Radiological Impact Assessment to Recommence Depositioning at the Lower Mponeng Tailings Storage Facilities

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Prepared by AquiSim Consulting (Pty) Ltd on Behalf of:

Environmental Impact Management Services (Pty) Ltd (EIMS)

8 Dalmeny Road, Pine Park
Randburg, JHB
South Africa

For Attention:

Vukosi Mabunda

Tel: + (011) 789 7170
Email: vukosi@eims.co.za

Compiled by:

JJ van Blerk
PhD. Geohydrology UFS
Pr.Sci.Nat (RPS)

AquiSim Consulting (Pty) Ltd Offices	
109 Bosduif Crescent	5 Binga Place
Wierda park x1	Faerie Glen, Pretoria
P.O. Box 51777	P.O. Box 1490
Wierda park	Faerie Glen
CENTURION 0149, South Africa	PRETORIA 0043, South Africa
Tel. No.:+27 (12) 654 0212	Tel. No.:+27 82 784-2023
Fax. No.:+27 866896006	Fax. No.:+27 866843449
e-mail:aquisim@netactive.co.za	e-mail: aquisim-hvr@mweb.co.za

Authorisation

	Name	Signature	Date
COMPILED	JJ van Blerk		23.01.2025
Radiation Protection Specialist			
COMPILED			
CHECKED			
CHECKED			
CHECKED			
APPROVED			

Distribution

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List of Acronyms

AADQ	Annual authorised discharge 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 polyethene
IAEA	International Atomic Energy Agency
ICR	International 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

Executive Summary

Harmony Gold Mining Company Limited (Harmony) owns and operates several Gold Mines and Plants in the West Wits region in the Gauteng Province. The Savuka Plant currently deposits tailings onto the Savuka 7a & 7b Tailings Storage Facilities (TSFs). However, these facilities are approaching their final and approved height, and the current planned Life of Mine (LoM) for the West Wits region exceeds the available deposition capacity of these TSFs. Accordingly, the applicant is undertaking a feasibility assessment to recommence deposition on the Mponeng TSF Lower Compartment (hereafter referred to as the Project).

The purpose of this report is to present the radiological safety and impact of the Project. The assessment serves as input to the ESHIA/EIA process prepared by EIMS, in accordance with NEMA, the National Nuclear Regulator Act (NNRA) (Act 47 of 1999), as amended in the National Nuclear Regulator Amendment Act (NNRAA) (Act 26 of 2024), and the Nuclear Energy Act (NEA) (Act No. 46 of 1999), and the relevant requirements, guidance, and regulations set forth by the National Nuclear Regulator (NNR).

A systematic approach is followed that includes 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.

Evaluating the potential radiological impact on members of the public requires consideration of relevant environmental pathways of concern, notably atmospheric, groundwater, and surface water. Although not a contaminant in the usual sense, the inherent radiological properties of some primary radiation sources may result in continuous gamma radiation, potentially exposing members of the public to *external gamma radiation*.

Following a systematic Source-Pathway-Receptor analysis, two public exposure conditions were derived to represent the area, namely a Resident Area Exposure Condition and a Commercial Agricultural Area Exposure Condition. The atmospheric pathway contributes to both exposure conditions, whereas the groundwater pathway was included as a contributing pathway for the Commercial Agricultural Area Exposure Condition. It was argued that these public exposure conditions are broadly representative of the human behavioural conditions near the Project. In addition, other potential exposure conditions will result in lower levels of radiation exposure.

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

- The contribution from the groundwater pathway was evaluated, with the Project TSFs being the primary contributing source. It was shown that the potential radiological impact is only visible over thousands of years, with a maximum total effective dose of less than 100 μSv.year^{-1}, indicating that it cannot be considered a contributing pathway for the Commercial Agricultural Exposure Condition during the operational phase of the Project.
- The most significant contribution from the atmospheric pathway is inhalation of airborne radon. This is due to the presence of Ra-226 in the source material.
- 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, despite the proximity of the receptor locations to surface infrastructure, the doses remain below the dose constraint for all age groups, with a maximum contribution from the atmospheric pathway of less than 250 μSv.year^{-1}.

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 µSv.year^{-1}.

These total effective dose assessment results were used to determine the radiological impact rating during the different phases of the Project. The table below summarises the radiological impact and a significance rating of the redeposition of tailings at the lower Mponeng TSF during the operational and post-closure phases of the Project, respectively.

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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a 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 redepositioning of tailings at the lower Mponeng 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, but at a 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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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.	-5		-2.5
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}			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Reversibility	2	The impact is reversible, but at a significant time and cost to reduce 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			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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}	-2.5		
Reversibility	2	The impact is reversible, but at a significant time and cost to reduce 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			
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.			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan for the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	1	Likely to result in a positive impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The practical implementation of the decommissioning plan will have irreversible impacts that will persist after closure.			
Magnitude	4	The impact on members of the public will be high and widespread	16		
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					16
Nature	1	Likely to result in a positive impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The practical implementation of the decommissioning plan will have irreversible impacts that persist after closure.			
Magnitude	4	The impact on members of the public will be high and widespread	-2.5		
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			
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	Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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 $\mu Sv.year^{-1}$	-5		
Reversibility	2	The impact is reversible, but at a significant time and cost to reduce 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			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			-2.5
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 $\mu Sv.year^{-1}$	-2.5		
Reversibility	2	The impact is reversible without incurring significant time or cost to mitigate 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			
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	Leaching and migration of radionuclides from the TSF during the post-closure phase of the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
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			-6
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 $\mu Sv.year^{-1}$	-6		
Reversibility	3	The impact is reversible only by incurring significant time and cost to reduce radionuclide migration 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			
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}	-6		
Reversibility	2	The impact is reversible only by incurring significant time and cost to reduce radionuclide migration 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			
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.			

The proposed radiological monitoring programme for the Project includes recommendations for monitoring surface water, groundwater, sediment, environmental radon, and dust fallout, including the frequency and type of analyses. Most proposed monitoring points coincide with the environmental pathways monitoring programme (e.g., soil, surface water, and groundwater), which is consistent with the current Public Radiation Protection Programme (PRPP). Considering the surface infrastructure that will be developed for the Project, the following was noted:

- The surface water monitoring locations should align with the existing surface water monitoring points 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 align with the existing ones. 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 (2026).
- The environmental radon monitoring locations need not coincide with specific locations. The principle is to apply it across the mining rights area, in the dominant wind direction where receptors are located, and to complement it with monitoring locations in the background. The exact location is often determined by the availability of a secure location, which can improve the recovery rate of RGMs.

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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, during which he was responsible for the post-closure safety assessment of the Vaalputs National Radioactive Waste Disposal Facility. 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 fields of Radiation Science and Earth Science (Reg. no. 400239/05) with the South African Council for Natural Scientific Professions (SACNASP).

Through his role in the post-closure safety assessment of Vaalputs, he gained in-depth knowledge of the performance of near-surface radioactive waste disposal systems, particularly under arid conditions. After joining AquiSim in 2000, he continued to provide consultancy services to Necsa in radioactive waste management and post-closure safety assessment. He prepared the current Vaalputs post-closure safety assessment 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 gained through a project conducted in collaboration with Facilia AB (Sweden) to evaluate the post-closure safety of a borehole-type DSRS facility at Sandy Ridge in Western Australia, with Tellus Holding Ltd as the primary 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 applying the *IAEA safety standards for radioactive waste disposal and general radioactive waste management*. These include all stages of 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 decision-making at these stages.

He has extensive experience 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), 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 strong working knowledge of a range of environmental processes and disciplines, including 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 to reviewing waste disposal programmes and assessing their impacts on human health and the environment 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-reclamation 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 Harmony's South African interests are divided into four discrete operations: the Free State Operations, the West Rand Operations, the Klerksdorp goldfields, and the Kraaipan Greenstone Belt (Kalgold Operations). Through these operations, Harmony has made significant economic contributions to the provinces of South Africa where it is located, through job creation and the 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 approximately 4,176 hectares of mine lease area. The assets acquired from AGA comprise two distinct but integrated mining entities, namely 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), marginal ore dumps (MOD), return water dams (RWD), transfer pipelines for water and tailings material, offices and living quarters.

The applicant owns and operates several Gold Mines and Plants in the West Wits region in the Gauteng Province. The Savuka Plant currently deposits tailings onto the Savuka 7a & 7b TSFs. However, these facilities are approaching their final and approved height, and the current planned Life of Mine (LOM) for the West Wits region exceeds the available deposition capacity of these TSFs. Accordingly, the applicant is undertaking a feasibility assessment to recommence deposition on the Mponeng TSF Lower Compartment (hereafter referred to as the Project).

The Mponeng TSF is an existing TSF located at 26°27'11.18"S; 27°24'43.88"E. However, the Mponeng Lower Compartment TSF (hereafter referred to as the Mponeng TSF) is no longer in operation and is currently utilised as a Holding Dam, with a portion used as an authorised Landfill Facility.

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).

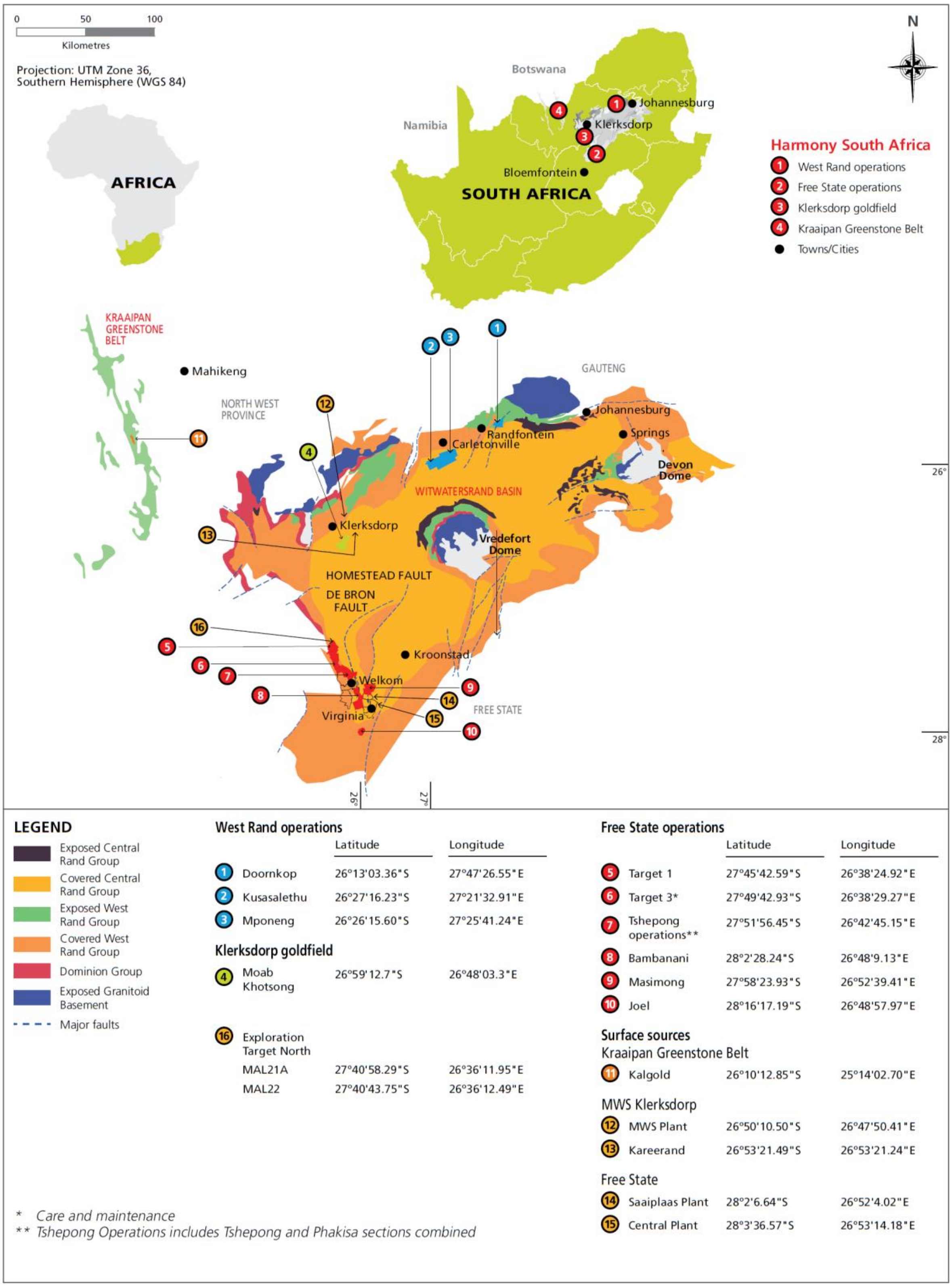

Figure 1.1 Locality map showing the distribution of the four discrete Harmony operations in South Africa.

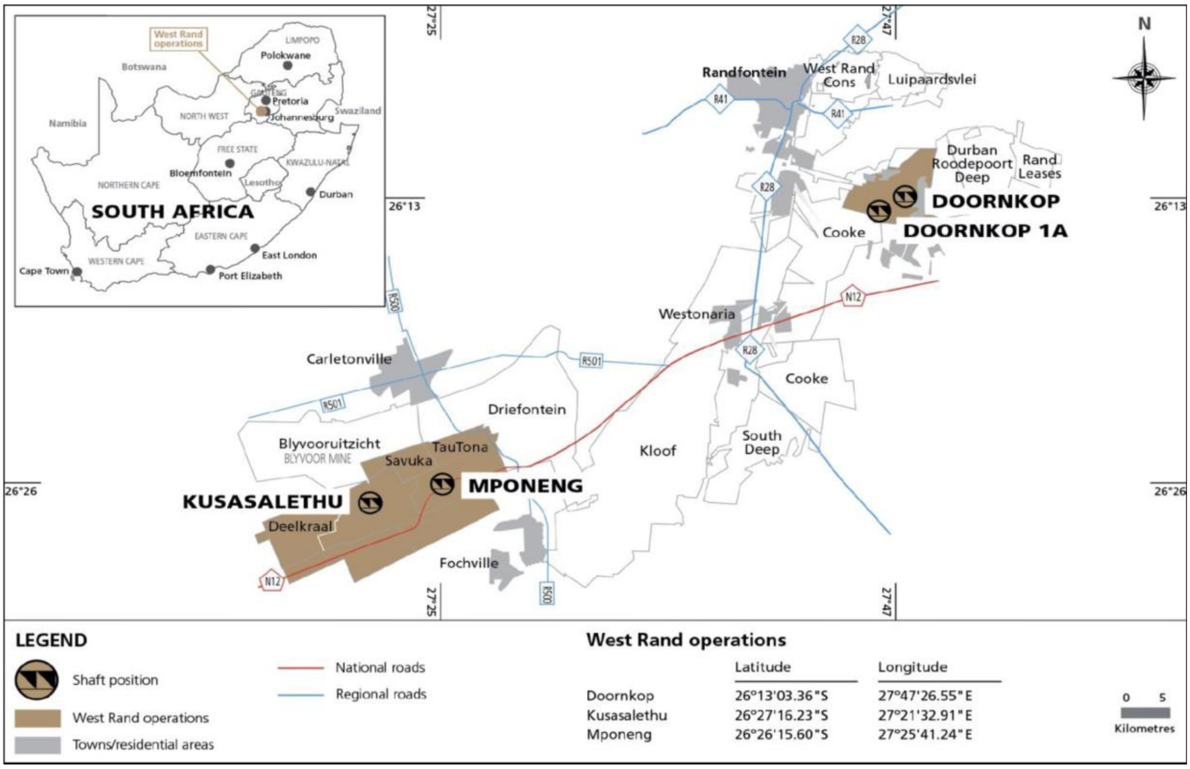

Figure 1.2 **Locality map showing the Harmony West Rand Operation relative to other mining operations and towns.**

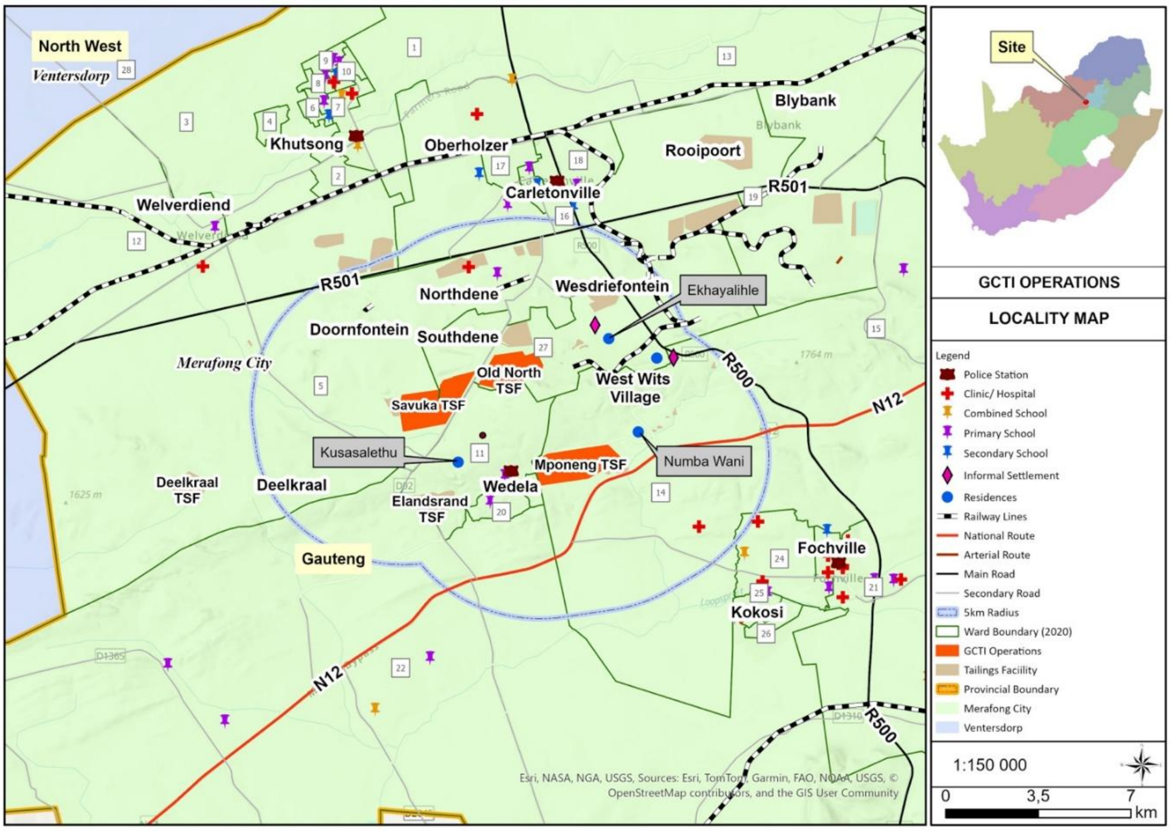

Figure 1.3 **Map showing the Mponeng Operations are located within the Merafong City Local Municipality of the West Rand District Municipality of the Gauteng Province of South Africa (Equispectives, 2025).**

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) series, named after the radionuclides that serve as progenitors (or parents) of 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, 2006a).

