary of full-spectrum radioanalytical results for samples of tailings from the Project TSFs, collected in 2009.

Radionuclide	Mponeng TSF	Old North Complex TSF	Savuka TSF
	Activity Concentration (Bq.kg^{-1})		
U-238	548	462	442
U-234	589	466	446
Ra-226	266	618	367
Pb-210	383	676	480
U-235	26.9	21.3	20.4
Th-232	20.9	26.7	22.6
Ra-228	<MDA	<MDA	<MDA
Th-228	21	24	<MDA

Assuming the following secular equilibrium between parent radionuclides and their progeny, where radioanalysis data were lacking, the activity concentration of radionuclides that would make the most significant contribution can be derived from the radioanalytical data (see Section 2.3.4.4):

- Po-210 = Pb-210 = Ra-226 = Th-230 = U-234 = U-238.
- Ra-223 = Ac-227 = Pa-231 = U-235.
- Th-228 = Ra-228 = Th-232.

Table 3.15 Full spectrum analysis results of tailings samples submitted to the Necsa Laboratories in May 2014 (RA-15889 dated 4 December 2014).

Radionuclide	Mponeng C1	Mponeng C12	Dormant	Savuka 5A	Savuka 7B	Savuka 7A	Savuka 5B
	Activity Concentration (Bq.kg^{-1})						
U-238	442	225	283	364	454	516	530
U-234	446	227	285	367	458	520	534
Ra-226	779	245	292	411	494	524	555
Pb-210	938	360	428	526	613	691	781
U-235	20.4	10.3	13	16.8	20.9	23.8	24.4
Th-232	32.3	26.1	23.4	28.2	24.3	24	25.3
Ra-228	< MDA	< MDA	< MDA	< MDA	< MDA	43	< MDA
Th-228	47	37	27	26	40		23
Gross α	5690	4220	4620	2990	4070	4100	2880
Gross β	266	2320	1480	2300	2640	2580	2540

Table 3.16 summarises the resulting average activity concentration for the TSFs as derived from the data presented in Table 3.14 and Table 3.15, and the secular equilibrium assumptions.

3.5.3 Radon Exhalation Rates

Parc Scientific (2006) summarised radon exhalation rates measured from residue storage facilities in the South African gold mining industry and reported a methodology that can be used to estimate radon exhalation rates from TSFs. The report used radon exhalation rates measured from a variety of TSFs and WRDs for 8 years to derive source characteristic radon diffusion coefficients. These diffusion coefficients are used with concentrations of Ra-226 measured in the tailings material (see Table 3.14 and Table 3.15) to estimate the radon exhalation rate in units of Bq.m^{-2}.s^{-1}. Parc Scientific (2006) presented the measured data as 'average' and 'maximum' values based on the statistical distribution of the data. The derived diffusion coefficients, therefore, also represent average and maximum values and were used to estimate a range of potential radon exhalation from the three TSFs at the Project.

Table 3.16 Summary of the average activity concentration for the Mponeng Operations TSFs, as derived from the data presented in Table 3.14 and Table 3.15, and the secular equilibrium assumptions.

Radionuclide	Mponeng TSF	North Complex	Savuka 5A&5B	Savuka 7A&7B
	Activity Concentration ($Bq.kg^{-1}$)			
U-238	405	373	445	471
U-234	421	376	449	475
Th-230	421	376	449	475
Ra-226	430	455	444	462
Pb-210	560	552	596	595
Po-210	560	552	596	595
Th-232	26	25	25	24
Ra-228	26	25	25	30
Th-228	35	26	24	35
U-235	19	17	21	22
Pa-231	19	17	21	22
Ac-227	19	17	21	22
Ra-223	19	17	21	22

The equations and coefficients used for deriving radon exhalation rates for the Project TSFs are as follows (Parc Scientific, 2006):

Average: Radon exhalation rate ($Bq.m^{-2}.s^{-1}$) = (0.000554 ±0.0000014) x Ra-226 ($Bq.kg^{-1}$)

Maximum: Radon exhalation rate ($Bq.m^{-2}.s^{-1}$) = (0.000609 ±0.0000017) x Ra-226 ($Bq.kg^{-1}$)

The average and maximum radon exhalation rates estimated from the measured radium concentration in the tailings material of the Mponeng Operations TSFs are listed in Table 3.17.

Table 3.17 Estimated average and maximum radon exhalation rates for the Mponeng Operations TSFs.

TSF Complex	Average	Maximum
	$Bq.m^{-2}.s^{-1}$	
Mponeng TSF	0.24	0.26
North Complex	0.25	0.28
Savuka 5A&5B	0.25	0.27
Savuka 7A&7B	0.26	0.28

3.5.4 Upcast Ventilation Shafts

Upcast ventilation shafts (or vent shafts) release air circulated through the underground workings to the atmosphere. Associated with this air is radon gas released from the underground working environment, which has the potential to expose members of the public living downwind of the release points to radioactivity. Radon release estimates from underground workings, via upcast ventilation shafts, were reported in a previous public safety assessment (Ellis, 2006).

Radon concentrations measured in underground workings over several years were used to estimate the radon released from upcast ventilation shafts. The estimated value for each operational shaft was derived using specific release heights and exit velocities, and the average values and reasonable maximum values reported are listed in Table 3.18.

Table 3.18 Radon release concentrations from the Mponeng Operations upcast ventilation shafts (Ellis, 2006).

Parameter	Units	Savuka	Mponeng	TauTona
Average	$Bq.m^{-3}$	1,252	521	2,291
90th percentile		1,988	807	3,751

4 Develop and Justify Public Exposure Conditions

4.1 Introduction

The main objective of the radiological public safety assessment is to assess the potential impact on members of the public that may occur during the operational phase of the Project, with due consideration of the impact that may occur during the post-closure phase. How members of the public are exposed to ionising radiation induced by the Project may be different depending on the operational conditions and the specific point in time (either present or future).

Consistent with the assessment framework presented in Figure 1.5, the radiological public impact is evaluated through the development of site-specific public exposure conditions. As used here, an exposure condition is defined as follows:

> *An exposure condition is a sequence of features, events, and processes (FEPs) and is one of a set devised to illustrate normal or potential situations of radiation exposure to receptors.*

The purpose of this section is to use the current understanding of the Project and its surroundings (see Section 3), bounded by the conditions and assumptions defined in the assessment context (see Section 2), to develop relevant site-specific public exposure conditions. Different approaches can be used to derive a discrete set of public exposure conditions. A Source-Pathway-Receptor (SPR) analysis approach was judged appropriate for the assessment (see Figure 1.5). The SPR analysis approach is inherently systematic, traceable, and transparent, and provides the opportunity to identify and evaluate all possible exposure situations that may exist both now and in the future.

The section is structured as follows. Section 4.2 defines a few key concepts used in the SPR analysis approach, while the elements of the Source-Pathway-Receptor linkages relevant to the Project are evaluated and discussed in Section 4.3 to Section 4.5. Section 4.6 introduces the way conceptual models are represented in the definition of the exposure conditions. The outcome of the SPR analysis approach is then used for the definition and justification of the public exposure conditions in Section 4.7.

4.2 Key Concepts Used in the SPR Analysis Approach

The SPR analysis approach is inherently systematic, traceable, and transparent, and comprises three interrelated steps. The first step is to identify all current, future and where applicable, historical *sources* of radiation exposure relevant to the Project. The sources are characterised in terms of their unique composition (i.e., specific radioactive substances present or emitted) and their characteristics that will determine how contaminants may be distributed in the environment.

Secondly, all relevant pathways and routes of exposure that relate to the identified sources are evaluated. In this context, *pathways* refer to the means, by which radionuclides may be dispersed or transferred within or between compartments of the environmental system, to a point where humans interact with the compartment. An *exposure route* refers to the route of entry into the human body to pose a radiation risk, such as through ingestion, inhalation, or external exposure.

Finally, *receptors* are defined and characterised. Receptors refer to humans that may potentially be subject to radiation exposure (i.e., a radiation dose) from the applicable sources and through the exposure pathways of concern.

4.3 Source Identification

4.3.1 General

Sources of radiation exposure to members of the public associated with mining and mineral processing facilities are often advertently induced. Although the key elements responsible for radiation exposure are naturally occurring radionuclides, human-induced conditions and activities may enhance concentrations of naturally occurring radionuclides in the accessible environment. Alternatively, the potential for human exposure to naturally occurring radionuclides in products, by-products, residues, and other wastes may be enhanced by moving these radionuclides from inaccessible locations to locations where humans can be subject to radiation exposure.

To pose a radiological risk to members of the public and the environment, the naturally occurring radionuclides must first be released from the sources of radiation exposure into the environment. As used here, *sources* refer to any entity that contains radioactivity *and* has the potential to release radioactivity into the environment. Release mechanisms can be generalised into the following natural and human-induced conditions:

- The release of radionuclides through natural conditions:
  - Solid release (e.g., windblown dust);
  - Water-mediated release (e.g., leaching through tailings storage facility); and
  - Gas-mediated release (e.g., radon gas exhalation).
- Direct gamma radiation; and
- Controlled or uncontrolled releases of radionuclides as solids or liquids into the environment.

Controlled releases are human-induced as part of the normal operating conditions, while uncontrolled releases are associated with accidents and incidents that are outside the scope of normal operating conditions (e.g., excessive water erosion, pipeline bursts, releases from storage dams overflowing their capacity, or the breaking of dam walls).

4.3.2 Primary and Secondary Sources of Radiation Exposure

A distinction can be made between primary and secondary sources of radiation exposure. The *primary sources* are associated with physical features or entities at a mining and mineral processing operation, with the potential of naturally occurring radionuclides to be released into the environment. Examples of primary sources that are generally associated with mining and mineral processing operations include:

- Tailings Storage Facilities (TSFs), Waste Rock Dumps (WRDs) or any other stockpile facility used to store waste or other residue material on the surface, from which naturally occurring radionuclides may be dispersed in solid (dust), liquid (seepage), or gaseous (radon gas) form;
- Open pits that developed following open cast mining to extract rock or minerals from the orebody, from which naturally occurring radionuclides may be dispersed in solid (dust), liquid (seepage), or gaseous (radon gas) form;
- Mineral processing activities, where radioactive gasses and dust may be released from the commination (e.g., crushing, milling, and screening) and beneficiation of ore containing radionuclides;
- Water management facilities (e.g., return water dams, process control dams, and evaporation ponds), used to manage excess water generated through mining, mineral processing, and residue disposal activities, and where water may be released to the environment;

- Materials handling activities (e.g., the transfer of material containing naturally occurring radionuclides from one point or facility to another), during which radioactive dust may be released to the environment; and
- Mine ventilation shafts increase airflow in underground workings, where gasses and dust generated underground may be released with the outflowing air.

Radioactivity released from the primary sources into the environment may accumulate in the physical compartments of the environmental system (e.g., groundwater, surface water bodies, surface soils, sediments, etc.), potentially resulting in what can be termed *secondary sources* of radiation exposure. The following serve as examples of secondary radiation sources:

- Continuous deposition and accumulation of naturally occurring radionuclides associated with airborne dust or contaminated irrigation water on surface soils, resulting in the development of a secondary source at the soil surface;
- Continuous deposition of naturally occurring radionuclides associated with airborne dust in a surface water body, resulting in the development of a secondary source in the sediments and surface water body;
- Uncontrolled release of contaminated mine residue (e.g., tailings material) through surface water erosion of existing TSFs or other stockpile facilities;
- Uncontrolled release (e.g., spillage) of contaminated mine residue (e.g., tailings material) or water on surface soils from pipelines or storage dams, resulting in the development of a secondary source at the soil surface; or
- Uncontrolled release (e.g., spillage) of contaminated mine residue (e.g., tailings material) or water in a surface water body from pipelines or storage dams (as appropriate), resulting in the development of a secondary source in the sediments and surface water body.

Members of the public may potentially be subject to radiation exposure from both primary and secondary sources at a mining and mineral processing operation, with expected differences in modes and duration of exposure.

4.3.3 Primary Sources Associated with the Project

4.3.3.1 General

Facilities, activities, and associated surface infrastructure of the Project that are known to contain or emit ionising radiation were presented in detail in Section 3.3. Some primary sources of radiation exposure are expected to change during the life cycle of the Project.

Primary sources of radiation exposure include existing ventilation shafts, TSFs, WRDs, water management facilities and pipelines used for the transfer of water and tailings material that form part of the baseline conditions. The Project-specific facilities and activities include the Savuka 7A and 7B TSF, as well as the associated water management facilities and pipelines.

The *Assessment Context* as defined in Section 2 made a distinction between an operational and post-operational period. The nature of mining and mineral processing operations is such that some of the sources that are present during the operational period will no longer be active after closure. The operational phase, therefore, represents the 'worst case' as it has the highest number of identified sources associated with it and serves as the basis for the development of public exposure conditions for radiological public safety and impact assessment of the Project. Other surface infrastructure such as roads, offices and laboratories does not release naturally occurring radionuclides to the environment and is not considered a source of radiation exposure to members of the public *per se*.

4.3.3.2 Tailings Storage Facilities

The tailings storage facilities of concern for the Project are the existing TSFs, as well as the heigh extension of the Savuka 7A and 7B TSF.

A TSF can measure a few kilometres in circumference and can be tens of metres high. The surface of operational or dormant TSFs is generally amenable to wind erosion. Rehabilitation efforts on unused sections of an operational TSF can reduce the formation of windblown dust. TSFs may also be equipped with under-drains and a double high-density polyethylene (HDPE) liner to prevent seepage as well as a diversionary system of drains around the perimeter of the TSF to store and control stormwater and sediment washed off the walls of the TSF. Both seepage and run-off are drained back into the return water or process water dams for re-use. A TSF generally serves as a source of radiation exposure through solid-, gas- and water-mediated release of contaminants in the following manner:

- Windblown dust emitted from the facility contains long-lived alpha-radiating isotopes, which are dispersed into the atmosphere (solid-mediated release of contaminants, resulting in an increased concentration of airborne radioactivity). This dust is generally referred to as long-lived radioactive dust (LLα). The heavier particulates (greater than 10 microns in size) are deposited into the environment (solid-mediated release of contaminants, resulting in an increased concentration of radioactivity in surface soil).
- The radionuclide content of the tailings material and Ra-226 specifically results in the emission of radon gas into the air (gas-mediated release of contaminants, increasing the airborne concentration of radon).
- Infiltration and subsequent percolation of water through the tailings material induce the leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing radioactivity concentrations in groundwater).
- Water erosion of the TSF may induce the solid-mediated release of contaminants, increasing the radioactivity concentration in surface soil.

Although not a contaminant in the usual sense, the inherent radiological properties of the tailings material may result in the continuous emission of gamma radiation from these sources (*external gamma radiation*).

4.3.3.3 Waste Rock Dumps

The waste rock dumps of concern for the Project are the existing WRDs. Generally, a WRD serves as a source of radiation exposure through solid-, gas- and water-mediated release of contaminants in a similar manner as TSFs (see Section 4.3.3.2). However, the radioactivity content associated with waste rock is generally lower than that of the tailings. This results in WRDs being less significant sources of public radiation exposure. The associated radiological source terms for the waste rock are thus expected to be proportionally less significant.

The relative size of the material present in the WRD is much larger compared to the finely divided material deposited at a TSF. Although a fraction of small particulates may be found in a WRD, the potential for dust entrainment in the air (wind erosion) is much reduced by the presence of larger rocks and the relatively small surface area of the WRD. However, the recovery and processing of the material as an aggregate can result in an increased emission of airborne particulates. Loading and offloading of material, as well as crushing and screening activities, can serve as source activities.

Infiltration and subsequent percolation of water through the waste rock may induce the leaching of water-soluble contaminants and dispersion into the underlying geosphere. Water seeping from the stockpiles may also contain leached radionuclides, which are then transported to the underlying geosphere from where it can contaminate groundwater and surface water resources. Although the waste rock material has been removed, the plume of the contamination may remain in the unsaturated zone and continue to be transferred away from the source area of the former WRD footprint.

Low levels of gamma radiation can be emitted from the waste rock. However, members of the public will not have direct access to the stockpiles, and external gamma radiation exposure is therefore unlikely.

4.3.3.4 Ventilation Shaft

The ventilation shaft of concern for the Project is the Masomong 5 Vent Shaft. Up-cast ventilation shafts are the points on the surface where the air from underground is vented to the atmosphere. The contribution of the ventilation shafts as a point source of airborne radioactivity includes:

- The release and dispersion of dust particulates (containing LLα) into the atmosphere, resulting in a quantifiable concentration of airborne radioactivity; and
- The emission of radon gas in the air results in a quantifiable concentration of airborne radon.

The ventilation shafts will remain operational for as long as the underground working is operational, which implies that it would serve as a potential source of radiological exposure only for the operational life of the mine.

Generally, underground air can contain significant quantities of radon and once expelled from the ventilation shafts, may contribute to a notable increase in activity concentrations of airborne radon in the environment. Radon release estimates for the up-cast ventilation shafts are summarised in Section 3.5.3 and were used with dispersion estimates to approximate radon exposure from these shafts.

Due to dust control measures applied in underground working environments, a comparatively small volume of particulates is entrained in the up-cast ventilation air. In addition, the high moisture levels inside the shaft and ventilation mean that the LLα concentrations released from the shaft are low.

4.3.3.5 Water Management Facilities

The nature of water management facilities (e.g., return water dam) is such that the only contribution as a source is through water infiltration and subsequent leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing *groundwater activity concentrations*). However, the return water dam is fitted with a double HDPE liner to prevent seepage. While these dams are within the mining authorization of the Project, public access to these facilities cannot be excluded.

4.3.3.6 Pipelines

It follows from the *System Description* (see Section 3.3) that the Project make use of an extensive pipeline surface infrastructure to transfer water and tailings material over vast distances. Under normal operating conditions, these pipelines do not serve as a significant source of radiation exposure. It is only under accident and incident conditions (e.g., pipeline bursts) that these pipelines may serve as a potential secondary source of radiation exposure (see Section 4.3.4).

4.3.4 Secondary Sources Associated with the Project

4.3.4.1 General

Generally, secondary sources of radiation exposure as introduced and defined in Section 4.3.2 and Section 4.3.2 may be induced by natural processes and events, but also as part of the normal operating conditions of a mining and mineral processing operation.

4.3.4.2 Natural Processes and Events

Secondary sources induced by natural processes and events refer to the release of naturally occurring radionuclides from the primary sources (see Section 4.3.3), their distribution through the environmental system (see Section 4.4), and the subsequent build-up of activity in the associated environmental compartments with time (e.g. surface soils, surface water bodies and sediments). The development of secondary sources through these natural processes and events is thus a gradual but continuous process that can be regarded as an extension of the environmental pathways (see Section 4.4) and as a result, is addressed as such in the assessment.

The second category of natural processes and events that contribute to secondary sources is induced by natural surface water erosion. During higher rainfall events and over time, surface water erosion of the tailings storage facility results in the transfer of material during run-of (solid-mediated release of contaminants). Due to the nature of these events, the tailings will be deposited in lower-lying areas that are often associated with surface water streams and wetlands, resulting in secondary sources associated with these areas.

4.3.4.3 Normal Operating Conditions

While natural processes and events, as discussed in Section 4.3.4.2 may also be classified under normal operating conditions, this category of secondary sources relates more to release conditions approved as part of the normal operational conditions. For illustrative purposes, two examples can be noted:

- The first example relates to the annual authorised discharge quantities (AADQ) of water to the environment from the operation during high rainfall events or decanting water from the underground working that is raised because of the cessation of pumping. Water released to the environment under these conditions may introduce a potential secondary source of radiation exposure to members of the public.
- The second example relates to the gradual but continuous spillages (or windblown dust) from trucks transporting product or residue material from Point A to Point B as part of the mining operation, *on public roads*. The deposition of these materials in the environment alongside the public road introduces the development of a secondary source of radiation exposure to members of the public.

Both examples would require pre-authorisation from the relevant authorities before being included in the environmental management programme. For example, the conditions of water released to the environment would normally be approved as part of the water use license of the mine. The importance from a public radiation protection perspective is that if such conditions exist within the Project, then they *should be defined and included in the radiological public safety assessment as a potential source of radiation exposure*.

4.3.5 Secondary Sources Due to Events Outside Normal Operating Conditions

This category of secondary sources manifests itself through discrete disruptive events outside the normal operating conditions of a mining and mineral processing operation, resulting in water or solid-mediated release of naturally occurring radionuclides into the environment. Given the nature of these events, they can be considered accidents or incidents that occur over a relatively short period compared to the operational period. Several entities within the scope of the Project may potentially be subject to this type of disruptive event. These include the following:

- *Pipelines* are used to transfer water or tailings materials between components of the operation. If implemented, operated, and maintained as designed and planned (i.e., under *normal operating conditions*), pipelines do not serve as a primary or secondary source of radiation exposure to members of the public. However, a pipeline burst could occur, during which solid-mediated release of contaminants may result in either an increase in *surface soil activity concentrations* or if the spillage occurred at or near a surface water crossing, in an increase in s*urface water activity concentrations*. Under these conditions, the pipelines may induce secondary sources of radiation exposure.
- *Water management facilities,* whether lined or unlined, are engineered, designed, and built to contain a certain volume of water under normal operating conditions. This is normally done in line with regulations published in Government Notice No. 704 on 4 June 1999 (Government Gazette No. 20119) aimed at protecting water resources from mining and related activities. If these facilities do not function as planned or are designed to contain water, releases to the environment are possible, which may increase *surface soil* or *surface water activity concentrations*. Under these conditions, water management facilities may induce secondary sources of radiation exposure.
- *Tailings storage facilities* are designed and built based on engineered and geotechnical principles to contain the total volume of tailings material that will be generated during the Life of Mine. These facilities are large and include features such as underdrains, toe paddocks, and dams to capture seepage and runoff that may occur from the facility. However, excessive water erosion may lead to the discharge of tailings material into the environment.

  The more extreme case is where the TSF loses stability giving way and spilling into the environment (e.g., Merriespruit).

The above-mentioned cases serve as examples of disruption events outside the normal operating conditions of a mining and mineral processing operation that might lead to secondary sources of radiation exposure. More examples may be defined on a site and operational-specific basis. What is important to note is that the probability of the occurrence of these events is uncertain. Consequently, so too is the magnitude of the event, both in terms of scale and duration. This means that the significance of secondary sources induced by such events is equally uncertain since the potential radiation exposure to members of the public is related to the magnitude and characteristics of the event. For example, a pipeline burst lasting for a full year will have different radiological consequences than one that lasts for a day. Similarly, a spillage of tailings material occurring in the open veld will have different consequences than a spillage into a surface water body. The risks associated with a catastrophic (Merriespruit type) event are different from localised water-induced erosion of tailings storage facilities.

While it is important to note that these discrete and isolated events may occur, the parameter values that must be postulated to assess the impact on members of the public from secondary sources resulting from such disruptive events would be hypothetical and uncertain. The many uncertainties inherent in the occurrence and nature of the event mean that it simply cannot form part of the operational radiological public safety assessment process, as outlined in RG-002 NNR (2013). However, this does not mean that the potential radiological consequence of disruptive events is ignored within the broader radiation protection framework implemented in the Project.

The approach followed in the event of such disruptive events, is described in detail in the NNR-approved Radiation Management Plan, consisting of various procedures (e.g., physical security, radiation function, emergency preparedness procedure, occurrence reporting procedure, etc.). In terms of the emergency preparedness procedures, the emergency response plan is initiated as soon as the accident or incident is identified, with an emphasis on keeping radiation doses as low as reasonably achievable (ALARA).

Under the responsibilities as outlined in the radiation function procedure, specific actions need to be taken the day the incident or accident is identified, while several actions need to be taken as soon as possible after the event. These include, amongst others:

- Assessing the extent of physical damage to property, people, and the environment, as well as the extent of the contamination in and around where the event occurred using appropriate radiation survey equipment and taking water samples upstream and downstream of the incident, as appropriate;
- Inform the NNR about the event, including the current situation and its development, measures are taken to protect workers and members of the public, and the exposures that have occurred and those expected to be incurred;
- Initiate the clean-up process, with due consideration of the extent of the contamination, the potential radiological impact on workers and members of the public, and appropriate mitigation measures that can be implemented in the interim to contain the risks; and
- Capture all relevant information in an Occurrence Report to be submitted to the NNR according to the Procedure for the Reporting of Occurrences, taking cognisance of how, when and where the event happened, corrective actions and clean-up operations, and the radiological impact on workers and members of the public.

While the steps listed above are not necessarily comprehensive in terms of the emergency preparedness procedure, they certainly illustrate a due process to ensure that members of the public are protected from disruptive events outside the normal operating conditions of a mining and mineral processing operation that might lead to secondary sources of radiation exposure. For this reason, the potential secondary sources of radiation exposure induced by events outside the normal operating conditions will not be considered explicitly in the Project. However, recommendations will be made, as appropriate, to ensure that they are sufficiently covered in the broader Radiation Management Plan of the Project.

4.4 Pathways

4.4.1 General

The most significant environmental pathways through which members of the public may be exposed to radiation at a mining and mineral processing operation may be generalised as follows (IAEA, 2002):

- Atmospheric pathways that can give rise to doses due to inhalation of airborne gases (e.g., radon and its progeny) and airborne radioactive particles;
- Atmospheric and associated terrestrial pathways that can give rise to doses resulting from the ingestion of contaminated soil and foodstuff and external radiation; and
- Aquatic pathways that can give rise to doses from the ingestion of contaminated water, foods produced using contaminated irrigation water, fish, and other aquatic biota, food derived from animals drinking contaminated water, and external radiation.

This is consistent with the potential sources of radiation exposure listed in Section 4.3. The purpose of this section is to illustrate how contaminants may be released and dispersed through the different pathways into the environment and how the interaction between pathways may redistribute contaminants to receptor locations. A distinction is made between the atmospheric and aquatic pathways and their associated routes of exposure.

Given the potential sources of radiation exposure listed in Section 4.3, the pathways of concern are the atmospheric and groundwater pathways, and to a lesser extent the surface water pathway. The purpose of this section is to illustrate how contaminants may be transported through these different pathways and how the interaction between pathways may distribute contaminants to receptor locations.

4.4.2 Atmospheric Pathway

4.4.2.1 General

The significance of the atmospheric pathway is due to the presence of naturally occurring radionuclides in the particulates and gases released into the atmosphere from the activities and features associated with the Project. The contribution of the atmospheric pathway to the total effective dose is expected to occur through the following pathways:

- The release and distribution of radon gas into the atmosphere and the subsequent inhalation of this gas by members of the public;
- The release and distribution of dust particulates containing radionuclides (associated with the PM_{10} particulates and (generally referred to as Long-Lived Alpha particles or LLα) into the atmosphere and the subsequent inhalation of the dust by members of the public; and
- The deposition of airborne dust particulates containing radionuclides (associated with the Total Suspended Particulates or TSP) onto the ground, and the subsequent interaction of members of the public with the deposited dust on the soil surface or crops.

Airborne particulates and radon gas concentrations are expected to be the highest close to the source and decrease with distance from the source, depending on meteorological conditions, the physical characteristics of the contaminants and facilities from which the contaminants are released.

The sources identified in Section 4.3 that are relevant to the atmospheric pathway include the existing TSFs, WRDs and ventilation shaft that contribute to the baseline conditions, as well as the proposed Savuka 7A and 7B TSF. Using emission estimates from these sources, modelled airborne concentrations of PM_{10}, radon and rates of dust fallout, were determined for the area of concern as part of an air quality impact assessment performed for the Project (Airshed, 2025). These results confirm that airborne particulates, as well as radon gas concentrations, are highest close to the source and decrease with distance from the sources. The general direction of air dispersion of the particulates and radon gas dispersion is predominantly in a southwesterly direction.

4.4.2.2 Baseline Conditions

The baseline conditions reflect the contribution of the existing surface infrastructure. Figure 4.1 shows a graphical representation of the PM_{10} concentrations in air attributed to the existing TSFs, WRDs and ventilation shaft (in units of $\mu g.m^{-3}$). A similar representation of the annual quantity of dust deposited onto topsoil (in units of $mg.m^{-2}.day^{-1}$) is presented in Figure 4.2, while Figure 4.3 presents the estimated airborne radon concentration for the baseline conditions.

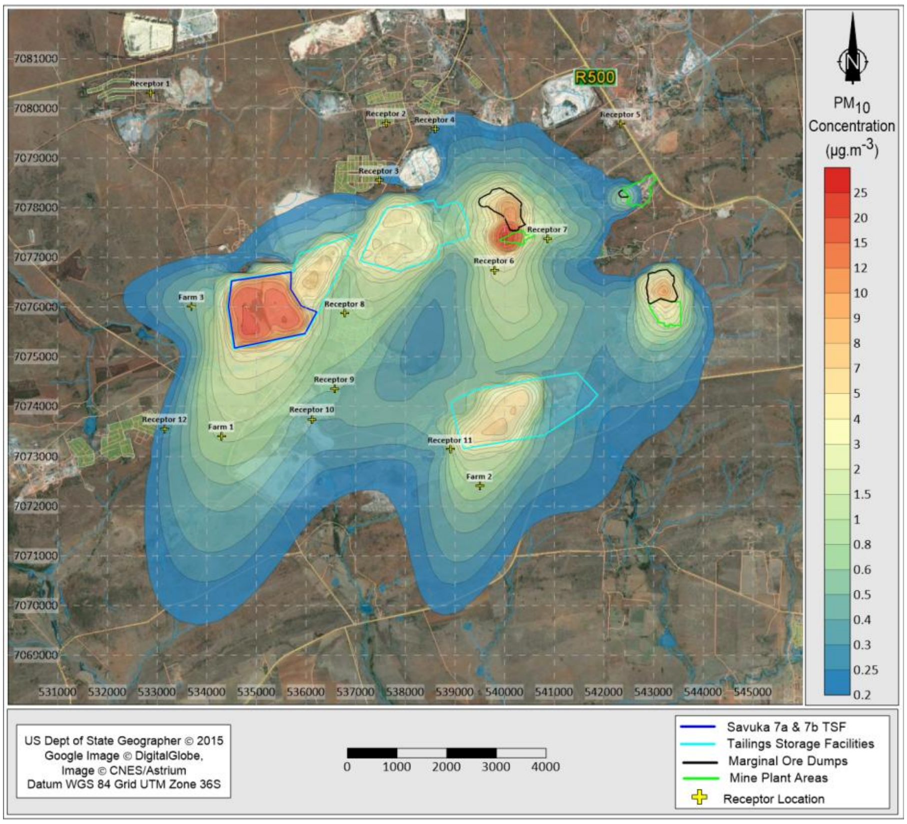


Figure 4.1 **The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to the current baseline conditions from existing surface infrastructure.**

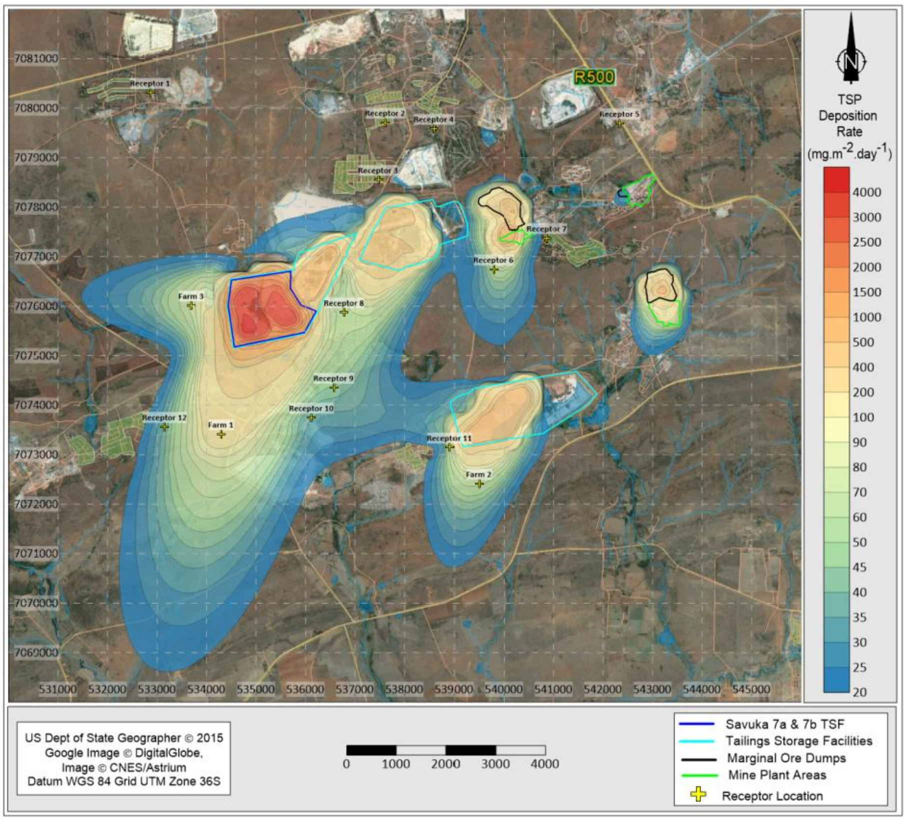


Figure 4.2 **The simulated annual average TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to the current baseline conditions from existing surface infrastructure.**

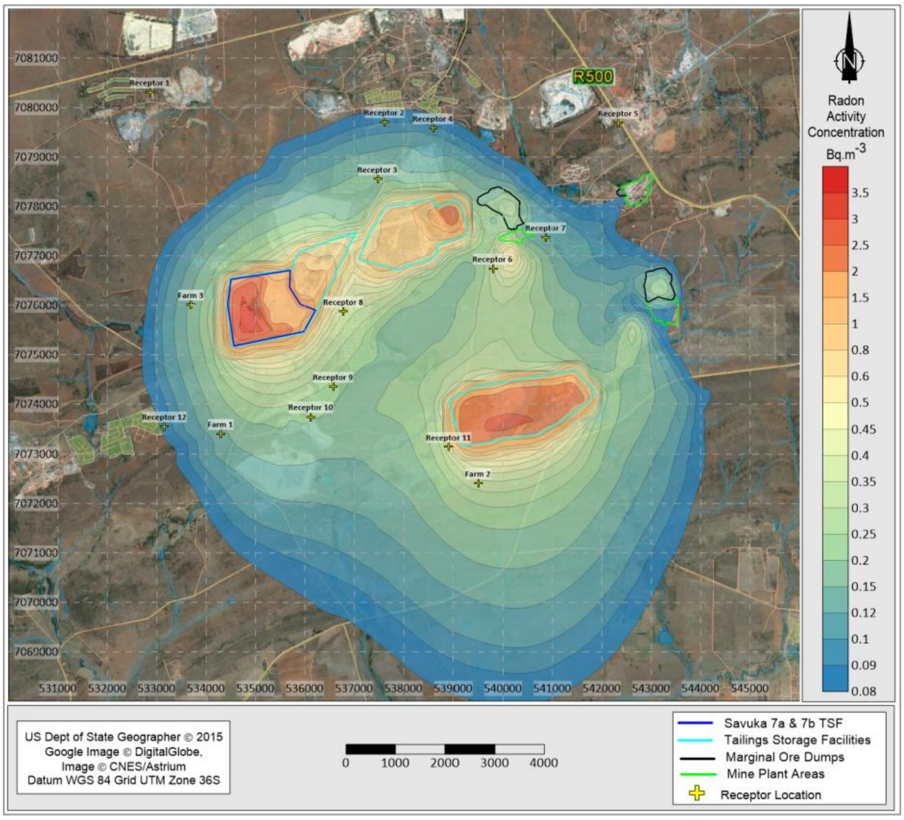


Figure 4.3 The simulated annual average radon concentration (in units of Bq.m^{-3}) attributed to the current baseline conditions from existing surface infrastructure.