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, and the food they eat (Kathren, 1998).

The annual dose averaged across the global population is about 2.8 mSv. As indicated in Figure 1.4, over 85% of this total comes from natural sources (~2.4 mSv), with about half originating from radon decay products in the home. Medical exposure to 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%. Other natural background radiation sources include cosmic radiation, gamma radiation, and internal radiation in our bodies (IAEA, 2004a).

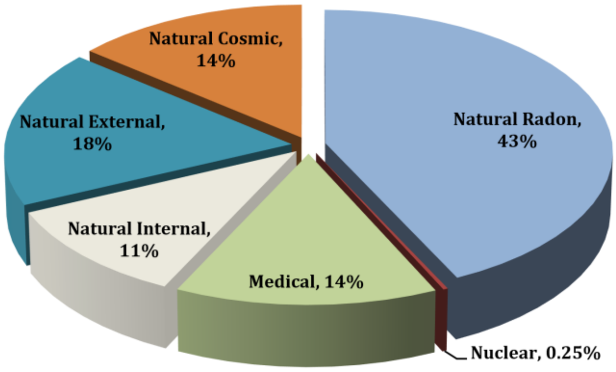

Figure 1.4 Distribution of the natural background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

In addition to natural background radiation, anthropogenic activities that exploit Earth's resources may increase 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.
- 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).

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 ionising 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, are carried into mining and mineral-processing residues, such as waste rock or tailings. Materials and residues that contain naturally occurring radionuclides are generally referred to as Naturally Occurring Radioactive Materials (NORM) (IAEA, 2007). Due to naturally occurring radionuclides, NORM can negatively affect human health (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) as amended in the National Nuclear Regulator Amendment Act (NNRAA) (Act 26 of 2024), 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 and NORM associated with mining and mineral processing. 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 activity, not contemplated in Section 21(1), (2), (3) or (4), must apply in the prescribed form and manner to the chief executive officer for a certificate of registration, certificate of exemption, authorisation to design or authorisation to manufacture and must furnish such information as the board requires*".

Harmony holds a Certificate of Registration (CoR-03) issued by the NNR for its Mponeng Operations. Any changes to the scope of the CoR-03, such as recommencing deposition on the Mponeng TSF Lower Compartment (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, among other things, a quantification of the potential radiological impact of these changes or listed activities on members of the public.

The Project involves the upgrade of existing infrastructure, with several National Environmental Management Act (NEMA) (Act 107 of 1998), as amended, listed activities to be considered. 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 to the NNR as part of an ACR is the Radiological Public Safety Assessment (RPSA), which evaluates the potential radiological impacts and public safety associated with the proposed changes or listed activities. 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) or Environmental Impact Assessment (EIA) process in terms of NEMA.

1.4 Purpose of the Report

The Project represents a scope change to CoR-03 and, therefore, requires the preparation and submission of an ACR to the NNR in accordance with 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 to the ESHIA process prepared by EIMS, in accordance with 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 for inclusion in the ESHIA/EIA process prepared by EIMS, in accordance with NEMA.

The report assumes a basic understanding of ionising radiation and its effects 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, allowing the continual improvement of the assessment or its components through successive iterations. The assessment framework comprises several interrelated elements, which will be presented in a separate section of this report. The report has been structured as follows:

- Section 2 presents an overview of the assessment context, defining 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, including 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 public exposure conditions considered in 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 discusses the calculation approach used to estimate total effective doses, to calculate doses for public exposure conditions, and to evaluate results against 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, including the monitoring programme and the proposed monitoring locations.
- Section 9 presents overall conclusions and recommendations for improving public radiation safety, with the safety and impact assessment of the Project serving as a basis for the conclusions and recommendations.

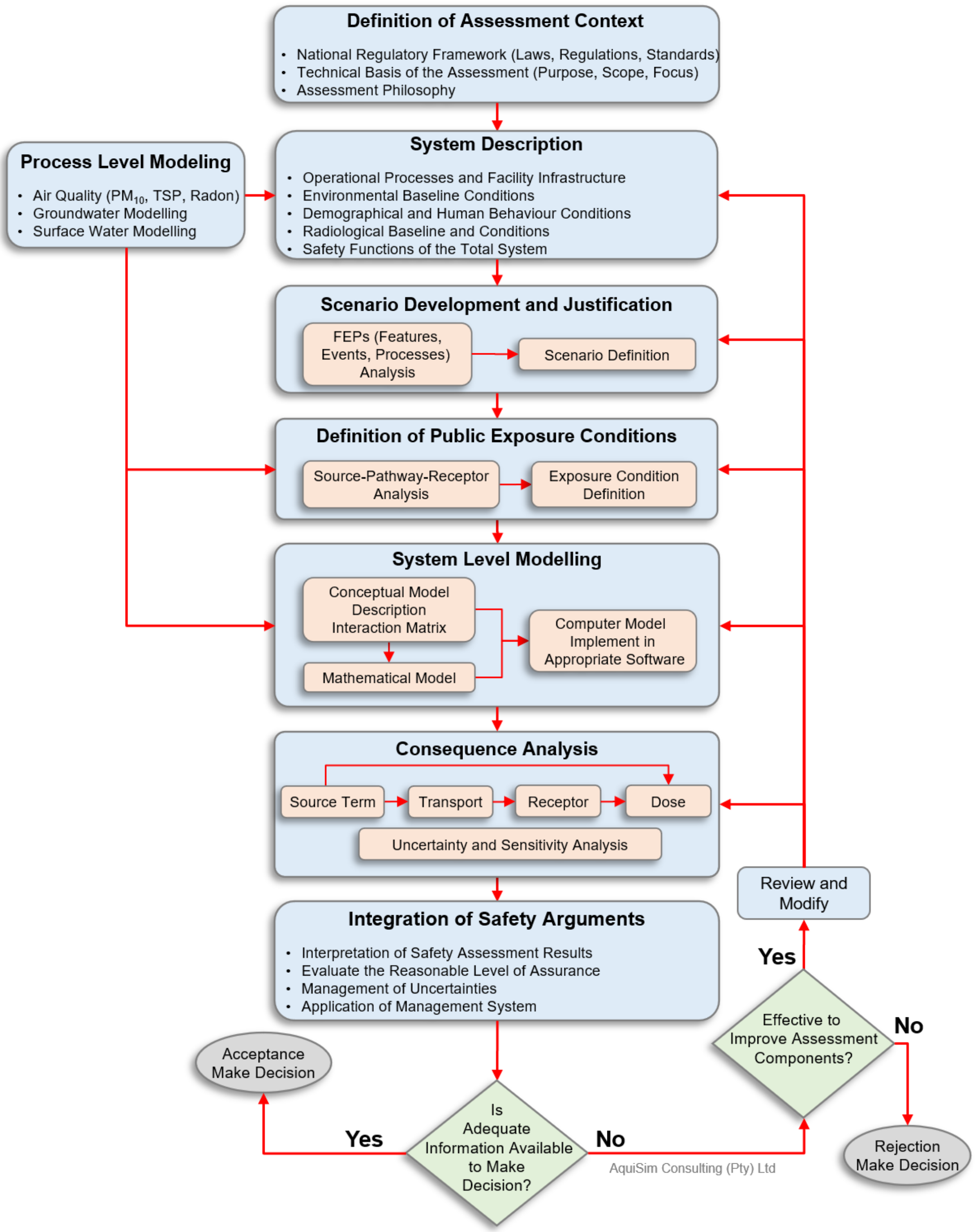

Figure 1.5 **Schematic illustration of the conceptual safety assessment framework used to perform the RPSA of the Project.**

2 Assessment Context

2.1 General

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

From this perspective, the assessment context defines the boundary conditions for the assessment. This includes the regulatory framework that applies to the assessment (see Section 2.2) and the technical basis of the assessment (e.g., its purpose, scope, and focus) (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 issued under 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 addresses Safety Standards and Regulatory Practices. It 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 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 provides guidelines for holders and prospective holders of NNR authorisations on conducting 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 widely 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 United Nations General Assembly, is to assess and report on the levels and effects of ionising radiation exposure. Governments and organisations worldwide rely on the Committee's estimates as the scientific basis for evaluating radiation risk and 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. Still, they contribute to the overall framework for protecting human health and the environment from exposure to ionising radiation.

2.2.2 The ICRP System of Radiological Protection

The ICRP is a non-governmental, independent, scientific organisation 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 200 volunteer members from approximately 30 countries across six continents, who represent the world's leading scientists and policymakers in 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 regularly publish recommendations on protection against ionising radiation (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 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 while reducing existing exposure and 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), taking into account economic and societal factors.
- *The Principle of Application of Dose Limits*: The total dose to any individual from regulated sources during planned exposure situations (excluding medical exposure of patients) should not exceed appropriate limits.

In its revised System of Protection, the ICRP recognises three types of exposure situations 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 are unexpected events that may occur during the execution of a planned operation, as a result of a malicious act, or in other unforeseen circumstances that require urgent action to prevent or mitigate adverse consequences.
- *Existing Exposure Situations*: Existing exposure situations are those that already exist when a control decision must be made, including prolonged exposure following emergencies or exposure from natural background radiation.

The principles of *justification* and *optimisation* apply to all three exposure situations. In contrast, the principle of *applying dose limits applies only to doses expected to be incurred with certainty in* planned exposure situations. The principle of *justification* requires that the net benefit of any radiation-related action be positive. The Harmony Operation is an existing operation, while the Project falls under the Planned Exposure Situation category.

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 ionising radiation and the safety of radiation sources. Section 1 does not constitute requirements; instead, it 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,* which 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 to optimise protection and safety, with the intended outcome that all exposures are controlled to levels as low as reasonably achievable (ALARA), while economic, societal, and environmental factors are considered.
- *Protection of the Environment,* which recognised the need to assess environmental protection while allowing flexibility in incorporating the results of environmental assessments into decision-making processes, in a manner commensurate with radiation risks.
- *The Interface between Safety and Security*, both of which aim to protect human life, health, and the environment. Additionally, safety and security measures must be designed and implemented in an integrated manner so that neither compromises the other.

Requirements specified in Sections 2 to Section 5 distinguish among the three types of exposure situations: occupational, public, and medical.

2.2.4 Safety Standards for the Protection of the Public

To avoid severely inequitable outcomes in the optimisation procedure, restrictions should be imposed on the doses or risks imposed on individuals from a source. Regulatory tools used to reduce risk include *dose or risk constraints* and *reference levels*. In planned exposure situations, the ICRP recommends that public exposure be controlled by optimisation procedures that keep it below the source-related constraint, as well as by 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 exceptional 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 per year to the lens of the eye and 50 mSv per 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., authorised, justified, and planned operational activities that result in transitory increases in exposure), a higher effective dose in a single year may 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.
- 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 accounted for to ensure that the total dose received by an individual member of the public does not exceed the dose limit. For this reason, *dose constraints* below the dose limit, typically 0.1 to 0.3 mSv per year, are proposed to ensure that the annual dose does not exceed 1 mSv. Dose constraints are set separately for each source under control and serve as boundary conditions for defining the range of optimisation options.

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 1 mSv per year criterion adopted in South Africa for public protection under Regulation No. 388 is consistent with ICRP and IAEA recommendations on public exposure. The Regulation No. 388 dose constraint of 0.25 mSv per 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 the 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 serves as the starting point for defining and selecting an appropriate radioactive waste management solution.

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 considering options for radioactive waste management, the document takes cognisance of the IAEA's radioactive waste management principles (IAEA, 1995). To guide the national strategy for radioactive waste management, several key reference points 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/m³. **OR** 2 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels > levels specified for LILW-LL **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) 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/m³) **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/m³. **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 NORM classification: 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 NORM waste class.

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 an 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 has occurred) and *process waste*. For *process waste*, there is a potential risk that it may have become radioactively contaminated, either directly through involvement in a process known to be radioactively contaminated, or indirectly by being near known or potentially radioactively contaminated waste. *Homogeneous Process Waste* refers to *process waste* in bulk or homogeneous form, including materials such as tailings, pyrite, baddeleyite, and calcine. Table 2.3 summarises the categorisation of homogeneous 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 for Category III waste (more than 1,000 $Bq.g^{-1}$) is to store it at a licensed site in an approved storage facility. This is because a long-term (permanent) solution for managing this waste (i.e., high-level waste) is not currently available in South Africa.

Table 2.3 The categorisation of homogeneous 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 WRD
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 TSF 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 serve multiple purposes within 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 prospective pre-operational safety assessment is conducted to determine whether the proposed operations do not pose a radiological risk to workers and the public that exceeds the applicable regulatory compliance criteria. Once operational, the prospective assessment is updated to include 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 primarily determined 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 in consideration of how the assessment results are presented. For this reason, the list of interested parties must be included in the technical basis of the assessment context report.

Generally, the interested parties include management and technical staff responsible for the design, implementation, and operation of facilities or activities; regulatory authorities; workers; members of the public; and 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 for monitoring the process to ensure that operational activities comply with 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, who are responsible and involved in the implementation of the Project.
- Members of the public living near the Mponeng Operations and, more specifically, near the Mponeng TSF 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.
- Officials from the Local, Provincial, and National Government Departments responsible for evaluating applications for environmental authorisation must ensure that environmental investigations are conducted in accordance with relevant regulatory guidance and requirements.
- Technical, scientific, and environmental groups, who may be interested in the assessment approach and the resulting findings.

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 Project area will not be exposed to levels of ionising radiation released to the environment above the regulatory compliance criteria set for public exposure as defined in Section 2.2.3.
- To assess the radiological impact on members of the public living near 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 from the Project *above the natural background radiation*. This means that background radiation is excluded from comparisons of the total effective dose with 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 environmental media measurements (e.g., soil, water, sediment, crops) and observations to quantify the actual dose contribution to the public.

2.3.4.2 Site-Specific Assessment

The radiological public safety assessment is based on site-specific data, where practicable and justified. Where appropriate and justified, the site-specific data and information are supplemented with values from the literature or analogous 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, mineral handling, and processing activities may pose hazards to humans and the environment, not only from naturally occurring radioactivity but also from toxic elements and compounds present in the products, by-products, residues, and wastes generated by these activities. The radiological public safety assessment focuses on radiation exposure from ionising radiation and excludes health risks arising from non-radioactive substances or other health and safety considerations.

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 is a 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: 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, usually included in assessments of 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 occurs naturally as black Thorium oxide and is approximately three times as abundant as uranium.

Exposure to the isotopes of uranium and thorium, and their progeny (i.e., daughter products), has been linked to detrimental health impacts in humans due to their ability to emit ionising radiation and the extensive weight of evidence from epidemiological studies of radiogenic health effects in humans (Klaassen, 2001). However, not all the radionuclides in these decay series contribute equally to the 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 the total effective dose are considered. Table 2.4 lists the radionuclides explicitly considered in the RPSA of the Project.

Where applicable, radioactive decay and ingrowth of daughter products are taken into consideration in the assessment. This serves the dual purpose of avoiding overly conservative results for slower transport processes and of accounting for the effects of 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 to protect human health and the environment from all radiation exposure situations and 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 the 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. Harmony owns other mining operations in the area, but they have different CoRs. The scope of the assessment does not encompass a regional radiological safety assessment that includes *all* potential operational activities and sources in the area. However, recognition is given to the potential contributions of these and other operations to the total effective dose, subject to the regulatory dose constraint.

2.3.4.6 Worker Safety Assessment

The NNRA and associated national safety standards provide for the protection of both workers (occupational exposure) and members of the public from ionising radiation. For this purpose, both worker and public safety assessments must be submitted to the NNR. The scope of the assessment is limited to radiological safety and its 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 ICRP has introduced the concept of establishing dose limits for non-human biota in Publication 103 (ICRP, 2008) and Publication 108 (ICRP, 2009a). A radiation assessment of non-human biota focuses on evaluating radiation effects on ecosystems, including animals, plants, and microorganisms, rather than on human populations. This assessment aims to understand how ionising 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 recognised method for assessing impacts on non-human biota is the Environmental Risk from Ionising Contaminants: Assessment and Management (ERICA) approach, which uses the ERICA software tool. This tool accounts for radionuclide concentrations across media and species-specific concentration ratios to standardise the measurement of radiological impact on reference species.

While environmental protection is a key principle in IAEA safety standards, the current assessment does not consider non-human biota. Furthermore, the NNR regulatory framework does not currently require the assessment of non-human biota.

2.3.4.8 Human Behavioural Conditions and Age Groups

The assessment considers, to the extent possible, site-specific human behavioural conditions observed in the vicinity of the Project area. It justifies this by defining a discrete set of public exposure conditions for all relevant age groups (see Section 4.7). Consistent with the guidance provided in RG-002 (NNR, 2013), the assessment considers the age groups and age ranges 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 for the radiological public safety assessment is primarily determined by understanding the processes governing radionuclide movement and the potential environmental exposure pathways for the groups at risk. While physical boundaries cannot be rigorously applied to some of these processes, a 3 to 5 km radius around the environmental release points defines the area in which environmental pathways must be considered. If justified, a larger study area may be defined to account for processes governing radionuclide movement beyond these boundaries. Since the analysis aims to evaluate critical groups, the exposure locations are likely near the sources, which constrains the spatial scale to the selected public exposure conditions.