4.4.2.3 Height Increase of Savuka 7A and 7B TSFs

Figure 4.4 shows a graphical representation of the PM_{10} concentrations for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions (in units of µg.m^{-3}). A similar representation of the annual quantity of dust deposited onto topsoil (in units of mg.m^{-2}.day^{-1}) is presented in Figure 4.5, while Figure 4.6 presents the estimated airborne radon concentration for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions. Figure 4.4 to Figure 4.6 clearly illustrate the effect of the proposed Savuka 7A and 7B TSF relative to the baseline conditions.

4.4.2.4 Contribution of the Atmospheric Pathway to Radiological Impact

The flow diagram in Figure 4.7 can be used to evaluate the contribution of the atmospheric pathway to a quantitative total effective dose. It follows from the source description in Section 4.3 that airborne radioactivity near the Project can be attributed to the emissions of dust that contain long-lived alpha-emitting radionuclides (LLα) and radon gas. Note that the airborne contaminant plume will contribute to the external gamma radiation dose (plume immersion), and inhalation of the airborne radioactivity contributes to the inhalation dose.

As shown in Figure 4.7, airborne contaminants may be deposited onto the surface soils, resulting in a soil concentration. Depending on the prevailing atmospheric conditions, the contaminants deposited onto the soil may go into re-suspension, resulting in the further distribution of airborne contaminants. Exposure to the soil concentration also contributes to an external gamma radiation dose (ground shine). Similarly, airborne contaminants may be deposited onto the surface water bodies, contributing to the surface water pathway (see Section 4.4.4).

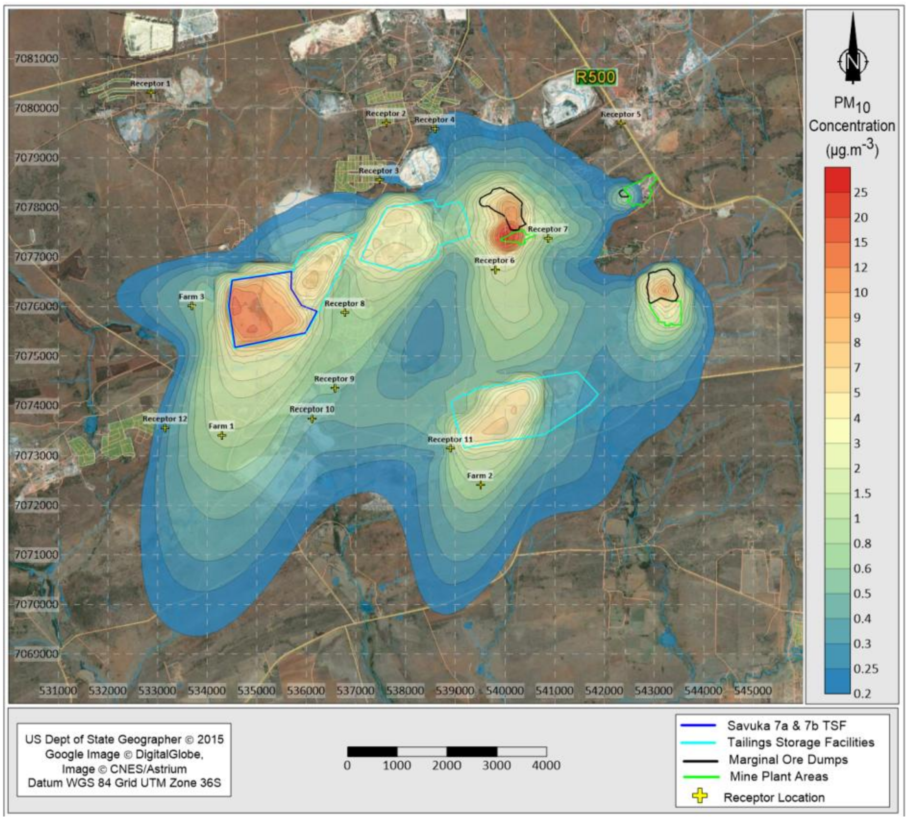


Figure 4.4 **The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions.**

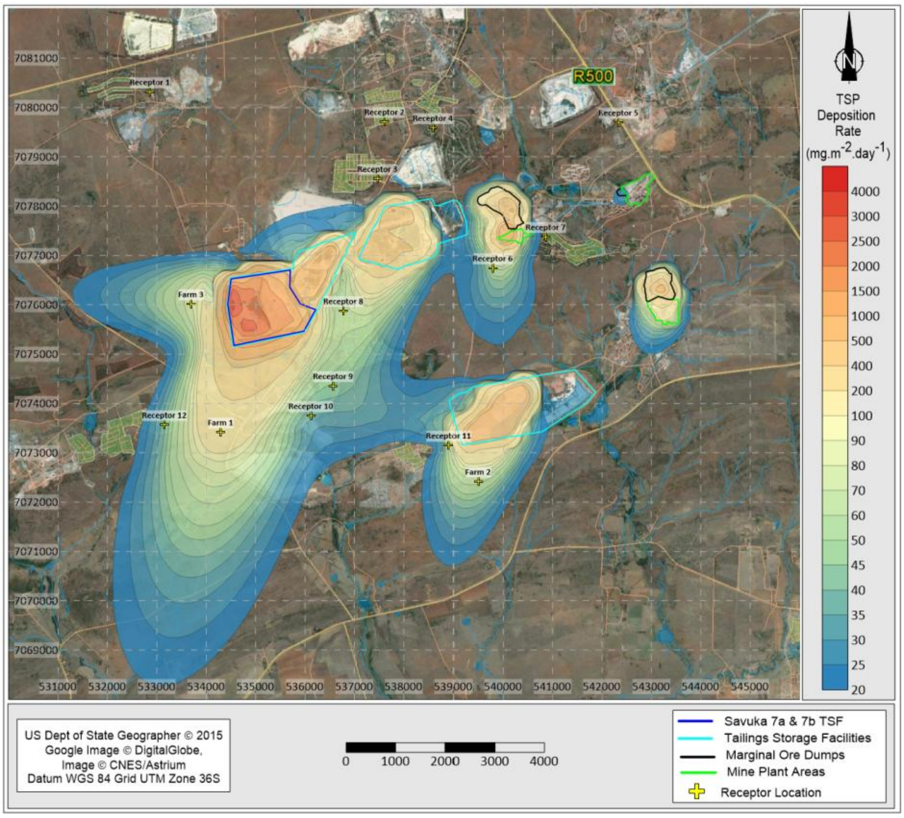


Figure 4.5 **The simulated annual average TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions.**

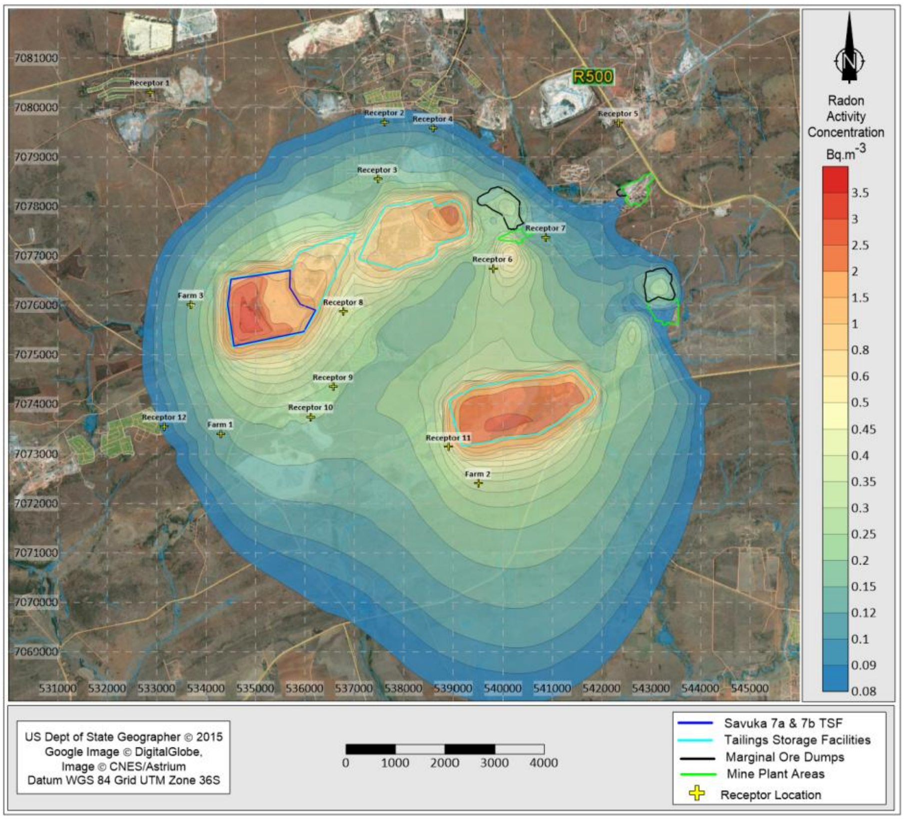


Figure 4.6 **The simulated annual average radon concentration (in units of Bq.m^{-3}) for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions.**

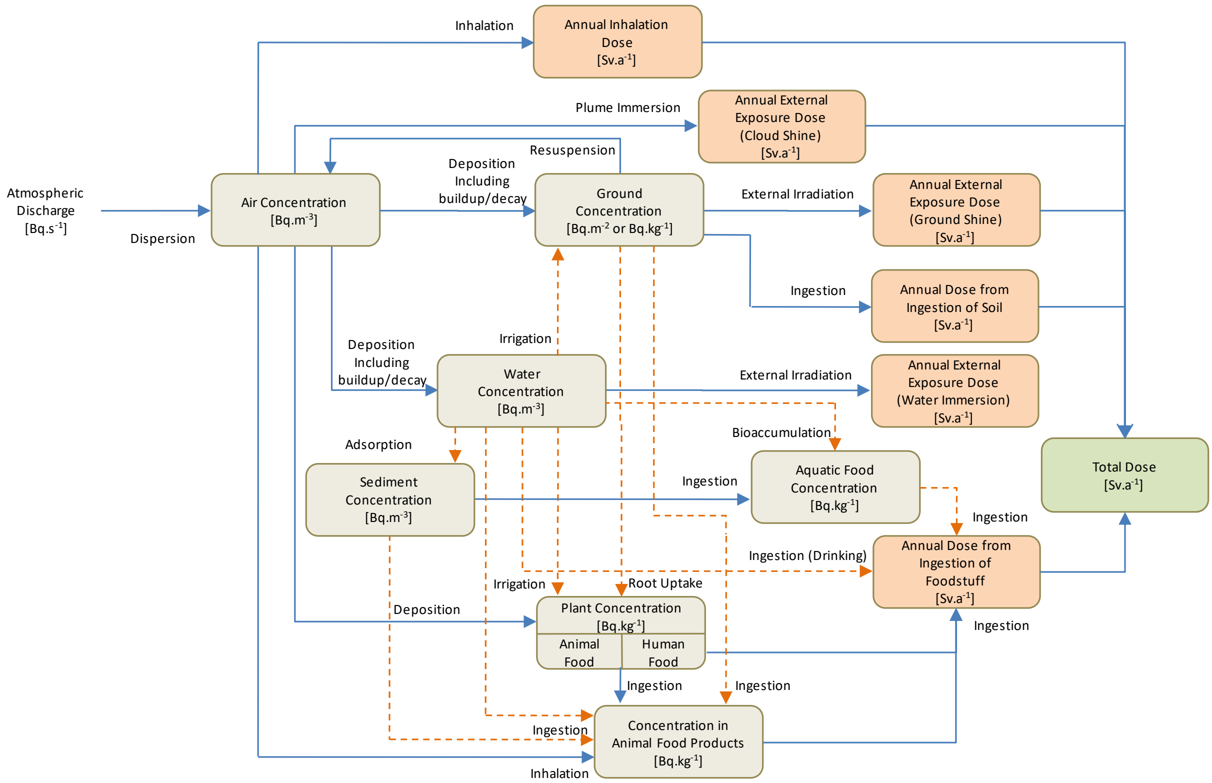


Figure 4.7 **Features, processes and associated exposure modes that should be considered to calculate the contribution of the atmospheric pathway to a total dose.**

The deposition of airborne contaminants can introduce secondary pathways that may contribute to a total effective dose. Of importance is the uptake of radioactive contaminants into the food chain. Several processes influence the transfer of airborne contaminants to crops (including animal feed and human food) as part of the atmospheric pathway:

- Direct deposition and interception of contaminants onto crops;
- Deposition of airborne contaminants onto the soil surface, followed by root uptake of contaminants from the soil (or *vice versa*, biological decay of crops containing radionuclides may increase the soil concentration); and
- Transfer (through translocation) of the deposited contaminants to the plant structure.

Some of the contaminants will be lost during food preparation, while some will be washed off the plant (contributing to a soil concentration). Contaminants deposited on the soil can be taken up by plants and so contribute to the annual effective dose of individuals that consume the plants. Animal ingestion of contaminated crops or soil or inhalation of airborne radioactivity may lead to the contamination of animal products such as dairy, eggs, and meat. Humans who utilise the affected animals for food will receive a dose through consumption of the contaminated animal products.

Human ingestion of contaminated crops, soil, or animal products or the inhalation of airborne radioactivity will result in an internal dose. The total effective dose received through the atmospheric pathway is the sum of the individual doses received through the ingestion, inhalation, and external gamma exposure routes.

4.4.3 Groundwater Pathway

The primary sources of radiation exposure (see Section 4.3) for the groundwater pathway is associated with existing TSFs and the associated water management facilities in the area. Section 3.4.5 provides a summary overview of the hydrogeological conditions in the Project area as documented in MvB Consulting (2025). A detailed characterisation of the hydrogeological flow regime of the Mponeng Operations is also provided in Aquisim (2020b).

The Mponeng Operations are locally divided into three water management areas, namely the North Boundary Dam, Varkenslaagte, and Aquatic Dam sub-catchments. These three sub-catchments are separated from one another by topographical features that lie across the lease area and represent the three major "outflow" points of both surface water and groundwater from the site. Drainage from all three sub-catchments follows a shallow path within the top weathered shale and quartzite and is generally correlated with the surface topography. Groundwater from the Varkenslaagte sub-catchment drains towards the southwest and west. It is thought to move towards the Wonderfontein Spruit, a tributary to the Mooi River. However, it is stopped at the Turffontein Dolomite Compartment, which has been dewatered by mining activities. It is theorised that once the groundwater levels in this Dolomite Compartment recover after the cessation of mining activities, the flow toward the Wonderfontein Spruit will resume.

Given the nature of the sources of radiation exposure, the near-surface unconsolidated aquifer is of importance. Any contaminants released from the sources have the potential to seep into the underlying aquifer, which may lead to an increase in the concentration of radionuclides in the groundwater. Based on the assertion that the local groundwater gradient is towards the low-lying areas that coincide with the surface water bodies, one can expect the radionuclides released from the sources into the underlying aquifer might contribute to a surface water concentration. This, together with the abstraction of groundwater in the direction of the contaminant plume, may contribute to a radiological impact through the aquatic pathways.

The rate of contaminant migration is consistent with the advective flow rate of groundwater. However, geochemical reactions may retard the movement of radionuclides relative to the groundwater flow.

Consequently, radionuclides released from a source area may take tens to thousands of years to migrate to groundwater and even longer to migrate to discharge points such as boreholes and surface water bodies. Generally, radioanalytical results of groundwater samples collected from boreholes near these source areas confirm this notion. However, the groundwater pathway is considered part of the assessment of post-operational conditions in the area of concern.

The flow diagram in Figure 4.8 can be used to calculate the contribution of the groundwater pathway to a quantitative total effective dose. Depending on the radionuclide concentration of the groundwater as well as human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.8. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation of water contributes to the concentrations of radionuclides in crops or soil.

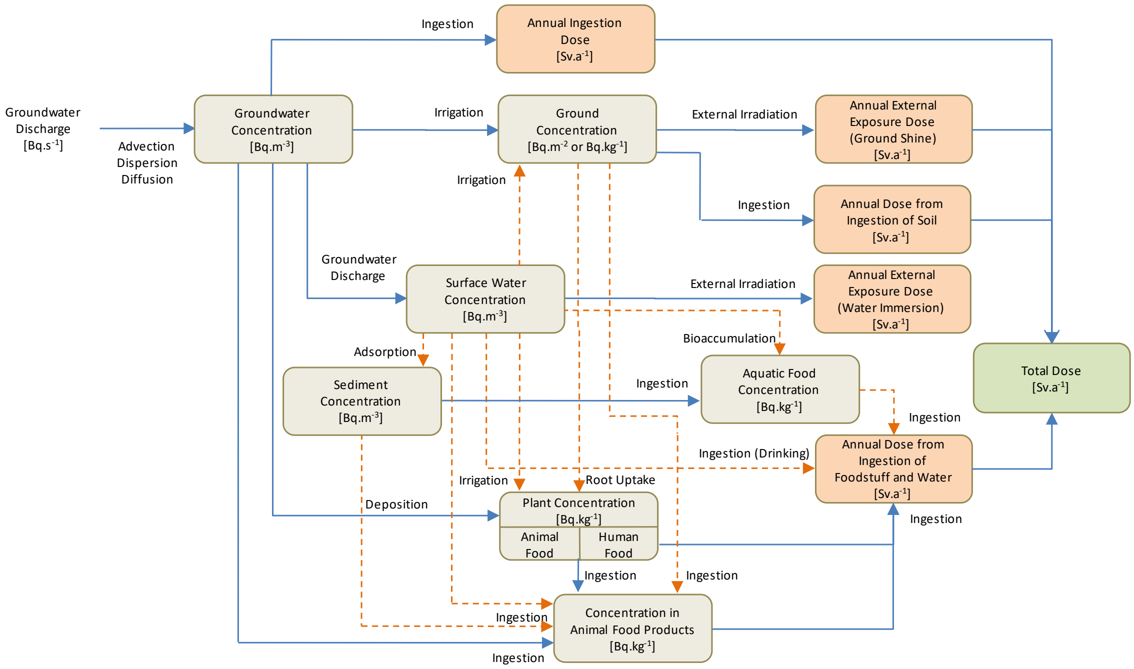


Figure 4.8 **Features, processes and associated exposure modes that should be considered to calculate the contribution of the groundwater pathway to a total dose.**

4.4.4 Surface Water Pathway

Under normal conditions, the surface water pathway is an extension of the groundwater pathway and, to a lesser extent, the atmospheric pathway. However, the controlled or uncontrolled release of contaminated water or mine residue material may serve as a direct source of radiation exposure associated with the surface water pathway. Once discharged into the surface watercourse, radionuclides are subject to a series of physical and chemical processes that affect their transport from the point of discharge. These processes illustrated in Figure 4.9, include the following (IAEA, 2001):

- Flow processes, such as down-current transport (advection) and mixing processes (turbulent dispersion);
- Sediment processes, such as adsorption/desorption on suspended, shore/beach and bottom sediments, and down-current transport, deposition, and re-suspension of sediment, which adsorbs radionuclides;
- Other processes, including radionuclide decay and other mechanisms that will reduce concentrations in water, such as radionuclide volatilization (if any).

The distribution of radionuclides into the surface water environment is thus much faster than in the case of radionuclides in groundwater, and large volumes of surface water and sediment can potentially become contaminated. However, the radionuclide concentrations in a surface watercourse may be diluted, depending on the volume of water that will be discharged into the surface watercourse and the volume of water flowing past the point of discharge.

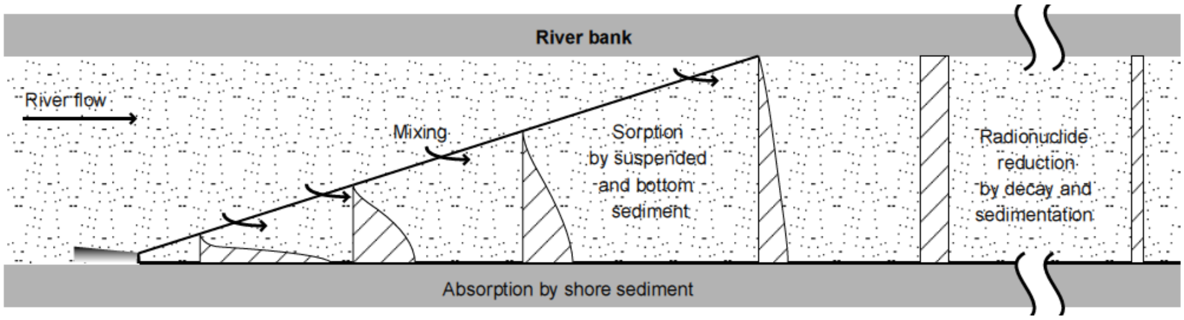


Figure 4.9 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001**).**

Section 3.4.3 and Section 3.4.5 provide a summary overview of the hydrological conditions in the Project area. The surface water drainage lines follow the topography to low-lying areas in a northwestern and southerly direction towards the Sand Spruit.

The flow diagram in Figure 4.10 can be used to calculate the contribution of the surface water pathway to a total effective dose. Deposition of airborne radionuclides onto surface water bodies may contribute to the concentration of radionuclides in surface water. Factors that will influence the migration of radionuclides in surface water include surface water/groundwater interaction (e.g., discharge rates), mean annual flow rates, seasonal variation, and adsorption of radionuclides onto sediments. Depending on the radionuclide concentration of the surface water as well as the human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.10. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation with contaminated water contributes to radionuclide concentrations in crops or soil.

Direct exposure to contaminated surface water (e.g., swimming) also contributes to an external gamma radiation dose (water immersion). Adsorption of the contaminants onto the sediments will result in a transfer and accumulation (build-up) of contaminants in the sediments (sediment concentration). Contaminants in the surface water can be transferred to aquatic animals such as fish (bioaccumulation), as well as from the ingestion of contaminated sediments.

4.4.5 External Gamma Radiation

Although not a contaminant in the usual sense, the inherent radiological properties of some of the primary sources of radiation may result in the continuous emission of gamma radiation, which could expose members of the public to *external gamma radiation*. The external gamma radiation would be the highest close to the source as radiation levels decrease by a factor of the square of the distance (i.e., inversely proportional to the square of the distance) away from the source (Martin, 2006a).

Members of the public can thus only be exposed if they come near the facilities. The main infrastructures that can be associated with external gamma radiation are the tailings storage facilities and any other areas that may be deemed contaminated with residue tailings material. Gamma radiation from releases of contamination to the environment (secondary sources) is expected to be limited.

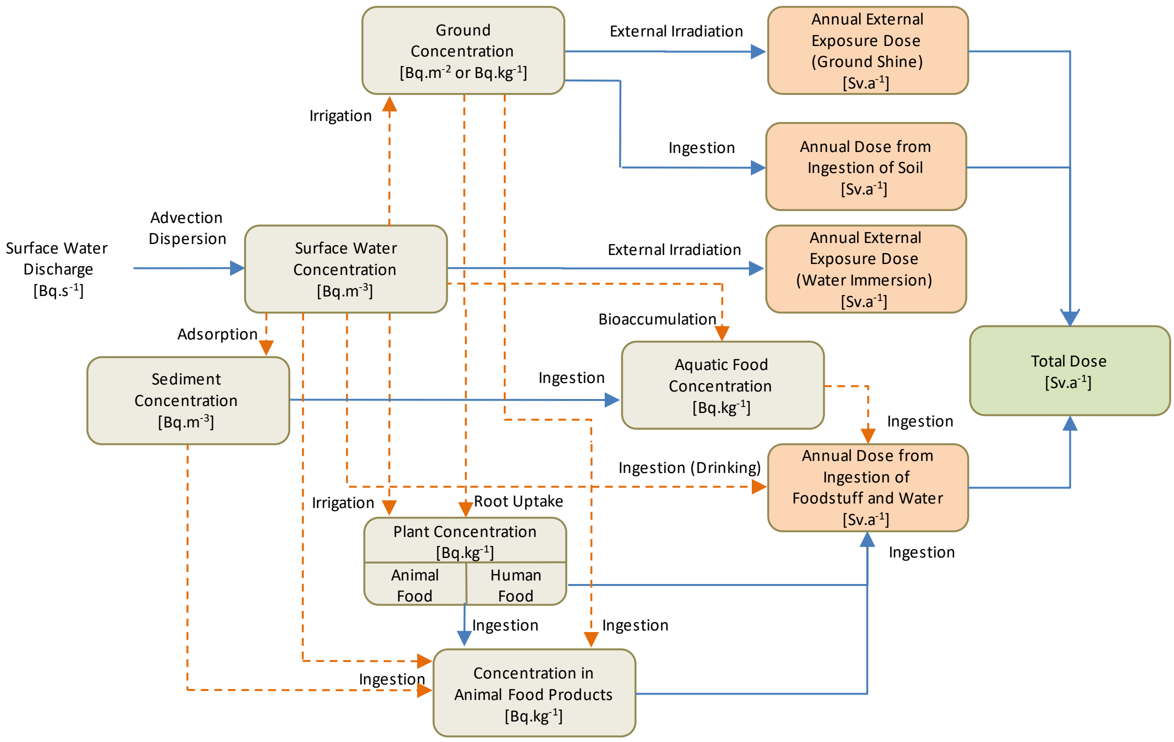


Figure 4.10 Features, processes and associated exposure modes that should be considered to calculate the contribution of the surface water pathway to a total dose.

4.5 Receptors

Receptors, as defined in Section 4.2, refer to members of the public who may potentially be subject to radiation exposure (i.e., a radiation dose) from releases from the applicable sources and through the exposure pathways of concern. The aim is to identify one or more groups of people whose habits, location, age, or other characteristics could cause them to receive a higher dose than the rest of the potentially exposed population.

The information presented in Section 3.4.7 indicates that the communities closest to the Project include the residents in the residential areas of Deelkraal, Elandsridge, Wedela, Southdene and Northdene. Agricultural activities are present in the northwest, west and southwest of the Project area.

A radiological impact on receptors can only occur if a complete Source-Pathway-Receptor linkage exists. It was demonstrated in Section 4.4.2 that the atmospheric pathway has the potential to transport radionuclides from the Project into the off-site environment. The spatial distributions of airborne particulates and contaminants can be used as a basis to determine whether members of the public could potentially be affected. The dispersion modelling results, as presented in Figure 4.1 to Figure 4.6 indicate that airborne particulate concentrations are highest close to the source and decrease rapidly with distance away from the sources. The spatial distributions of airborne particulates and contaminants indicate that areas around the Project area, and in particular in a southwesterly and southerly direction, are potentially the highest impacted areas (for PM_{10}, TSP and radon gas).

As far as the groundwater pathway is concerned, any potential off-site transfer of radionuclides would be towards the low-lying areas, with the main drainage towards the Wonderfontein Spruit in the north, but the impact during the operational phase of the Project is expected to be limited due to very slow migration rates of the associated radionuclides. However, any possible contaminant plume will discharge towards the low-lying areas associated with the Wonderfontein Spruit, albeit in the far future.

Under normal operating conditions, the surface water pathway is an extension of the groundwater pathway, and to a lesser extent, the atmospheric pathway. However, the contribution from both these pathways tends to be limited, especially over the timescales of concern. A more significant contribution can be expected from controlled and uncontrolled releases to surface water bodies. However, the Project operate in a closed water balance system, and releases, controlled or uncontrolled, are limited.

With the synopsis presented above as a basis, conservative receptor locations include most the the residential areas. The air quality sensitive receptors identified in Airshed (2025) for the air quality impact assessment is shown in Figure 4.11, with a description and coordinates of the locations listed in Table 4.1.

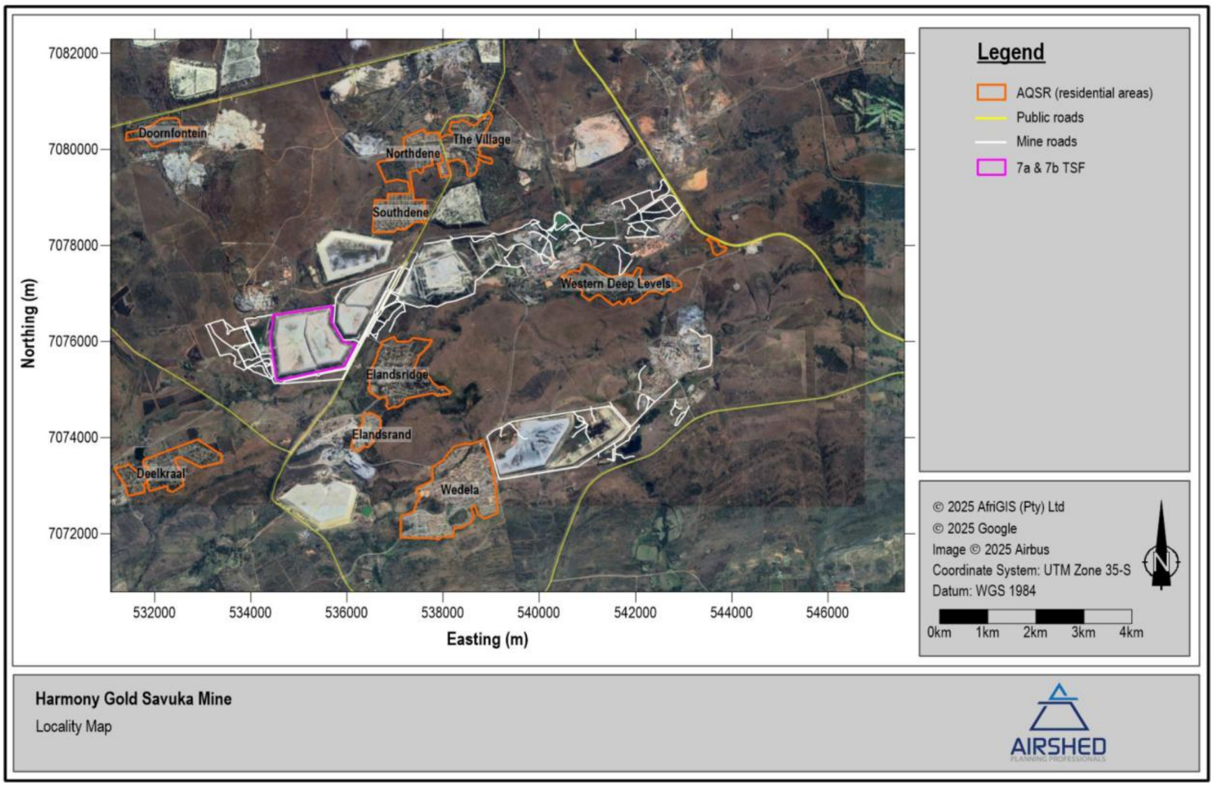


Figure 4.11 Location map and Air Quality Sensitive Receptors identified in Airshed (2025) for the air quality impact assessment (see Table 4.1 for description and the coordinates).

Table 4.1 Description and coordinates of the Air Quality Sensitive Receptors identified in Airshed (2025) for the air quality impact assessment (see Figure 4.11).

Receptor	Name	Type	Longitude	Latitude
AQSR1	Doornfontein	Residential	-26.3969	27.3295
AQSR2	Northdene		-26.4023	27.3772
AQSR3	Southdene		-26.4127	27.3758
AQSR4	The Village		-26.4034	27.3870
AQSR5	Lesley Williams Private Hospital		-26.4023	27.4245
AQSR6	AngloGold Hospital		-26.4290	27.3991
AQSR7	Western Deep Levels		-26.4233	27.4098
AQSR8	Elandsridge		-26.4369	27.3689
AQSR9	Elandsrand		-26.4507	27.3669
AQSR10	Harmony Hostel		-26.4561	27.3624
AQSR11	Wedela		-26.4615	27.3903
AQSR12	Deelkraal		-26.4579	27.3326

4.6 Conceptual Model Development

4.6.1 General

Models representing natural systems are often viewed as comprising two distinct but interconnected components: a *conceptual model* and a *mathematical model*. A conceptual model is expressed by ideas, words, and figures, while a mathematical model is expressed as mathematical equations. The two are closely related, and, in essence, the mathematical model results from translating the conceptual model into a mathematical problem that can be solved (NRC, 2003).

It is recognised that in the field of natural sciences, the term conceptual model is applied diversely. Its interpretation and use often depend on the field and purpose of the application. Various definitions of conceptual models can thus be found in the scientific and technical literature. These definitions are consistent in their fundamental meaning and differ mainly in scope, detail, and context. The statement of the conceptual model often reflects the key questions to be investigated (NRC, 2003). In its simplest form, a conceptual model can be considered a representation and simplification of reality as seen by the observer or analyst.

As applied in other fields of science, conceptual models are extensively used in radiological public safety assessments. The use of conceptual models in the development of exposure conditions is captured in Figure 1.5 and Figure 4.12.