2.3.6 Assessment Timescales

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

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

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 and the assessment's purpose, scope, and focus. In some cases, the target audience or stakeholders may determine additional assessment endpoints to consider. While quantitative endpoints are most used in safety assessments, 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 in the vicinity of the Project area (see Section 2.3.4). More specifically, the objective is to quantify the release and distribution of radioactivity into and through the environment, and the subsequent interactions of the public with 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 the public, as set out in the Safety Standards and Regulatory Practices 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 requirements of the NEMA ESHIA Regulations guide the impact assessment methodology. The broad approach to the significance rating methodology is to determine environmental risk (ER) by assessing the consequence (C) of each impact (Nature, Extent, Duration, Magnitude, and Reversibility) and relating 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 depends on the impact's consequence (C) and its probability of occurrence (P). 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:

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

Each 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):

$$\boldsymbol{ER = C \cdot P}$$

The environmental risk assessment will yield a score 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, both pre-mitigation (in the absence of relevant management and mitigation measures) and post-mitigation (with their implementation). This enables predicting the extent 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 they will permanently cease).
Reversibility	1	The impact is reversible at no cost or time.
	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 materialising 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 impact
- The degree to which the effect 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 decision-making authority's attention on the higher-priority/significant issues and impacts. The PF will be applied to the ER score, assuming that the relevant suggested management/mitigation measures are implemented.

Table 2.10 The criteria used to determine the prioritisation.

Public response (PR)	Low (1)	The issue was 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)	Given the potential incremental, interactive, sequential, and synergistic cumulative impacts, the outcome is likely to 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).

The final impact priority is represented as a single consolidated priority, determined by summing the criteria in Table 2.11. The impact priority is therefore determined as follows:

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

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

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**

To determine the final impact significance, the PF is multiplied by the post-mitigation scoring ER (see Table 2.12). The ultimate aim of the PF is to be able to increase the post-mitigation environmental risk rating by a whole 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 2.12 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 usually complemented by a description of the prevailing site characteristics and potentially affected human populations in the Project area, as well as the associated radiological conditions.

The level of detail in the system description is commensurate with the information required for a radiological public safety assessment. This means the system description is intended to provide a clear representation of the features relevant to the potential impacts under evaluation and, therefore, does not necessarily require a comprehensive, 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 by 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 map showing the location of the Mponeng TSF within the Mponeng Operations Mining Right. The Mponeng TSF is located at 26°27'11.18"S; 27°24'43.88"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 Mponeng TSF is located in the southern corner of the surface operations area (see Figure 3.1). Figure 3.2 shows the layout of the Mponeng TSF divided into two compartments. The Mponeng Lower Compartment TSF, which is an existing TSF, is no longer operational and is currently utilised as a Holding Dam. A portion of it is also utilised as an authorised landfill facility. To redeposit slurry from the Savuka Plant to the Mponeng TSF, slurry pipelines will need to be constructed from the Savuka Plant to the TSF. The proposed slurry and return water pipes extend from the south of the Savuka Plant, starting at 26°25'24.95"S; 27°23'58.94"E, and run southward, parallel to each other, until they reach the northern extent of the Mponeng TSF, where they split. Thereafter, the slurry pipeline extends west before connecting to the Mponeng TSF. The return water pipeline extends east, then south around the TSF to the return water dam. There is an alternative slurry and return water pipeline route that extends east through Western Deep Levels, then south along the Mponeng Gold Mine before heading west, where it connects to the Mponeng TSF.

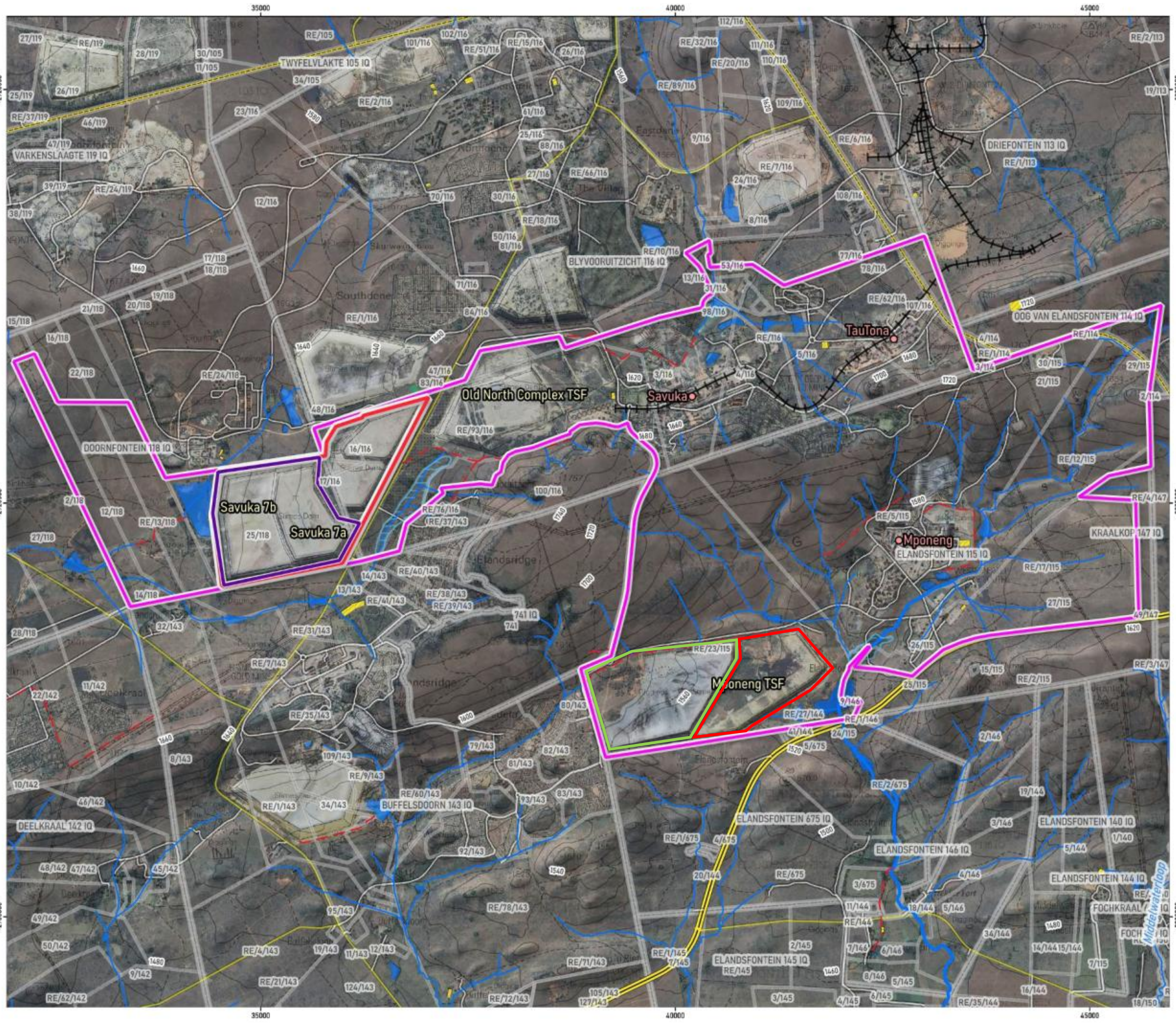

Figure 3.1 **The location of the Mponeng TSF relative to the Mining Right of the Mponeng Operations, with the lower compartment indicated in red (HydroLogic, 2025).**

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 public interaction 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, 2026; Equispectives, 2025; GCS, 2024; HydroLogic, 2025; MvB Consulting, 2025). These reports were used and referenced for information on topography and drainage, geology and hydrogeology, soils, meteorological conditions, and human behavioural and social conditions, as appropriate and justified.

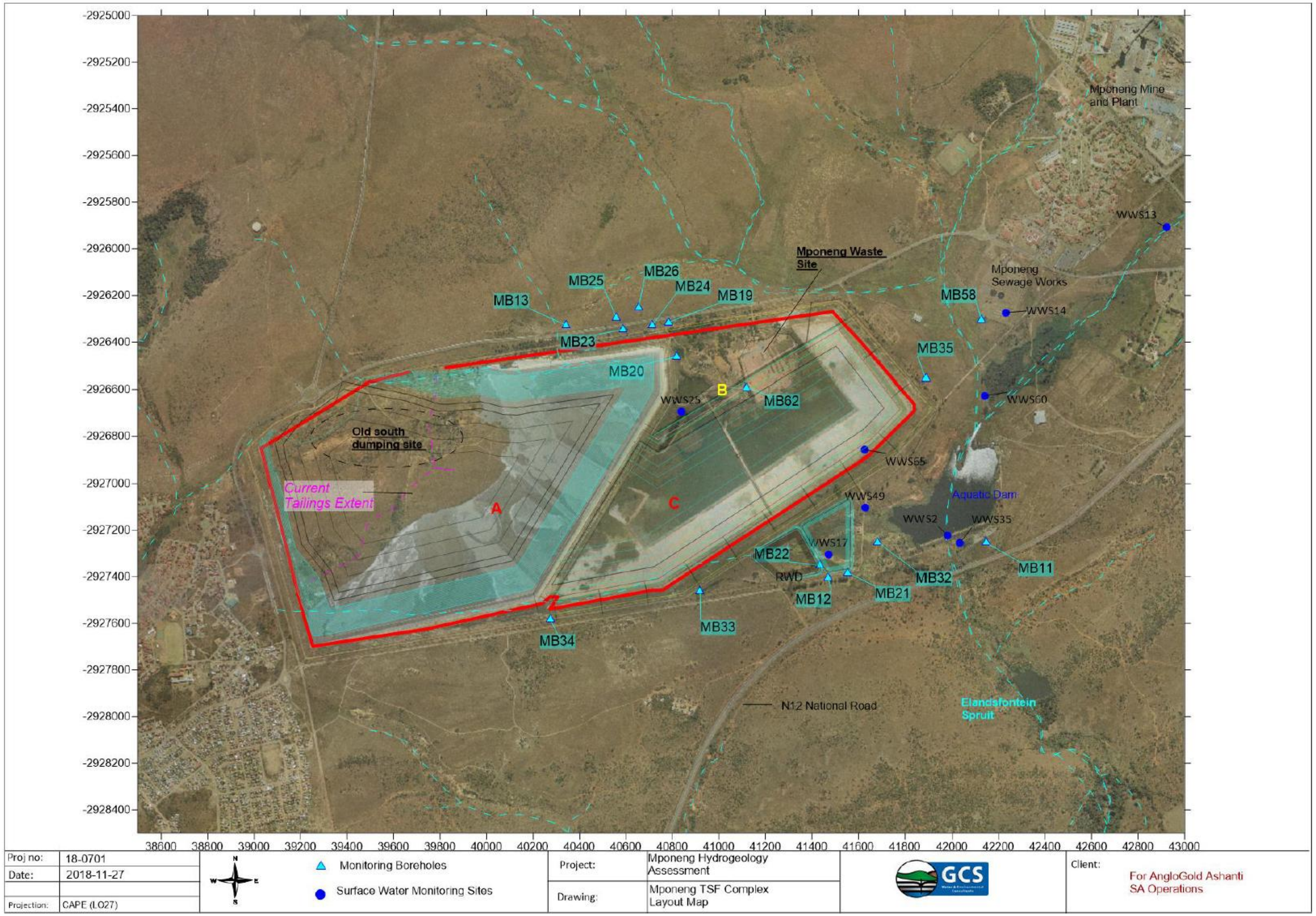

Figure 3.2 Layout of the Mponeng TSF, showing the two compartments of the existing TSF.

Note that, unlike for the Savuka TSF height extension Project (Aquisim, 2025a), specific reports that address the hydrogeological conditions for the recommencement of deposition at the lower Mponeng TSF are not available. Where necessary, reports examining broader regional conditions were sourced, such as GCS (2024).

3.4.2 Topography and Drainage

The South African landscape is dominated by a high, interior plateau, bordered by a narrow strip of coastal lowlands. South Africa has an average elevation of approximately 1,200 m above mean sea level (mamsl), with at least 40% of the surface above this elevation. The West Rand region is approximately 1,700 mamsl, well above the average, and is characterised by a relatively flat to rolling topography.

The Project is situated in the West Rand Region, on the boundary between quaternary catchments C23E and C23J of the Upper Vaal Water Management Area, as indicated in Figure 3.3 and Figure 3.4. The elevation across the Project ranges from 1,452 mamsl in the south to 1,750 mamsl, which is associated with a prominent rocky ridge locally known as the Gatsrand. The Gatsrand extends from east to west and forms the topographical high between the two quaternary catchments. The hydrological parameters associated with the two quaternary catchments are summarised in Table 3.1.

Figure 3.4 shows that the quaternary catchment C23E to the north of the Gatsrand is drained by an unnamed tributary of the Wonderfontein Spruit (also referred to as the Mooirivierloop). The Mooirivierloop flows to the Boschkop Dam and onto the Vaal River. The Elandsfonteinspruit and Kaalkopspruit drain the quaternary catchment C23J into the Loopspruit. The Loopspruit flows to the Klipdrif Dam and also onto the Vaal River.

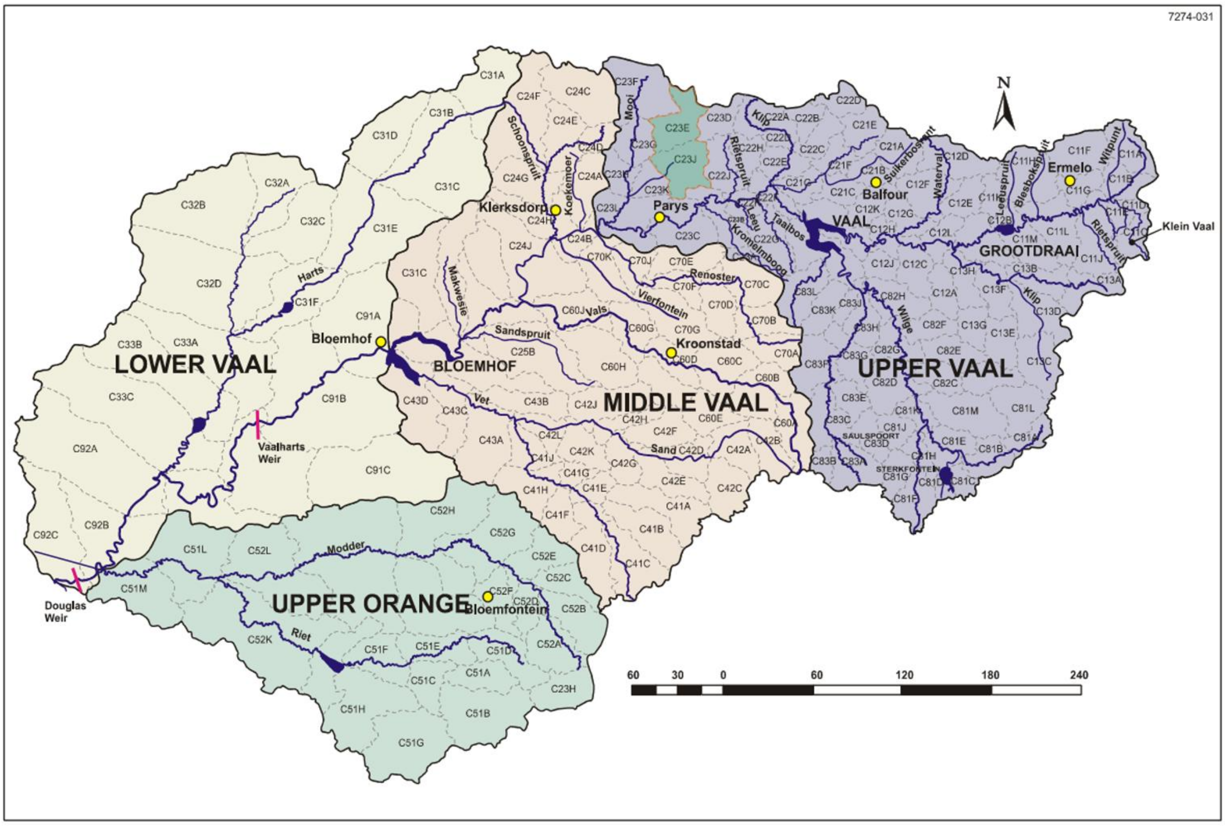

Figure 3.3 **Map showing the Project is located in the upper catchments of the Vaal Water Management Area (WMA) and more specifically on the border between Quaternary Catchment C23E and Quaternary Catchment C23J.**

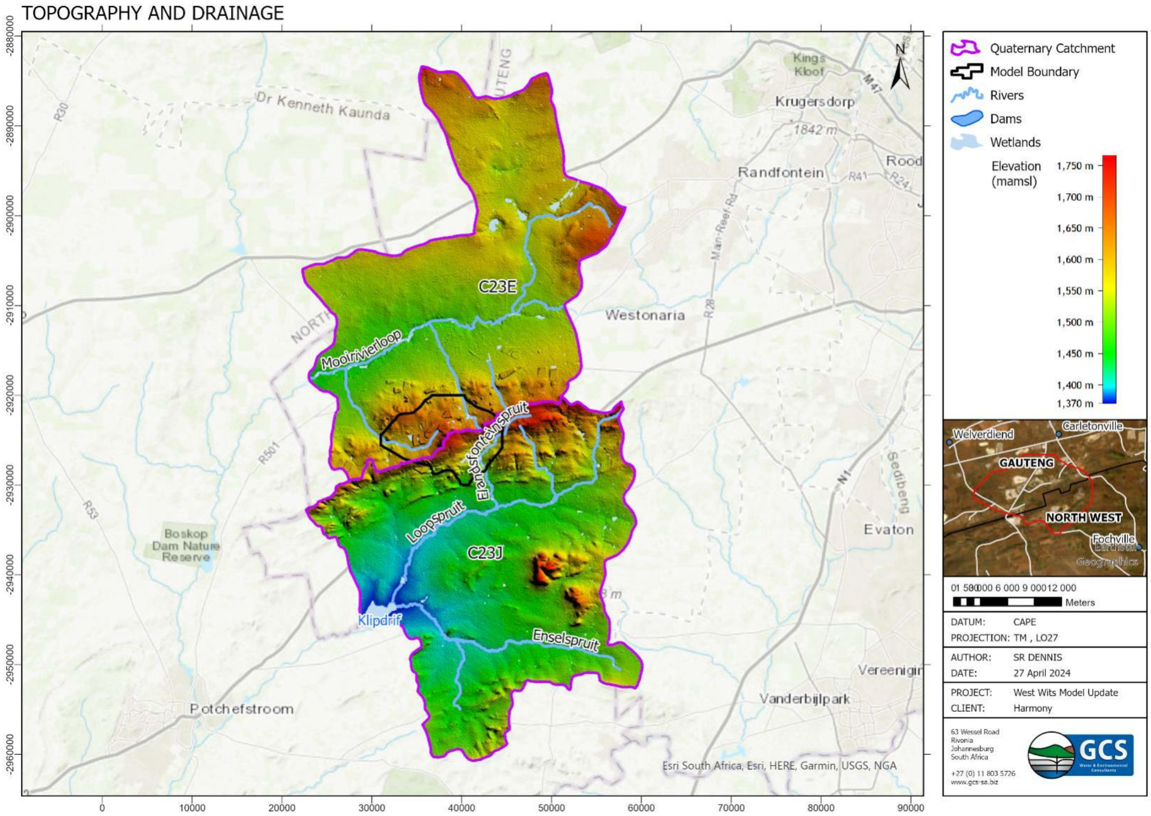

Figure 3.4 Topography and drainage features associated with the Quaternary catchments C23E and C23J (GCS, 2024).