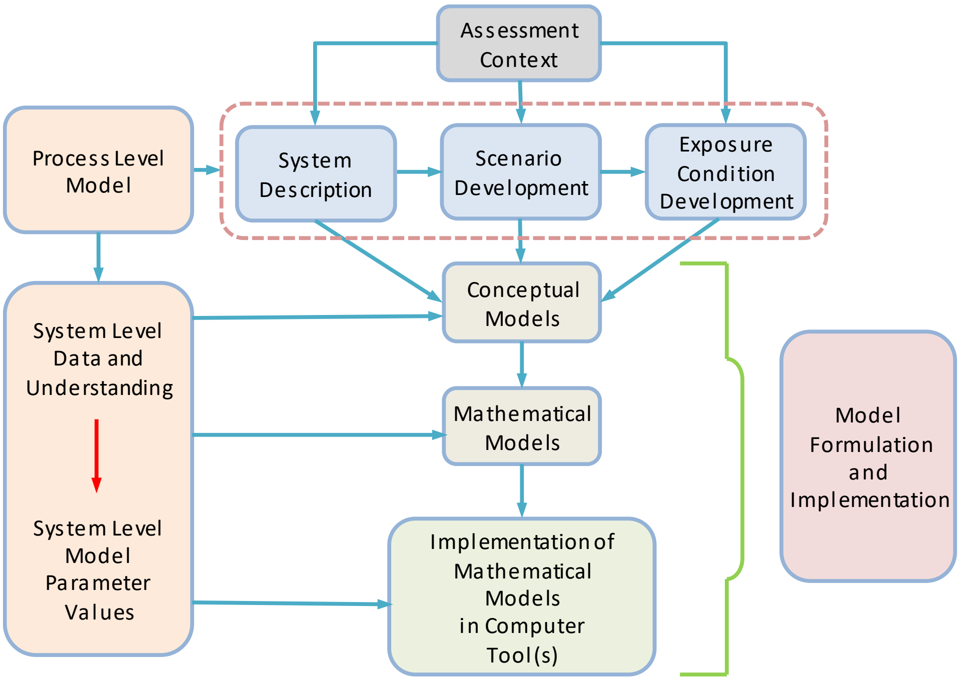


Figure 4.12 The model development process relative to other elements of the assessment framework presented in Figure 1.5.

4.6.2 Conceptual Models for Environmental Pathway Analysis

Three environmental pathways tend to be of importance in radiological public safety assessments of mining and mineral processing operations, namely the atmospheric pathway, the groundwater pathway, and the surface water pathway. To a lesser extent, external gamma radiation may also contribute to the total effective dose (see Section 4.4.5).

Specialist studies to quantify the behaviour of some of these environmental pathways have been done as part of the ESHIA process for the Project (Airshed, 2025; HydroLogic, 2025; MvB Consulting, 2025). Conceptual models developed as part of these studies that were performed on a Process Level will not be repeated here.

4.6.3 Representation of Conceptual Models for Exposure Conditions

The conceptual model for the development of exposure conditions is a schematic representation of reality, aimed at increasing the readability, transparency, and traceability of the assessment process. Viewed from this perspective, it may also be regarded as a *conceptual schema* or *conceptual data model*, which is a map of concepts and their relationships. Minor as it may seem, it all contributes to the overall confidence in the assessment process.

Two methods are used to represent the exposure conditions conceptually: a process flow diagram and a RES Matrix or Interaction Matrix (Kozak and Zhou, 1998). In an Interaction matrix, the main variables or parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. A simple example of a 2x2 matrix is illustrated in Figure 4.13, with the atmospheric (radioactive dust concentration) and topsoil layer as diagonal elements. Deposition represents an interaction between the atmosphere and the surface soil, while some of the deposited dust may be resuspended back into the atmosphere.

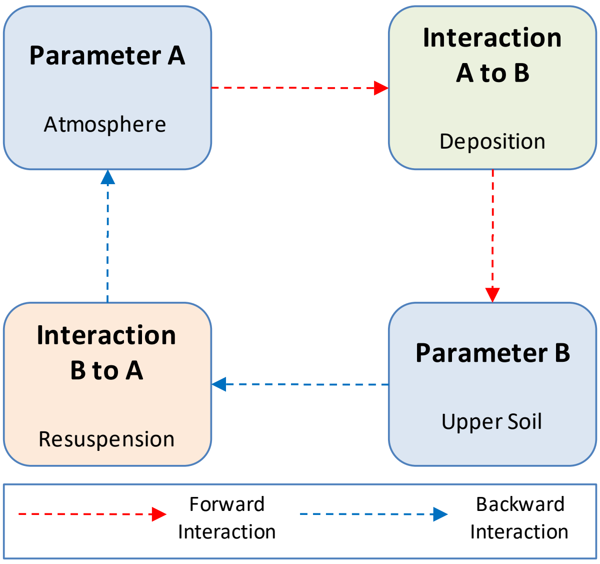


Figure 4.13 A simple 2x2 Interaction Matrix, showing the interaction between features, events, and processes in a safety assessment.

It is thus clear that the different elements of the system can be included in the Interaction Matrix and analysed in detail by creating one or more sub-matrices. This approach suggests that the elements on the main diagonal can be represented by a specific theme, such as the migration pathway of radionuclides from the sources to receptors. The off-diagonal elements represent the interaction of events and processes that cause or influence the migration of the radionuclides from one diagonal element (system feature) to another along the identified pathway. Those above the diagonal represent the influence on forwarding motion, while those below influence the backward moment. This is illustrated in Figure 4.14, which represents a 5x5 matrix and the potential migration pathway of radionuclides from element D, through various interactions between diagonal and off-diagonal elements, to element E.

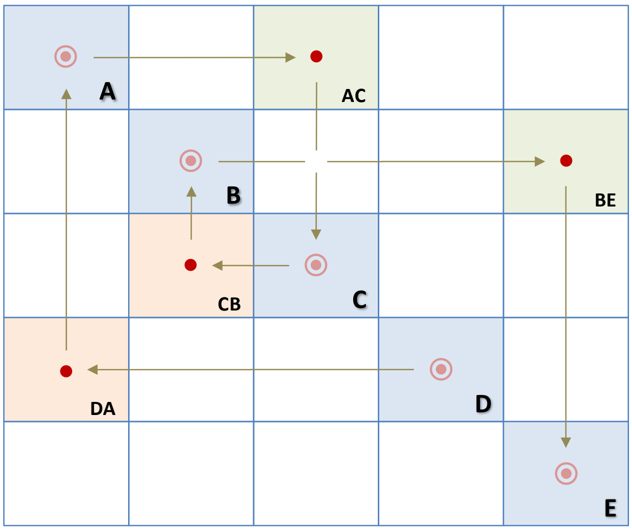


Figure 4.14 Principle of a radionuclide migration path through the Interaction Matrix.

Figure 4.15 is an example of a flow diagram as a conceptual model, showing the pathway of concern (e.g., atmospheric sources), the exposure pathways, and their relationship through processes with the different components or compartments in the system of concern. Similar to the Interaction Matrix, the transfer of radioactivity from the source to the receptor can be traced.

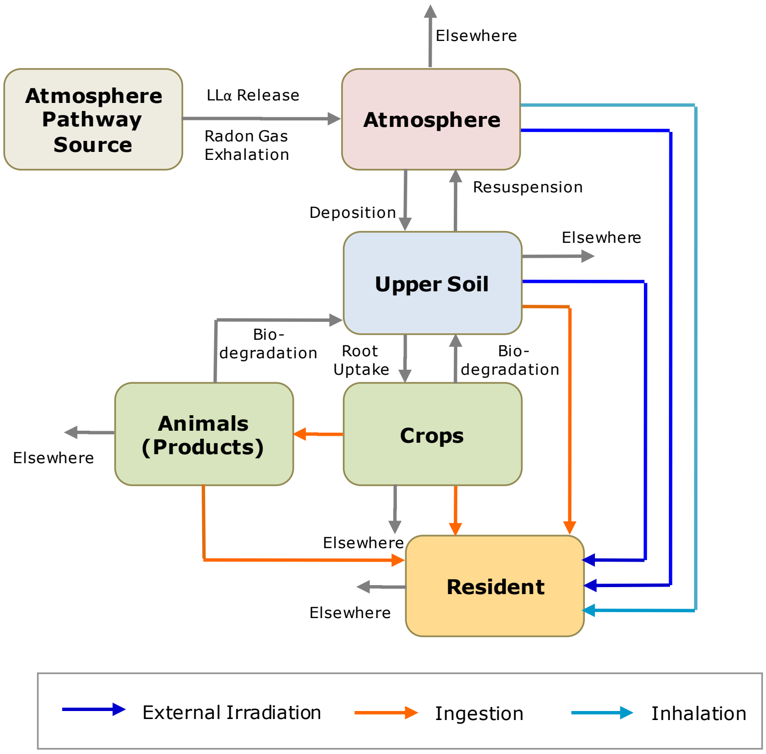


Figure 4.15 A flow diagram is an example of a conceptual model for a specific exposure condition, showing the exposure pathways and the relationship between the different compartments of the system.

4.7 Public Exposure Conditions for the Project

4.7.1 General

It follows from Section 4.3 that several potential sources of radiation exposure are associated with the Project that may contribute to releases to the atmospheric and aquatic pathways. The extent and timescales over which this might happen, vary. The release mechanisms (source terms) for the groundwater pathway, for example, tend to be a slow process. Releases from the atmospheric pathway sources are much faster. Direct releases to the surface water pathway (e.g., overflow of a water management facility) are often specific to the event and may only have an impact over a brief period.

Consistent with the source analysis, the main environmental pathways of concern as identified in Section 4.4 are the atmospheric, surface water and groundwater pathways. The sources will contribute to the atmospheric pathway in terms of particulate matter and radon gas released into the atmosphere. The dispersion is localised around the surface infrastructure of the Project and dissipates with distance away from the sources. This impact through the atmospheric pathway will continue for as long as the sources are present at the site.

The release mechanisms for the groundwater pathway sources and the subsequent dispersion into and through the environment are different from the atmospheric pathways. The groundwater pathway is a slow process mainly due to the adsorptive properties of radionuclides onto porous media, with the potential radiological impact only occurring in the far future. The migration path extends through the unsaturated zone (vertically downwards) before it follows the groundwater flow path to the lower-lying areas.

The release mechanisms for the surface water pathway sources are due to releases of contaminated water to surface water bodies (e.g., streams). Besides direct releases to surface water resources (e.g., pipeline spillages or the overflow of a surface impoundment), the surface water pathway is only significant as an extension of the atmospheric pathway (e.g., following deposition) and the groundwater pathway (e.g., following discharge of groundwater into a surface water body.

The receptors identified in Section 3.4 around the Project area mainly consist of residential areas that may include densely populated low-cost housing areas. Given the proximity to the surface infrastructure and available social and land use data, these population groups could cause them to receive a higher radiological dose than the rest of the exposed population. These groups are assumed to consist of members of the public of all ages.

Other potentially less exposed groups may include agricultural areas that may include commercial farming or small-scale farming (e.g., on an agricultural holding).

4.7.2 Criteria Used to Define the Discrete Set of Exposure Conditions

Given the nature of a mining and mineral processing operation, the definition of an exposure condition depends on several factors, such as:

- Different exposure conditions may be of importance during different phases of the mining and mineral processing operation;
- Exposure conditions may vary depending on variations in the operational conditions on a site-specific basis;
- Different sources of radiation exposure (e.g., point or diffuse sources) may result in different exposure conditions to receptors;

- The importance of environmental (e.g., atmospheric, surface water or groundwater) or direct exposure pathways depends on the characteristics of sources and human behavioural characteristics; or
- Variations in human behavioural conditions near the mining and mineral processing operation may result in different exposure conditions of concern.

Understandably, defining all exposure conditions for every potential receptor of radiation exposure at a mining and mineral processing operation is an impossible task, especially to evaluate the potential radiological consequences. For this reason, the approach is to revert to a limited number of exposure conditions that capture the diversity and complexity associated with the environment.

While the SPR analysis approach systematically derives exposure conditions, expert judgment may still be needed to combine the information on sources, pathways, and receptors into a well-defined and justified exposure condition. The following criteria are used for this purpose:

- Consistent with the ICRP principles, the radiological protection of each member of the public is of concern. However, it is impractical to derive an exposure condition for each individual. The emphasis is, therefore, on the definition of exposure conditions that are representative of a wide range of individuals and human behavioural conditions;
- In doing so, the emphasis is also on the definition of exposure conditions that are representative of the group of individuals receiving the highest exposure. This does not suggest that other exposed groups are of lesser importance; and
- As far as possible, actual conditions are considered to derive exposure conditions that are representative and realistic.

Where justified, a set of alternative and more hypothetical exposure conditions is defined. These hypothetical conditions tend to be more conservative and have the benefit that a wide range of conditions can be postulated. Often, these exposure conditions would be representative of the most exposed individual, albeit hypothetical.

4.7.3 Definition and Justification of Public Exposure Condition for the Project Area

With due consideration of the sources, pathways and receptors described above and consistent with the exposure groups defined for the 2020 GCTI Operations RPSA (Aquisim, 2020a), the following two public exposure conditions can be defined to evaluate the potential radiological impact of the Project to members of the public under normal operating conditions:

- Residential Area Exposure Condition; and
- Commercial Agricultural Exposure Condition.

More exposure conditions can be defined that would be relevant to the area. The key point of judgment on whether the discrete set of exposure conditions is representative of the radiological public safety assessment is whether potential receptors of radiation exposure can relate to at least one of these exposure conditions. The potential radiation exposure to nearby industry workers, for example, will be less than that of members of the public residing in residential areas. Similarly, the potential radiation exposure to small-scale agricultural farmers on smallholdings, for example, would be less than a conservatively defined Commercial Agricultural Exposure Condition.

4.7.4 Residential Area Exposure Condition

The purpose of the Residential Area Exposure Condition is to evaluate the radiological consequences to members of the public residing in residential areas such as Deelkraal, Elandsrand, Wedela, the mine villages and residences, as well as Wedela and the Mohaleshoek informal settlement. This may include formal and informal residential structures.

One can assume that members of the public residing in residential areas may have a household garden to supplement their daily source of food. However, it is reasonable to expect that informal settlements might be more dependent on these sources of food and, therefore, include more crops such as mealies. It is also reasonable to expect that they kept livestock such as chickens, cattle, and goats to supplement their daily requirements of protein (eggs, milk, and meat). However, as for residents in formal areas, residents of the informal areas generally do not have access to plots of land large enough to sustain their total annual requirement for food products.

The main contributor to the total effective dose in the residential areas was shown to come from the atmospheric (i.e., the ambient air conditions) and associated secondary pathways. No evidence was presented to suggest that any of the residents in the informal settlements have access to a groundwater supply point, and there are no surface water resources near enough to the areas to imply that surface water may be utilised. It is thus assumed that members of informal residential areas are supplied with water by the local municipality.

Routes of radiological exposure to members of the Residential Area Exposure Condition thus include external gamma radiation, internal exposure following ingestion of contaminated soil, crops and animal products, and internal exposure from the inhalation of airborne radon and LLα dust. In addition to the conditions and assumptions presented above, the following are assumed for the Residential Area Exposure Condition:

- The exposure groups consist of members of the public from all age groups.
- The exposure group maintain a small household garden consisting of fruits, vegetables (leafy and root) and cereal (mealies), which fulfils 50% of their annual requirement of fruit, vegetables, and cereal.
- The exposure group keep animals in the form of chickens, goats, and cattle. These serve as a source of protein in the form of eggs, milk, and meat. For the assessment, it is conservatively assumed that it contributes to 50 % of their daily rate of protein consumption.
- Food preparation (e.g., peeling, boiling) may contribute to a reduction in radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in any food produced in the area remain the same irrespective of the preparation methods used.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.2 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.
- As a conservative assumption, the rate of incidental soil ingestion is maintained at 100% of the value published in RG-002 (NNR, 2013).

Table 4.2 Age group-specific indoor and outdoor occupancy factors (NNR, 2013).

Activity	0 to 2 Years	2 to 7 Years	7 to 12 Years	12 to 17 Years	Adult
Time spent indoors	7,914	7,775	7,568	7,665	7,050
Time spent outdoors	846	985	1,192	1,092	1,710

The conceptual model for the Residential Area Exposure Condition is presented in Figure 4.16 and Figure 4.17 using a flow diagram and an Interaction Matrix, respectively.

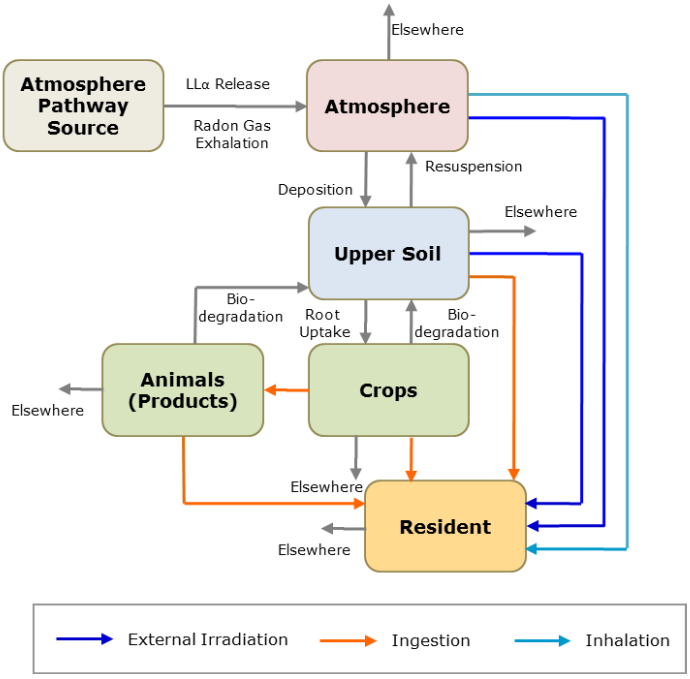


Figure 4.16 Conceptual flow diagram of the exposure pathways associated with a Residential Area Exposure Condition.

	1	3	4	6	7	8	9	10
A	Atmospheric Pathway Sources	LLα Suspension Dispersion	Radon Exhalation Dispersion					
C		Atmosphere LLα Conc.		Deposition	Deposition Interception		Inhalation External Exposure	Dispersion
D			Atmosphere Radon Conc.				Inhalation	Dispersion
F		Re-suspension		Upper Soil	Root Uptake Crop Contam.	Ingestion	External Exposure Ingestion	Erosion Leaching
G				Bio-degradation	Crops	Ingestion	Ingestion	Washed Away Weathering
H				Bio-degradation Excrement		Animals	Ingestion	
				Irrigation Tilling Ploughing	Plant crops Food preparation	Feed	Resident	Excrement
J								Elsewhere

Figure 4.17 Conceptual Interaction Matrix of the exposure pathways associated with Residential Area Exposure Condition.

Radon gas and LLα released from the atmospheric pathway sources are dispersed into the environment, contributing to the increase in concentrations of airborne radionuclides. Some of the airborne radionuclides are deposited onto the upper soil surface and crops (fruits, vegetables, and cereal), contributing to an increase in the concentrations of radionuclides in soil and crops. Root uptake processes transfer some of the radionuclides from the soil to the crops. Exposure routes associated with the Residential Area Exposure Condition include radon gas and LLα inhalation, as well as ingestion of contaminated crops (fruits, vegetables, and cereal) and animal products (meat, eggs, and milk). Inadvertent soil ingestion is also assumed. Contributions to the total effective dose from external gamma radiation are also expected from airborne LLα (cloud immersion) and radionuclides deposited on the upper soil layer (ground shine).

Note that, as illustrated in Figure 4.16 and Figure 4.17, biodegradation of crop material may also contribute to the upper soil concentration, while resuspension of deposited dust may contribute to the airborne activity concentration. Also illustrated in Figure 4.16 and Figure 4.17, is the transfer of some of the radioactivity released from the atmospheric pathway sources, to “elsewhere” through processes such as dispersion, leaching, washing, weathering and excretion. “Elsewhere” as used here refers to a place where humans will not be affected by the radionuclides of concern.

4.7.5 Commercial Agricultural Exposure Condition

The purpose of the Commercial Agricultural Exposure Condition is to evaluate the radiological consequences to members of the public practising commercial farming near the Project. However, the exposure condition is equally relevant to agricultural practices anywhere near the Project. This means that this exposure condition relates to any farming activity under the conditions and assumptions presented below.

The main contributor to a total effective dose is from the atmospheric, groundwater and associated secondary pathways. This resulted in contributions from external gamma radiation, internal exposure following ingestion of contaminated water, soil and crops, and internal exposure from the inhalation of airborne radon and LLα dust. In addition to the conditions and assumptions presented above, the following are assumed for the Commercial Agricultural Exposure Condition:

- The exposure groups (farmers and farm workers) consist of members of the public from all age groups.
- The exposure group maintain a commercial farm system consisting of fruits, vegetables, and cereal (mealies). It is conservatively assumed that the farm contributes 100% to its annual consumption rate.
- The exposure group keep animals in the form of chickens, sheep, and cattle. These serve as a source of protein in the form of eggs, milk, and meat. For the assessment, it is conservatively assumed that it contributed 100% to their annual consumption rate.
- Food preparation (e.g., peeling, boiling) may contribute to a reduction in radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in any food produced in the area remain the same irrespective of the preparation methods used.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.2 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.

The conceptual model for the Commercial Agricultural Exposure Condition is presented in Figure 4.18 and Figure 4.19 using a flow diagram and an Interaction Matrix, respectively.

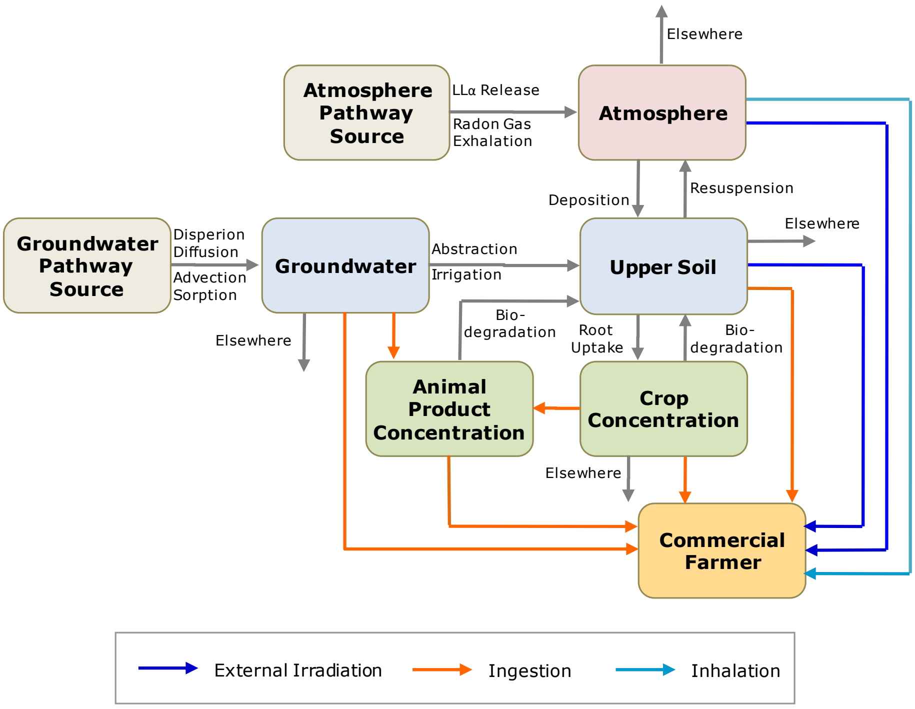


Figure 4.18 **Conceptual flow diagram of the exposure pathways associated with the Commercial Agricultural Exposure Condition.**

Radon gas and LLα released from the atmospheric pathway sources are dispersed into the environment, contributing to an airborne radionuclide concentration. Some of the airborne radionuclides are deposited onto the crops (fruits, vegetables, and cereal), contributing to an increased concentration of radionuclides in crops and the upper layer of soil. Root uptake processes transfer some of the radionuclides from the soil to the crops.

Radionuclides leached from the groundwater pathway sources enter the underlying aquifer, from where it is dispersed into the groundwater and surface water environments. Members of the public practising agriculture use groundwater abstracted from a borehole for their consumption and to maintain a commercial farm system (i.e., irrigation and water supply), consisting of crops, poultry, and cattle. Radionuclides in the water are deposited onto the crops, contributing to the radionuclide concentration in the crops and the upper layer of soil. Root uptake processes transfer some of the radionuclides from the soil to the crops. Products such as meat, milk and eggs from animals that consume the contaminated water and crops can contain increased concentrations of radionuclides.

Exposure routes associated with the Commercial Agricultural Exposure Condition include radon gas and LLα inhalation, as well as ingestion of contaminated groundwater, crops, and animal products (meat, eggs, and milk). Inadvertent or incidental soil ingestion is also assumed to occur. Contributions to the total effective dose from external gamma radiation occur through exposure to airborne LLα (cloud immersion) and radionuclides deposited on the upper soil layer (ground shine).

Note that, as illustrated in Figure 4.18 and Figure 4.19, biodegradation of crop material may also contribute to the concentration of radionuclides in the upper layer of soil, while resuspension of deposited dust may contribute to airborne radioactivity. Also illustrated in Figure 4.18 and Figure 4.19, is the transfer of some of the radioactivity released from the atmospheric pathway sources, to “elsewhere” through processes such as dispersion, leaching, washing, weathering and excretion. “Elsewhere” as used here refers to a place where humans will not be affected by the radionuclides of concern.

	1	2	3	4	5	6	7	8	9	10
A	Atmospheric Pathway Sources		LLα Suspension Dispersion	Radon Exhalation Dispersion						
B		Groundwater Surface Water Pathway Sources			Advection Dispersion Diffusion Sorption					
C			Atmosphere LLα Conc.			Deposition	Deposition Interception		Inhalation External Exposure	Dispersion
D				Atmosphere Radon Conc.					Inhalation	Dispersion
E					Water (Borehole)	Deposition	Interception	Ingestion	Ingestion	Advection Dispersion Diffusion Sorption
F			Re-suspension			Upper Soil	Root Uptake Crop Contam.	Ingestion	External Exposure Ingestion	Erosion Leaching
G						Bio-degradation	Crops	Ingestion	Ingestion	Washed Away Weathering
H						Bio-degradation Excrement		Animals	Ingestion	
					Abstract	Irrigation Tilling Ploughing	Plant crops Food preparation	Feed	Commercial Farmer	Excrement
J										Elsewhere

Figure 4.19 Conceptual Interaction Matrix of the exposure pathways associated with the Commercial Agricultural Exposure Condition.

5 Consequence Analysis

5.1 Introduction

The purpose of the consequence analysis is to assess the potential radiological consequences of the public exposure conditions defined for the Project in Section 4.7. Consistent with the safety assessment framework and technical approaches therein (see Figure 1.5), the assessment results are then interpreted in terms of the total annual effective dose as compliance criteria (boundary conditions) as defined in the *Assessment Context* (see Section 2). The methodological approach used to calculate the total effective dose is described in Appendix B.

The section is structured as follows. Section 5.2 evaluates the potential contribution of the groundwater pathway included in the definition of the Commercial Agricultural Exposure Condition. Section 5.3 then evaluates the radiological consequences of all the exposure conditions defined in Section 4.7 in terms of the total effective dose.

5.2 Contribution from Groundwater Pathway

5.2.1 General

The use of groundwater as a source of water for agricultural use cannot be excluded with confidence. In principle, the groundwater abstracted from a borehole may be contaminated following leaching from facilities associated with the Project (e.g., TSF or RWD). However, the leaching and subsequent lateral migration of radionuclides is a slow process. This is because the radionuclides migrate at a much slower rate than the advective flow due to isotope-specific adsorption properties of the tailings materials and the underlying aquifer host medium.

Although little information is available to evaluate this scenario, some assumptions can be made to assess the radiological consequences, albeit for illustrative purposes. Consequently, presented here is a simplified one-dimensional numerical groundwater model using a compartmental modelling approach to represent the migration and fate of contaminants in the environment with the TSF as the source of contamination. The conceptual representation of the *System Level* compartmental model implemented in AFRY Intelligent Scenario Modelling (Version 8.5) (https://www.intelligentscenariomodelling.com/) (AFRY ISM) is presented in Appendix D.

The groundwater pathway consists of several compartments that need to be considered in an integrated manner to evaluate the potential contribution to a total effective dose. Figure 5.1 depicts the relevant compartments and the interaction between them. Figure 5.2 presents the AFRY ISM implementation of Figure 5.1, which can be used to evaluate the contribution of the groundwater pathway.

To evaluate the potential radionuclide concentration in groundwater and the subsequent ingestion dose, hypothetical conditions complemented with site-specific conditions are used to illustrate the relative insignificance of the groundwater pathway over a brief period (e.g., operational period).

5.2.2 Parameter Values

As a conservative assumption, the average activity concentrations listed in Table 3.16 for the CoR-03 tailings material generated at the Mponeng Operations, were used as the initial activity concentrations, while Table 5.1 summarises a few additional parameter values assumed for the leaching analysis. Note that these parameter values are selected to be conservative.

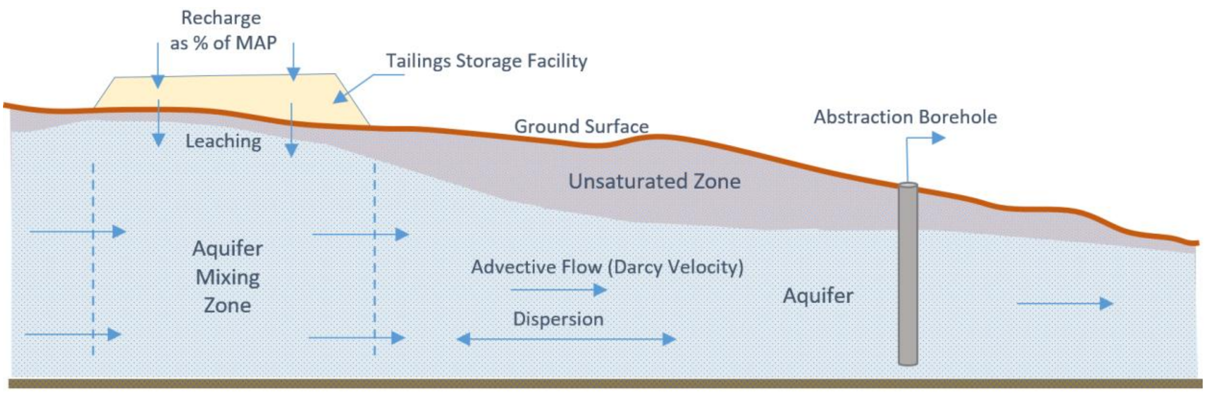


Figure 5.1 Conceptual representation of the model compartment included in the System Level modelling of the groundwater pathway (Not to Scale).

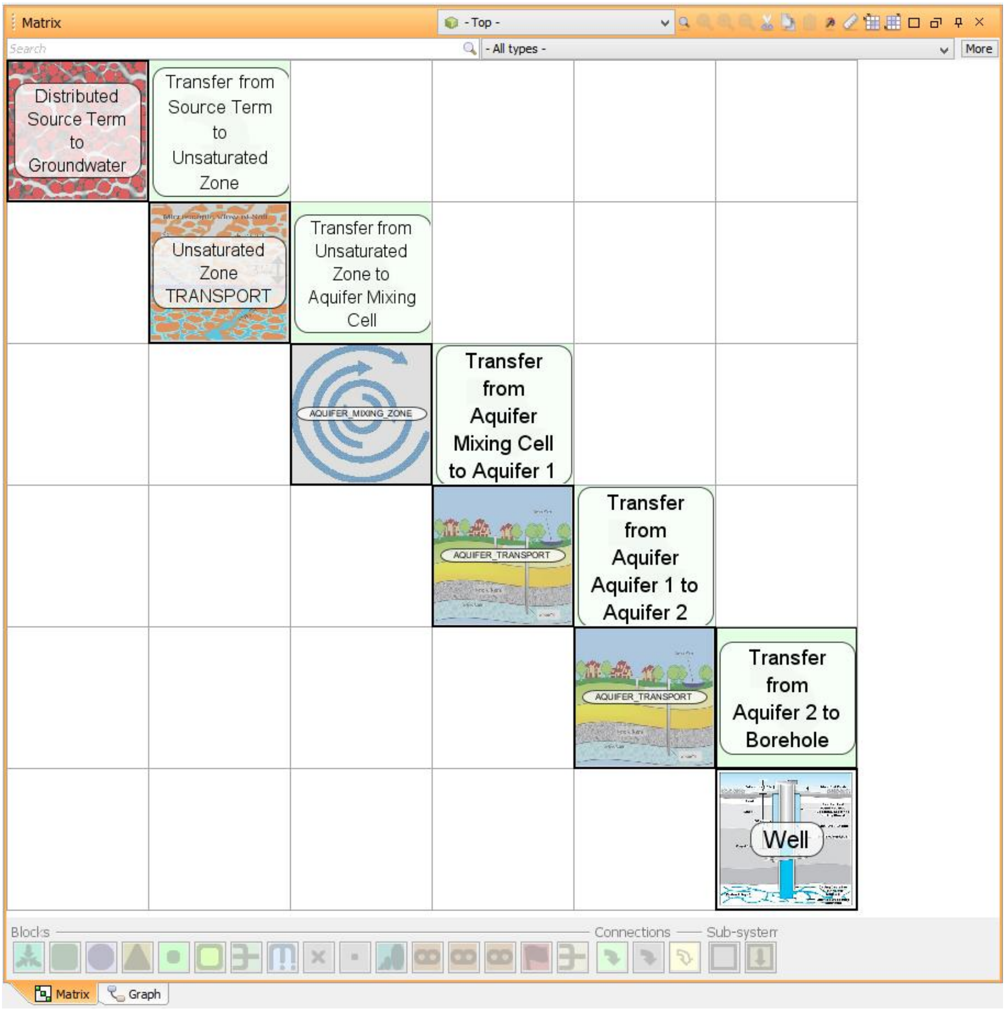


Figure 5.2 Screen capture of the model implementation in AFRY ISM used to evaluate the contribution of the groundwater pathway for the Project.

It was assumed that the recharge (or infiltration) rate of water through the TSF decreases with time after the assumed operational period of 50 years to a natural recharge rate of 3% of the MAP. It is further assumed that the TSF remain as a source at the surface for 1,000 years. This is conservative, given the uncertainty of how long the TSF will remain at the surface in future. However, it is more realistic to assume the TSF will remain at the surface for 1 million years, which is the duration assumed for the simulations.

Table 5.1 Summary of facility-specific parameter values necessary to calculate the leaching of radionuclides from the Project TSFs.

Parameter			Units	Savuka 7A and 7B TSFs (Before Height Extension)	Savuka 7A and 7B TSFs (After Height Extension)
Mean Annual Precipitation (MAP)			[mm]	781	
Recharge (Infiltration) Rate Through TSF as % of MAP	< 50 years	15% of MAP	[m.year^{-1}]	1.17E-01	
	50 to 75 years	10% of MAP		7.81E-02	
	75 to 100 years	5% of MAP		3.91E-02	
	> 100 years	3% of MAP		2.34E-02	
Volumetric Moisture Content			[m^3.m^{-3}]	3.0E-01	
The density of Tailings Material			[kg.m^{-3}]	2.625E+03	
Average Height			[m]	60	70
Average Area			[m^2]	3.01E+06	3.01E+06
Assumed Length and Width (√Area)			[m]	1.73E+03	1.73E+03
Volume			[m^3]	1.81E+08	1.81E+08

The most sensitive parameters in the TSF radionuclide leaching equation are the distribution coefficient (or K_d-value) and the solubility limits. Low K_d values were used as distribution coefficients for the TSF, unsaturated zone, and aquifer. This is very conservative, assuming little absorption to retard the migration of radionuclides through the system. For this assessment, no solubility limits were applied, which implies that all activity in the tailings is available for dissolution and leaching. *In practice, this is not the case and represents a very conservative approach*.

The approach adopted for the analysis presented here is to use a conservative range of K_d values from the literature for illustrative purposes. Table 5.2 lists soil distribution coefficients for selected radionuclides published in RG-002 (NNR, 2013), as well as the range of values from the literature for different soil types as published by the Argonne National Laboratory (Yu *et al.*, 1993). The comparison shows that the values of the distribution coefficients found in the literature can vary significantly.

Table 5.2 Distribution coefficients from the literature for the elements of concern, as well as the K_d values in the analysis for illustrative purposes (NNR, 2013; Yu *et al.*, 1993).

Element	RG-002	Comparative Values				K_d-values Used
		Sand	Loam	Clay	Resrad Default	
	K_d-values (m^3.kg^{-1})					
Th	1.90E+00	3.20E+00	3.30E+00	5.80E+00	6.00E+01	2.00E-01
Ra	2.50E+00	5.00E-01	3.60E+01	9.10E+00	7.00E-02	3.00E-01
U	2.00E-01	3.50E-01	1.50E-02	1.60E+00	5.00E-02	2.00E-02
Pb	2.00E+00	2.70E-01	1.60E+01	5.50E-01	1.00E-01	2.70E-01
Po	2.10E-01	1.50E-01	4.00E-01	3.00E+00	1.58E+00	1.50E-01
Pa	2.00E+00	5.50E-01	1.80E+00	2.70E+00	5.00E-02	5.50E-01
Ac	1.70E+00	4.50E-01	1.50E+00	2.40E+00	2.00E-02	4.50E-01

Table 5.3 lists additional aquifer parameters needed for the calculations. The unsaturated zone underneath the TSF is conservatively assumed to be only 5 m thick, with a dry bulk density of 1,400 kg.m^{-3} and a volumetric moisture content of 0.3 m^3.m^{-3}. A thicker unsaturated zone will retard the migration of radionuclides to the point of abstraction even further. Here, the hydraulic gradient is in the order of 6.4% (or 0.02), while the hydraulic conductivity in the weathered aquifer can be set at 1.45E+00 m.day^{-1}, which equates to a relatively low Darcy velocity of 1.06E+01 m.year^{-1} (or 2.9E-02 m.day^{-1}). With an effective porosity of 2%, the advective flow velocity is in the order of 2.9E+00 m.year^{-1} for the area as listed in Table 5.1,

Table 5.3 Aquifer parameters assumed for the areas of concern to calculate the advective flow and migration of radionuclides.

Parameter	Units	Value
Depth to Water Table	m	1
Aquifer Thickness		20
Hydraulic Conductivity	$m.day^{-1}$	1.45
Effective Porosity	-	0.02
Hydraulic Gradient		0.02
Darcy Velocity	$m.day^{-1}$	2.90E-02
Actual Velocity		1.45E+00
Longitudinal dispersivity (α_L)	m	25
Dry Bulk Density	$kg.m^{-3}$	1,800
Distance to Borehole	m	500
Borehole Fraction in Contaminant Plume	-	1

5.2.3 Results

5.2.3.1 Savuka 7A and 7B TSF

Figure 5.3 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 5,000 years (the Th-232 decay chain only becomes visible after 40,000 years). If one assumes the RG-002 (NNR, 2013) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.3 translate to water ingestion doses shown in Figure 5.4. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a point 500 m from the TSF is only visible in thousands of years, and potentially at doses that are in the order of 60 $\mu Sv.year^{-1}$ and lower.

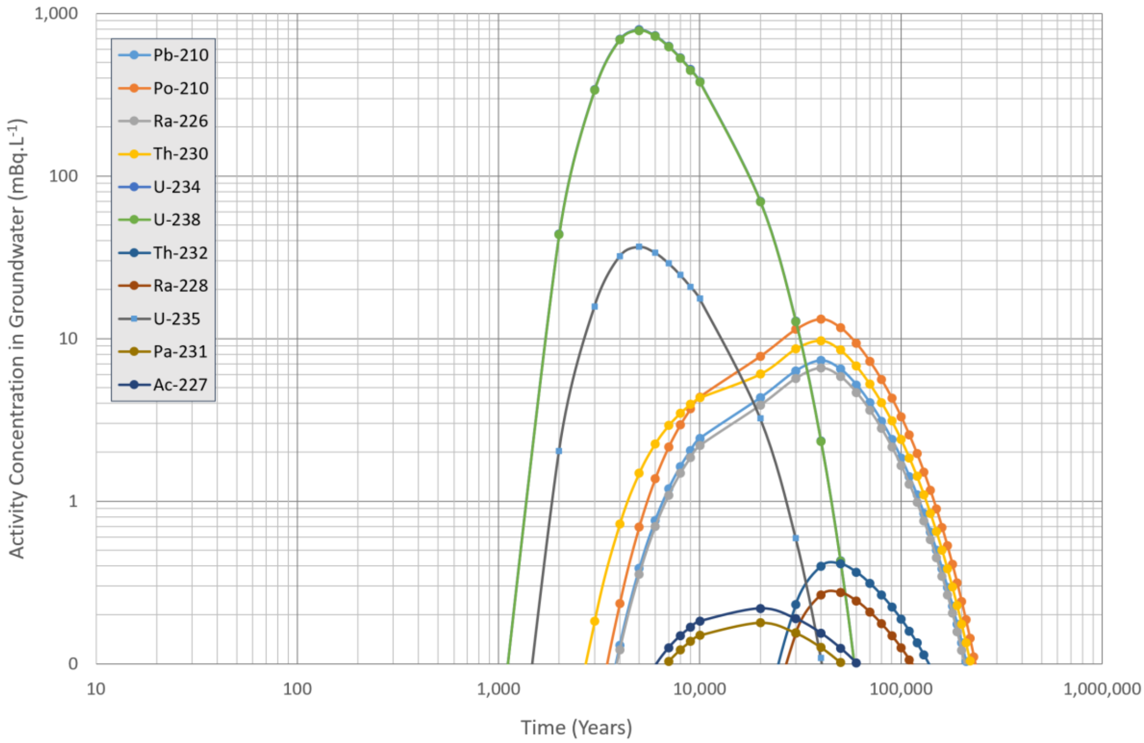


Figure 5.3 The simulated activity concentration in groundwater abstracted from a borehole 500 m from the Savuka 7A and 7B TSF.

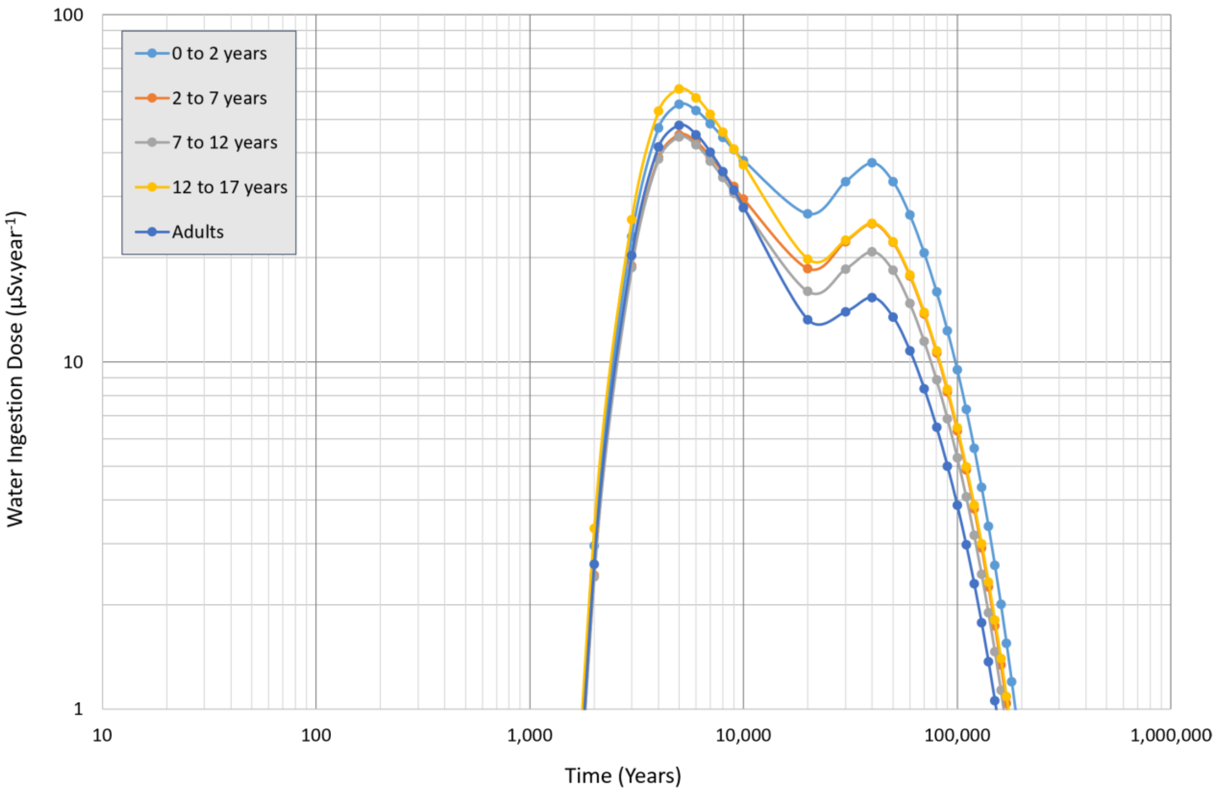


Figure 5.4 The simulated water ingestion dose to the different age groups 500 m from the Savuka 7A and 7B TSF, using the activity concentrations in Figure 5.3.

5.2.3.2 Savuka 7A and 7B TSF Extension

Figure 5.5 and Figure 5.6 present the same results as presented in Figure 5.3 and Figure 5.4 for the current Savuka 7A and 7B TSF. It shows that the results are the same without any variation in the water ingestion doses over the timescales of concern.

5.2.3.3 Discussion

The results presented in Figure 5.3 to Figure 5.6 suggest that a contribution from the groundwater pathway is only possible during the post-closure period and unlikely within the next 1,000 years and then only at doses of less than 70 µSv.year^{-1}. This applies to the current Savuka 7A and 7B TSF, as well as a Savuka 7A and 7B TSF with a height extension of 10 m.

5.3 Total Effective Dose Calculation for Exposure Conditions

5.3.1 General

The purpose of this section is to present the results of the total effective dose calculations for the public exposure conditions defined for the Project in Section 4.7. Due to the nature of these exposure conditions and the potential contribution of the different environmental pathways to the total effective dose, the focus of the results presented here is the contribution through the atmospheric pathway. This is a function of the sources of airborne contaminants associated with the atmospheric pathway, as well as the radioactivity concentration in the airborne and deposited dust.

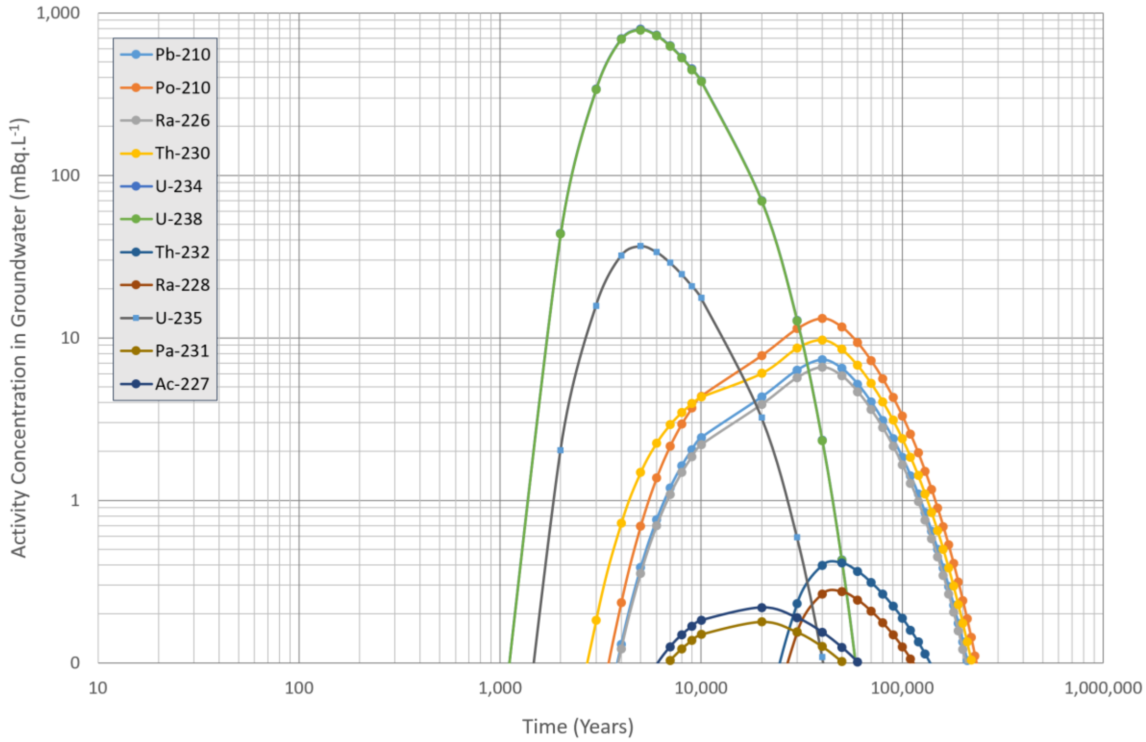


Figure 5.5 The simulated activity concentration in groundwater abstracted from a borehole 500 m from the height extended Savuka 7A and 7B TSF.

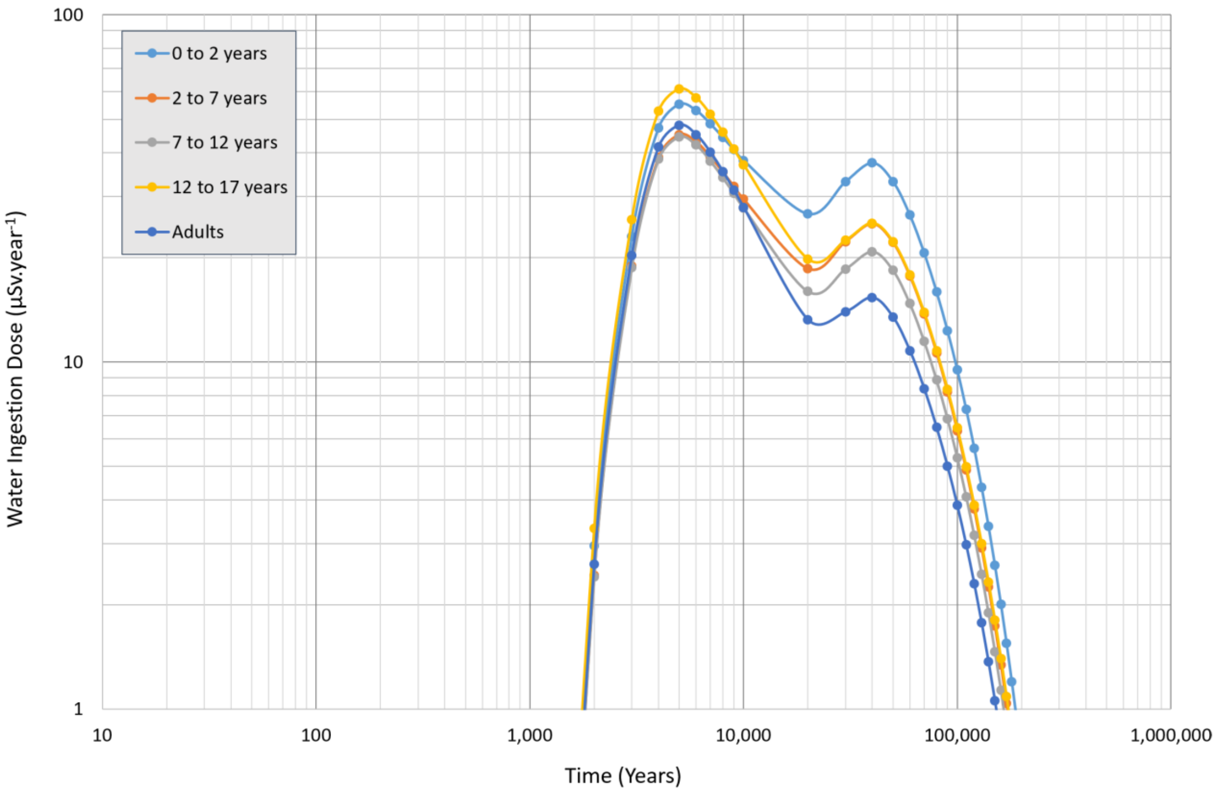


Figure 5.6 The simulated water ingestion dose to the different age groups 500 m from the height extended Savuka 7A and 7B TSF, using the activity concentrations in Figure 5.3.

The dose contribution presented here is in terms of LLα dust inhalation, radon gas inhalation, the contribution of cloud shine and ground shine (following deposition) to external gamma radiation, as well as the ingestion of crop and animal products at rates as defined for each exposure condition.

5.3.2 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2 represent the consolidated concentrations from all atmospheric pathway sources of concern. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well. The radioanalysis results available for the Project are presented in Section 3.5.2. As a conservative assumption, the average activity concentrations listed in Table 3.16 were used for the Mponeng Operations TSFs, for which no full-spectrum analysis is available at present.

Multiplication of the radionuclide specific activity concentrations with the PM_{10} (in units of $\mu g.m^{-3}$) and TSP (in units of $g.m^{-2}.year^{-1}$) concentrations presented in Section 4.4.2, result in nuclide-specific airborne activity concentration (in units of $Bq.m^{-3}$) and deposition rate estimates (in units of $Bq.m^{-2}.day^{-1}$). The resulting nuclide-specific airborne concentrations and deposition rates can then be used in the dose assessment calculations. The radon exhalation rate for the TSFs, WRDs and ventilation shafts is presented in Section 3.5.3.

5.3.3 Residential Area Exposure Condition

5.3.3.1 Dose Assessment

The purpose of the Residential Area Exposure Condition is to evaluate the radiological consequences to members of the public residing in formal structures (houses) in the affected residential areas near the Project. This includes residential areas and suburban areas such as Welkom (e.g., Bronville) and Virginia (e.g., Saaiplaas), but are equally relevant to other residential areas that might be affected. This may include formal and informal residential structures. It is conservatively assumed that these residents maintain a household garden that contributes to 50% of their annual consumption rate of cereal, fruit, and vegetables, as well as animal products that include eggs, milk, and meat.

The main contributor to the total effective dose in the informal residential areas was shown to come from the atmospheric (i.e., the ambient air conditions) and associated secondary pathways. This means that the exposure routes of concern include inhalation, ingestion, and external exposure. The expected exposures associated with each route include (see Section 4.7.4):

- Inhalation of radon gas and dust containing LLα;
- Ingestion of contaminated produce (fruit, leafy and root vegetables) harvested from the household garden (50% annual consumption rate);
- Ingestion of contaminated animal products (meat and eggs) rearing the yard (50% annual consumption rate);
- Inadvertent ingestion of contaminated soil; and
- External exposure to radionuclides deposited in the upper soil layer (ground shine) and external exposure to airborne LLα (cloud shine).

A dust deposition period of 100 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative.

5.3.3.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Project and the surrounding area. The dose isopleths in Figure 5.7 represent the total effective dose for the 12 to 17-year age group for the Baseline Conditions. Based on the dose estimate, the 12 to 17-year age group was shown to receive the highest total effective dose (see also Figure 5.9). Figure 5.8 presents the total effective dose for the 12 to 17-year age group for the height extension of the Savuka 7A and 7B TSF and the current baseline conditions (see also Figure 5.10).

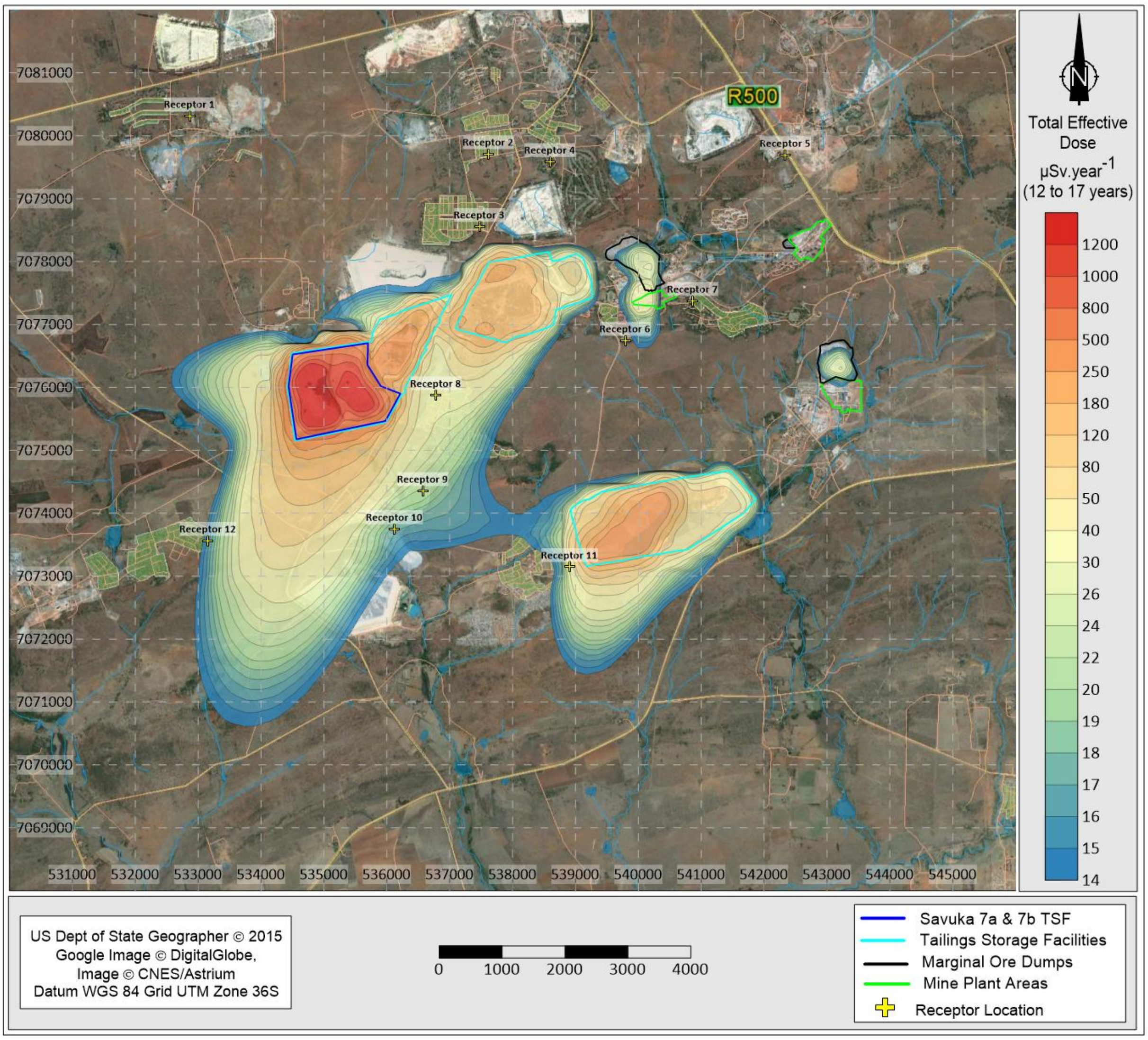


Figure 5.7 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of µSv.year^{-1}) of the **Residential Area Exposure Condition attributed to the baseline conditions.**

5.3.3.3 Interpretation of Results

The dose isopleth results presented in Figure 5.7 show that the effect of the baseline condition on the residential areas is minimal and does not reach residential areas at doses more than 1 to 40 µSv.year^{-1}. Figure 5.8 shows that the contribution of the height extension is also minimal, with an insignificant increase in the total effective dose. However, it still does not reach residential areas in doses of less than 40 µSv.year^{-1}.

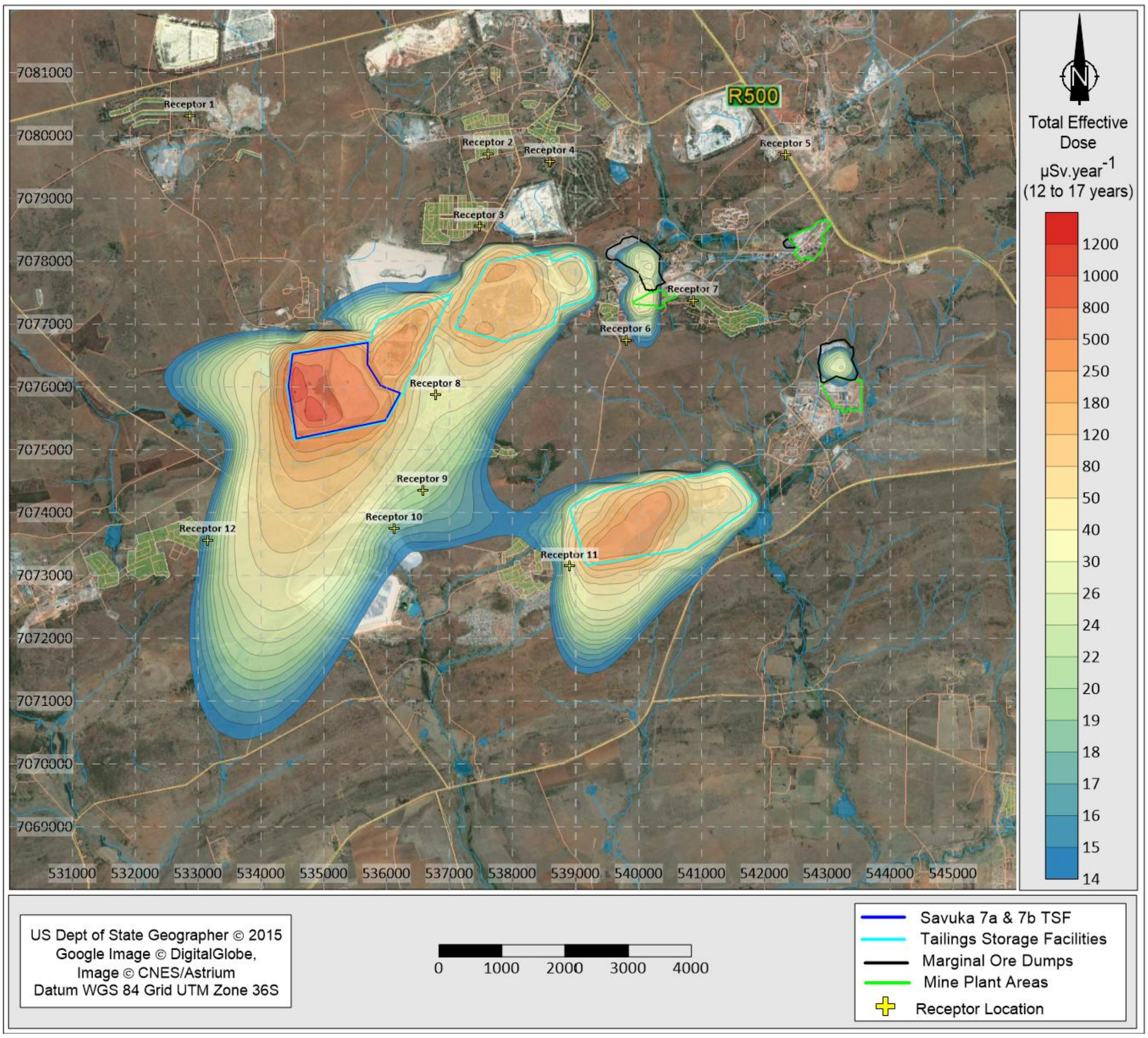


Figure 5.8 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Residential Area Exposure Condition attributed to the height extension of the Savuka 7A and 7B TSF and the current baseline conditions.

To put the dose isopleth result into perspective, the total effective dose results at several receptor locations in residential areas are presented in Figure 5.9 and Figure 5.10 (see Figure 5.7 for location). These locations correspond to the locations identified in the air quality impact assessment (Airshed, 2025). The results are for all the age group categories listed in Table B 1.

The results suggest that at the selected locations for the Residential Area Exposure Condition, the total effective dose is well below 40 μSv.year^{-1}, with the highest point of impact at Elandsridge. With the height extension included, the dose in this area is still less than 40 μSv.year^{-1}.

Figure 5.9 and Figure 5.10 suggest that for some locations, the main contributor to the total effective dose is from ingestion, followed by radon inhalation. At others, it is the other way around, with radon inhalation the main contributor to the total effective dose. External gamma radiation (product of cloud and ground shine) is insignificant.

Note that these results are in direct correlation with the air quality impact assessment results for PM_{10}, TSP and radon gas concentrations as calculated as part of the air quality impact assessment (Airshed, 2025).

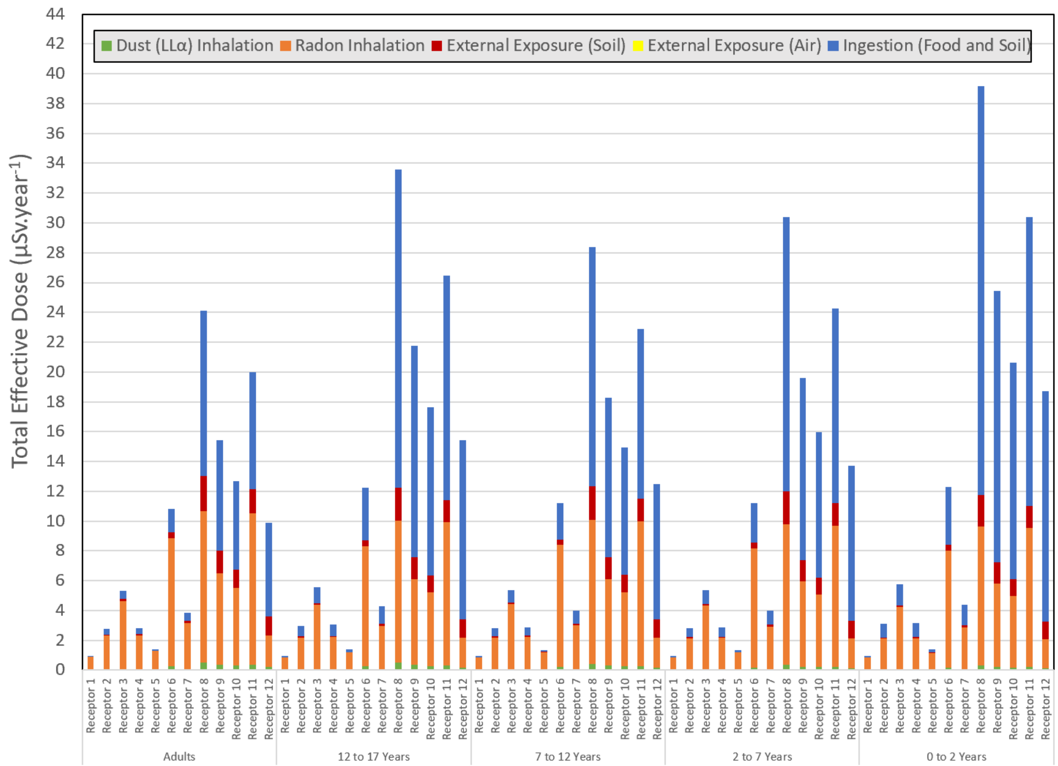


Figure 5.9 **Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.7 for locations).**

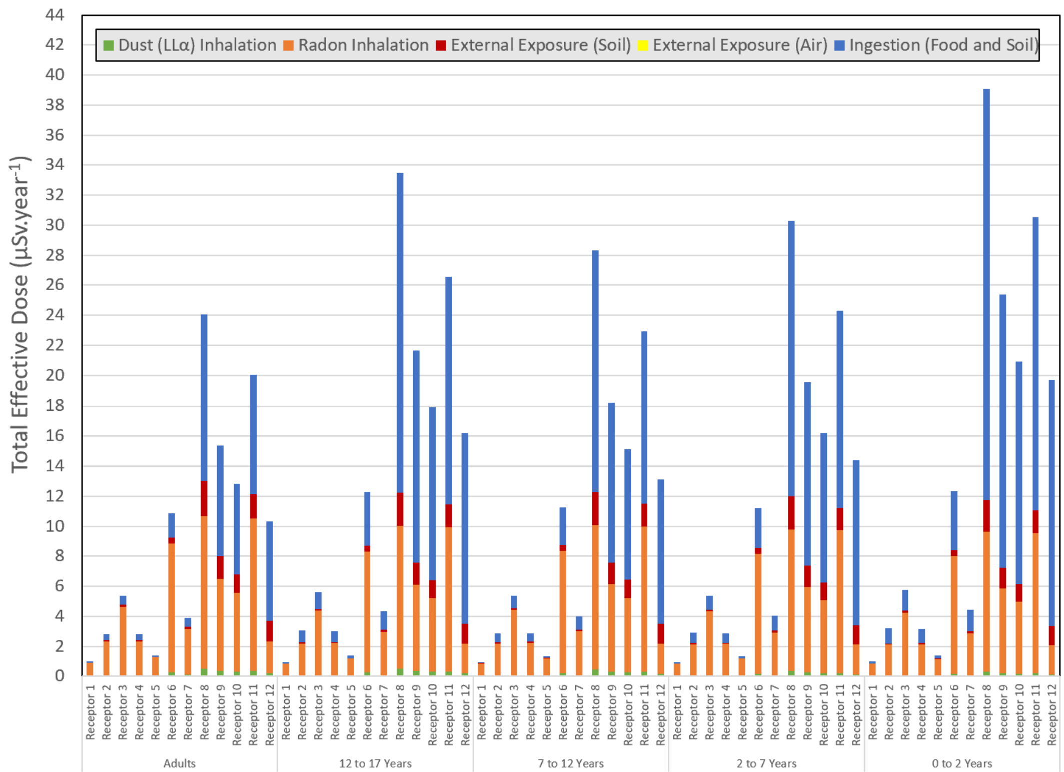


Figure 5.10 **Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the Savuka 7A and 7B TSF in addition to the baseline conditions (see Figure 5.7 for locations).**

5.3.4 Commercial Agricultural Exposure Condition

5.3.4.1 Dose Assessment

The purpose of the Commercial Agricultural Exposure Condition is to evaluate the radiological consequences to members of the public practising commercial farming near the Project. However, the exposure condition is equally relevant to agricultural practices anywhere near the Project This means that this exposure condition relates to any farming activity under the conditions and assumptions included in the definition of the Commercial Agricultural Exposure Condition.