Table 3.1 Summary of the hydrological parameters associated with the area (WR2012) (GCS, 2024).

Quaternary	MAP (mm.year^{-1})	MAR (Mm^3.year^{-1})	MAE (mm.year^{-1})
C23E	631	6.05	1,675
C23J	620	29.2	1,670

3.4.3 Geological Setting

3.4.3.1 General

The Project are located in the Far West Rand Goldfield (West Wits Line), on the northwestern rim of the geologically unique Witwatersrand Basin (see Figure 3.5). The Witwatersrand Basin remains the world's largest unmined gold source, and the deposits have been worked for well over 100 years. Gold is produced from seven goldfields within the basin, mainly from conglomerate horizons of the Witwatersrand, Ventersdorp and Transvaal Supergroups. The gold mineralisation occurs within quartz pebble conglomerates, termed reefs, distributed across nine separate goldfields along the eastern, northern and western margins of the basin.

The Witwatersrand Supergroup is underlain by an Archaean (>3.1 Ga) granite-greenstone basement and the 3.086 to 3.074 Ma Dominion Group. It is unconformably overlain by rocks of the Ventersdorp (2.7 Ga), Transvaal (2.6 Ga) and Karoo (302-180 Ma) Supergroups. The Witwatersrand Supergroup can be further divided into two groups, the West Rand Group and the Central Rand Group.

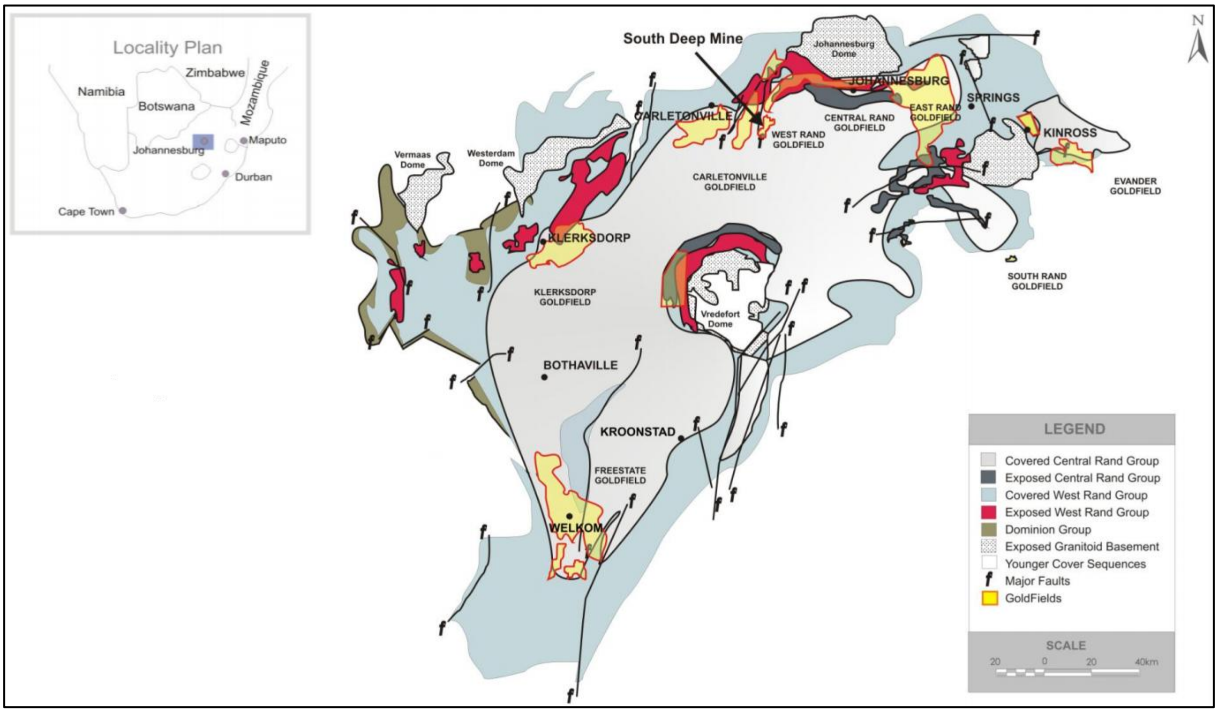

Figure 3.5 **Map of the regional geology, showing that the Project falls in the Far West Rand Goldfield (West Wits Line), on the northwestern rim of the geologically unique Witwatersrand Basin (Minxcon, 2010).**

The Witwatersrand Basin comprises a 6 km vertical thickness of argillaceous and arenaceous sedimentary rocks situated within the Kaapvaal Craton, extending laterally for some 350 km east-northeast and 150 km south-southeast. Sedimentary rocks generally dip at shallow angles towards the basin centre, though locally this may vary. The basin sediments outcrop to the south of Johannesburg, but further west, these are overlain by up to 4 km of Archaean, Proterozoic and Mesozoic volcanic and sedimentary rocks.

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

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

Figure 3.6 presents the stratigraphy, and Figure 3.7 presents the regional surface geology. This overview presents the regional geology as reported in GCS (2024). The Project exploit the Carbon Leader (CLR) and the Ventersdorp Contact (VCR) gold-bearing reefs present in the deep conglomerates of the Witwatersrand Supergroup, at the base of the Transvaal Supergroup. Nearer to the surface, lava intrusions from the Bushveld Complex form dykes predominantly striking from north to south in the dolomites. These impervious intrusions are approximately 50 m wide and spaced 5 to 15 km apart, which results in the compartmentalisation of the dolomitic catchments into several groundwater compartments.

3.4.3.2 Witwatersrand Supergroup

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

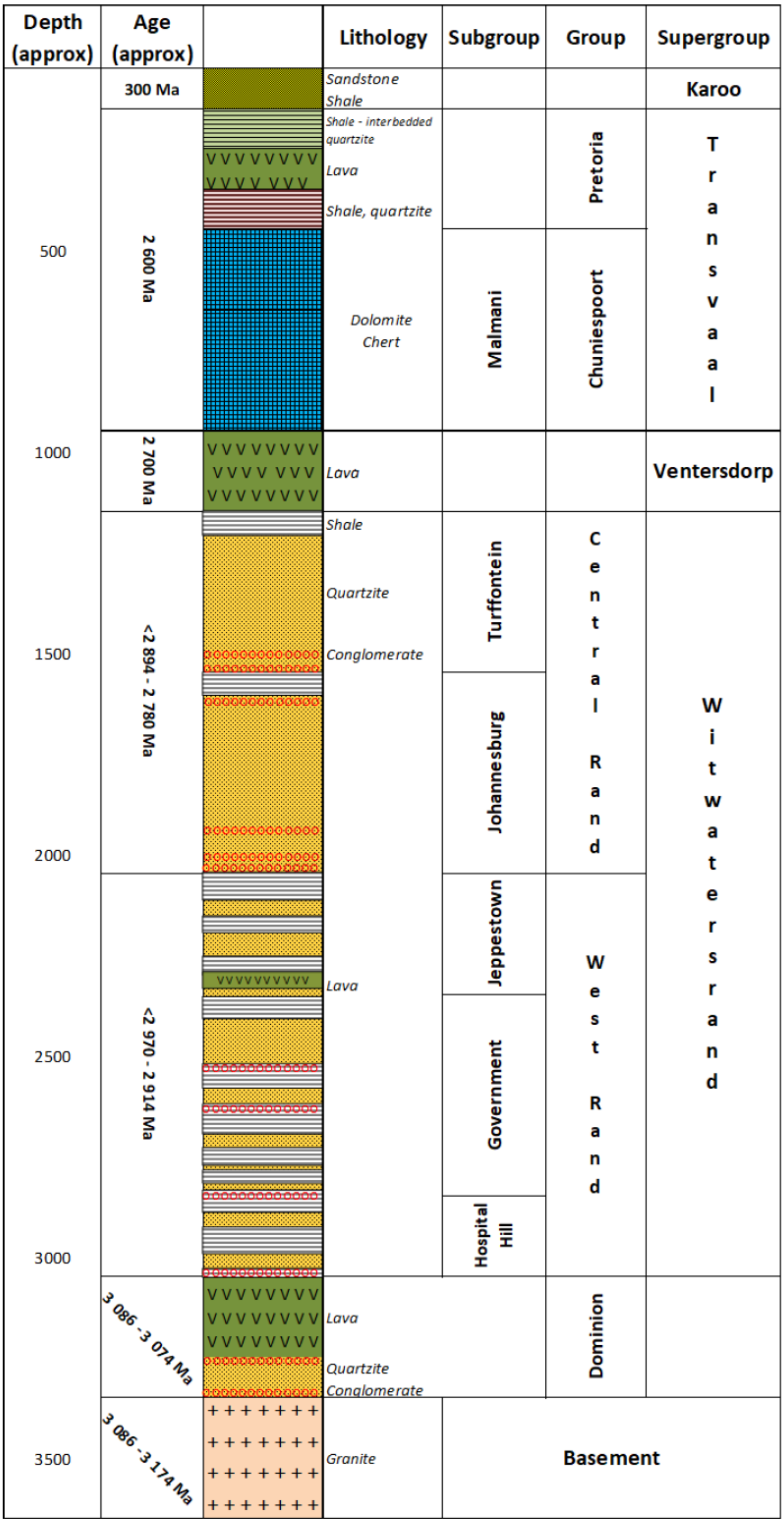

Figure 3.6 The stratigraphy of the Project area (MvB Consulting, 2025).

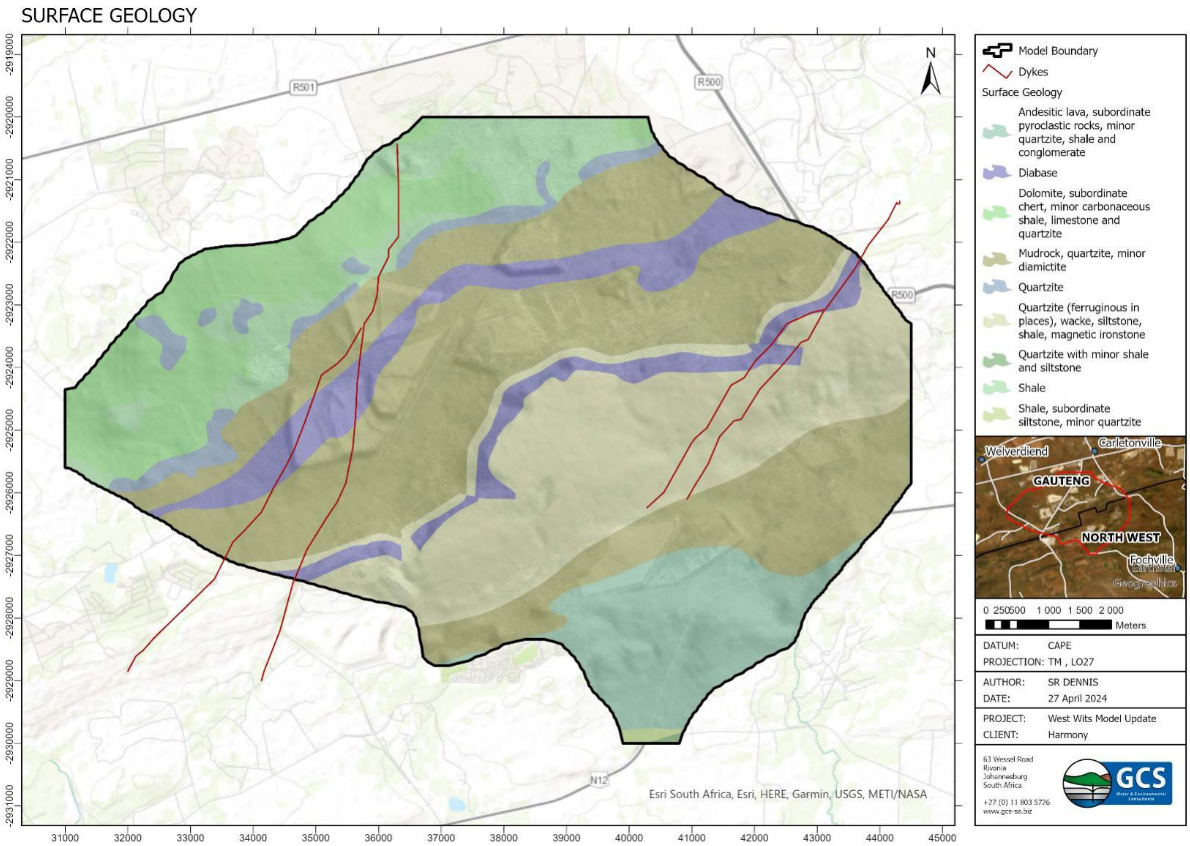

Figure 3.7 The regional surface geology near the Project area as reported in GCS (2024).

The West Rand Group is divided into three subgroups: 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 underwent low-grade metamorphism, making the shale 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 mainly of quartzite, within which numerous conglomerate zones occur. 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.

3.4.3.3 Ventersdorp Supergroup

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

3.4.3.4 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 during 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 gold is not as widespread as in the Witwatersrand and is mainly restricted to north-south trending channels. A dark, siliceous quartzite with occasional grits or small pebble bands overlies the Black Reef—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 range in thickness from 200 m to 1,500 m. 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.

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 conformably overlies the Black Reef Formation, with a transitional mixed zone consisting of carbonaceous, 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 constitute the surface geology at the Mponeng mine. The Rooihoogte Formation is the basal member of the Pretoria Group and consists 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 to 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 in size from pebbles to cobbles.

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 challenging to identify in the field, mainly 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.

3.4.3.5 Transvaal Supergroup

The Karoo Supergroup was deposited approximately 345 million years ago. It commenced during the glacial period, when most of South Africa was covered by a thick sheet of ice. This ice cap slowly moved southward, causing extensive erosion due to accumulated debris at its base. This debris was eventually deposited as the Dwyka tillite. The Dwyka, which generally forms an impermeable barrier to groundwater percolation, 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, forming a relatively even topography that is visible today.

3.4.4 Geohydrological Setting

3.4.4.1 General

The geohydrological setting of the Project area is described in MvB Consulting (2025). It 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 terrain types.

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

3.4.4.2 Weathered and Fractured Aquifer

Groundwater occurs in the near-surface geology of weathered and fractured sedimentary deposits (quartzite and shale) within the Transvaal strata. The lava of the Hekpoort Formation has weathering characteristics similar to those of the shale and is therefore considered part of the same aquifer. These formations are not considered to contain economic, sustainable aquifers, but localised high-yielding boreholes may 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, including transmissivity and storativity, are generally low, and groundwater movement through this aquifer is therefore also slow.

3.4.4.3 Dolomite 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), whereas groundwater levels exceed 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 formed due to karstification that occurred before the deposition of the Karoo sediments on top of the dolomites. There is general agreement that this aquifer is a significant water source 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 depths where dissolution has been less pronounced. It is doubtful that any significant groundwater flow occurs below these depths except along intersecting structural conduits to the underlying mine workings.

3.4.4.4 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 3.8 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, which is, in part, attributed to the well-defined karstification in the northern dolomites.

3.4.4.5 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 concentration in rainfall for areas inland is approximately 1.0 mg.L-1, and the harmonic mean of the chloride concentrations in groundwater samples from the mining area is 25.88 mg.L^{-1}. Using the chloride method, MvB Consulting (2025) calculated recharge to be approximately 3.9% of the MAP. This recharge is slightly less than the average recharge rates of 4.3 for the MAP (C23E) and 4.7 for the MAP (C23J) reported in GCS (2024) for the two quaternary catchment areas, respectively.

3.4.4.6 Aquifer Parameters

Table 3.2 summarises the aquifer parameters of the weathered and fractured aquifer, derived from aquifer testing undertaken in the region, as reported in MvB Consulting (2025).

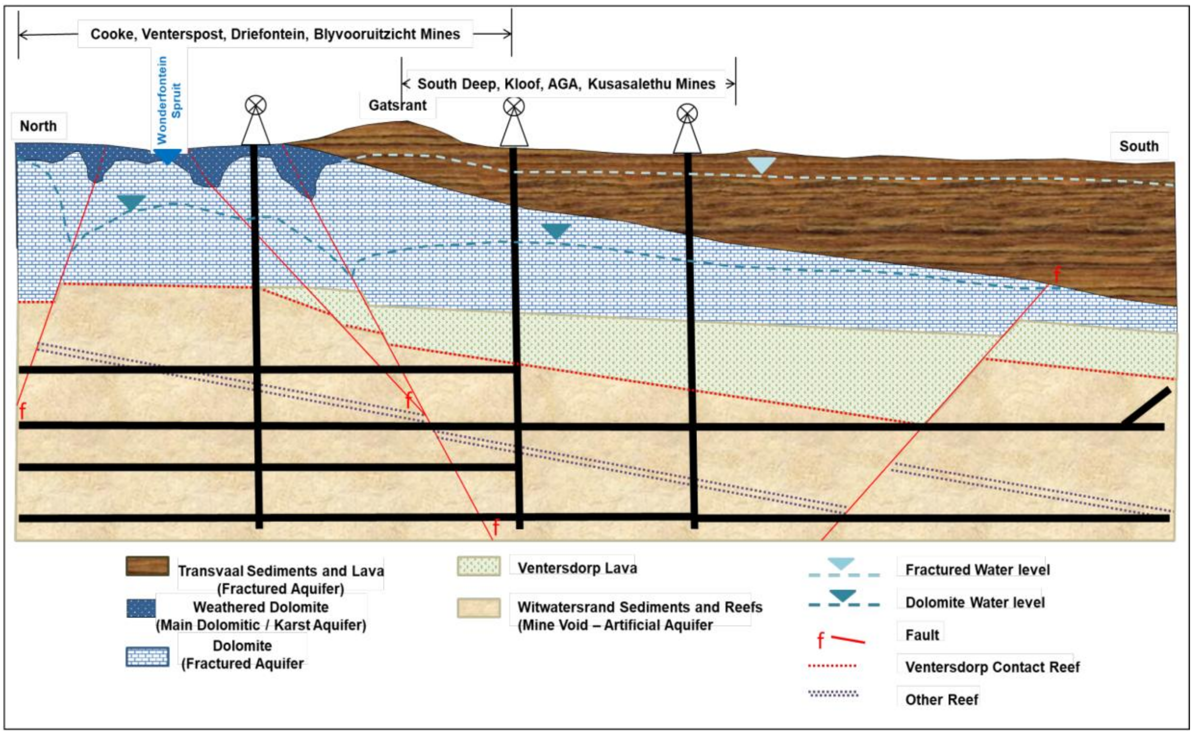

Figure 3.8 Schematic geological section showing the relationship between the aquifers in the study area (MvB Consulting, 2025).

No hydraulic parameters derived from aquifer testing are reported in GCS (2024). The calibrated hydraulic conductivities for the four-layer numerical hydrogeological model are presented in Figure 3.9 and Figure 3.10, respectively. Figure 3.9 shows that the calibrated model horizontal hydraulic conductivities vary from 0.06 to 1.8 m.day^{-1} for the weathered aquifer that is represented by Layer 1.

Table 3.2 Transmissivity and hydraulic conductivity values in the weathered and fractured aquifers (MvB Consulting, 2025).

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**	

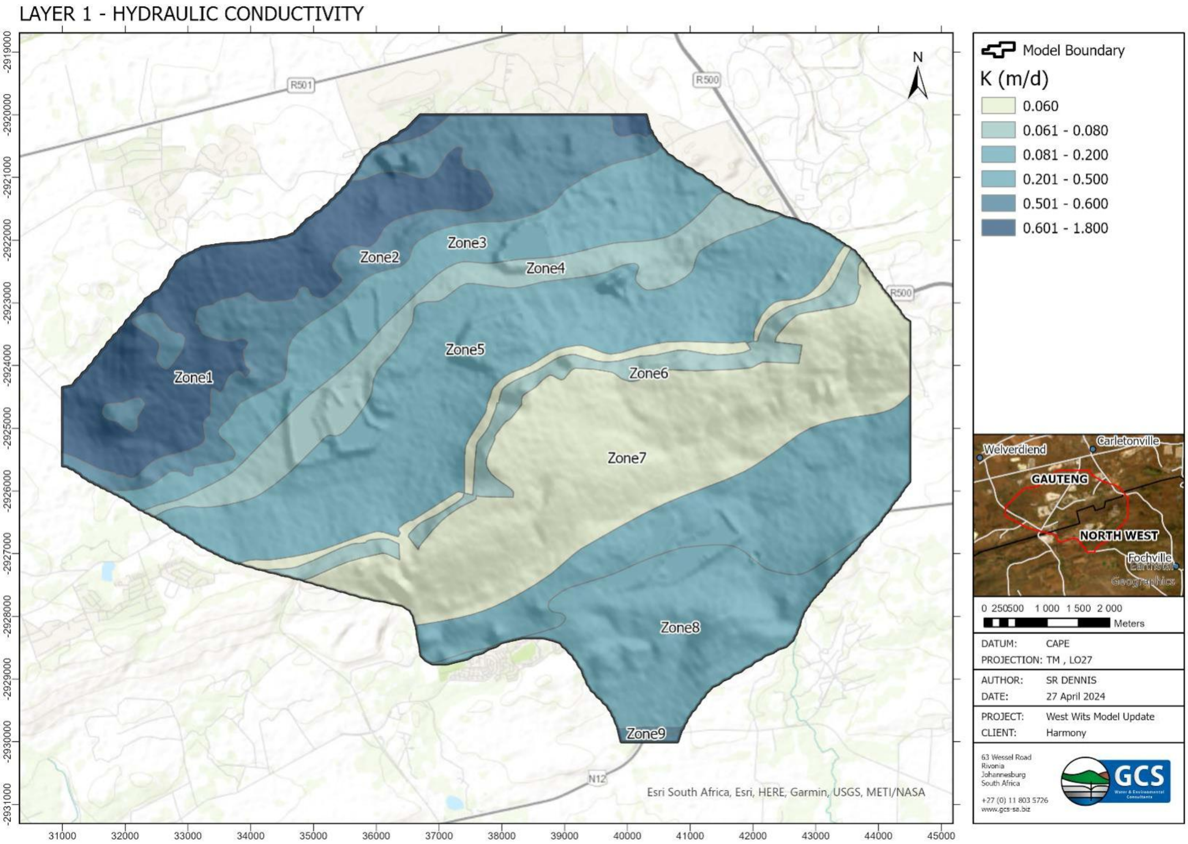

Figure 3.9 Model layer 1 horizontal hydraulic conductivities as reported in GCS (2024).

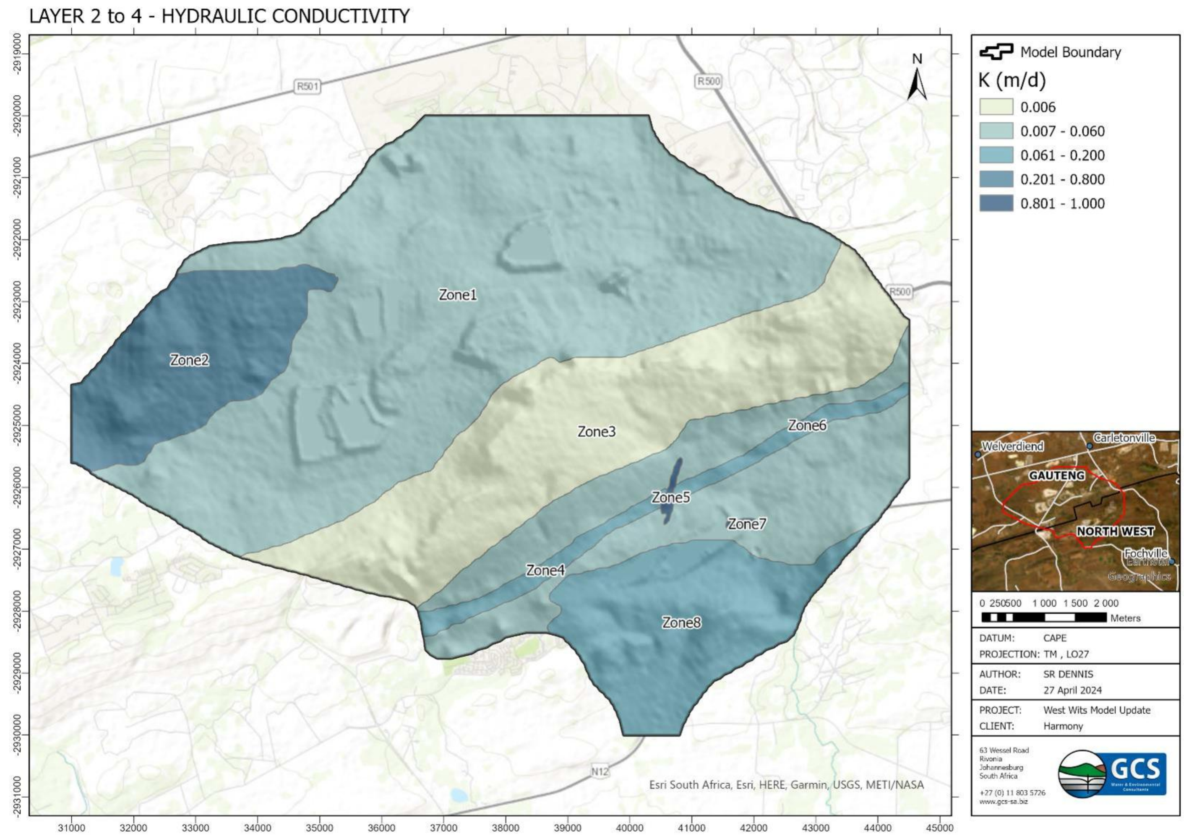

Figure 3.10 Model layer 2 to layer 4 horizontal hydraulic conductivities as reported in GCS (2024).

The spatial distribution of the horizontal hydraulic conductivities closely resembles the surface geology presented in Figure 3.7. In addition to the presented hydraulic conductivity zones, a horizontal hydraulic conductivity of 1 m.day-1 was assumed for the dykes presented in Figure 3.7.

3.4.4.7 Groundwater Flow and Gradients

In most geological terrains, the groundwater mimics the topography. The spatial distribution of groundwater depth information is presented in Figure 3.11. There is a strong correlation between surface topography and groundwater level, as shown in Figure 3.19, suggesting that groundwater flow will follow the topographical gradient. A distinction is made between shallow groundwater levels below 12 mbgl and deeper groundwater levels above 12 mbgl. A high correlation between surface topography and water level indicates unconfined conditions within the weathered system.

Figure 3.13 depicts the groundwater level elevations as reported in GCS (2024), which, as expected, mimic the surface contours. Groundwater flow is, therefore, from the high-lying areas associated with the Gatsrand towards the low-lying areas towards the south-southwest and north-northeast. MvB Consulting (2025) reported groundwater gradients that average about 0.64% in the area. MvB Consulting (2025) estimated the porosity of the aquifer material to be between 3% to 7% (a value of 5% was used). GCS (2024) used porosities of between 1% and 1.5%

3.4.4.8 Contaminant Transport

Simulations of the contaminant plume (SO_4) are reported in GCS (2024), assuming the spatial distribution of the SO_4 source concentrations as depicted in Figure 3.14. The initial concentrations shown in Figure 3.22 were used to simulate plume propagation from the current distribution over 5 to 50 years. Figure 3.16, Figure 3.17 and Figure 3.18 present the plumes after 10, 20 and 50 years, respectively.

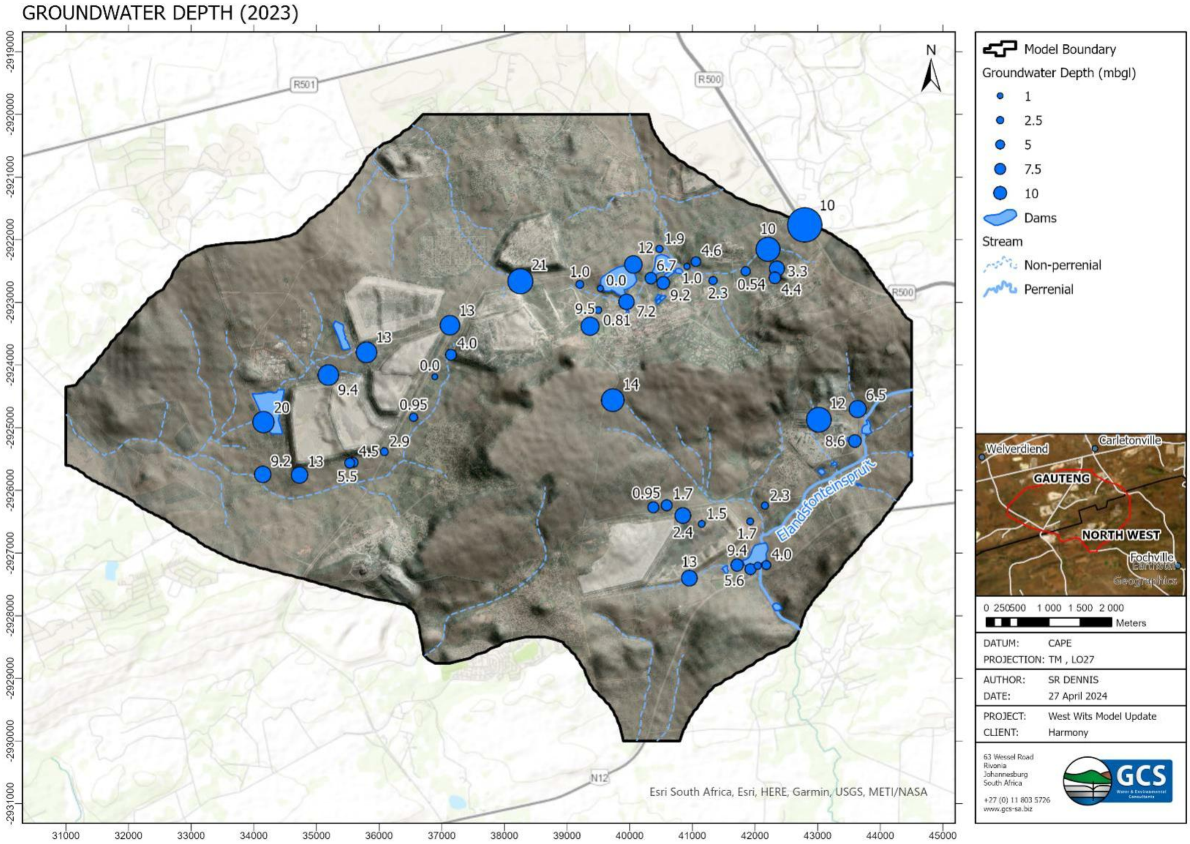

Figure 3.11 Average groundwater depth measured in 2023, as reported in GCS (2024).

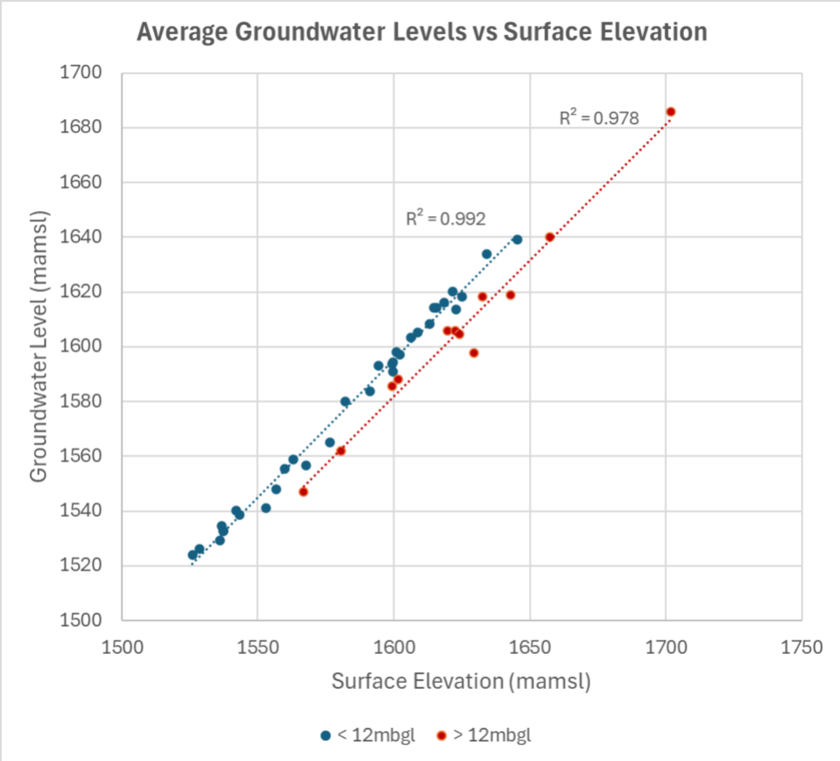

Figure 3.12 Correlation between the topography and the groundwater level near the Project area as reported in GCS (2024).