It is conservatively assumed that the farmer, farm workers and their families are dependent on the land for the annual consumption rate of cereal, fruit, and vegetables, as well as animal products that include eggs, milk, and meat.

The main contributors to a total effective dose for the Commercial Agricultural Exposure Condition are the atmospheric, groundwater and associated secondary pathways. Groundwater is used to sustain the farm system through irrigation and to supply livestock with water. In addition to the conditions and assumptions presented above, the following are assumed for the Commercial Agricultural Exposure Condition:

- Inhalation of radon gas and dust containing LLα;
- Ingestion of contaminated produce (grain/maize, fruit, leafy and root vegetables) harvested from the subsistence farm (100% annual consumption rate);
- Ingestion of contaminated animal products (meat, milk, and eggs) rearing the farm (100% annual consumption rate);
- Inadvertent ingestion of contaminated soil;
- Ingestion of contaminated groundwater;
- External exposure to radionuclides deposited in the upper soil layer (ground shine) and external exposure to airborne LLα (cloud shine); and
- External exposure to contaminated groundwater (during bathing).

A dust deposition period of 100 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative (see Section 4.7.5).

While a contribution of groundwater was realistically included in the definition of the Commercial Agricultural Exposure Condition, the result presented in Section 5.2 suggests that a possible contribution from the groundwater pathway will only be in thousands of years and, therefore, cannot realistically be added to contributions from the atmospheric pathway.

5.3.4.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Project and the surrounding area. The dose isopleths in Figure 5.11 represent the total effective dose for the 12 to 17-year age group for the baseline conditions. Based on the dose estimate, the 12 to 17-year age group was shown to receive the highest total effective dose (see also Figure 5.13). Figure 5.12 presents the total effective dose for the age group 12 to 17 years age group attributed to the height extension of the Savuka 7A and 7B TSF and the current baseline conditions (see also Figure 5.14).

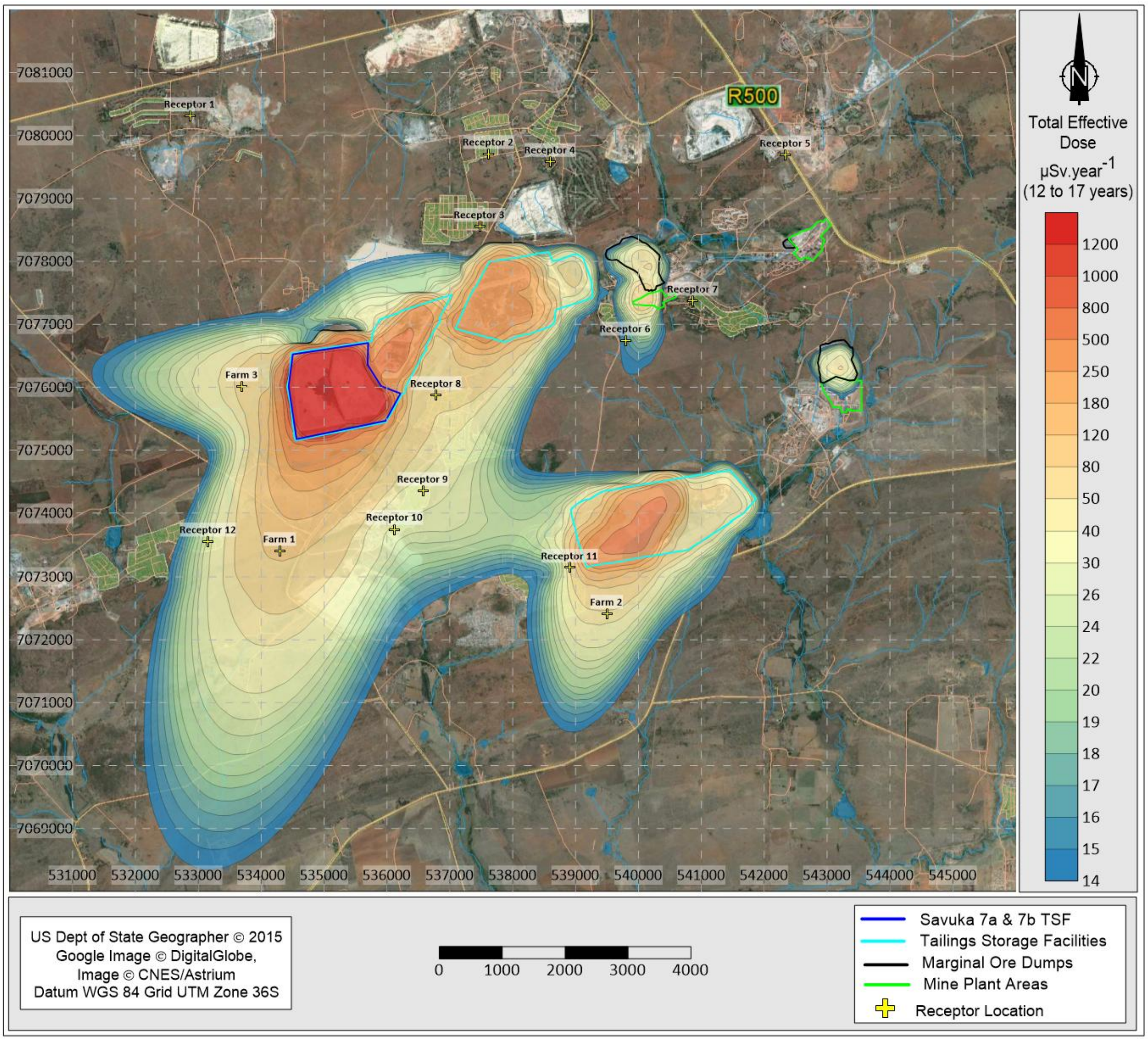


Figure 5.11 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of µSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the baseline conditions.

5.3.4.3 Interpretation of Results

As expected, the radiological impact of the Commercial Agricultural Exposure Condition is more significant compared to the Residential Area Exposure Conditions since more exposure pathways at higher ingestion rates are included. The impact is still more significant near the TSFs and decreases significantly with distance away from the TSFs. The dispersion is almost predominantly towards the west and southwest. The impact of the height extension of the Savuka 7A and 7B TSF is noticeable, but not significant.

To put the dose isopleth result into perspective, the total effective dose results at several receptor locations are presented in Figure 5.13 and Figure 5.14 (see Figure 5.11 for location). Some of these locations correspond to the locations identified in the air quality impact assessment (Airshed, 2025). However, there are no farm homesteads near the Project and the surrounding area. The 3 Farm locations are, therefore, hypothetical. The residential areas are maintained for comparative purposes. The results are for all the age group categories listed in Table B 1.

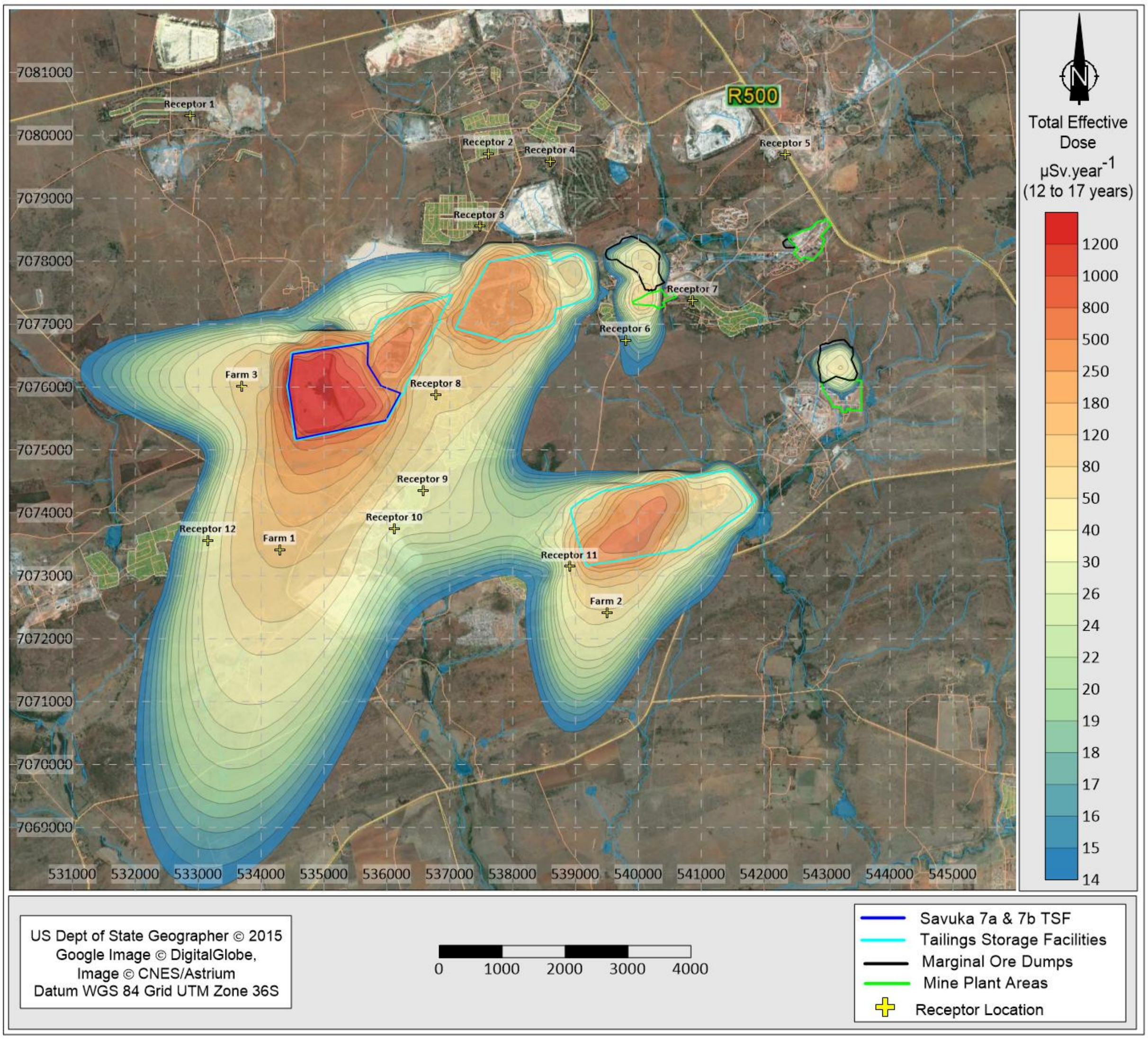


Figure 5.12 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the height extension of the Savuka 7A and 7B TSF and the current baseline conditions.

Figure 5.13 and Figure 5.14 in comparison with Figure 5.9 and Figure 5.10 confirm that the total effective dose is higher than for the Residential Area Exposure Condition. As with the Residential Area Exposure Condition, for some locations, the main contributor to the total effective dose is from ingestion, followed by radon inhalation. At others, it is the other way around, with radon inhalation the main contributor to the total effective dose. External gamma radiation (product of cloud and ground shine) is insignificant. It also shows that the height extension of the Savuka 7A and 7B TSF complex has a marginal impact on the total effective dose.

What is also clear from Figure 5.11 to Figure 5.14 is that the impact of the Savuka 7A and 7B TSF complex is more significant than that of the other TSFs. This is reflected in the total effective dose of the Farm 1 location, which is in the direction of dispersion from the Savuka 7A and 7B TSF complex.

Note that these results are in direct correlation with the air quality impact assessment results for PM_{10}, TSP and radon gas concentrations as calculated as part of the air quality impact assessment (Airshed, 2025).

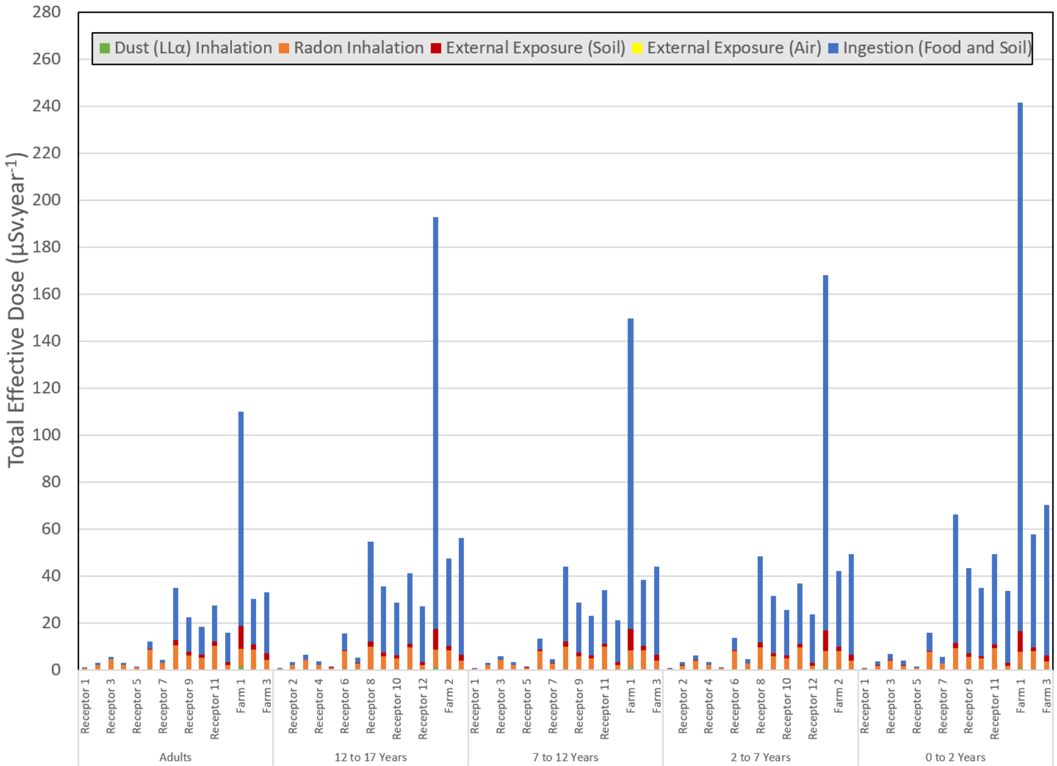


Figure 5.13 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.11 for locations).**

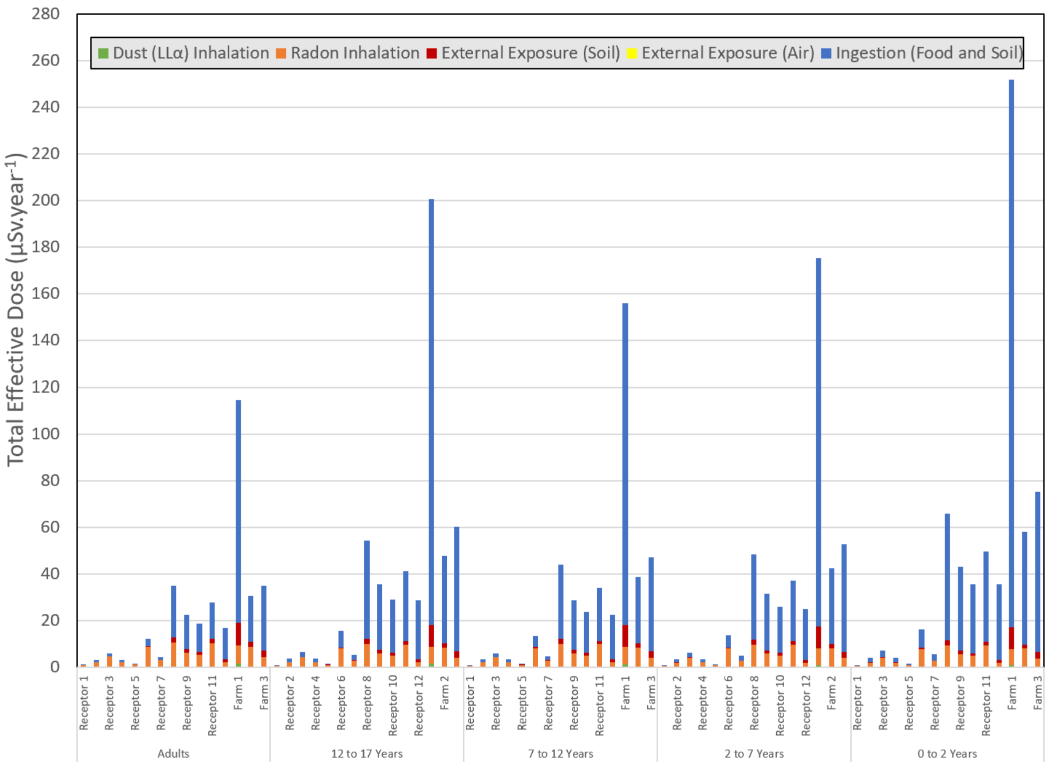


Figure 5.14 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the height extension of the Savuka 7A and 7B TSF and the current baseline conditions (see Figure 5.11 for locations).**

6 Sensitivity and Uncertainty Analysis

6.1 General

The consequence analysis presented in Section 5 is based on several conditions and parameter values that were presented in the *System Description (see Section 3)*, the *Definition and Justification of Public Exposure Conditions* (see Section 4) and the *Mathematical Model Development* (see Appendix B). These results are viewed as the most realistic and representative of the potential radiological impact on members of the public residing near the Project. However, the inherent nature of a safety assessment for a mining and mineral processing operation is such that uncertainties exist, both in the conditions assumed and the parameter values used. It was from this perspective that the inexact nature of safety assessments was highlighted in the *Assessment Context* (see Section 2).

The purpose of this section is to address some of these uncertainties and to evaluate the sensitivity of the assessment results to variations in conditions and parameter values. Viewed from this perspective, it serves as a “what if” analysis in support of the overall safety case for the Project.

The section is structured as follows. Section 6.2 then discusses the cumulative effect of other facilities and operations in the area, while Section 6.3 discusses the effect of variations in the public exposure conditions defined for the Project. In Section 6.4, the variation in parameter values is discussed.

6.2 Cumulative Radiological Impact

On a local scale, it can be noted that the assessment calculated the total effective dose to members of the public from all relevant exposure pathways included in the public radiation exposure conditions defined for the assessment. To the extent justified, the results, therefore, include the cumulative contribution from all exposure routes (e.g., inhalation, ingestion, and external gamma radiation).

On a more regional scale, it can be noted that the results presented in Section 5 only represent the contribution of the Project to a total effective dose to members of the public in addition to the current baseline conditions. The national safety standards and associated regulatory compliance criteria are clear that members of the public should be protected from *all* contributing sources or operations. In terms of national and international regulations, the total effective dose from all contributing sources should be below 1 mSv.year^{-1} (or 1,000 μSv.year^{-1}). The national safety standards also make provision for the application of a dose constraint of 0.25 mSv.year^{-1} (or 250 μSv.year^{-1}) for each operation holding its own CoR.

All facilities and activities considered in this assessment are from CoR-3 of Harmony. It is outside the scope of this report to address the contribution from *all* other contributing facilities or operational areas. For a regional assessment that considers every contributing source from all applicable CoRs, the *dose limit* will be applicable, whereas for facility-specific assessments, the *dose constraint* is more applicable, especially to address the issue of multiple contributions. However, the question may still be asked: “*Is there a possibility for a cumulative effect from multiple operations, and is there a reason for concern?*”

The focus of the assessment is on the contribution of the Project to the annual effective dose to members of the public. There are no other Harmony or other mining operations that would contribute to the total effective dose to members of the public. It follows from Section 5 that the potential total effective dose as a contribution from the Project will be less than 250 μSv.year^{-1}. This means that even if similar contributions from other mining operations were possible, the resulting total effective dose would be less than the dose limit of 1,000 μSv.year^{-1}.

6.3 Variations in Public Exposure Conditions

6.3.1 General

The public exposure conditions that were evaluated as part of the Project were defined following a systematic Source–Pathway–Receptor analysis approach (see Section 4). An attempt was made to be comprehensive but also to limit the number of exposure conditions to a selected few, since it is virtually impossible to define an exposure condition for every individual member of the public. The test of whether a discrete set of exposure conditions is comprehensive is whether individual members of the public can relate to at least one of the defined exposure conditions. In most cases, the defined conditions were on the conservative side.

6.3.2 Variation in the Defined Exposure Conditions

Two public exposure conditions were defined in Section 4, namely a Residential Area Exposure Condition and a Commercial Agricultural Exposure Condition. An attempt was made to be cautiously realistic and comprehensive in the definition of these conditions. However, variations may still be expected.

For example, members of the public who work in industries in the area may be subject to different exposure routes from those defined for the Project. However, their exposure will be lower than that of the residents in the area because it is most likely limited to inhalation and external exposure and also for shorter periods. In addition, the Commercial Agricultural Exposure Condition is very conservative and assumes that the exposure group is dependent on the land for all its food. It is thus unlikely that any variation in exposure conditions would result in higher doses than what was calculated for the Commercial Agricultural Exposure Condition.

6.3.3 Alternative Exposure Conditions

6.3.3.1 General

The public exposure conditions that were defined and evaluated in the Project was considered comprehensive and representative of a wide range of site-specific conditions. It was also argued that variations can be expected, but that these variations will lead to a lower radiological impact than those considered in the assessment.

For example, the Source–Pathway–Receptor analysis suggests that an alternative public exposure condition can be those induced during accident and incident conditions, such as pipeline bursts or other spillages of water or tailings material into the environment. The *Definition and Justification of Public Exposure Conditions* (see Section 4) describe in detail that these conditions are best handled and treated as part of the emergency response and other programs as part of the radiation management plan.

6.3.3.2 Tailings Spillage

Several factors determine the potential level of radiation exposure to members of the public, which makes it difficult or almost impossible to provide a general assessment, especially given the widespread and diverse nature of the Project. These include:

- What was spilt (i.e., water or tailings) and what is the activity concentration of the water or tailings material that was spilt;
- Where the spillage took place (i.e., open field or at or near surface water bodies or a nearby residential area), how long the spillage lasted and the lateral extent (area) that was contaminated; and

- How long has the potential contamination been left unattended before remedial action for the area is instituted, and is there a possibility that members of the public have access to the contaminated area?

It is thus clear that every spillage event would be different and would lead to a different potential radiological impact. However, one can assume that for the tailings material considered in this assessment, the absolute maximum radiological impact would be less than the total effective doses calculated on top of the facilities presented in Section 5.

To evaluate the potential radiological impact of a tailings spill, the following hypothetical exposure conditions were assumed. Following the spillage of tailings material, it is assumed that an area of 1 ha (100m x 100m) is covered with a 0.5 m thick layer of tailings material. Members of the public have access to the area and, depending on the period of exposure, are subject to dust inhalation, external gamma radiation and radon gas inhalation.

Assuming a conservative set of parameter values to calculate the radon exhalation rate from the tailings layer and the airborne dust concentration, Figure 6.1 presents the total effective dose for the Savuka 7A and 7B tailings material as a function of the exposure period. The total effective dose is predominantly driven by the Ra-226 concentration in the tailings material and thus the radon inhalation dose.

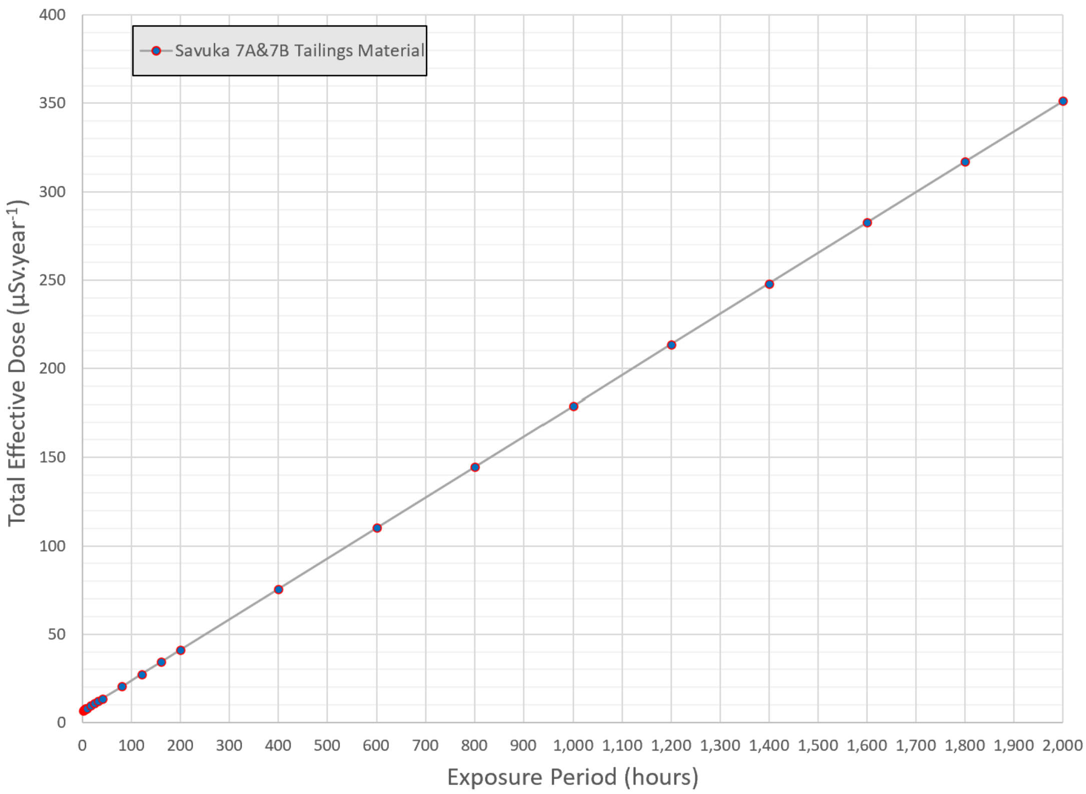


Figure 6.1 Total effective dose for the Savuka 7A and 7B TSF tailings material as a function of the exposure period.

From Figure 6.1 it is clear that for the assumed Savuka 7A and 7B TSF tailings material, an exposure period of 2,000 hours will still result in a total effective dose in the order of 350 µSv.year^{-1}. To keep the doses to less than 250 µSv.year^{-1}, the exposure period should not exceed 1,400 hours.

Note that these results should be treated with care since they represent hypothetical conditions. There is no justification to think members of the public will spend so much time on a tailings spillage area. However, what the results do emphasise is the need to clean a contaminated area as soon as possible to limit potential public exposure.

6.3.3.3 Water Spillage

Water spillages from pipeline bursts or overflow from surface impoundments are possible. Similar to tailings spillages, several factors determine the potential level of radiation exposure to members of the public, which makes it difficult or almost impossible to provide a general assessment. For a water spillage, it is even more uncertain since water will disperse horizontally downgradient and infiltrate vertically under the force of gravity.

6.4 Variation in Parameter Values

6.4.1 Human Consumption Values

The human consumption rates used in the Project are based on the rates proposed in RG-002 (NNR, 2013). Compared to literature values, some of these values are high and on the conservative side. This means that the definition and use of more realistic values will reduce the calculated ingestion doses. Since most of the calculated ingestion doses for the different exposure conditions are relatively low, lower consumption rates will just reduce the ingestion doses even further (linearly).

One exception is probably the grain ingestion rate, which was reduced to 10% of the value specified in RG-002. Using a 100% grain consumption rate will increase the grain ingestion dose significantly. However, this will not influence the general conclusions of the exposure conditions defined for the Project. Note that the grain consumption rate was reduced to 10% of the RG-002 specified value since the proposed value is unrealistically high for a total diet.

On the other hand, using 100% grain consumption together with all the other ingestion pathways becomes unrealistic in terms of the mass of food a human being can consume annually. Under these conditions, the consumption rate of other products will have to be reduced drastically to be realistic in terms of the mass of food a human of all groups can consume annually.

6.4.2 Dust Deposition Period

The dose calculations for the different exposure conditions were performed assuming a 100-year deposition period, which was assumed to be realistic given the history of the Project. The dose assessment models assumed a build-up of activity on the soil surface over this period, which, by implication, influenced the total effective dose. One can thus assume that the surface soil concentration will continue to increase steadily with time.

Experience shows that the rate of build-up increases until about 2,000 years, after which equilibrium is reached with removal processes such as radiological decay and leaching. Over this period, the ingestion doses can potentially increase more than threefold, but with an accompanying increase in uncertainties.

7 Impact Assessment for the Proposed Savuka 7A and 7B TSF

7.1 General

The purpose of this section is to present the radiological impact assessment rating for the proposed Savuka 7A and 7B TSF. Section 2.3.7.3 presents the criteria for the impact assessment rating as an endpoint. The basis for the impact assessment rating is the quantitative and qualitative assessment of the potential radiological consequences to receptors identified for the Project, as presented in Section 5.

The impact assessment rating makes a distinction between the different phases of the Project (i.e., operation and post-closure) as well as the contribution of the atmospheric, surface water and groundwater pathways, as appropriate. The reason for the latter is that the timescales over which the pathways contribute to a potential radiological impact on members of the public differ. Where required, mitigation measures are proposed for activities during the different Project phases, followed by an impact rating for the revised (mitigated) conditions.

The section is structured as follows. The most significant radiological impact is expected during the operational phase, as presented in Section 7.2, followed by the post-closure phase presented in Section 7.3. Section 7.4 discusses any cumulative impact that might be of concern.

7.2 Operational Phase

7.2.1 General

The radiological impact assessment for the operational phase considers the potential contribution through all three environmental pathways (i.e., surface water, groundwater and atmospheric). However, due to the slow-moving nature of any radionuclide contaminant plume that originates from the facilities through the groundwater system, the potential radiological impact through the groundwater pathway will only occur during the post-closure (see Section 7.3).

7.2.2 Activities

During the operational phase, the following activities were identified that may result in a radiological impact on members of the public:

- Emission and dispersion of particulate matter containing radionuclides from the existing and proposed TSFs; and
- Exhalation and dispersion of radon gas from the existing and proposed Savuka 7A and 7B TSF.

Table 7.1 summarises the activities associated with the operational phase that may have a potential radiological impact on the receptors.

Table 7.1 Summary of the activities and the impact of the activities during the operational phase of the proposed Savuka 7A and 7B TSF.

Interaction	Impact
Exhalation and dispersion of radon gas into the atmosphere	Radon gas generated in the tailings due to the presence of Ra-226 will be exhaled into the atmosphere. Inhalation of the radon gas contributes to the total effective dose.

Interaction	Impact
Emission and dispersion of particulate matter into the atmosphere	Wind erosion at the TSF areas will cause particulate matter containing radionuclides to be emitted into the atmosphere. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion, and external radiation exposure routes.

7.2.3 Exhalation and Dispersion of Radon Gases

7.2.3.1 Impact Description

During the operational phase, radon gases are generated in the tailings material at the TSF areas due to the presence of Ra-226 This means that these gases are exhaled continuously from this facility into the atmosphere.

Following the exhalation and subsequent dispersion of the radon gas into the atmosphere, inhalation of the airborne gas contributes to the total effective dose to receptors.

7.2.3.2 Management/Mitigation Measures

The management objective would be to first ensure that radiation exposure is below the regulatory compliance criteria (i.e., the dose constraint), and secondly to optimise the radiation protection by applying the ALARA principle (As Low As Reasonable Achievable, economic, and social factors taken into consideration).

The total effective dose as a contribution from radon gas released from the tailings material at the TSF areas is well below the regulatory compliance criteria, which means that from a compliance perspective, no additional management or mitigation measures are required for radon inhalation. From a dose optimisation perspective, the following can be noted:

- The radon exhalation rate from the surface of tailings material is determined by several factors, of which moisture content is one. This means that for the area at a TSF that is wet (i.e., beach area), the radon exhalation rate will be reduced marginally. However, it is not effective to wet the TSF deep enough (2 to 4 m) to reduce the radon exhalation rate marginally.
- The most effective way to reduce the radon exhalation rate for the TSF is to provide a covering layer. This will increase the diffusion length to allow for the decay of the radon progeny before being released from the tailings surface.

7.2.3.3 Impact Rating

Table 7.2 presents the impact significant rating for the exhalation and dispersion of radon gas during the operational phase.

Table 7.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-2.75

Nature	-1	Likely to result in a negative impact	-5.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF.			
Probability	2	There is a low probability that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.75		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF.			
Probability	1	It is improbable that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

7.2.4 Emission and Dispersion of Particulate Matter

7.2.4.1 Impact Description

During the operational phase, the TSF areas will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere for the duration of the operational period. These particulate matter containing radionuclides are dispersed into the environment through the atmospheric pathways. The emission and subsequent dispersion of the particulate matter into the atmosphere results in an airborne radionuclides concentration associated with the PM_{10}, and a soil radionuclides concentration following the deposition of the TSP. Through secondary pathways, the radionuclides in the soil may be transferred to crops and animal products. Contributions to the total effective dose to receptors identified for the Project include inhalation of airborne dust, ingestion of contaminated soil, crops and animal products, and external gamma radiation through cloud shine and ground shine.

7.2.4.2 Management/Mitigation Measures

The management objective would be to first ensure that radiation exposure is below the regulatory compliance criteria (i.e., the dose constraint), and secondly to optimise the radiation protection by applying the ALARA principle.

The contribution of dust inhalation is less than 0.2% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for dust inhalation. The contribution of external exposure (cloud shine and ground shine) is less than 1% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for external gamma radiation. The contribution of animal and crop ingestion is less than 11% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for the ingestion pathways. In addition, the total effective dose at the same locations is less than 13% (on average) of the dose constraint of 250 $\mu Sv.year^{-1}$ for public exposure.

From a dose optimisation perspective, the following mitigation measures can be applied. These measures, which are in line with the measures proposed in the air quality impact assessment (Airshed, 2025), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Develop an air quality management plan for the proposed Savuka 7A and 7B TSF, including air quality monitoring to ensure compliance at upwind and downwind locations; and
- Vegetation of exposed areas of the TSF and wind barriers to reduce wind erosion and/or the application of dust suppressants.

7.2.4.3 Impact Rating

Table 7.3 presents the impact significant rating for the emission and dispersion of particulate matter that contains radionuclides during the operational phase.

7.3 Post-Closure Phase

7.3.1 General

Before the actual closure of the proposed Savuka 7A and 7B TSF and as part of the anticipated licensing conditions and requirements, a decommissioning and closure plan will be prepared for submission and approval by the regulatory authorities. Amongst others, this plan will define in detail all the activities that will be performed and how the associated radiological impact during the decommissioning and closure phase will be managed.