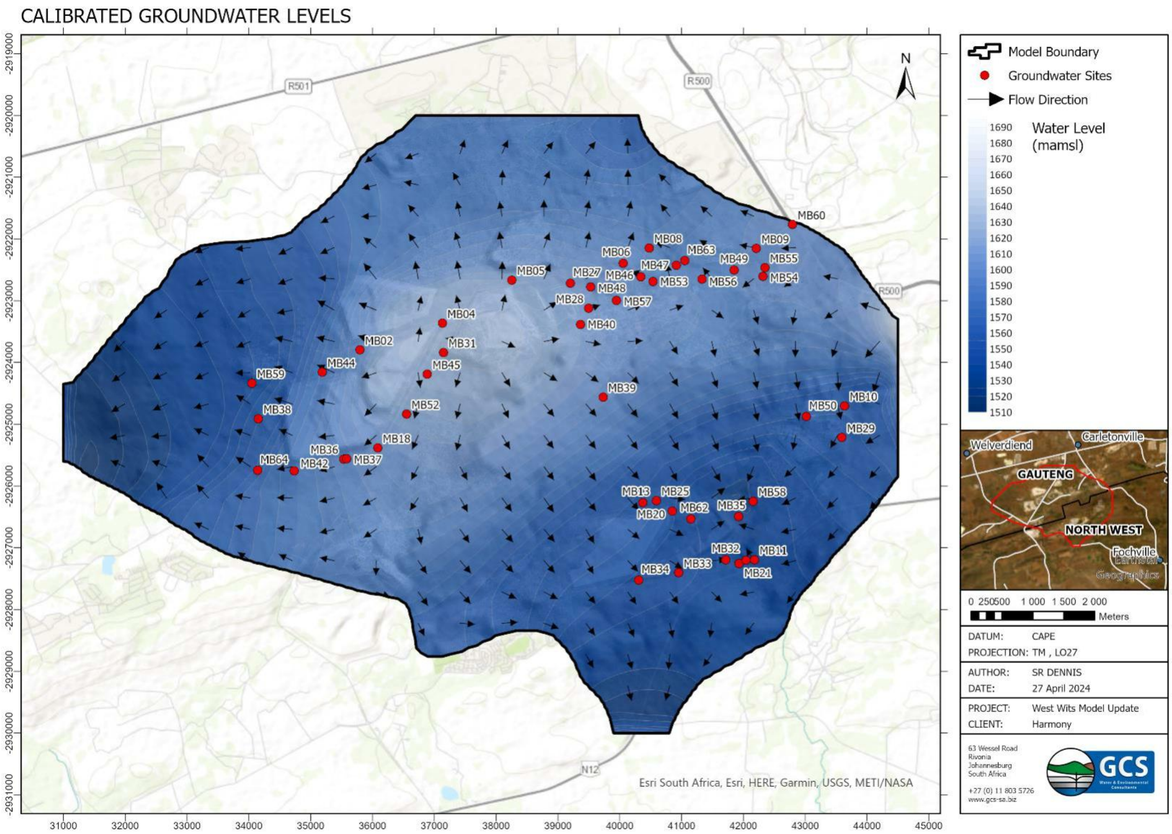

Figure 3.13 The regional interpolated groundwater gradient near the Project area as reported in GCS (2024).

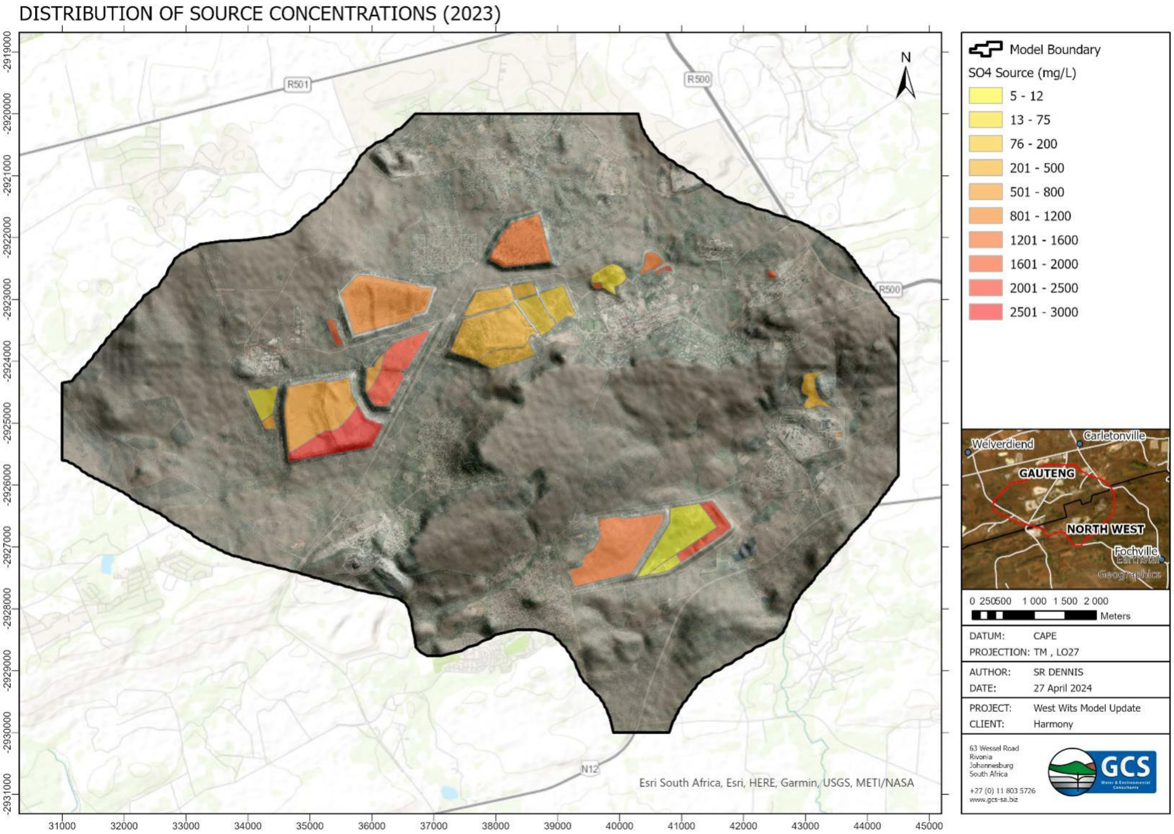

Figure 3.14 **The SO_4 concentrations assumed for the source as reported in GCS (2024).**

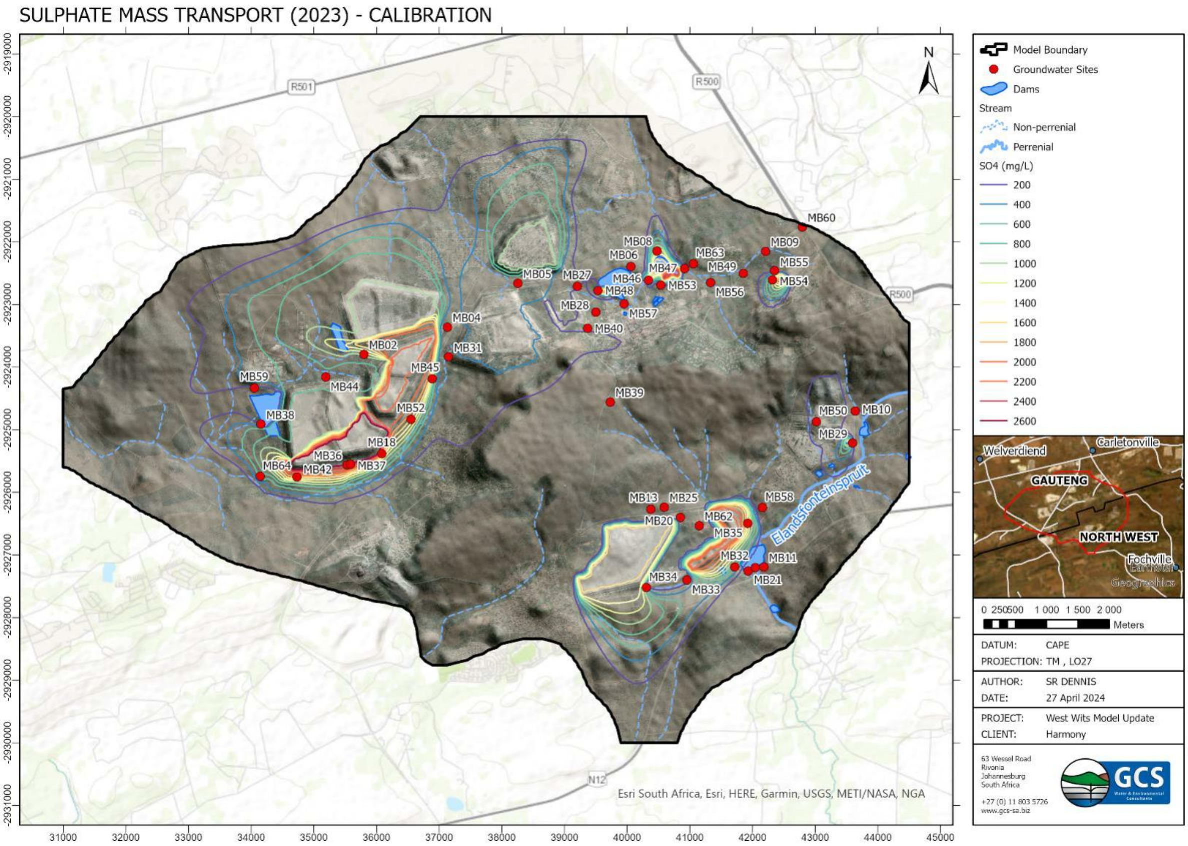

Figure 3.15 **The calibrated SO_4 concentration plume for 2023 as reported in GCS (2024).**

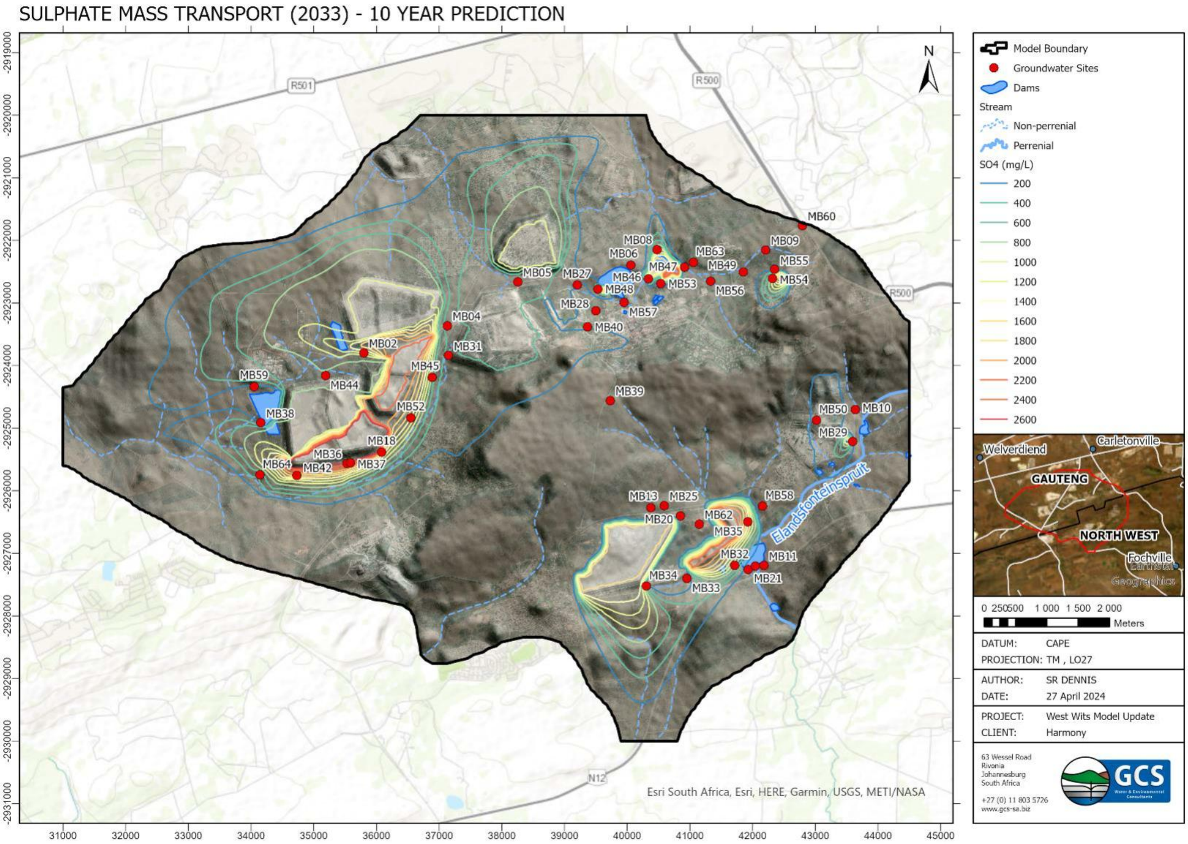

Figure 3.16 **The calibrated SO_4 concentration plume after 10 years as reported in GCS (2024).**

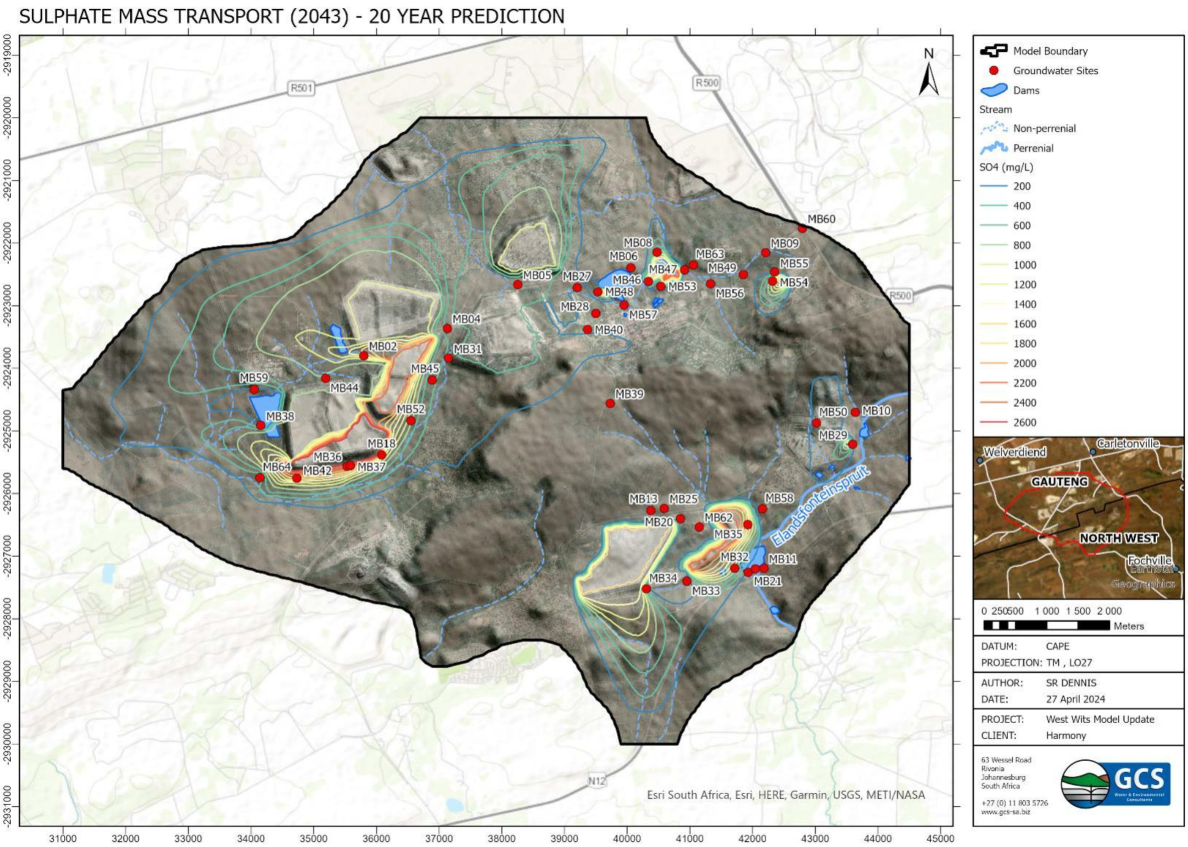

Figure 3.17 **The calibrated SO_4 concentration plume after 20 years as reported in GCS (2024).**

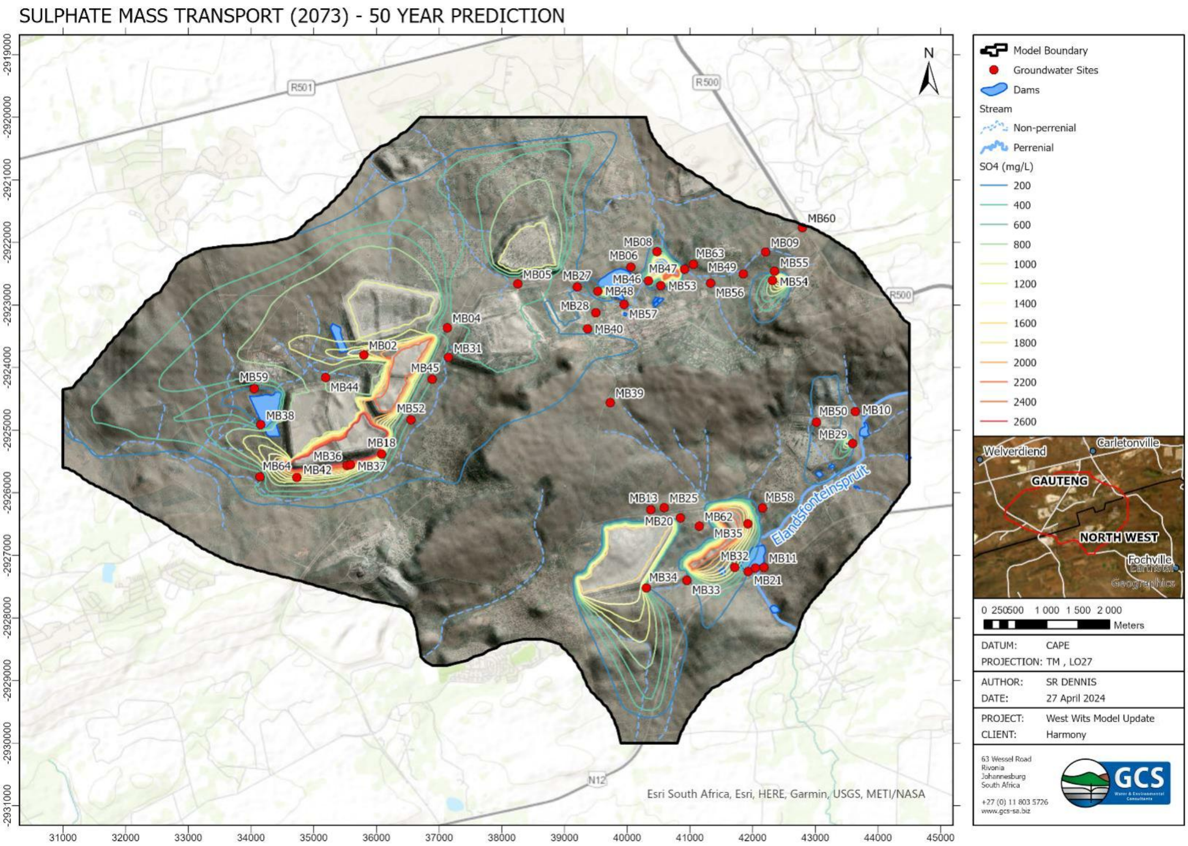

Figure 3.18 The calibrated SO_4 concentration plume after 50 years as reported in GCS (2024).