7.3.2 Activities

Considering that a decommissioning plan of the proposed Savuka 7A and 7B TSF is not available at present but will be defined and implemented as mentioned in Section 7.3.1, the following activities were identified that may result in a radiological impact on the receptors during the post-closure phase:

- Implementation of the approved decommissioning plan;
- Exhalation of radon gas and the emission of particulates matter (PM_{10} and TSP) that contain radionuclides from the remaining facilities (e.g., TSF); and
- Leaching and migration of radionuclides from the remaining facilities (e.g., TSF).

Table 7.3 Impact significant rating for the particulate matter emission and dispersion that contains radionuclides during the operational phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	2	There is a low probability that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	1	It is improbable that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

Table 7.4 summarises the activities associated with the post-closure phase that may have a potential impact on the receptors.

7.3.3 Implementation of the Decommissioning Plan

7.3.3.1 Impact Description

The implementation of the NNR-approved decommissioning plan will result in a positive impact in the sense that surface infrastructure that contained or that is contaminated with radionuclides is demolished, decontaminated (to the extent possible) and removed from the site and compliance with clearance criteria has been demonstrated.

Generally, this would involve performing a gamma radiation survey supplemented with full-spectrum radioanalysis of soil samples performed at the infrastructure sites, followed by appropriate rehabilitation and clean-up operations for conditional or unconditional clearance from the regulatory authority. However, in this case for the TSF that would remain at the surface during the post-closure period, the level of clean-up that can be performed is limited to areas outside the TSF footprint area that may have become contaminated during or because of operational activities. These areas outside the TSF footprint can still be rehabilitation and clean-up for conditional or unconditional clearance.

Table 7.4 Summary of the activities and the impact of the activities during the post-closure phase of the proposed Savuka 7A and 7B TSF.

Interaction	Impact
Implementation of the decommissioning plan	The execution of the decommissioning plan involves a site-wide plan to demolish, decontaminate and remove all the surface infrastructure that may contain or that is contaminated with radionuclides. These areas and any other area that was contaminated will be rehabilitated and cleaned for clearance by the regulatory authority.
Exhalation of radon gas and particulate matter from the remaining surface facilities (e.g., TSF) to the atmosphere	Radon gas generated in the remaining facilities (e.g., tailings material) due to the presence of Ra-226 will be exhaled into the atmosphere. Inhalation of the radon gas contributes to the total effective dose. Wind erosion at the remaining facilities will cause particulate matter containing radionuclides to be emitted into the atmosphere. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion, and external radiation exposure routes.
Leaching and migration of radionuclides from the TSF	Radionuclides will leach from the TSF into the underlying aquifer, after which they will migrate in the general groundwater flow direction. Abstraction and use of the contaminated water contribute to the total effective dose through the ingestion and possible external radiation exposure routes.

7.3.3.2 Impact Rating

Table 7.5 presents the impact significant rating for the implementation of the decommissioning plan of the Project.

7.3.4 Exhalation of Radon Gas and Particulate Matter

7.3.4.1 Impact Description

During the post-closure phase, some of the facilities (e.g., TSF) will remain at the surface and continue to serve as sources of radiation exposure to members of the public. These facilities will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere during the post-closure period. During the same period, radon gas generated in the tailings materials due to the presence of Ra-226 will continue to be exhaled into the atmosphere.

The emission and subsequent dispersion of the particulate matter into the atmosphere results in an airborne radionuclides concentration associated with the PM_{10}, and a soil radionuclides concentration following the deposition of the TSP. Through secondary pathways, the radionuclides in the soil may be transferred to crops and animal products. Contributions to the total effective dose to receptors include inhalation of airborne dust, ingestion of contaminated soil, crops and animal products, and external gamma radiation through cloud shine and ground shine.

Following the exhalation and subsequent dispersion of the radon gas into the atmosphere, inhalation of the airborne gas contributes to the total effective dose to receptors.

Table 7.5 Impact significant rating for the implementation of the decommissioning plan of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					16
Nature	1	Likely to result in a positive impact	16		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the closure.			
Magnitude	4	The impact on members of the public will be high and widespread			
Reversibility	5	The implementation of a good decommissioning plan is irreversible			
Probability	4	There is a low probability that the secondary pathway induced by wind erosion will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	1	Likely to result in a positive impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after closure.			
Magnitude	4	The impact on members of the public will be high and widespread			
Reversibility	5	The implementation of a good decommissioning plan is irreversible			
Probability	4	There is a low probability that the secondary pathway induced by wind erosion will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

7.3.4.2 Management/Mitigation Measures

The management objective would be to first ensure that radiation exposure is below the regulatory compliance criteria (i.e., the dose constraint), and secondly to optimise the radiation protection by applying the ALARA principle.

The total effective dose as a contribution from the windblown dust, as well as radon gas released from the remaining facilities, is well below the regulatory compliance criteria (dose constraint), which means that from a compliance perspective, no additional management or mitigation measures are required.

From a dose optimisation perspective, the following mitigation measures that are in line with the measures proposed by the air quality impact assessment (Airshed, 2025) can be applied for the post-closure phase:

- Vegetation of exposed areas of the TSF and wind barriers to reduce wind erosion and/or the application of dust suppressants; and
- Covering layer over the exposed area of the TSF areas to reduce wind erosion and radon exhalation.

7.3.4.3 Impact Rating

Table 7.6 presents the impact significant rating for the exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Savuka 7A and 7B TSF.

Table 7.6 Impact significant rating for the exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The contribution of dust and radon gas inhalation, as well as the dust deposition (and the subsequent secondary pathway) to the total effective dose, is significantly lower than the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	2	There is a low probability that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
Reversibility	2	The impact is reversible without incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	1	It is improbable that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

7.3.5 Leaching and Migration of Contaminants from the Proposed Savuka 7A and 7B TSF

7.3.5.1 Impact Description

From the commissioning of a TSF, radionuclides contained in the tailings material leach from the TSF to the underlying strata. The rate of leaching is controlled by complex geochemical and hydrological processes but generally is a slow process. Once in the underlying strata, migration of these radionuclides is equally slow along the groundwater flow path.

Abstraction of groundwater for personal or agricultural purposes may result in a radiological impact on receptors through direct ingestion of water or the ingestion of crops and animal products as secondary pathways. The radiological impact along the groundwater pathway only manifests itself during the post-closure period hundreds to thousands of years after closure.

7.3.5.2 Management/Mitigation Measures

The management objective would be to first ensure that radiation exposure is below the regulatory compliance criteria (i.e., the dose constraint), and secondly to optimise the radiation protection by applying the ALARA principle.

The total effective dose from the ingestion of groundwater as a contribution from the TSF was hypothetically illustrated to be below the regulatory compliance criteria (i.e., dose limit), which means that from a compliance perspective, no additional management or mitigation measures are required.

From the optimisation of radiation protection perspective for the post-closure period, the following management/mitigation measures can be implemented if it is assumed that the facility remains at the surface:

- Implementation of a passive groundwater remediation system downstream of the TSF to capture the contaminant plume.

Note that active remediation systems, such as cut-off trenches or a pump and treat system, might also be effective in the short to medium term. However, the timescales of concern are beyond what can be considered active institutional control periods.

Table 7.7 presents the impact significant rating for the leaching and migration of radionuclides from the TSF during the post-closure phase of the Project.

7.4 Cumulative Impact

The cumulative radiological impact associated with a mining operation can be considered at different levels.

Firstly, the radiological safety assessment process considers the cumulative contribution from all relevant exposure pathways including the surface water, groundwater, and atmospheric pathways, as appropriate. This means that the radiological impact assessment includes the cumulative impact of the exposure pathways, as appropriate and justified.

Secondly, the radiological safety assessment process considers the cumulative contribution from all relevant exposure routes and for each relevant exposure pathway. These include radon gas inhalation, dust inhalation, external gamma radiation (ground shine and cloud shine) as well as the ingestion routes for soil, water, crops, and animal products as appropriate and justified for each public exposure condition. This means that the radiological impact assessment includes the cumulative impact of the exposure routes, as appropriate and justified.

Table 7.7 Impact significant rating for the leaching and migration of radionuclides from the TSF during the post-closure phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Leaching and migration of radionuclides from the TSF during the post-closure phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-6
Nature	-1	Likely to result in a negative impact	-6		
Extent	3	Exposure extent beyond the mining rights area into the immediate surroundings with agricultural land use conditions in the direction of flow			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The impact is expected in the immediate surroundings and for the defined exposure conditions the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	3	The impact is reversible only by incurring significant time and cost to reduce the migration of radionuclides from the TSF into the environment.			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-6		
Extent	3	Exposure extent beyond the mining rights area into the immediate surroundings with agricultural land use conditions in the direction of flow			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The impact is expected in the immediate surroundings and for the defined exposure conditions the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	2	The impact is reversible only by incurring significant time and cost to reduce the migration of radionuclides from the TSF into the environment.			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

Thirdly, the radiological safety assessment process considers the cumulative contribution from all relevant sources of radiation exposure associated with the proposed Savuka 7A and 7B TSF, such as the existing TSFs in the area. This means that the radiological impact assessment includes the cumulative impact of these sources, as appropriate and justified.

Finally, on a more regional scale, the assessment context makes provision for a cumulative impact from all contributing operations (or practices) in the area that may contribute to the total effective dose to members of the public. This is important since the public dose limit of 1,000 μSv.year^{-1} is from all contributing sources and operations. However, as stated in Section 2.3.4.5, the scope of the assessment was limited to the

Project and did not make provision for a regional assessment to evaluate cumulative effects from all contributing operations.

8 Radiation Monitoring Programme

8.1 General

Within the framework of the broader radiation management plan, the purpose of the public Radiation Protection Programme (RPP), is to implement measures that will ensure that members of the public are protected from potential exposure to ionising radiation induced by the Project. The basis for the definition of the public RPP approved by the regulatory authority is the outcome of the comprehensive radiological public safety assessment and typically includes a radiation monitoring programme, a surveillance programme, and a control programme.

The purpose of this section is to define a radiation monitoring programme for the Project. The basis for the definition of the monitoring programme presented here is the outcome of the radiological impact assessment presented in this report, taking into consideration the radiological information available at present (see Section 3.5).

The section is structured as follows. Section 8.2 discusses the characterisation of the baseline conditions associated with the Project. Section 8.3 presents the proposed monitoring programme, while Section 8.4 presents the proposed monitoring locations.

8.2 Baseline Characterisation

The purpose of the radiological baseline characterisation programme is to establish the radiological conditions observed at the site and surroundings before the commissioning of the Project. No baseline characterisation has been done in the Project area yet. It should include, to the extent possible, soil, surface water and groundwater samples, as well as an airborne environmental radon survey in the area using RGMs.

In addition to these sampling and analysis, it is proposed that a full gamma radiation and dose rate survey on a grid basis be conducted after site preparation and cleaning. Soil samples should again be collected for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains in the affected areas at locations that will be informed by the gamma radiation survey.

8.3 Monitoring Programme

The Projects TSFs fall within the scope of CoR-3 with an approved public Radiation Protection Programme (RPP), which makes provision for environmental monitoring and analysis to ensure that members of the public are sufficiently protection from releases into the environment. The responsibility for the implementation and execution of the monitoring programme lies with the Radiation Protection Function (RP Function) which may include legally appointed persons consisting of a Radiation Protection Monitor(s) (RPM), a Radiation Protection Officer (RPO), and a Radiation Protection Specialist (RPS).

Table 8.1 summarises the proposed monitoring programme for the Project aimed at public radiation protection.

The full-spectrum analysis is suitable for detailed dose analysis but is an expensive procedure with long lead times to perform the analysis, which is why less frequent intervals are proposed. The total uranium and thorium analyses are relatively inexpensive with fast turnaround times. These results will monitor variations in activity concentration over the monitoring period.

Large variations in the activity concentration over a short period are not expected in groundwater, as opposed to surface water, for example. Therefore, a less frequent sampling schedule is proposed for groundwater. The same principle applies to the sediment samples at the same locations as the surface water sample.

Table 8.1 Summary of the environmental monitoring programme proposed for the Project aimed at public radiation protection.

Monitoring Element	Comment	Frequency
Surface water	Full-spectrum analysis (U-238, U-235, Th-232 and progeny)	Biannually
	Total Uranium and Thorium	Quarterly
Sediments	Full-spectrum analysis (U-238, U-235, Th-232 and progeny)	Annually
	Total Uranium and Thorium	Biannually
Groundwater	Full-spectrum analysis (U-238, U-235, Th-232 and progeny)	Once every two years
	Total Uranium and Thorium	Biannually
Radon gas	Environmental radon gas using Radon Gas Monitors (RGMs)	Quarterly for a period of 2 to 3 months
Dust fallout	Total Uranium and Thorium	Annually

The RGMs monitor the variation in radon gas works in monitoring periods of 2 to 3 months, after which the RGMs are replaced with new RGMs for the next monitoring period.

The dust fallout samples are generated quarterly but are used to generate an annual sample for the total U and Th analysis. The reason for this is that the volume of material collected in a dust bucket is too little for quarterly analysis.

8.4 Proposed Monitoring Points

Most monitoring points proposed to be part of the monitoring programme coincide with the monitoring programme for the environmental pathways (e.g., soils surface water and groundwater). Considering the surface infrastructure that will be developed for the Project, the following can be noted:

- The surface water monitoring locations should coincide with the existing surface water monitoring points currently included in the public RPP. The principle to be applied is that the monitoring locations should be upstream and downstream of the Project area in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the existing groundwater monitoring points. The principle to be applied is that the monitoring locations should be upstream and downstream of the Project area, as well as upstream and downstream of specific surface facilities. The exact location will be determined by the availability of water-bearing boreholes in the specific area.
- The dust fallout monitoring locations should coincide with the monitoring points (dust buckets) proposed in Airshed (2025).
- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

9 Conclusions and Recommendations

9.1 General

The purpose of the radiological public safety and impact assessment was defined as to demonstrate that members of the public living near the Project will not be exposed to levels of ionizing radiation above the regulatory compliance criteria for public protection and to assess the associated radiological impact as input into the ESHIA process. A systematic approach was followed that included the definition of the regulatory framework and technical basis of the assessment, a system description, the systematic definition of public exposure conditions, the consequence analysis of the exposure conditions and the radiological impact assessment.

The section is structured as follows. Section 9.2 presents some general conclusions as derived from the radiological impact assessment results, while Section 9.3 presents recommendations for the improvement of the radiological public safety and impact assessment.

9.2 Conclusions

Following a systematic Source-Pathway-Receptor analysis approach, two public exposure conditions were derived to be representative of the area, namely a Residential Area Exposure Condition and a Commercial Agricultural Exposure Condition. The atmospheric pathway was explicitly included in the definition of the exposure conditions, whereas the surface water and groundwater pathways were treated through sensitivity and uncertainty analysis. It was argued that the public exposure condition is broadly representative of the human behavioural conditions near the Project. In addition, other potential exposure conditions that may exist will result in lower levels of radiation exposure.

Given the pre-operational status of the Project, the radiological assessment is prospective based on available information and reports generated as part of the ESHIA process. The results and conclusion are presented here, therefore, for the conditions and parameter values assumed for the assessment. These may change for future iterations as and when site-specific data and information become available and are used.

The following was concluded from the total effective dose assessment results:

- The most significant contribution from the atmospheric pathway is from the inhalation of airborne radon gas. This is due to the presence of Ra-226 in the source material.
- The contribution from the groundwater pathway was evaluated with the Project TSFs as the main contributing source. It was illustrated that the potential radiological impact is only visible in thousands of years at maximum total effective doses of less than 100 μSv.year^{-1}, which means that it cannot be considered as a contributing pathway for the Commercial Agricultural Exposure Condition during the operational phase of the Project;
- The results for the two public exposure conditions were presented as dose isopleths for the different age groups, with more detailed exposure route-specific results at the receptor locations conservatively selected to be close to the infrastructure of the Project. The results show that notwithstanding the proximity of the receptor locations to the surface infrastructure, the doses are still less than the dose constraint for all age groups, with a maximum contribution of less than 250 μSv.year^{-1} from the atmospheric pathway.

It can, therefore, be concluded with a reasonable level of assurance that members of the public who can associate themselves with one of the exposure conditions will not be subject to a total effective dose of more than the public dose constraint of 250 $\mu Sv.year^{-1}$.

These total effective dose assessment results were used to derive the radiological impact rating during the different phases of the Project. Table 9.1 summarises the radiological impact significant rating for the operational phase of the Savuka 7A and 7B TSF, while Table 9.2 summarises the radiological impact significant rating for the post-closure phase of the proposed Savuka 7A and 7B TSF.

9.3 Recommendations

The radiological impact assessment made use of assumptions for conditions and parameter values required for the dose assessment, which is not ideal. To improve the radiological public safety and impact assessment, Recommendations were made for the baseline site characterisation programme and the radiological monitoring programme. Based on the outcome of the preliminary baseline site characterisation and the outcome of the radiological public impact and safety assessment, the following is recommended as an extension of the baseline site characterisation programme of the Project:

- Perform gamma radiation and dose rate surveys on a grid basis of all potentially affected areas;
- Perform an airborne radon gas survey in the Project area using RGMs on a campaign basis;
- Collect surface water, groundwater and sediment samples on an upstream and downstream basis that is representative of the Project area for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains; and
- Collect soil samples at selected locations that coincide with selected locations that represent potentially hot-spot areas identified during the gamma radiation survey for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains.

The proposed radiological monitoring programme for the Project includes recommendations for the monitoring of surface water, groundwater, sediment, environmental radon, as well as dust fallout, including the frequency and type of analysis. Most monitoring points proposed to be part of the monitoring programme coincide with the monitoring programme for the environmental pathways (e.g., soils surface water and groundwater). Considering the surface infrastructure that will be developed for the Project, the following was noted:

- The surface water monitoring locations should coincide with the existing surface water monitoring points currently included in the public RPP. The principle to be applied is that the monitoring locations should be upstream and downstream of the Project area in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the existing groundwater monitoring points. The principle to be applied is that the monitoring locations should be upstream and downstream of the Project area, as well as upstream and downstream of specific surface facilities. The exact location will be determined by the availability of water-bearing boreholes in the specific area.
- The dust fallout monitoring locations should coincide with the monitoring points (dust buckets) proposed in Airshed (2025).
- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind

direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

Table 9.1 Summary of the radiological impact significant rating for the operational phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}	-5.5		
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF.			
Probability	2	There is a low probability that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			-2.75
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}	-2.75		
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF.			
Probability	1	It is improbable that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction			
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.		1	
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			
Impact	Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}	-5		-2.5
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	2	There is a low probability that the contribution of dust inhalation and dust deposition (and the subsequent			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
		secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	1	It is improbable that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

Table 9.2 Summary of the radiological impact significant rating for the post-closure phase of the proposed Savuka 7A and 7B TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					16
Nature	1	Likely to result in a positive impact	16		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the closure.			
Magnitude	4	The impact on members of the public will be high and widespread			
Reversibility	5	The implementation of a good decommissioning plan is irreversible			
Probability	4	There is a low probability that the secondary pathway induced by wind erosion will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	1	Likely to result in a positive impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the closure.			
Magnitude	4	The impact on members of the public will be high and widespread			
Reversibility	5	The implementation of a good decommissioning plan is irreversible			
Probability	4	There is a low probability that the secondary pathway induced by wind erosion will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			
Impact	Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The contribution of dust and radon gas inhalation, as well as the dust deposition (and the subsequent secondary pathway) to the total effective dose, is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	2	There is a low probability that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	2	The extent of potential impact for the Savuka 7A and 7B TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface.			
Magnitude	1	Minor. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	2	The impact is reversible without incurring significant time and cost to reduce the wind erosion from the TSF.			
Probability	1	It is improbable that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			
Impact	Leaching and migration of radionuclides from the TSF during the post-closure phase of the proposed Savuka 7A and 7B TSF				
Pre-Mitigation					-6
Nature	-1	Likely to result in a negative impact	-6		
Extent	3	Exposure extent beyond the mining rights area into the immediate surroundings with agricultural land use conditions in the direction of flow			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The impact is expected in the immediate surroundings and for the defined exposure conditions the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Reversibility	3	The impact is reversible only by incurring significant time and cost to reduce the migration of radionuclides from the TSF into the environment.			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-6		
Extent	3	Exposure extent beyond the mining rights area into the immediate surroundings with agricultural land use conditions in the direction of flow			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	1	Minor. The impact is expected in the immediate surroundings and for the defined exposure conditions the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	2	The impact is reversible only by incurring significant time and cost to reduce the migration of radionuclides from the TSF into the environment.			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change.			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources.			

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APPENDIX A:
RADIONUCLIDE AND ELEMENT-DEPENDENT DATA

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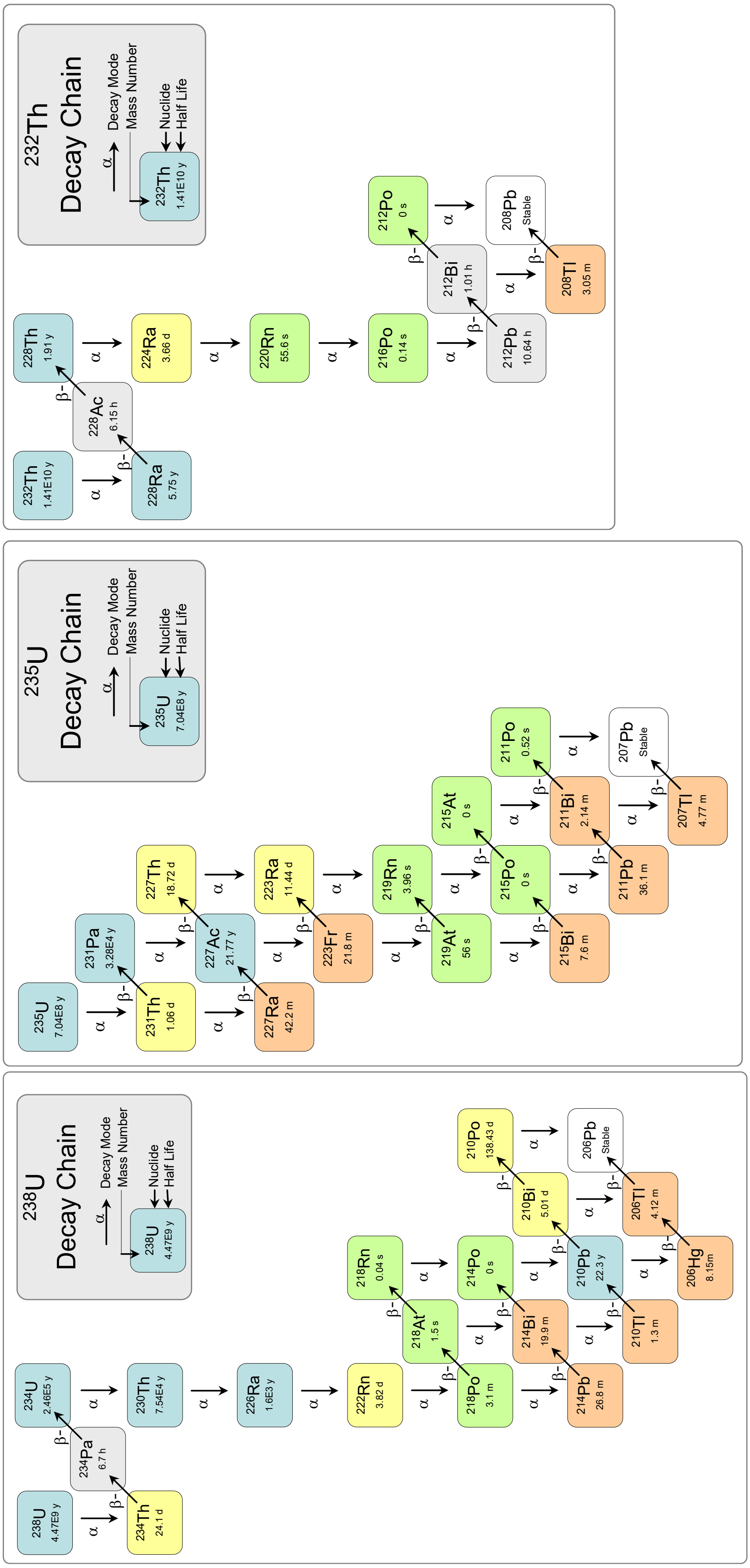

Figure A 1 **Schematic illustrations of the U-238, U-235, and Th-232 decay chains.**

Table A 1 Radiological properties for the Uranium decay chain of radionuclides.

Element	Radionuclide	Decay Mode	Half-Life	Units	Decay Constant	Half-Life (years)	Decay Constant (years)	Atomic Mass	Specific Activity (Bg.kg^{-1})
Uranium	U-238	α	4.468E+09	y	1.551359E-10	4.468000E+09	1.551359E-10	238.05	1.243803E+07
Thorium	Th-234	β	2.410E+01	d	2.876129E-02	6.598220E-02	1.050506E+01	234.04	8.566645E+17
Protactinium	Pa-234m	β	1.170E+00	m	5.924335E-01	2.224504E-06	3.115963E+05	234.04	2.541002E+22
Uranium	U-234	α	2.445E+05	y	2.834958E-06	2.445000E+05	2.834958E-06	234.04	2.311871E+11
Thorium	Th-230	α	7.700E+04	y	9.001911E-06	7.700000E+04	9.001911E-06	230.03	7.468842E+11
Radium	Ra-226	α	1.600E+03	y	4.332170E-04	1.600000E+03	4.332170E-04	226.03	3.658113E+13
Radon	Rn-222	α	3.824E+00	d	1.812860E-01	1.046817E-02	6.621473E+01	222.02	5.692148E+18
Polonium	Po-218	α	3.050E+00	m	2.272614E-01	5.798920E-06	1.195304E+05	218.01	1.046437E+22
Lead	Pb-214	β	2.680E+01	m	2.586370E-02	5.095445E-05	1.360327E+04	214.00	1.213218E+21
Bismuth	Bi-214	β	1.990E+01	m	3.483152E-02	3.783558E-05	1.831998E+04	214.00	1.633890E+21
Polonium	Po-214	α	1.643E+02	us	4.218790E-03	5.206353E-12	1.331349E+11	214.00	1.187399E+28
Lead	Pb-210	β	2.230E+01	y	3.108283E-02	2.230000E+01	3.108283E-02	209.98	2.825159E+15
Bismuth	Bi-210	β	5.012E+00	d	1.382975E-01	1.372211E-02	5.051317E+01	209.98	4.591209E+18
Polonium	Po-210	α	1.384E+02	d	5.009013E-03	3.788638E-01	1.829542E+00	209.98	1.662905E+17

Table A 2 Radiological properties for the Actinium decay chain of radionuclides.

Element	Radionuclide	Decay Mode	Half-Life	Units	Decay Constant	Half-Life (years)	Decay Constant (years)	Atomic Mass	Specific Activity (Bg.kg^{-1})
Uranium	U-235	α	7.038E+08	y	9.848639E-10	7.038000E+08	9.848639E-10	235.04	7.997165E+07
Thorium	Th-231	β	2.552E+01	h	2.716094E-02	2.911248E-03	2.380928E+02	231.04	1.966867E+19
Protactinium	Pa-231	α	3.276E+04	y	2.115834E-05	3.276000E+04	2.115834E-05	231.04	1.747878E+12
Actinium	Ac-227	β	2.177E+01	y	3.183517E-02	2.177300E+01	3.183517E-02	227.03	2.676315E+15
Thorium	Th-227	α	1.872E+01	d	3.703105E-02	5.124709E-02	1.352559E+01	227.03	1.137068E+18
Radium	Ra-223	α	1.143E+01	d	6.062158E-02	3.130459E-02	2.214203E+01	223.02	1.894897E+18
Radon	Rn-219	α	3.960E+00	s	1.750372E-01	1.254848E-07	5.523753E+06	219.01	4.813713E+23
Polonium	Po-215	α	1.780E-03	s	3.894085E+02	5.640480E-11	1.228880E+10	215.00	1.090890E+27
Lead	Pb-211	β	3.610E+01	m	1.920075E-02	6.863640E-05	1.009883E+04	210.99	9.135254E+20
Bismuth	Bi-211	α	2.140E+00	m	3.239006E-01	4.068750E-06	1.703587E+05	210.99	1.541051E+22
Thallium	Tl-207	β	4.770E+00	m	1.453139E-01	9.069131E-06	7.642929E+04	206.98	7.047673E+21

Table A 3 Radiological properties for the Thorium decay chain of radionuclides.

Element	Radionuclide	Decay Mode	Half-Life	Units	Decay Constant	Half-Life (years)	Decay Constant (years)	Atomic Mass	Specific Activity (Bg.kg^{-1})
Thorium	Th-232	α	1.405E+10	y	4.933432E-11	1.405000E+10	4.933432E-11	232.04	4.057876E+06
Radium	Ra-228	β	5.750E+00	y	1.205473E-01	5.750000E+00	1.205473E-01	228.03	1.008957E+16
Actinium	Ac-228	α	6.130E+00	h	1.130746E-01	6.992927E-04	9.912118E+02	228.03	8.296243E+19
Radium	Ra-224	α	3.660E+00	d	1.893845E-01	1.002053E-02	6.917268E+01	224.02	5.893270E+18
Radon	Rn-220	α	5.560E+01	s	1.246668E-02	1.761858E-06	3.934184E+05	220.01	3.412859E+22
Polonium	Po-216	α	1.500E-01	s	4.620981E+00	4.753213E-09	1.458271E+08	216.00	1.288515E+25
Lead	Pb-212	β	1.064E+01	h	6.514541E-02	1.213781E-03	5.710647E+02	211.99	5.141324E+19
Bismuth	Bi-212	β	6.055E+01	m	1.144752E-02	1.151228E-04	6.020936E+03	211.99	5.420695E+20
Polonium	Po-212	α	3.050E-01	us	2.272614E+00	9.664867E-15	7.171823E+13	211.99	6.456921E+30

APPENDIX B:
METHODOLOGICAL APPROACH TO DOSE CALCULATION

Dose Conversion Factors

Radiation dose is a term used to describe the amount of energy that ionizing radiation deposits in a mass of matter, such as human tissue. Types of ionizing radiation differ in the way in which they interact with biological materials. Hence, equal energy amounts deposited in a mass of human tissue do not necessarily have equal biological effects. For example, a dose of one unit of alpha radiation energy is more harmful than 1 unit of energy from beta radiation, since an alpha particle, being slower and more heavily charged, loses its energy more densely along its path.

The radiation dose associated with each radionuclide is calculated using a specific numerical factor, developed taking into account the relative effectiveness of the radiation to cause biological harm and other parameters relating to the likelihood of harm to particular tissues or organs exposed to the radiation (Eckermann *et al.*, 1988). These numerical factors referred to as 'dose conversion factors, are used to convert radioactivity concentrations members of the public are exposed to, to a total effective dose. The estimation of the **total annual effective radiation dose** that an individual is exposed to is the sum of the internal and external effective doses. Radioactivity that enters the body fluids from inhalation (respiratory tract) and ingestion (gastrointestinal tract) constitutes the internal effective doses.

The most pertinent guidance currently available for conducting prior and operational public safety assessments for NORM facilities is the Regulatory Guide RG-002 (NNR, 2013). This guide summarises dose conversion factors for use in the assessment of inhalation and ingestion exposure to radionuclides, as obtained from the ICRP Publication 72 (ICRP, 1996) and the IAEA Safety Standards Series (IAEA, 2011) documents. The dose conversion factors published in RG-002 make a distinction between different age groups, which represent the ranges of age groups as listed in Table B 1.

Table B 1 Age group ranges applicable to age-dependent dose conversion factors as published in RG-002 (NNR, 2013).

Ages specified in RG-002	Applicable Age Range
New-born	From 0 to 1 year of age
1 Year	From 1 year to 2 years
5 Year	More than 2 years to 7 years
10 Year	More than 7 years to 12 years
15 Year	More than 12 years to 17 years
Adult	More than 17 years

Table C 1 and Table C 2 (Appendix C) present the dose conversion factors for the different age groups for inhalation and ingestion, as derived from the values published in RG-002 (NNR, 2013).

In addition to ingestion and inhalation, radioactivity may also enter the body through the skin, which constitutes external radiation exposure. For external exposures, the kinds of radiation of concern are those sufficiently penetrating to traverse the overlying tissues of the body and deposit ionising energy in radiosensitive organs and tissues. Photons and electrons are the most important radiations emitted by radionuclides distributed in the environment that can penetrate the body from the outside. This situation contrasts with the intake of radionuclides by inhalation or ingestion, where the radiations are emitted inside the body.

Calculation of the effective dose contribution from external radiation exposure to a contaminated environmental medium (e.g., water, soil, or air) requires an indication of the exposure period to a unit volume of the contaminated medium and an estimate of the effective dose per unit time-integrated exposure to a radionuclide. The effective dose conversion factors for external exposure relate the concentrations of radionuclides in environmental media to the effective radiation doses to organs and tissues of the body.

Effective external dose conversion factors are published in the EPA Federal Guidance Document No. 12 (Eckerman and Ryman, 1993). The dose received through external exposure is a function of the intensity of the radiation and is assumed to constitute uniform irradiation of the body. The estimation of the dose is therefore independent of the age of the person exposed and the conversion factors are therefore age-independent.

Table C 3 in Appendix C presents the external exposure dose conversion factors as specified in RG-002 (NNR, 2013). The values presented are for external soil exposure (ground shine), external water exposure (water immersion) and external air exposure (cloud immersion), respectively.

Inhalation Exposure (LLα, Radon and Thoron)

The effective dose from the inhalation of dust containing LLα radionuclides ($ED_{Inh_{LL\alpha}}$, in μSv.year^{-1}) is calculated from measured or modelled airborne radionuclide concentrations (in Bq.m^{-3} nuclide specific), multiplied by appropriate inhalation dose coefficients. The equation to calculate the LLα inhalation dose is given by:

Equation 1

$$ED_{Inh_{LL\alpha}} = C_{LL\alpha}\, DC_{inh}\, EP_h\, BR_h$$

where $C_{LL\alpha}$ is the airborne activity concentration for LLα (Bq.g^{-1}), DC_{inh}.is the dose coefficient for inhalation (μSv.Bq^{-1}), EP_h is the human exposure (occupancy) period to the LLα airborne concentration, and BR_h is the human air-breathing rate. The inhalation dose is directly linear to the breathing rate and exposure period. Breathing rates for different age groups as specified in RG-002 are listed in Table C 4 in Appendix C.

The dose received through the inhalation of airborne radon (ED_{Inh_Rn}, μSv.year^{-1}) can be calculated using the following equation:

Equation 2

$$ED_{Inh\_Rn} = C_{Rn}\, DC_{Rn}$$

where C_{Rn} is the airborne radon concentration (Bq.m^{-3}), and DC_{Rn} is the annual radon inhalation dose coefficient [(mSv.hour^{-1}) per (Bq.m^{-3})] (see Table B 2).

Table B 2 Values recommended for calculation of dose from the exposure of inhaled radon (IAEA BSS, ICRP 65; UNSCEAR).

Parameter	Indoors	Outdoors	At Work	Unit
Conversion Coefficient[1]	5.56E-06			(mJ.m^{-3}) per (Bq.m^{-3})
Radon progeny conversion	3.54			(mJ.h.m^{-3}) per (WLM)
Effective dose per unit exposure to radon	4.0	4.0	5.0	mSv per WLM
Dose conversion for effective dose per unit exposure	1.1	1.1	1.4	(mSv.hour^{-1}) per (mJ.m^{-3})
Exposure period	7 000	1 760	2 000	[hour]
Equilibrium factor	0.4	0.8	0.4	[-]
Annual exposure per unit radon concentration[2]	1.56E-02	7.83E-03	4.45E-03	(mJ.hour.m^{-3}) per (Bq.m^{-3})
	2.22E-06	4.45E-06	2.23E-06	(mJ.m^{-3}) per (Bq.m^{-3})
Annual dose conversion factor[3]	1.76E-02	8.85E-03	6.23E-03	(mSv) per (Bq.m^{-3})
	2.51E-06	5.03E-06	3.14E-06	(mSv.hour^{-1}) per (Bq.m^{-3})
Dose Coefficient (UNSCEAR)[4]	9.00E-06			(mSv.hour^{-1}) per (Bq.m^{-3})

1 Conversion Coefficient = Ratio of PAEC (Potential Alpha Energy Concentration) and EEC (Equilibrium Equivalent Concentration) of Radon
2 Annual exposure per unit radon concentration = 5.56E-06 x 0.4 x 7,000
3 Annual dose conversion factor = 1.56E-02 x 1.1
4 EEC of Radon

The approach followed to calculate the thoron inhalation dose according to Parc Scientific (2023) is to use the UNSCEAR (2006) recommended dose conversion factor for thoron decay products of:

Equation 3

$$DC_{Th} = \frac{40\ nSv}{EEC_{220}}$$

where EEC_{220} (in units of Bq.m^{-3}.h) is the Equilibrium Equivalent Concentration (EEC) exposure to thoron decay products. EEC_{220} is given by:

Equation 4

$$EEC_{220} = 0.913[A_B] + 0.087[A_C]$$

where A_B is the activity concentration of Pb-212 [in Bq.m^{-3}] and A_C is the activity concentration of Bi-212 [in Bq.m^{-3}]. Bi-212 follows Pb-212 in the thoron decay series. For indoor exposure, a ratio of 1:1 between the concentration of Pb-212 and Bi-212 is proposed, but no data is available for outdoors.

An indoor F factor of 0.04 and an outdoor F factor of 0.004 are proposed between the daughter products of thoron and the parent gas. It is, therefore, assumed that the outdoor ratio between the concentration of Pb-212 and Bi-212 is in the same ratio of 1:0.1. The annual average EEC_{220} is directly determined from the calculated Pb-212 concentration by:

Equation 5

$$EEC_{220} = (0.913[A_B] + 0.087[A_B]) * 7000 + (0.913[A_B] + 0.087[0.1 * A_B]) * 1760$$

as the sum of the total annual indoor (7,000 h) and total annual outdoor (1,760 h) exposure.

Ingestion Exposure

Ingestion Rates

Table C 5 lists prescribed (RG-002) ingestion rates for adult members of the public compared to ranges of ingestion rates published in the literature. The comparison shows that the values prescribed in RG-002 fall within the range of literature values and are appropriately scaled to the South African population to be applicable for use in the assessment.

Table C 6 lists the ingestion rates for the different age groups as derived from the adult values prescribed in RG-002. The values for the other age groups are taken as a percentage of the annual ingestion rate for adults, according to the values listed in the first row of Table C 5. Where values for specific agricultural products are not available from RG-002, the values listed under the 'Average' column in Table C 5 are used.

Water Ingestion

The effective dose rate from the ingestion of contaminated water ($ED_{ing,water}$, in μSv.year^{-1}) is calculated from measured or modelled radionuclide concentrations of the water, multiplied with appropriate ingestion dose coefficients and water consumption rates, and is given by:

Equation 6

$$ED_{ing,water} = C_{water}\ DC_{ing}\ CR_{water}$$

where C_{water} is the radionuclide concentration in the water (Bq.m^{-3}), DC_{ing}.is the dose coefficient for ingestion (μSv.Bq^{-1}), and CR_{water} is the water consumption rate (m^3.year^{-1}) per age group.

Inadvertent Ingestion of Contaminated Soil

The effective dose rate from the ingestion of contaminated soil ($ED_{ing,soil}$, in µSv.year^{-1}) is calculated from measured or modelled radionuclide concentrations in the soil, multiplied with appropriate ingestion dose coefficients and soil consumption rates and is given by:

Equation 7

$$ED_{ing,soil} = C_{soil}\ DC_{ing}\ CR_{soil}$$

where C_{soil} is the radionuclide concentration in the soil (Bq.kg^{-1}), DC_{ing}.is the dose coefficient for ingestion (µSv.Bq^{-1}), and CR_{soil} is the individual soil consumption rate (kg.year^{-1}).

The activity concentration in the soil can increase over time through the continued deposition of airborne radionuclides. The approach used for estimating activity concentrations in soil (C_{soil}) is presented in Appendix D. The rate at which different age groups inadvertently consume soil on an annual basis is obtained from values published in RG-002.

Ingestion of Contaminated Crops

The soil contaminated with radionuclides could contaminate crops that are grown in it. The effective dose rate from the ingestion of contaminated secondary crops ($ED_{ing,crop}$, in µSv.year^{-1}) (e.g., fruit, cereals, leafy or root vegetables) is calculated as a summation of measured or modelled radionuclide concentrations of the secondary crop, multiplied with appropriate ingestion dose coefficients and crop consumption rates, and is given by:

Equation 8

$$ED_{ing,crop} = \sum_{crop} \left(C_{crop}\ CR_{crops}\ \ DC_{ing}\right)$$

where C_{crop} is the radionuclide concentration in the crop (Bq.kg^{-1}), DC_{ing}.is the dose coefficient for ingestion (µSv.Bq^{-1}), and CR_{crop} is the individual crop consumption rate (kg.year^{-1}). The age group specific consumption rates for individual crop types are listed in Table C 6. The activity concentration in the crop (C_{crop}, in Bq.kg^{-1}) can be calculated using the following equation:

Equation 9

$$C_{crop} = C_{soil}\left(CF_{crop} + \left(1 - f_{prep}\right)S_{crop}\right)\ +\ Int_{crop}\, f_{growth}\left(C_{water}\, I_{rate} + Dep_{rate}\right)\left(\frac{\left(1 - f_{prep}\right) + f_{trans}}{Y_c\ \lambda_{\mathrm{w}}}\right)$$

where C_{water} is the radionuclide concentration in the water (Bq.m^{-3}), C_{soil} is the radionuclide concentration in the soil (Bq.kg^{-1}), CF_{crop} is the soil-to-crop concentration factor (Bq.kg^{-1} fresh weight per Bq.kg^{-1} dry soil), S_{crop} is the soil contamination on the crop (kg.kg^{-1}). f_{growth} is the crop growth day per day of the year (unitless), Int_{crop} is the interception fraction (irrigation water and deposition) on the crop (unitless), I_{rate} is the annual depth of irrigation applied to the crop (m.year^{-1}), Dep_{rate} is the deposition rate of airborne contaminants (Bq.m^{-2}.year^{-1}). Y_c is the crop yield (kg.m^{-2}, fresh weight of crop), λ_{w} is the removal rate of contaminants on the crop (through irrigation or deposition) by weathering processes (year^{-1}), f_{trans} is the fraction of activity transferred from external to internal plant surfaces (unitless), and f_{prep}.is the fraction of activity removed from the crop surfaces after food preparation.

The concentration factor (CF_{crop}) defines the transfer of activity from the soil to the crops consumed by humans. Equation 9 makes provision for crops to become contaminated in the following ways:

- Internal intake of contaminants from the soil surface into the crop *via* the roots as well as the soil contamination on the crops itself, which is represented by the term, $C_{soil}\left(CF_{crop} + \left(1 - f_{prep}\right) S_{crop}\right)$;

- External contamination of the crop due to the deposition of airborne dust, represented by the term $Int_{crop}\, f_{growth}\, Dep_{rate}$; and
- External contamination of the crop due to irrigation of the crops, represented by the term $Int_{crop}\, f_{growth} C_{water}\, I_{rate}$.

A concentration factor (CF_{crop}) defines the transfer of activity from contaminated soil to crops planted in the soil and consumed by humans or animals. The concentration factor reflects only the uptake of radionuclides from the soil *via* roots and excludes the effects of deposition of radionuclides onto the plant surfaces by re-suspension, deposition, and fallout. Concentration factors prescribed in RG-002 (NNR, 2013) are presented for different soil groups. The RG-002 values are listed in Table C 7 in Appendix C, where it is listed alongside values from other literature sources. Where data for a specific nuclide are not available from RG-002, the values from Staven *et al.* (2003) will be used. Values for the other parameters given in Equation 9 are listed in Appendix C.

Ingestion of Contaminated Animal Products

The effective dose from the ingestion of contaminated animal products ($ED_{ing,Anm}$, in μSv.year^{-1}) (e.g. beef, mutton, pork, poultry milk, and eggs) is calculated from measured or modelled (using Equation 9) radionuclide concentrations of the secondary animal product, by multiplication with appropriate ingestion dose coefficients and animal product ingestion rates, and is given by:

Equation 10

$$ED_{ing,Anm} = \sum_{Anm} \left(C_{Anm}\ \ CR_{Anm}\ \ DC_{ing}\right)$$

where C_{Anm} is the radionuclide concentration in the animal product (Bq.kg^{-1} fresh weight of products), CR_{Anm} is the individual consumption rate of the animal products (kg.year^{-1} fresh weight of the product), and DC_{ing}.is the dose coefficient for ingestion (µSv.Bq^{-1}). Similarly, the effective dose from the ingestion of milk ($ED_{ing,milk}$, in µSv.year^{-1}) can be calculated using the following equation:

Equation 11

$$ED_{ing,milk} = C_{milk}\, CR_{milk}\, DC_{ing}$$

where C_{milk} is the radionuclide concentration in the animal product (Bq.L^{-1}), CR_{milk} is the individual consumption rate of animal products (L.year^{-1}), and DC_{ing}.is the dose coefficient for ingestion (µSv.Bq^{-1}). The age-specific annual ingestion rate for different animal products is listed in Table C 6 in Appendix C.

The concentration of the animal product (C_{Anm}) can be calculated using the following equation:

Equation 12

$$C_{Anm} = CF_{Anm}\left[C_{past}\, CR_{Ap} + C_{water}\, CR_{Aw} + C_{soil}\, CR_{Asoil} + C_{sed} CR_{Ased}\right]$$

where CF_{Anm} is the concentration factor for the animal product (d.kg^{-1} fresh weight of the product), C_{past} is the pasture radionuclide concentration (Bq.kg^{-1} fresh weight of the pasture), CR_{past} is the animal pasture consumption rate (kg.day^{-1} fresh weight of the pasture). Animals may obtain radionuclides *via* drinking water. This is expressed using C_{water} (Bq.m^{-3}), the radionuclide concentration of water provided for the animals, and CR_{water} is the animal water consumption rate (m.day^{-1}). Ingestion of soil is calculated using C_{soil}, the soil radionuclide concentration (Bq.kg^{-1}). CR_{As} is the animal soil consumption rate (kg.day^{-1} wet weight of soil). Similarly, sediment is calculated using $C_{sed,wet}$, the radionuclide concentration in the wet sediment (Bq.kg^{-1}). CR_{Ased} is the animal sediment consumption rate (kg.day^{-1} wet weight of sediment). Similarly, the concentration of animal milk from (C_{milk}) can be calculated using the following equation:

Equation 13

$$C_{milk} = CF_{milk}\left[C_{past}\ CR_{Ap} + C_{water}\ CR_{Aw} + C_{soil}\ CR_{Asoil} +\ C_{sed}CR_{Ased}\right]$$

where CF_{milk} is the concentration factor for the animal milk (day.L^{-1}), and the remainder of the parameters are listed above. Values for the consumption rates of water, soil and fodder for beef, sheep/goat/pig, and poultry respectively, are summarised in Table C 8 in Appendix C.

The transfer of radionuclides from animal feed (CF_{Anm}] to animal products such as milk and meat is described by using a transfer coefficient. The transfer coefficients obtained from RG-002, are listed in Table C 10 in Appendix C. The transfer coefficients for milk taken from RG-002 apply to cow milk only, but the values from other references (also listed in Table C 10) may be applied to cow, goat, and sheep milk. The coefficients listed for the transfer of radionuclides from animal feed (pasture, grass, forage) to meat may be applied to all types of beef products, as well as pigs, goats, horses, and game animals. The poultry values may be applied to all types of poultry. The values from RG-002 will be used in the analysis. Where transfer coefficients for specific elements or animal products were not available from RG-002, values from Staven *et al.* (2003) will be used.

The concentration in the pasture is calculated using an equation similar to Equation 9 but without the food preparation loss term. The activity concentration in the pasture (C_{past}, in Bq.kg^{-1}) can be calculated using the following equation:

Equation 14

$$C_{past} = CF_{past}\ C_{soil}\ S_{crop} +\ Int_{crop}\ f_{growth}(C_{water}\ I_{rate} + Dep_{rate})\left(\frac{f_{trans}}{Y_c\ \lambda_{\mathrm{w}}}\right)$$

where C_{water} is the radionuclide concentration in the water (Bq.m^{-3}), C_{soil} is the radionuclide concentration in the soil (Bq.kg^{-1}), CF_{past} is the soil-to-pasture concentration factor (Bq.kg^{-1} fresh weight per Bq.kg^{-1} dry soil), and Int_{past} is the interception fraction (irrigation water and deposition) on pasture (unitless). I_{rate} is the annual depth of irrigation applied to the pasture (m.year^{-1}) and Dep_{rate} is the deposition rate of airborne contaminants (Bq.m^{-2}.year^{-1}). Y_{past} is the pasture yield (kg.m^{-2}, fresh weight of pasture), λ_{w} is the removal rate of contaminants on the pasture (through irrigation or deposition) by weathering processes (year^{-1}), and $\mathrm{Ing_{past}}$ is the consumption rate of pasture by the animals (kg.day^{-1} fresh weight of pasture).

External Gamma Irradiation: Air

The effective dose from external exposure to contaminated air (ED_{Ext_a}, in µSv.year^{-1}) is calculated from measured or simulated radionuclide concentration of the air, multiplied with appropriate dose coefficients and the period exposed to the air. The external (cloud immersion) dose can be calculated using the following equation:

Equation 15

$$ED_{ext\_air} = C_{air}\ DC_{ext\_a}\ EP_a$$

where C_{air} is the radionuclide concentration in the air (Bq.m^{-3}), DC_{ext_w}.is the dose coefficient for external exposure to air (µSv.hour^{-1} per Bq.m^{-3}), and EP_w is the annual human exposure period to contaminated air (hour.year^{-1}). Exposure is age group specific, and the values used in this assessment, as obtained from RG-002, are summarised in Table C 10 in Appendix C.

External Gamma Irradiation: Soil

The effective dose from external exposure to the contaminated soil of various extents (ED_{Ext_s}, in µSv.year^{-1}) is calculated from measured or simulated radionuclide concentration of the soil, multiplied with appropriate dose coefficients and the period exposed to the soil. The external (ground shine) dose can be calculated using the following equation:

Equation 16

$$ED_{ext\_soil} = C_{soil}\, DC_{ext\_s}\, EP_s$$

where C_{soil} is the radionuclide concentration in the soil (Bq.kg^{-1}), DC_{ext_s}.is the dose coefficient for external exposure to soil (µSv.hour^{-1} per Bq.kg^{-1}), and EP_s is the annual human exposure period to contaminated air (h.year^{-1}). The duration of exposure for different age groups is presented in Table C 11 in Appendix C.

External Gamma Irradiation: Water

The effective dose from external exposure to contaminated water (ED_{Ext_w}, in µSv.year^{-1}) is calculated from measured or simulated radionuclide concentration of the water, multiplied with appropriate dose conversion coefficients and the period exposed to the water. The external (water immersion) dose can be calculated using the following equation:

Equation 17

$$ED_{Ext\_w} = C_{water}\, DC_{ext\_w}\, EP_w$$

where C_{water} is the radionuclide concentration in the water (Bq.m^{-3}), DC_{ext_w}.is the dose coefficient for external exposure to water (µSv.hour^{-1} per Bq.m^{-3}), and EP_w is the annual human exposure period to contaminated water (hour.year^{-1}). The duration of exposure for different age groups is presented in Table C 11 in Appendix C.

Time-Dependent Soil Concentration

The radionuclide concentration in the topsoil layer (rooting zone) of previously uncontaminated soil can increase in two ways: the deposition of dispersed airborne radionuclides onto the surface, and the transfer of radionuclides in water to the soil during irrigation. Some of the radionuclides in the rooting zone will leach to greater depths (deeper zone), while root systems will take some of the radionuclides up into plants and crops. Some of the radionuclides will be adsorbed to soil particles, while bioturbation processes may transfer radionuclides between soil layers. The net effect is a change in soil radionuclide concentration in the rooting zone with time.

The radionuclide concentration in the soil can be calculated using the following equation:

Equation 18

$$C_{soil} = \frac{Soil_{RZ}}{(h_{RZ} * \rho_{RZ} * Area)}$$

where C_{soil} (Bq.kg^{-1}) is the radionuclide concentration in the soil rooting zone, $Soil_{RZ}$ (Bq) is the radionuclide inventory in the soil rooting zone, $Area$ (m^2) is the area of the soil layer, h_{RZ} (m) is the depth of the soil rooting zone and ρ_{RZ} (kg.m^{-3}) is the density of the soil rooting zone. The change in the radionuclide inventory ($Soil_{RZ}$) in an area is given by the differential equation:

Equation 19

$$\frac{dSoil_{RZ}}{dt} = (\lambda * Soil_{RZ}) + (Soil_{DZ} * \lambda_{Eros,DZ}) + (Soil_{DZ} * \lambda_{BioT,DZ}) + (Dep_{air} + I_{rrig}) - (Soil_{RZ} * \lambda_{Leach,RZ}) - (Soil_{RZ} * \lambda_{Eros,RZ}) - (Soil_{RZ} * \lambda_{BioT,RZ}) - (Soil_{RZ} * \lambda_{RootU,RZ})$$

where λ (year^{-1}) is a radionuclide specific decay/ingrowth function that together with the $Soil_{RZ}$ is an expression for the decay and ingrowth of radionuclides, $\lambda_{Eros,DZ}$ (year^{-1}) is the apparent transfer of radionuclides from the deep soil to the rooting zone, $\lambda_{BioT,DZ}$ (year^{-1}) is the transport of radionuclides from the deep soil to the rooting zone due to bioturbation, $Soil_{DZ}$ (Bq) is the radionuclide inventory in the deep zone of the soil, due to erosion processes, Dep_{air} (Bq.year^{-1}) is the total deposition of radionuclides from the atmosphere on the area, I_{rrig} (Bq.year^{-1}) is the transfer of radionuclides from water to soil due to irrigation, $\lambda_{Leach,RZ}$ (year^{-1}) is the transport of radionuclides from the soil rooting zone to deeper parts of the soil by leaching, $\lambda_{Eros,RZ}$ (year^{-1}) is the transport of radionuclides from the rooting zone due to erosion processes, $\lambda_{BioT,RZ}$ (year^{-1}) is the transfer of radionuclides from the rooting zone to the deep soil due to bioturbation, and $\lambda_{RootU,RZ}$.(year^{-1}) is the transfer of radionuclides from the rooting zone to plants through root uptake.

Dep_{air} (Bq.year^{-1}) is calculated by:

Equation 20

$$Dep_{air} = Rate_{dep} * Area,$$

where $Rate_{dep}$ (Bq.m^{-2}.year^{-1}) are the deposition rate on the soil layer and $Area$ (m^2) is the area of the soil layer. I_{rrig} (Bq.y^{-1}) is calculated by:

Equation 21

$$I_{rrig} = C_{water,irr} * Rate_{irr} * Area,$$

where $C_{water,irr}$ (Bq.m^{-3}) is the radionuclide concentration in nearby irrigation water and $Rate_{irr}$ (m^3.m^{-2}.year^{-1}) is the irrigation rate for the area. $\lambda_{Eros,DZ}$ (year^{-1}) is calculated by:

Equation 22

$$\lambda_{Eros,DZ} = \frac{Rate_{eros}}{(h_{soil,DZ} * \rho_{soil,DZ})},$$

where $Rate_{eros}$ (kg. m^{-2}.year^{-1}) is the erosion rate of soils in the area, $h_{soil,DZ}$ (m) is the depth of the deep soil zone and $\rho_{soil,DZ}$ (kg. m^{-3}) is the density of the deep zone soil. Similarly, $\lambda_{Eros,RZ}$ (year^{-1}) is calculated by:

Equation 23

$$\lambda_{Eros,RZ} = \frac{Rate_{eros}}{(h_{soil,RZ} * \rho_{soil,RZ})},$$

where $h_{soil,RZ}$ (m) is the depth of the root zone and $\rho_{soil,RZ}$ (kg. m^{-3}) is the density of the root zone. $\lambda_{BioT,DZ}$ (year^{-1}) is calculated by:

Equation 24

$$\lambda_{BioT,DZ} = \frac{BioT}{(h_{soil,DZ} * \rho_{soil,DZ})},$$

where $BioT$ (kg. m^{-2}.year^{-1}) is the bioturbation in the soil. Similarly, $\lambda_{BioT,RZ}$ (year^{-1}) is calculated by:

Equation 25

$$\lambda_{BioT,RZ} = \frac{BioT}{\left(h_{soil,RZ} * \rho_{soil,RZ}\right)}.$$

$\lambda_{Leach,RZ}$ (year^{-1}) is calculated by:

Equation 26

$$\lambda_{Leach,RZ} = \frac{I_{nfil}}{\left(h_{soil,RZ} * \varepsilon_{soil,RZ} * Ret_{RZ}\right)},$$

where I_{nfil} (m^3.m^{-2}.year^{-1}) is the infiltration rate into the soils, normally defined by the difference between the local precipitation rate and the evapotranspiration rate, $\varepsilon_{soil,RZ}$ (m^3.m^{-3}) is the porosity of the soil rooting zone and Ret_{RZ} (-) is the retardation factor for the soil rooting zone that can be calculated by:

Equation 27

$$Ret_{RZ} = 1 + \frac{\rho_{soil,RZ} * K_{d\ soil,RZ}}{\varepsilon_{soil,RZ}},$$

where $K_{d\ soil,RZ}$ (m^3.kg^{-1}) is the distribution coefficient for the soil rooting zone. Similarly, $\lambda_{Leach,DZ}$ (year^{-1}) is calculated by:

Equation 28

$$\lambda_{Leach,DZ} = \frac{I_{nfil}}{\left(h_{soil,DZ} * \varepsilon_{soil,DZ} * Ret_{DZ}\right)}$$

where $\varepsilon_{soil,DZ}$ (m^3.m^{-3}) is the porosity of the soil-rooting zone and $RetD_{DZ}$ (-) is the retardation factor for the deep soil zone that can be calculated by:

Equation 29

$$Ret_{DZ} = 1 + \frac{\rho_{soil,DZ} * K_{d\ soil,DZ}}{\varepsilon_{soil,DZ}},$$

where $K_{d\ soil,DZ}$ (m^3.kg^{-1}) is the distribution coefficient for the deep soil zone. The transfer of radionuclides from the root zone through root uptake is calculated by:

Equation 30

$$RootU_{RZ} = \frac{Y_{crop} * Num_{crop} * CF_{crop}}{\left(h_{soil,RZ} * \rho_{soil,RZ}\right)}$$

where Y_{crop} is the annual crop yield (kg.m^{-2}), Num_{crop} is the number of crops harvested annually (year^{-1}), CF_{crop} is the soil-to-crop concentration factor for the crop (Bq.kg^{-1} fresh weight / Bq.kg^{-1} dry soil).

Similarly, the radionuclide inventory $Soil_{DZ}$ (Bq) in an area is calculated using the differential equation:

Equation 31

$$\frac{dSoil_{DZ}}{dt} = (\lambda * Soil_{DZ}) + (Soil_{RZ} * \lambda_{Leach,RZ}) + (Soil_{RZ} * \lambda_{BioT,RZ}) + (Soil_{RZ} * \lambda_{RootU,RZ}) - (Soil_{DZ} * \lambda_{Leach,DZ}) - (Soil_{DZ} * \lambda_{Eros,DZ}) - (Soil_{DZ} * \lambda_{BioT,DZ})$$

Calculation of the Airborne Radon Concentration

Radon release from a mineralised stockpile facility to the environment involves two mechanisms. The first is the liberation from the particle in which the radon is formed, which is characterised by the radon emanation coefficient. The second is the transport of radon through the bulk medium to the atmosphere, which is characterised by the diffusion coefficient in the bulk medium.

The release to the environment will also be affected by the presence of covering layers and the prevailing meteorological conditions. The flux from an uncovered stockpile facility is also directly related to the Ra-226 activity concentration, the emanation coefficient, and the bulk density. If any of these variables increases, then the surface radon flux increases proportionally. The flux also increases as the diffusion coefficient increases. It has been shown that the thickness has no effect beyond about 2 to 4 m (IAEA, 1992).

The radon flux at the surface of stockpile material $Flux_t$, (Bq.year^{-1}) with a surface area (m^2), uniform density ρ_b (kg.m^{-3}) and Ra-226 concentration C_{Ra} (Bq.g^{-1}) is presented by (IAEA, 2013):

Equation 32

$$Flux_t = Area \cdot C_{Ra} \cdot \rho_b \cdot E \cdot L_r \cdot \lambda \cdot \tanh\frac{z_r}{L_r}$$

where E is the emanation coefficient of the material (unitless) assumed to be 0.2, λ is the decay constant for Rn-222 (2.06E-06 s^{-1}), and z_r is the thickness of the facility (m). The parameter L_r is defined as the radon diffusion length, which is a function of the material-specific radon diffusion coefficient (D) and the decay constant for radon and is given by (IAEA, 2013):

Equation 33

$$L_r = \sqrt{\frac{D}{\lambda}}$$

The radon diffusion coefficient (*D*) is specific to the material and a function of its physical parameters. The effective radon diffusion coefficient in the open air is estimated at 1.10E-05 m^2.s^{-1}. Inside a material, it is proportional to the porosity and moisture saturation of the material. In different materials, the radon diffusion length can vary from low numbers (~ 0.2) to a maximum of approximately 1.4 m for high porosity materials that contain no moisture. The material-specific radon diffusion coefficient is estimated using the following empirical correlation derived from a database of measured effective diffusion coefficients (Rogers and Nielson, 1991):

Equation 34

$$D = D_0 n \, exp(-6Sn - 6S^{14n})$$

where D_0 denotes the radon diffusion coefficient in air, *n* denotes the porosity of the material and *S* is the saturation of the material. The thickness of the facility (z_r) is a parameter that is required for the radon flux calculation. However, the value of the term in Equation 32 that requires this parameter ($\tanh\frac{z_r}{L_r}$), changes very little over a layer thickness of 0.1 m to 4 m, where it is at its maximum value. Any thickness beyond 4 m results in a value approaching 1. To simplify the calculation, it is therefore conservatively assumed that the facility will be 5 meters or more. A thinner layer will only have the effect of reducing the radon exhalation rate. Alternatively, a much thicker layer (>10 m) will not significantly increase the radon exhalation rate calculated with an assumed 5 m thickness.

Placing a cover (e.g., a layer of sand or crushed rock) over a source of radon gas will reduce the rate at which radon is emitted into the atmosphere. The effect of a mine tailings cover or similar layer on the flux of radon from the facility is given by (IAEA, 2013):

Equation 35

$$F_c = \frac{2F_r \cdot e^{\left(\frac{-Z_c}{L_c}\right)}}{\left[1 + \frac{n_r L_r}{n_c L_c} \tanh \frac{Z_r}{L_r}\right] + \left[1 - \frac{n_r L_r}{n_c L_c} \tanh \frac{Z_r}{L_r}\right] e^{\left[-2\frac{Z_c}{L_c}\right]}}$$

where the radon flux at the surface of the cover material F_c ($Bq.m^{-2}.s^{-1}$) is a function of the radon flux F_r ($Bq.m^{-2}.s^{-1}$) from the *uncovered* source material. F_c is adjusted with the thickness of the cover material and rejects (z_c and z_r in meter), the radon diffusion lengths of the cover and rejects (L_c, and L_r in m), and the porosity of the cover and reject materials (n_c and n_r).

The associated airborne radon concentration at the surface of the stacked mineralogical material ($C_{Rn,air}$, $Bq.m^{-3}$) can be approximated by the following equation (Yu *et al.*, 2001):

Equation 36

$$C_{Rn,air} = \frac{F_c}{\lambda h}\left[1 - e^{-\frac{\lambda W}{2u}}\right]$$

Here, F_c is the radon flux at the surface of the tailings or cover ($Bq.m^{-2}.s^{-1}$), whichever applies, W is the width of the source perpendicular to the wind direction (m), u is the mean wind speed ($m.s^{-1}$), and h is the height for vertical mixing (taken as 2 m).

Calculation of the Radon and Thoron Exhalation Rates for Sembehun

The exhalation rate for a source with a thickness > 4 m is given by:

Equation 37

$$\Phi = \varepsilon R \rho \sqrt{\lambda D}$$

Where: Φ = exhalation rate [$Bq.m^{-2}.s^{-1}$]

ε = emanation rate

ρ = bulk density [$kg.m^{-3}$]

R = Ra-226 content [$Bq.kg^{-1}$]

λ = radon decay constant [s^{-1}]

D = gas diffusion coefficient [$m^2.s^{-1}$]

The thoron exhalation rate is deduced from the radon exhalation rate as follows.

Radon and thoron have characteristic diffusion distances through a porous material. This diffusion length of radon and thoron is given by:

Equation 38

$$Z_R = \sqrt{\frac{D_R}{\lambda_R}} \quad \text{and} \quad Z_T = \sqrt{\frac{D_T}{\lambda_T}}$$

Where D_R and D_T are the diffusion coefficients, and λ_R and λ_T are the decay constants of radon and thoron respectively. Radon and thoron atoms are physically and chemically similar (apart from radioactive properties), while diffusion is controlled by physicochemical processes. It is, therefore, assumed that the diffusion coefficient for the two isotopes will be the same, $D_R = D_T$. From this assumption it then follows that:

Equation 39

$$\frac{Z_T}{Z_R} = \sqrt{\frac{\lambda_R}{\lambda_T}}$$

The decay constants of radon and thoron are 2.098 x 10^{-6} and 0.0126 s^{-1} respectively. The ratio of the diffusion length of thoron and radon then becomes:

Equation 40

$$Z_R / Z_T = 77.5$$

This relationship is used to calculate the exhalation rate of thoron from the exhalation rate value for radon (Equation 37). From Equation 37, the exhalation rate of thoron is given by:

Equation 41

$$\Phi_T = \varepsilon T \rho \sqrt{\lambda_T D_T}$$

Where T is the Ra-228 content, and the subscript T indicates thoron. The emanation fraction, ε in equations 1 and 4 has no subscript because it is assumed that the value is the same for both radon and thoron. This assumption is conservative based on findings reported by Lawrence (2005) that the emanation fraction for thoron is approximately 10 % lower than the value for radon. The ratio of thoron to radon exhalation rate is then:

Equation 42

$$\frac{\Phi_T}{\Phi_R} = \frac{T}{R}\sqrt{\frac{\lambda_T}{\lambda_R}} = \frac{T}{R} \times 77.5$$

The thoron exhalation rate is calculated from the radon value by using the ratio of Ra-228 to Ra-226 content.

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APPENDIX C:
CALCULATION PARAMETER VALUES

Table C 1 Dose conversion factors (Sv.Bq^{-1}) for inhalation exposure to various radionuclides, taken from RG-002 (NNR, 2013).

Radionuclide	0 to 1 year	1 to 2 years	2 to 7 years	7 to 12 years	12 to 17 years	Adult
Th-232	8.30E-05	8.10E-05	6.30E-05	5.00E-05	4.70E-05	4.50E-05
Ra-228	4.90E-05	4.80E-05	3.20E-05	2.00E-05	1.60E-05	1.60E-05
Th-228	1.80E-04	1.50E-04	8.30E-05	5.20E-05	3.60E-05	2.90E-05
Ra-224	1.20E-05	9.20E-06	5.90E-06	4.40E-06	4.20E-06	3.40E-06
U-238	2.90E-05	2.50E-05	1.60E-05	1.00E-05	8.70E-06	8.00E-06
U-234	3.30E-05	2.90E-05	1.90E-05	1.20E-05	1.00E-05	9.40E-06
Th-230	2.10E-04	2.00E-04	1.40E-04	1.10E-04	9.90E-05	1.00E-04
Ra-226	3.40E-05	2.90E-05	1.90E-05	1.20E-05	1.00E-05	9.50E-06
Pb-210	1.80E-05	1.80E-05	1.10E-05	7.20E-06	5.90E-06	5.60E-06
Po-210	1.80E-05	1.40E-05	8.60E-06	5.90E-06	5.10E-06	4.30E-06
U-235	3.00E-05	2.60E-05	1.70E-05	1.10E-05	9.20E-06	8.50E-06
Pa-231	2.20E-04	2.30E-04	1.90E-04	1.50E-04	1.50E-04	1.40E-04
Ac-227	1.70E-03	1.60E-03	1.00E-03	7.20E-04	5.60E-04	5.50E-04
Ra-223	3.20E-05	2.40E-05	1.50E-05	1.10E-05	1.10E-05	8.70E-06

Table C 2 Dose conversion factors (Sv.Bq^{-1}) for ingestion exposure to various radionuclides taken from RG-002 (NNR, 2013).