3.4.5 Meteorological Conditions

3.4.5.1 General

The Project area is located within the Merafong City Local Municipality (LM) of the West Rand District Municipality in Gauteng Province. The meteorological characteristics of the area presented and used in the Air Quality Impact Assessment (Airshed, 2026) 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 to generate general climatic information, such as diurnal temperature variations, atmospheric stability estimates, and dispersion modelling.

3.4.5.2 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 indicate different wind-speed categories; for example, red represents winds greater than 10 $m.s^{-1}$.

The dotted circles indicate the frequency 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 3.19, while the seasonal variations are shown in Figure 3.20.

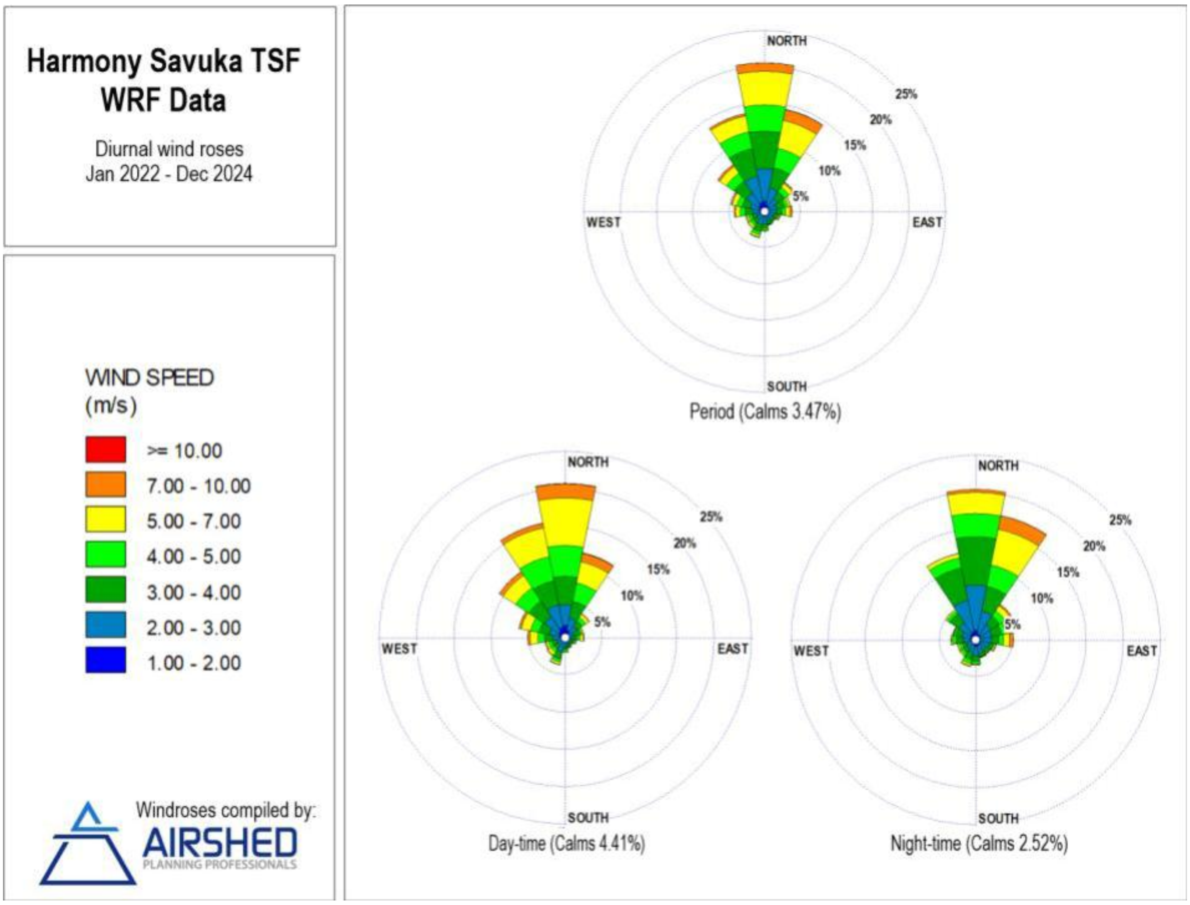

Figure 3.19 Period, day- and night-time wind roses for the Project area (WRF data, January 2022 to December 2024) (Airshed, 2026).

Northerly winds dominate the wind field. The strongest winds (>6 m/s) occurred mainly from the north-northeastern sector. Calm conditions occurred 3.5% of the time, with an average wind speed of 3.63 m.s-1 over the period. Both daytime and nighttime show dominant northerly wind fields, with calm conditions occurring 4.4% of the time during the day and 2.52% at night. The dominant northerly winds prevail throughout the seasons, with higher wind speeds during the spring months, as shown in Figure 3.20.

3.4.5.3 Ambient Temperature

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

Diurnal and average monthly temperature trends are presented in Figure 3.21. The monthly average and hourly maximum and minimum temperatures are given in Figure 3.22. Temperatures ranged between -4°C and 37°C. The highest temperature occurred in January and the lowest in July. During the day, temperatures peak around 14:00, and ambient air temperature drops to a minimum around 06:00, just before sunrise.

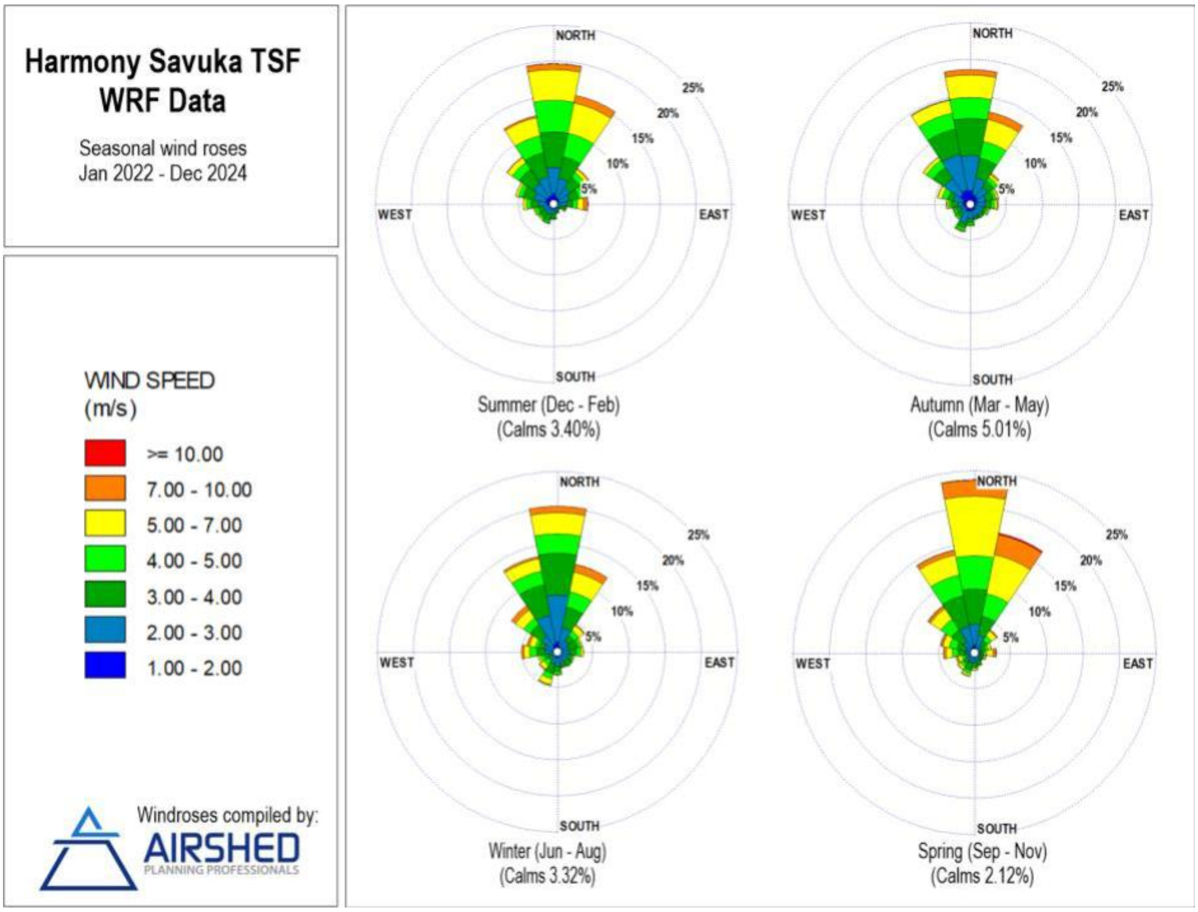

Figure 3.20 Seasonal wind roses for the Project area (WRF data, January 2022 to December 2024) (Airshed, 2026).

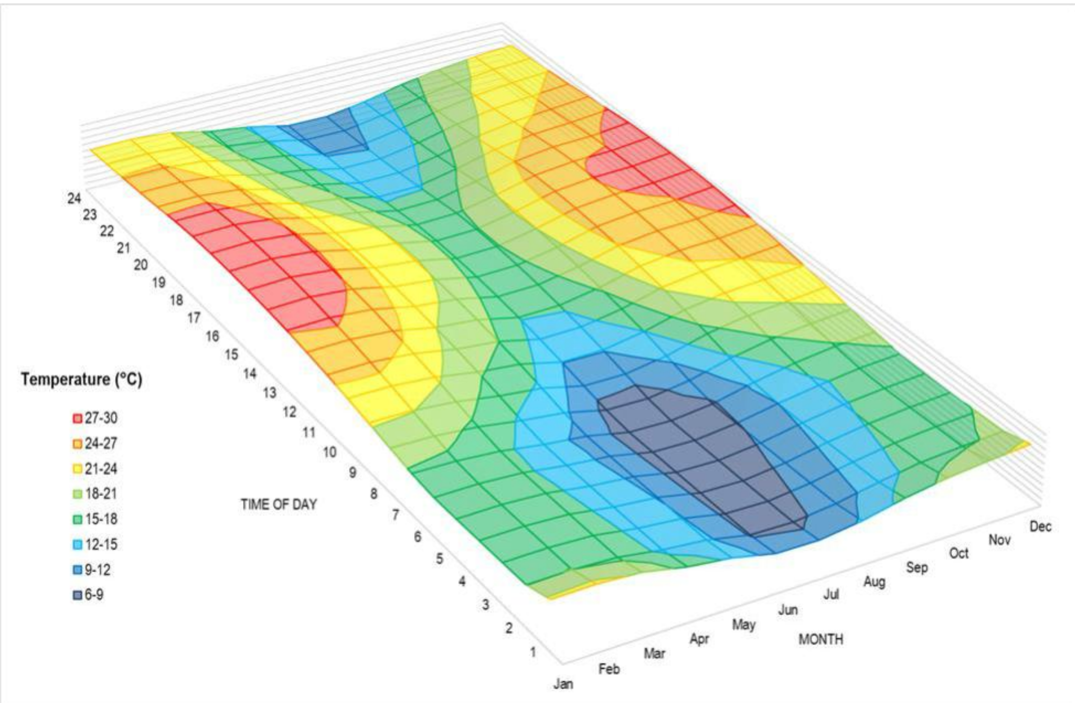

Figure 3.21 Diurnal temperature profile (WRF data, January 2022 to December 2024) (Airshed, 2026).

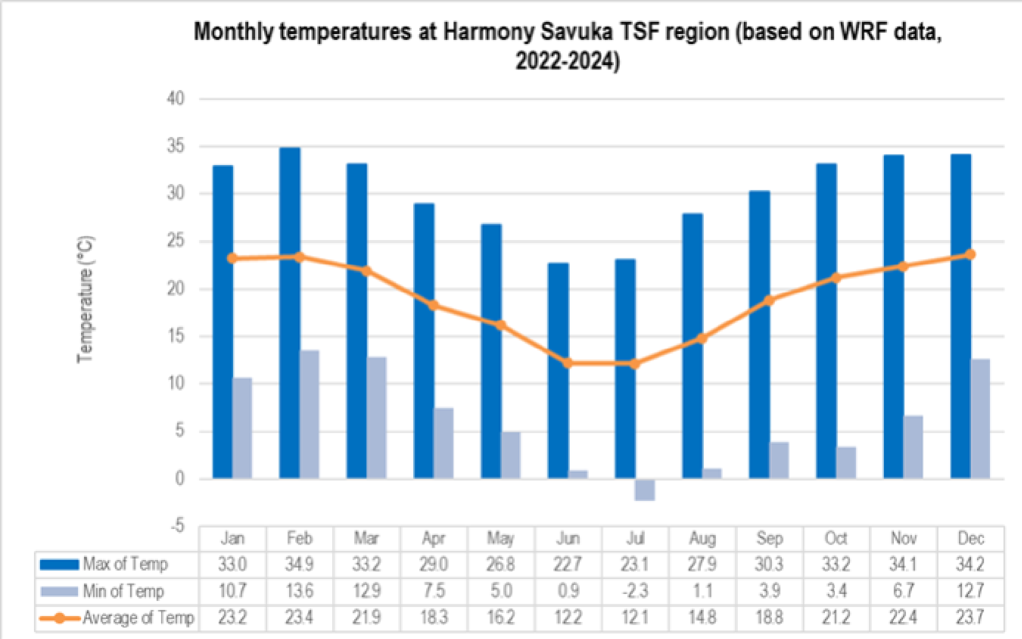

Figure 3.22 Monthly average and hourly minimum and maximum temperatures (°C) (Airshed, 2026).

3.4.5.4 Precipitation

Rainfall is essential in air pollution studies because it is an effective mechanism for removing atmospheric pollutants. The monthly rainfall derived from the on-site data did not appear accurate. Rainfall in this area occurs mainly during the summer months. However, it also rains in spring and autumn, while the winter months are dry, even though the relative humidity is higher in winter than in other seasons. Colder air can hold less moisture than warmer air; thus, the same moisture content corresponds to a higher percentage of saturation, resulting in higher relative humidity during colder periods than during warmer ones.

3.4.6 Socio-Economic Baseline Conditions

3.4.6.1 General

The socio-economic baseline conditions relevant to the Project area are described in Equispectives (2015; 2020; 2025). This summary outlines the underlying conditions that shape human behaviour and its interactions 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.

3.4.6.2 Community Types

Communities can be classified as belonging to one of the following groups (Equispectives, 2025):

- 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 both formal and informal dwellings on a stand, creating a community with *a mix of 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 refers to farms on which farmers earn a livelihood through crop, livestock, or game farming. Areas with smallholdings are categorised by character. If the residents of the smallholdings practise agriculture, the area is classified as commercial agriculture; if they reside in the area or have a business on the smallholding unrelated to agriculture, the area is classified as formal residential.

- Small-scale Subsistence Farming

  Small-scale subsistence farming is large-scale food gardening on land outside someone's backyard. Different members of the community typically cultivate the land and may belong to a formalised group. Food gardens in the backyard of an organisation, such as a school or crèche, would also fall into this category. Keeping livestock in the community or on its outskirts would fall within this group.

  Agricultural projects conducted as part of a mine's Social and Labour Plan can exhibit characteristics of both commercial agriculture and subsistence farming. To classify these projects, the following guidelines are used. If projects have reached a stage at which they are sustainable and operate 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 3.23 shows the 5 km radius around the Project surface infrastructure and potentially sensitive receptors within that radius. The following residential areas were identified in 2025 near the Project:

- AngloGold Ashanti residences (now part of GCTI operations)

  The Project had four residences for employees in 2020, namely Ntshonalanga, Motabong, 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 developed paraplegia after injuries on duty. Motabong housed employees from the TauTona mine, while Ntshonalanga housed employees from the Savuka mine, which was integrated with TauTona.

  Both the Ntshonalanga and Motabong residences have been demolished since 2020. Numba Wani hosted employees from the Mponeng mine. **The operations also had facilities for visiting wives, which were demolished since 2020**.

- West Wits Village

  Historically, West Wits Villages housed employees of AngloGold Ashanti. The 2024/20205 Housing Plan of the Merafong City Local Municipality indicates the establishment of West Wits Village Extension, which is part of the formalisation of West Wits Village, and that township establishment is underway.

- Deelkraal Estate

  Deelkraal Estate was formerly a mining village and was privately owned in 2015, with the owners in the process of having the estate declared a township. Future development plans include the construction of 648 Community Residential Units (CRUs) as part of a broader housing initiative in the municipality (Merafong City LM IDP 2024/25; Merafong City Housing Plan 2024/25). Despite its economic role, Deelkraal faces ongoing challenges, including fragmented planning from provincial departments, limited land for expansion, and sustainability concerns tied to environmental degradation and inadequate service provision in informal areas.