Radionuclide	0 to 1 year	1 to 2 years	2 to 7 years	7 to 12 years	12 to 17 years	Adult
Th-232	4.60E-06	4.50E-07	3.50E-07	2.90E-07	2.50E-07	2.30E-07
Ra-228	3.00E-05	5.70E-06	3.40E-06	3.90E-06	5.30E-06	6.90E-06
Th-228	3.70E-06	3.70E-07	2.20E-07	1.50E-07	9.40E-08	7.20E-08
Ra-224	2.70E-06	6.60E-07	3.50E-07	2.60E-07	2.00E-07	6.50E-08
U-238	3.40E-07	1.20E-07	8.00E-08	6.80E-08	6.70E-08	4.50E-08
U-234	3.70E-07	1.30E-07	8.80E-08	7.40E-08	7.40E-08	4.90E-08
Th-230	4.10E-06	4.10E-07	3.10E-07	2.40E-07	2.20E-07	2.10E-07
Ra-226	4.70E-06	9.60E-07	6.20E-07	8.00E-07	1.50E-06	2.80E-07
Pb-210	8.40E-06	3.60E-06	2.20E-06	1.90E-06	1.90E-06	6.90E-07
Po-210	2.60E-05	8.80E-06	4.40E-06	2.60E-06	1.60E-06	1.20E-06
U-235	3.50E-07	1.30E-07	8.50E-08	7.10E-08	7.00E-08	4.70E-08
Pa-231	1.30E-05	1.30E-06	1.10E-06	9.20E-07	8.00E-07	7.10E-07
Ac-227	3.30E-05	3.10E-06	2.20E-06	1.50E-06	1.20E-06	1.10E-06
Ra-223	5.30E-06	1.10E-06	5.71E-07	4.50E-07	3.70E-07	1.00E-07

Table C 3 External irradiation dose conversion factors for various radionuclides, taken from RG-002 (NNR, 2013).

Nuclide	Water Immersion	Air Submersion	Exposure to contaminated soil		
			Surface contamination	Contaminated to 15 cm deep	Contaminated to infinite depth
	$Sv.m^3.Bq^{-1}.s^{-1}$	$Sv.m^3.Bq^{-1}.s^{-1}$	$Sv.m^2.Bq^{-1}.s^{-1}$	$Sv.m^3.Bq^{-1}.s^{-1}$	$Sv.m^3.Bq^{-1}.s^{-1}$
Th-232	1.99E-20	8.72E-18	5.51E-19	2.78E-21	2.79E-21
Ra-228	-	-	-	-	-
Th-228	2.05E-19	9.20E-17	2.35E-18	4.17E-20	4.25E-20
Ra-224	1.03E-18	4.71E-16	9.57E-18	2.62E-19	2.74E-19
U-238	7.95E-21	3.41E-18	5.51E-19	5.52E-22	5.52E-22
U-234	1.75E-20	7.63E-18	7.48E-19	2.14E-21	2.15E-21
Th-230	3.94E-20	1.74E-17	7.50E-19	6.39E-21	6.47E-21
Ra-226	6.59E-19	3.15E-16	6.44E-18	1.65E-19	1.70E-19
Pb-210	1.31E-19	5.64E-17	2.13E-18	1.31E-20	1.31E-20
Po-210	9.03E-22	4.16E-19	8.29E-21	2.45E-22	2.80E-22
U-235	1.59E-17	7.20E-15	1.48E-16	3.75E-18	3.86E-18
Pa-231	-	-	-	-	-
Ac-227	1.30E-20	5.82E-18	1.57E-19	2.62E-21	2.65E-21
Ra-223	1.35E-17	6.09E-15	1.28E-16	3.10E-18	3.23E-18

Table C 4 Summary of daily inhaled volumes for different age groups as taken from RG-002 (NNR, 2013).

Age Group	Inhalation Rate ($m^3.day^{-1}$)
0 to 2 years	5.28
2 to 7 years	8.88
7 to 12 years	15.36
12 to 17 years	20.16
Adults	22.08

Table C 5 Ingestion rates for adult members of the public as proposed in RG-002 (NNR, 2013), compared to ranges of literature values.

Ingestion Pathway	Unit	RG-002	NUREG-5512 Vol. 4		
			Average	Minimum	Maximum
Water	$L.year^{-1}$	6.00E+02	4.78E+02	8.44E+01	1.84E+03
Milk		1.20E+02	2.33E+02	9.51E-01	1.21E+03
Soil	$kg.year^{-1}$	3.70E-02	1.83E-02	9.31E-04	3.58E-02
Grain		2.50E+02	1.44E+01	1.62E-01	9.70E+01
Fruit		-	5.28E+01	1.24E-01	6.53E+02
Leafy Vegetables		-	2.14E+01	3.58E-02	2.13E+02
Root Vegetables		-	4.46E+01	3.41E-01	3.79E+02
Meat (beef)		3.00E+01	3.98E+01	1.20E-01	2.22E+02
Meat (mutton)		2.50E+01	-	-	-
Meat (pork)		2.00E+01	-	-	-
Poultry		5.00E+01	2.53E+01	5.77E-01	7.29E+01
Eggs		1.50E+01	1.91E+01	2.62E-01	1.21E+02

Table C 6 Ingestion rates for different age groups as defined by the adult ingestion rates.

Ingestion Pathway	Unit	Ingestion Rates for Different Age Groups				
		0 - 2 Years	2 - 7 Years	7 - 12 Years	12 – 17 Years	Adult
% of Adult Rate	-	40	50	60	85	100
Water	L.year^{-1}	2.40E+02	3.00E+02	3.60E+02	5.10E+02	6.00E+02
Milk		4.80E+01	6.00E+01	7.20E+01	1.02E+02	1.20E+02
Soil	kg.year^{-1}	1.48E-02	1.85E-02	2.22E-02	3.15E-02	3.70E-02
Grain		1.00E+01	1.25E+01	1.50E+01	2.130E+01	2.50E+01
Fruit		2.11E+01	2.64E+01	3.17E+01	4.49E+01	5.28E+01
Leafy Vegetables		8.56E+00	1.07E+01	1.28E+01	1.82E+01	2.14E+01
Root Vegetables		1.78E+01	2.23E+01	2.68E+01	3.79E+01	4.46E+01
Meat (beef)		1.20E+01	1.50E+01	1.80E+01	2.55E+01	3.00E+01
Meat (mutton)		1.00E+01	1.25E+01	1.50E+01	2.13E+01	2.50E+01
Meat (pork)		8.00E+00	1.00E+01	1.20E+01	1.70E+01	2.00E+01
Poultry		2.00E+01	2.50E+01	3.00E+01	4.25E+01	5.00E+01
Eggs		6.00E+00	7.50E+00	9.00E+00	1.28E+01	1.50E+01

Table C 7 Parameters used in describing radionuclide uptake in plants and crops.

Parameter	Unit	Root	Leafy	Fruit	Cereal	Forage	Grain	Hay
Crop Yield	kg.m^{-2}	2.4E+00	2.9E+00	2.4E+00	3.9E-01	1.9E+00	6.6E-01	1.9E+00
Growing Period	Days	9.0E+01	4.5E+01	9.0E+01	9.0E+01	3.E+01	9.0E+01	4.5E+01
Translocation Factor	-	1.0E-01	1.0E+00	1.0E-01	1.0E-01	1.0E+00	1.0E-01	1.0E+00
Food processing	-	9.0E-01	9.0E-01	9.0E-01	9.0E-01	0.0E+00	0.0E+00	0.0E+00
Weathering rates	year^{-1}	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01
Crop Interception Factor	-	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01
Soil contamination of crop	-	2.0E-03	1.2E-03	4.0E-03	3.4E-03	1.0E-03	1.0E-03	1.0E-03
Mass Interception Factor	m^{-2}.kg^{-1}	3.0E-01	3.0E-01	3.0E-01	3.0+00	3.0+00	3.0+00	3.0+00

Table C 8 Annual water, soil, and fodder consumption rates by animals (beef, sheep, goats, pigs, and poultry) compiled from various sources.

Water	Fodder	Soil	Reference
Beef Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			
75	16	1.25	RG-002
60	55 (wet)	0.6-	(IAEA, 2003)
80	10	0.6	(Kozak and Stenhouse, 2002)
20 to 200	9 to 300	0.1 to 2.2	(Kozak and Stenhouse, 2002)
35.6	33	1.5	(Penfold *et al.*, 1999)
20 to 100	10 to 25	-	(IAEA, 1994a)
50 to 60	25	0.5	(IAEA, 2003)
Sheep/Pig Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			Reference
15	1.5	0.8	RG-002
3 to 10	0.5 to 3.5	-	(IAEA, 1994a)
Poultry Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			Reference
0.3	0.15	-	RG-002
0.1 to 0.3	0.05 to 0.15	-	(IAEA, 1994a)
0.3	0.15	0.01	

Table C 9 Soil to secondary crop concentration factors (Bq.kg^{-1} crop per Bq.kg^{-1} dry soil) compiled from various sources.

U	Th	Ra	Pb	Po	Pa	Ac	Reference
Leafy Vegetables							
2.0E-02	1.2E-03	9.1E-02	8.0E-02	7.4E-03	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
8.3E-04	1.8E-04	4.9E-03	1.0E-03	1.1E-05	1.1E-04	1.1E-04	(De Beer, *et al.*, 2002)
3.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	2.1E-02	3.2E-04	(Penfold *et al.*, 1999)
1.7E-03	3.6E-04	9.8E-03	2.0E-03	2.4E-04	9.4E-05	9.4E-05	(Staven *et al.*, 2003)
Root Vegetables							Reference
8.4E-03	8.0E-04	7.0E-02	1.5E-02	5.8E-03	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
2.2E-03	4.8E-05	7.8E-03	1.6E-03	1.8E-05	1.8E-04	1.8E-04	(De Beer, *et al.*, 2002)
3.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-03	5.0E-04	3.0E-01	6.0E-02	2.0E-04	2.0E-02	6.0E-04	(Penfold *et al.*, 1999)
3.0E-03	8.5E-05	5.0E-04	1.5E-03	1.8E-03	8.8E-05	8.5E-05	(Staven *et al.*, 2003)
Fruit							Reference
1.5E-02	7.8E-04	1.7E-02	1.5E-02	1.9E-04	-	-	RG-002[2]
2.2E-03	4.8E-05	7.8E-03	1.6E-03	1.8E-05	1.8E-04	1.8E-04	(De Beer, *et al.*, 2002)
7.2E-04	4.5E-05	1.1E-03	1.8E-03	2.2E-04	4.5E-05	4.5E-05	(Staven *et al.*, 2003)
Cereal							Reference
1.5E-02	6.4E-05	2.4E-03	1.2E-03	2.4E-04	-	-	RG-002[1,3]
1.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
1.1E-03	2.9E-05	1.0E-03	4.0E-03	4.4E-04	4.4E-04	4.4E-04	(De Beer, *et al.*, 2002)
1.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-04	1.0E-03	4.0E-02	1.0E-02	2.0E-04	1.3E-02	1.9E-04	(Penfold *et al.*, 1999)
1.2E-03	3.1E-05	1.1E-03	4.3E-03	2.1E-03	2.0E-05	2.0E-05	(Staven *et al.*, 2003)
Grain (Animal Feed)							Reference
7.8E-03	1.8E-03	1.8E-02	2.8E-03	2.4E-04	-	-	RG-002[1,4]
1.2E-03	3.1E-05	1.1E-03	4.3E-03	2.1E-03	2.0E-05	2.0E-05	(Staven *et al.*, 2003)
Forage, Hay (Animal Feed)							Reference
4.6E-02	9.9E-02	7.1E-02	9.2E-02	1.2E-01	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
2.3E-02	1.1E-02	8.0E-02	1.1E-03	2.0E-02	2.0E-02	2.0E-02	(De Beer, *et al.*, 2002)
8.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
5.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	3.2E-02	4.8E-04	(Penfold *et al.*, 1999)
8.3E-03	1.8E-03	4.9E-02	1.0E-02	1.2E-03	4.7E-04	4.7E-04	(Staven *et al.*, 2003)
Average Crop Concentration Factors							Reference
2.7E-03	3.9E-04	1.0E-02	4.0E-03	1.3E-03	1.2E-04	1.2E-04	(Staven *et al.*, 2003)

(1) Concentration factors from RG-002 are given based on dry weight concentration in the plant to the dry weight concentration in the soil, (2) RG-002 values for fruit are given as wet weight concentration in fruit per dry weight concentration in soil. (3) Values for grain from RG-002 are specifically for maize. (4) Animal feed from grain is for maize stalks and roots, which are commonly used as animal feed.

Table C 10 Transfer coefficients from the animal feed to animal products in d.kg^{-1} and d.L^{-1} compiled from various sources.

U	Th	Ra	Pb	Po	Pa	Ac	Reference
Transfer Coefficients for Meat (d.kg^{-1})							
3.9E-04	2.3E-04	1.7E-03	7.0E-04	5.0E-03	-	-	RG-002 (Beef)
3.0E-02	5.0E-03	5.0E-03	7.1E-03	5.0E-03	-	-	RG-002 (Mutton)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	5.0E-05	1.6E-04	(IAEA, 2003)
3.4E-04	9.0E-04	9.4E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
6.0E-04	2.7E-03	1.3E-03	1.0E-02	4.0E-03	5.0E-05	1.6E-04	(Kozak and Stenhouse, 2002)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	2.6E-05	1.6E-04	(Penfold *et al.*, 1999)
3.0E-04	4.0E-05	9.0E-04	4.0E-04	5.0E-03	4.0E-05	4.0E-04	(Staven *et al.*, 2003)
Transfer Coefficients for Milk (d.L^{-1})							Reference
1.8E-03	5.0E-06	3.8E-04	1.9E-04	2.1E-04	-	-	RG-002
4.0E-04	5.0E-06	1.3E-03	3.0E-04	3.4E-04	5.0E-06	4.0E-07	(IAEA, 2003)
4.0E-04	1.7E-06	1.3E-03	2.0E-04	1.0E-03	1.0E-03	1.0E-03	(De Beer, *et al.*, 2002)
3.7E-04	5.0E-06	1.3E-03	3.0E-04	3.0E-04	5.0E-06	4.0E-07	(Kozak and Stenhouse, 2002)
4.0E-04	5.0E-06	1.3E-03	2.7E-04	3.4E-04	5.0E-06	4.0E-07	(Penfold *et al.*, 1999)
4.0E-04	5.0E-06	1.3E-03	2.6E-04	3.4E-04	5.0E-06	2.0E-05	(Staven *et al.*, 2003)
Transfer Coefficients for Poultry (d.kg^{-1})							Reference
7.5E-01	4.0E-03	9.9E-04	2.0E-03	2.4E+00	-	-	RG-002
3.0E-04	9.0E-04	9.0E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
1.0E+00	6.0E-03	3.0E-02	8.0E-01	2.3E+00	6.0E-03	6.0E-03	(Staven *et al.*, 2003)
Transfer Coefficients for Eggs (d.kg^{-1})							Reference
1.1E+00	2.0E-03	2.0E-05	2.0E-03	3.1E+00	-	-	RG-002
1.0E+00	2.0E-03	2.0E-05	2.0E-03	1.8E-02	1.8E-02	1.8E-02	(De Beer *et al.*, 2002)
1.0E+00	4.0E-03	3.1E-01	1.0E+00	7.0E+00	4.0E-03	4.0E-03	(Staven *et al.*, 2003)

Table C 11 Occupancy factors taken from RG-002 (NNR, 2013).

Activity	0 – 2 Years	2 – 7 Years	7 – 12 Years	12 – 17 Years	Adult
Time spent indoors	7 914	7 775	7 568	7 665	7 050
Time spent outdoors	846	985	1 192	1 092	1 710
Working on contaminated sediments and land	0	0	0	0	2 000
Playing on contaminated sediments and land	200	383	383	300	0
Swimming	19.2	27.4	30.2	27.8	9
Boating	0	78	76	110	170
Fishing	0	78	76	110	170

APPENDIX D: CONCEPTUAL REPRESENTATION OF THE GROUNDWATER MODEL IN ECOLEGO

Figure D 1 to Figure D 3 present simplified representations of the groundwater pathway for different site-specific conditions. Viewed simplistically, the main components of the groundwater system are a source, an unsaturated zone of limited thickness, a saturated zone, a mixing zone between clean and contaminated water in the aquifer, and a receptor of groundwater contamination that could be in the form of an abstraction borehole or a surface water body such as a river or a lake. The source as used here could be a contaminated soil layer with a relatively limited thickness and lateral extent, a surface stockpile facility (e.g., Tailings Storage Facility or Waste Rock Dump) with a relatively large lateral extent and thickness, or a below-grade layer of contaminated waste material.

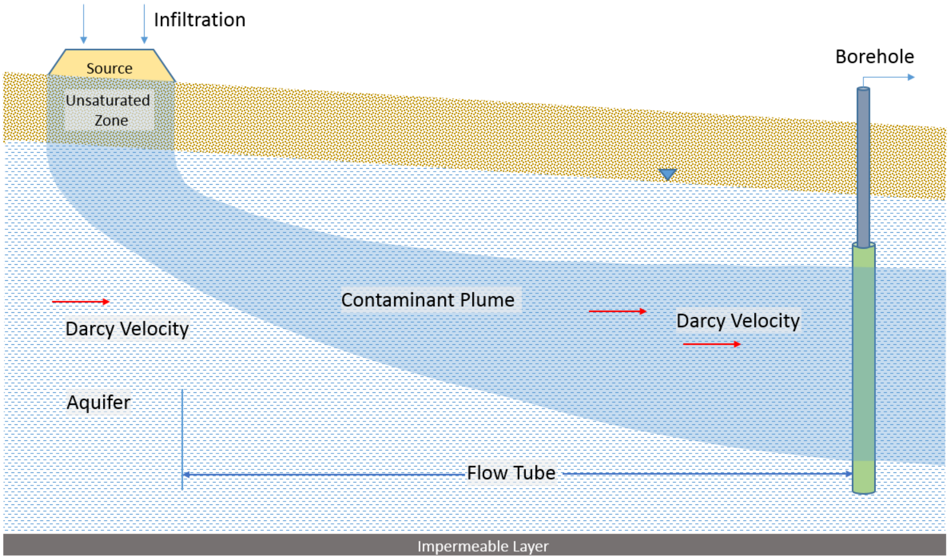

Figure D 1 Schematic representation of the groundwater system to calculate the migration of radionuclides through a deep (thick) aquifer system and a relatively small lateral extent source term, with an abstraction borehole as a receptor.

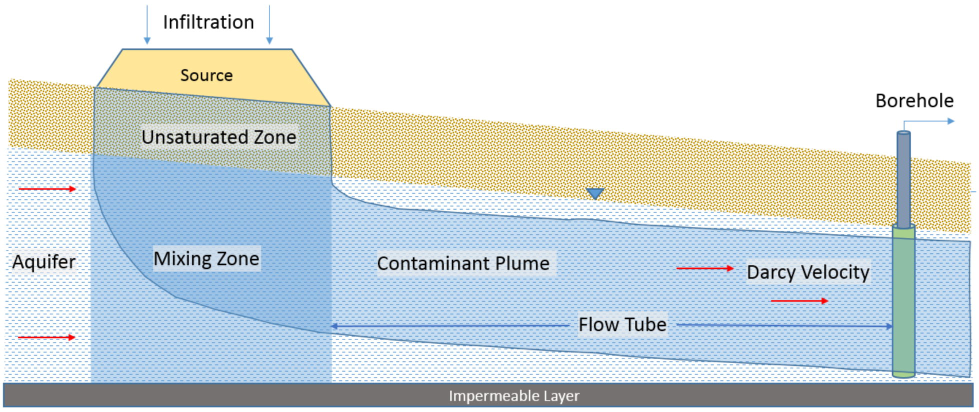

Figure D 2 Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with an abstraction borehole as a receptor.

It is assumed that radionuclides contained in the source are released following the infiltration and dissolution of precipitation into and through the source. The radionuclides that leach from the source migrate vertically through the unsaturated zone towards the groundwater table (i.e., an interface between the unsaturated and saturated zone). Upon entering the aquifer (saturated zone), mixing between contaminated and uncontaminated water will occur, after which the radionuclides migrate along with the groundwater flow path towards the downstream borehole or surface water body.

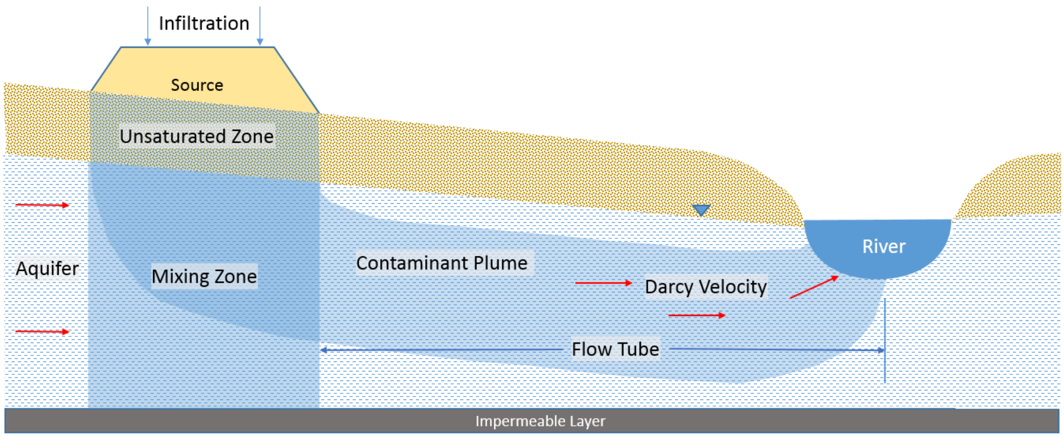

Figure D 3 Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with a river as a receptor.

Steady-state flow conditions are assumed for radionuclide migration. The processes consider advection, hydrodynamic dispersion, radioactive decay, and radionuclide sorption by the soil matrix. For the latter, instantaneous and reversible sorption described by a linear isotherm (also known as a K_d-model or sorption distribution coefficient) is assumed. Figure D 1 is a conceptual representation of a source term with limited thickness and lateral extent, with a thick aquifer system that underlies the source, whereas Figure D 2 and Figure D 3 represent a shallow (thin) aquifer system and a relatively large lateral extent source term.

The *System Level* model that was used to evaluate the contribution of the groundwater pathway was implemented in Ecolego® Version 6 (http://ecolego.facilia.se/ecolego/show/HomePage). A conceptual representation of the different compartments of the *System Level* Model is presented in Figure D 4 to Figure D 8.

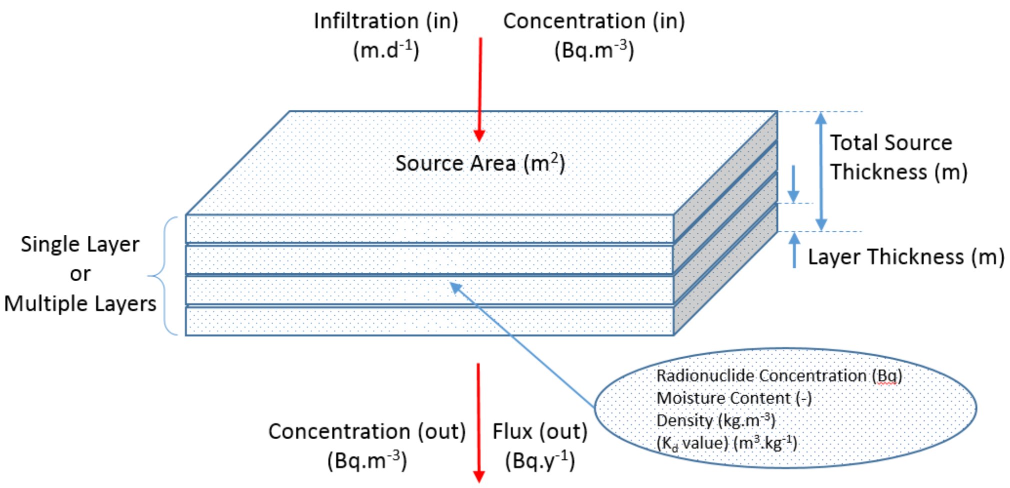

Figure D 4 Conceptual representation and associated parameter values for the source term model.

Figure D 4 shows that the source term model is a function of the radionuclide specific activity concentration (Bq), the volumetric moisture content ($m^3.m^{-3}$), the dry bulk density of the source material ($kg.m^{-3}$), and the radio element-specific distribution coefficient or K_d-value ($m^3.kg^{-1}$). The advective transfer coefficient that represents the loss of radionuclides from the total source, or from one layer to the next, is given by the model described in IAEA (2004b) and :

Equation 43

$$\lambda_w = \frac{I_w}{\theta_w H_w R_w}$$

where I_w is the infiltration rate to the source layer (m.year^{-1}), θ_w is the soil moisture content in the source (unitless) and H_w is the thickness of source (m) R_w is the retardation coefficient in the source (unitless):

Equation 44

$$R_w = 1 + \frac{\rho_w K_{dw}}{\theta_w}$$

where, ρ_w is the soil bulk density in the source (kg.m^{-3}) and $K_{d,w}$ is the sorption distribution coefficient in the source (m^3.kg^{-1}). For multiple layers with different properties, the transfer coefficient is defined for each layer with its associated parameter values. Figure D 4 shows that the output from the source term model is the radionuclide concentration (Bq.m^{-3}) or flux (Bq.year^{-1}) leaving the compartment.

The transfer coefficient accounting for the effect of dispersion in transport from compartment *i* to compartment *j* ($\lambda_{D,ij}$, year^{-1}) is calculated using the following equation (IAEA, 2004b):

Equation 45

$$\lambda_{D,ij} = \frac{\alpha_L}{H_i} \cdot \lambda_{w,ij}$$

where α_L is the longitudinal dispersivity (m) and H_i is the compartment thickness. Note that the transfer coefficient in Equation 45 represents the dispersion of radionuclides between the compartments in both directions.

Figure D 5 shows that the unsaturated zone model is a function of the volumetric moisture content (m^3.m^{-3}) and the dry bulk density of the unsaturated zone (kg.m^{-3}), the radioelement-specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the unsaturated soils, as well as the dispersivity (m). The advective and dispersive transfer coefficients that represent the transfer and loss of radionuclides from the unsaturated zone to the saturated zone (aquifer) are similar to those presented in Equation 43 to Equation 45, except that it is for the unsaturated zone parameter values.

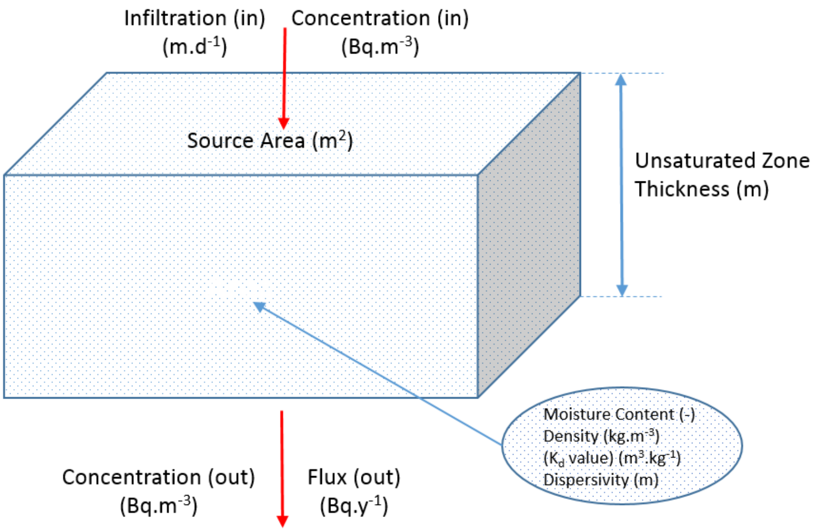

Figure D 5 **Conceptual representation and associated parameter values for the unsaturated zone model.**

Figure D 6 is a simplified representation of the aquifer mixing zone and the most important parameters. The infiltration rate (m.year^{-1}) is assumed constant (i.e., steady-state conditions) and equal to the infiltration rate to the unsaturated zone. The radionuclide concentration (Bq.m^{-3}) of water (moisture) entering the mixing zone is equal to the concentration flowing from the unsaturated zone. It is assumed that the mixing zone is represented as one compartment of known thickness. The area is the same as that of the source, while the depth is equal to the aquifer thickness.

The water entering the mixing zone may contain a radionuclide concentration, but it is assumed that the radionuclide concentration (Bq.m^{-3}) of the water is zero. The Darcy velocity (m.year^{-1}) defines the flow rate entering the mixing zone and that flow rate through the zone. The output after mixing defines the concentration (Bq.m^{-3}) and flux (Bq.year^{-1}) into the flow tube (aquifer).

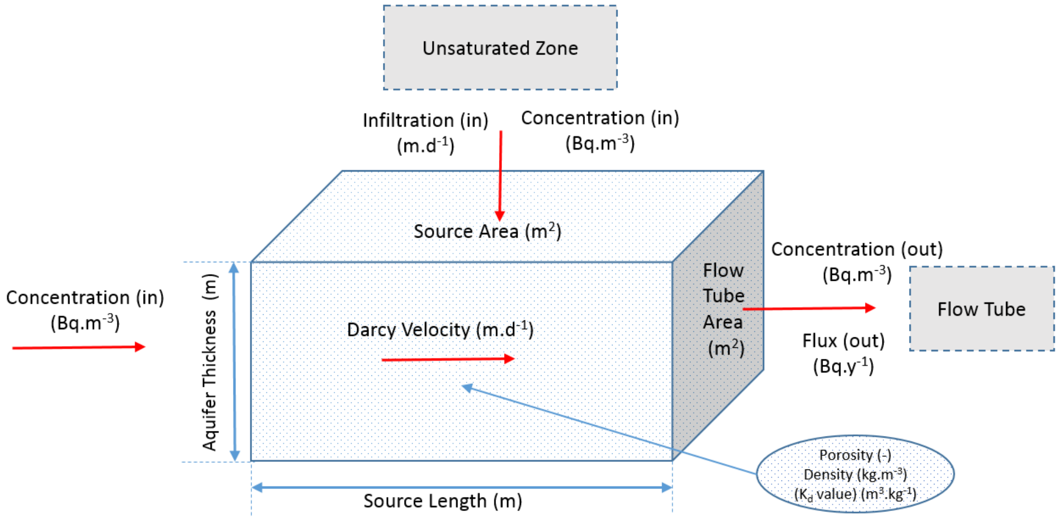

Figure D 6 Conceptual representation and associated parameter values for the aquifer mixing zone model.

Figure D 6 shows that the aquifer mixing zone model is a function of the Darcy velocity (m.year^{-1}), the dry bulk density of the aquifer (kg.m^{-3}), and the radio element-specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the aquifer.

The radionuclide concentration (Bq.m^{-3}) of water entering the aquifer compartment is equal to the outflow concentration from the aquifer mixing zone. The Darcy velocity (m.year^{-1}) in the aquifer is assumed to be constant with time. The output at the receptor point defines the concentration (Bq.m^{-3}) and flux (Bq.year^{-1}) at the borehole.

Figure D 6 shows that the aquifer model is a function of the Darcy velocity (m.year^{-1}), the aquifer porosity, the dry bulk density of the aquifer (kg.m^{-3}), the radioelement specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the aquifer, and the dispersivity (m). The advective and dispersive transfer coefficients that represent the transfer and loss of radionuclides from the aquifer are similar to those presented in Equation 43 to Equation 45, except that it is for the aquifer parameter values.

The concentration of the water abstracted from the borehole is simplistically taken as the sum of the flow tube concentration (Bq.m^{-3}) multiplied by the fraction of the borehole intersecting the plume, and the background concentration (Bq.m^{-3}) multiplied by the fraction intersecting the uncontaminated water. As a conservative assumption, it is assumed that the whole screen intersection the contaminant plume.

Figure D 8 is a simplified representation of the borehole abstraction module and the most important parameters.

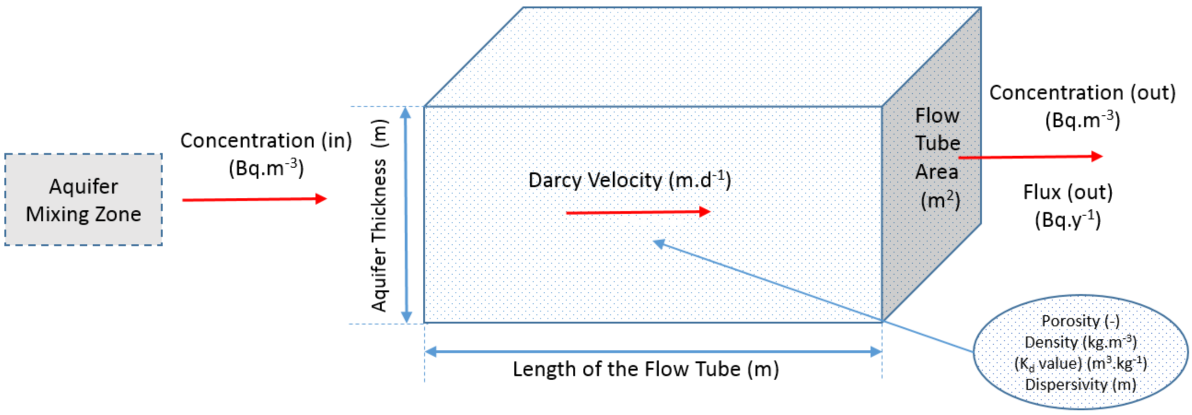

Figure D 7 Conceptual representation and associated parameter values for the aquifer (saturated zone) model.

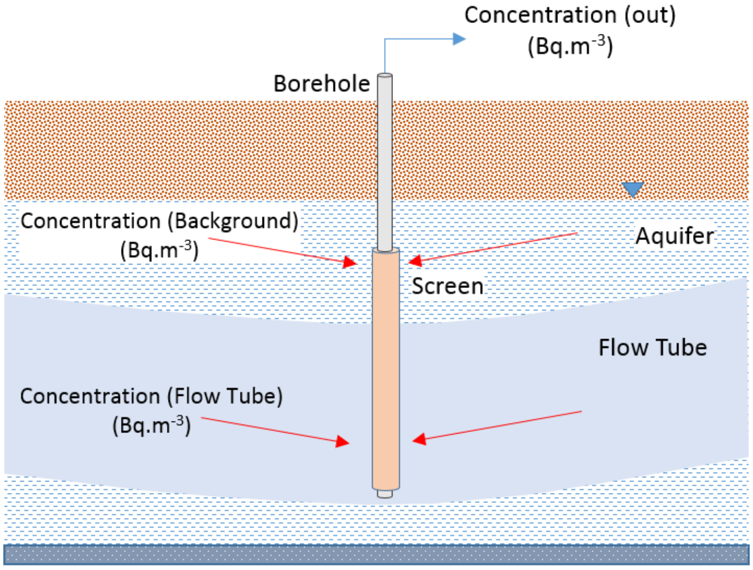

Figure D 8 Conceptual representation and associated parameter values for the borehole abstraction model.