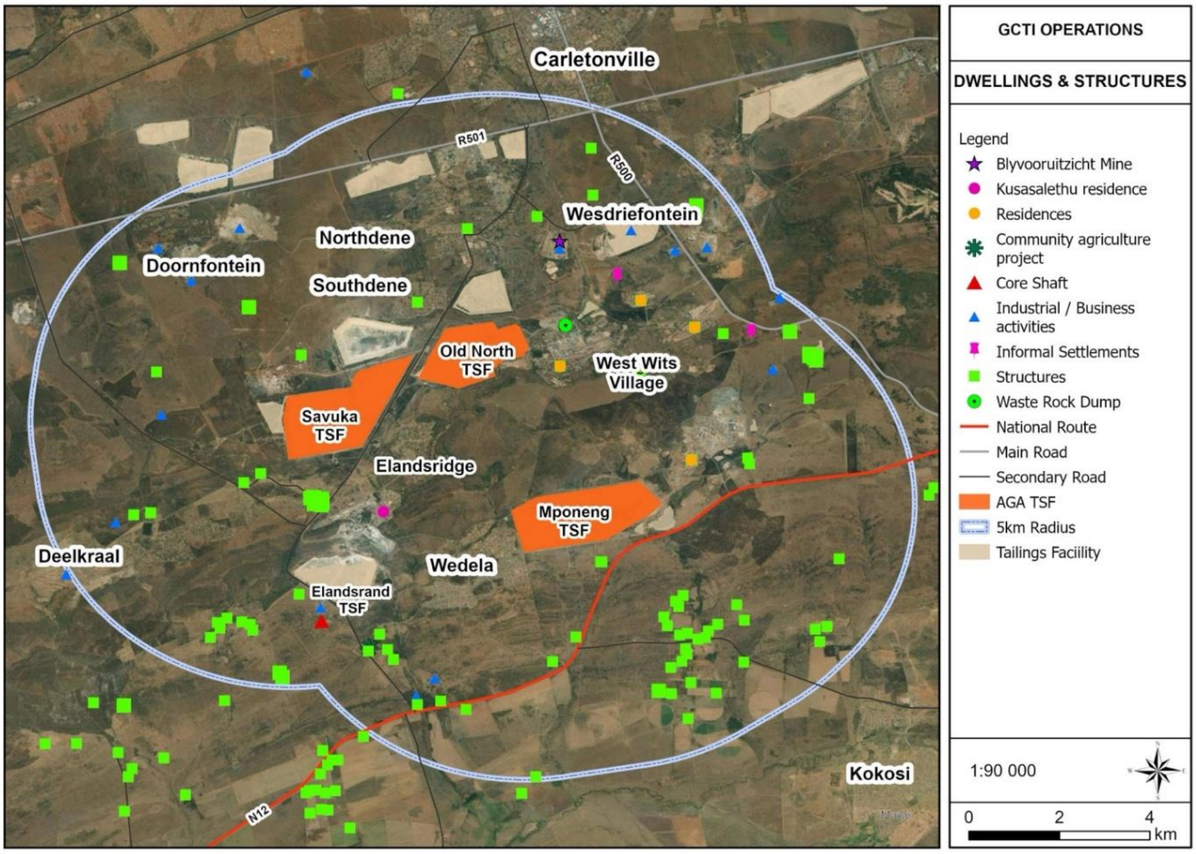

Figure 3.23 **Map indicating the study area used for the Project Baseline Social and Land Use Assessment (Equispectives, 2025).**

- Elandsridge

  Elandsridge/Elandsrand is a mining village where employees of Harmony's Kusasalethu mine reside. The Merafong City Local Municipality (2019/2020 IDP) has indicated that the Kusasalethu mine is expected to close within a few years and that, if it reopens, it would be operated through mechanisation and automation. The municipality would not assume responsibility for services, and the residential viability is considered low due to the absence of a new economic foundation, limited facilities, and the isolated location. It is anticipated that the area will be demolished and rehabilitated, potentially for agricultural or renewable energy uses.

- 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 primarily a formal settlement, but there is an informal settlement on the edge of Wedela, and many houses have backyard shacks. It is currently located near mining operations, which are not expected to continue indefinitely. The Merafong City LM (IDP 2025/26) includes several planned developments in Wedela, including an industrial hive, a marketplace, and an agri-village.

- 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 Local Municipality (IDP 2025/2026) reported 221 informal units. The settlement had access to water and sanitation but lacked electricity and waste services. Aerial photography indicates that most **households** have already been **relocated**. Some structures remain in the area, but it is unclear whether they are inhabited.

- Farming Community

  The farming community comprises farms and smallholdings in the Deelkraal area, adjacent to the Mponeng mine. Farming activities include crop farming, livestock production, game breeding, and hunting. Some of the farms offer tourist activities. Some farms have on-site workers, whereas others have off-site workers.

- Residential areas around the Blyvooruitzicht mine

  In 2015, people living in the area around the Blyvooruitzicht mine, which was placed in provisional liquidation in August 2013, lived in dire socio-economic conditions, a situation that still appears to persist (www.macua.org.za). The community successfully prevented Rand Water from disconnecting the piped water supply in the Constitutional Court. However, it was in vain, as the artisanal miners blocked the water from reaching the community. The community reports living in a state of persistent insecurity, citing ongoing violent conflict between residents and artisanal miners driven by competition over limited and finite resources, including water, electricity, and housing. Incidents of burglary and kidnapping have reportedly become commonplace, contributing to a pervasive climate of fear. Residents allege that police officers stationed in Carletonville are reluctant to enter the area due to safety concerns. The community further states that they are in limbo, having been informed by government representatives that intervention is not possible because the area is not formally included in the Integrated Development Plan (IDP). Additionally, they claim that their local councillor holds no effective authority or influence, having been appointed merely to satisfy legislative requirements, and is unable to provide meaningful support or representation.

  Aurous Resources acquired the Blyvooruitzicht mine in 2015 (www.blyvoorgold.com). Production resumed in 2022, and approximately 1,500 workers who had been unemployed following the mine's closure in 2013 were reemployed (www.miningweekly.com).

  The Merafong City Local Municipality (2019/2020 IDP) has indicated that the village has significant potential for integration into Carletonville, although buildings and infrastructure have been stripped and vandalised. There are dolomitic constraints in the area, and the Housing Development Agency is conducting a feasibility study into the potential to revive the village.

The Merafong City Local Municipality (2025/2026 IDP) urges mining companies to discontinue providing accommodation on mine properties and instead invest in integrated housing developments away from mining shafts.

Figure 3.23 shows the location of dwellings and structures relative to the West Wits Operations that are not located in a town or a village. The number of dwelling groups has remained essentially unchanged, as observed in aerial photography. In some dwelling clusters, new buildings have been observed. From Figure 3.23, it can be concluded that the land use near the Project is dominated by open grassland, agricultural (cropland), mining, and residential land uses. Equispectives (2020) divided communities into those living in formal structures, communities living in informal structures, commercial agricultural communities, and small-scale subsistence farming communities.

Table 3.3 presents the Census 2011 breakdown of households by geographic types. Similar data for the 2022 Census were not released. Most households in the area reside in urban areas.

3.4.6.3 Demographic and Socio-economic Characteristics

Population and Household Size

The population in the Merafong City LM increased by 14.15% and households by 16.47% between 2011 and 2022. As shown in Table 3.4, this is much lower than on the provincial and district levels, while average household sizes had decreased slightly. The data suggests increased demand for housing, infrastructure, and open space that can be converted to residential areas. According to the Merafong City Local Municipality IDP (2025/2026), rapid urbanisation and in-migration have intensified pressure on existing infrastructure and service delivery, especially in settlements located near mining areas.

Table 3.3 Breakdown of households according to geo types (source: Census 2011) (Equispectives, 2025).

Geo Type		Urban area	Tribal or Traditional area	Farm area	Total
Mining Wards	Ward 5	2,431	0	0	2,431
	Ward 11	3,586	0	0	3,586
	Ward 14	4,575	0	75	4,65
	Ward 27	3,827	0	0	3,827
Mixed Wards	Ward 12	1,475	0	68	1,543
	Ward 20	3,234	0	0	3,234
	Ward 22	2,040	0	374	2,414
	Ward 23	2,402	0	0	2,402

Table 3.4 Change in population and number of households between 2011 and 2016 (source: Census 2011 and Community Survey 2016) (Equispectives, 2025).

	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	
Population density	121.10	138.24	

Population density refers to the number of people per square kilometre, and the national population density increased from 42.45 people per km^2 in 2011 to 50.81 people per km^2 in 2022. The population density in all areas increased between 2011 and 2022, with all the areas well above the national average.

Table 3.5 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 was White, while in Ward 14, just over a third was White. 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 Mohaleshoek Informal Settlement. Between 2011 and 2022, the proportion of residents in the Black population group in the Merafong City LM increased from approximately 86.52% to 89.39%, while the proportion in the White population decreased from 11.79% to 8.82%.

Table 3.5 Breakdown of the population distribution in the different areas (source: Census 2011, Census 2022) (Equispectives, 2025).

Population		Black	Coloured	Indian	White	Other	Total
Mining wards	Ward 5	4,902	14	2	425	11	5,354
	Ward 11	6,610	27	2	336	23	6,997
	Ward 14	4,880	84	28	2,730	18	7,739
	Ward 27	5,964	30	4	257	22	6,276
Mixed wards	Ward 12	2,107	30	14	2,576	29	4,757
	Ward 20	8,652	2	9	5	23	8,691
	Ward 22	7,449	107	9	427	34	8,026
	Ward 23	6,699	20	6	4	49	6,777

Socio-economic Conditions

Census 2011 data summarised in Table 3.6 show that, in 2011, 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 employment levels, higher than at the local, district and provincial levels. It should be noted that large-scale retrenchments have occurred 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 unemployment rate in the area has increased since 2020.

Table 3.6 Employment status (persons aged 15 to 64 years, source: Census 2011, shown in percentage) (Equispectives, 2025).

Employment status		Employed	Unemployed	Discouraged work-seeker	Others who are not economically active	Total
Mining wards	Ward 5	53.99	10.61	1.03	34.37	100.00
	Ward 11	70.61	8.54	1.20	19.65	100.00
	Ward 14	74.99	6.14	1.15	17.72	100.00
	Ward 27	74.61	5.00	1.82	18.56	100.00
Mixed wards	Ward 12	45.15	8.05	2.12	44.68	100.00
	Ward 20	44.36	28.95	2.99	23.70	100.00
	Ward 22	34.24	15.93	5.06	44.77	100.00
	Ward 23	46.83	19.26	4.75	29.16	100.00

Population Composition, Age, and Gender

Census 2011 data summarised in Table 3.7 show that in 2011, more than half of households at 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. Wards 5 (64.85%), 11 (68.34%), 14 (71.55%) and 27 (75.89%) had the highest incidence of households consisting of only one person. All these areas contain mining residences or mining villages. Census 2022 shows that the proportion of single-person households has decreased, while the proportion of households consisting of three people has increased. These trends may indicate people cutting their living expenses by sharing a dwelling, given the shrinking number of employment opportunities in the area. Average household sizes decreased between 2011 and 2022.

Table 3.7 Household sizes (source: Census 2011, Census 2022) (Equispectives, 2025).

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

Census 2011 data summarised in Table 3.8 shows that males headed more than two-thirds of households in Merafong City. At the ward level, this proportion ranged from two-thirds to more than 90%. Census 2022 shows that between 2011 and 2022, the proportion of female-headed households increased, with females now heading more than 40% of households. Female-headed households are often financially less well off than similarly situated male-headed households and are considered more vulnerable.

Table 3.8 Gender of the head of household (source: Census 2011, Census 2022) (Equispectives, 2025).

Sex of head of household		Male	Female	Total
Mining wards	Ward 5	2,089	334	2,423
	Ward 11	3,172	413	3,585
	Ward 14	4,227	420	4,647
	Ward 27	3,585	235	3,821
Mixed wards	Ward 12	1,121	421	1,543
	Ward 20	2,182	1,052	3,234
	Ward 22	1,501	912	2,414
	Ward 23	1,633	769	2,402

Census 2011 data summarised in Table 3.9 show a bias towards males at the district, local, and ward levels, except in Ward 12, Ward 20, Ward 22, and Ward 23, where the split between males and females was approximately equal. These are the wards that do not primarily consist of mining residences and villages, and include Wedela, Deelkraal, and farming areas. The split between males and females in West Rand DM and Merafong City LM changed from male-biased in 2011 to approximately equal by 2022.

Table 3.9 Gender distribution (source: Census 2011, Census 2022) (Equispectives, 2025).

Sex distribution		Male	Female	Total
Mining wards	Ward 5	3,918	1,436	5,354
	Ward 11	4,592	2,405	6,997
	Ward 14	5,298	2,441	7,739
	Ward 27	4,634	1,643	6,276
Mixed wards	Ward 12	2,417	2,340	4,757
	Ward 20	4,435	4,256	8,691
	Ward 22	3,967	4,059	8,026
	Ward 23	3,431	3,347	6,777

The Census 2011 data presented in Figure 3.24 show that Ward 5, Ward 14 and Ward 27 had the highest proportions of people aged 17 years or older, while Ward 22 had the lowest. The 2022 profiles are very similar to those from 2011.

Child-headed households are considered highly vulnerable because there is usually no adult to provide food and other necessities, and these households often rely on the kindness of neighbours and other family members for survival. A child who heads a household often lacks the experience and maturity required to raise their siblings and may be compelled to leave school to do so.

Census 2011 data summarised in Table 3.10 show that Ward 20 (1.1%), Ward 22 (1.4%), and Ward 23 (1.2%) had the highest incidence of child-headed households with heads aged 10-19 years. These percentages remain slightly above the municipal-level incidence in Merafong City (1%). The areas with the highest incidence of heads of household who have reached retirement age were Ward 12 (9.7%) and Ward 22 (8.9%). Between 2011 and 2022, the incidence of household heads who were 19 years or younger decreased slightly, while the proportion of household heads who had reached retirement age (65+) increased. The proportion of households with a head aged between 20 and 34 years decreased, while the proportion of households with a head aged between 35 and 64 years increased significantly. These trends suggest an ageing population, with younger people leaving the area in search of opportunities elsewhere.

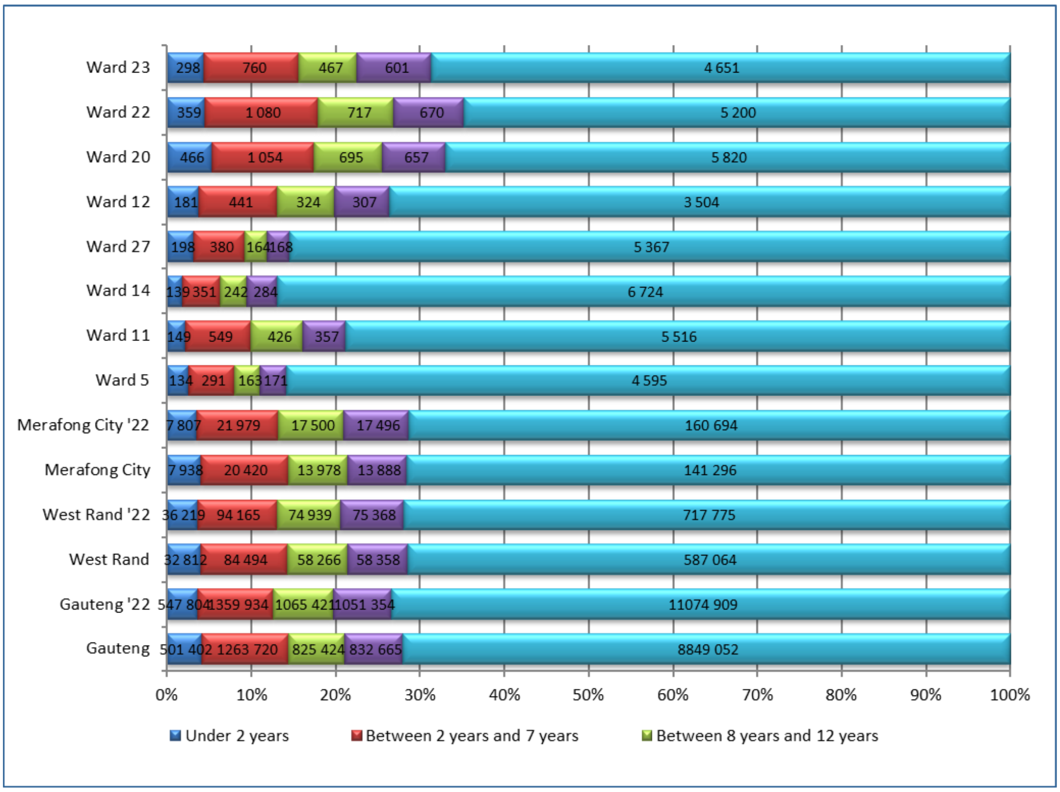

Figure 3.24 Age distribution of the population (shown in percentage; source: Census 2011, Census 2022) (Equispectives, 2025).

Table 3.10 Gender distribution (source: Census 2011, Census 2022) (Equispectives, 2025).

Age of the Head of Household		10-19 years	20-34 years	35-64 years	65+ years	Total
Mining wards	Ward 5	11	798	1,590	24	2,423
	Ward 11	14	910	2,622	39	3,585
	Ward 14	17	1,251	3,116	262	4,647
	Ward 27	18	1,064	2,721	17	3,821
Mixed wards	Ward 12	5	348	1,040	150	1,543
	Ward 20	34	1,256	1,886	58	3,234
	Ward 22	33	724	1,441	215	2,414
	Ward 23	29	825	1,485	63	2,402

3.4.6.4 Household Structures

The residential areas can be grouped by settlement type and the housing structures present in each area. Table 3.11 summarises the settlement types and representative residential areas discussed.

Table 3.11 A summary of community types and representative residential areas inside the study is 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 3.12 shows that Ward 12 (90.0%) and Ward 20 (79.5%) 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 town house 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. In comparison, 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 most likely refer to households living in mining residences.

Table 3.12 Main dwelling types (households, source: Census 2011) (Equispectives, 2025).

Dwelling Type		House or brick/concrete block structure on a separate stand or yard, or a farm	Traditional dwelling/hut/structure made of traditional materials	Flat or apartment in a block of flats	Cluster house in a complex	Townhouse (semi-detached house in a complex)	Semi-detached house	Informal dwelling (shack in backyard)"	Informal dwelling (shack not in backyard, e.g. in an informal/squatter settlement or on a farm)	Formal dwelling /house /flat/room in backyard/servants' quarters/granny flat/cottage	Caravan/tent	Other	Total
Mining wards	Ward 5	46.67	0.25	6.62	1.59	-	1.09	2.35	11.31	29.95	0.04	0.13	100
	Ward 11	42.08	0.37	0.54	0.11	-	0.28	0.25	0.20	5.04	0.11	51.07	100
	Ward 14	45.19	0.34	40.65	0.97	1.33	0.05	2.23	7.45	1.69	0.02	0.07	100
	Ward 27	37.28	0.27	41.21	16.47	0.11	0.16	0.19	2.36	1.78	-	0.19	100
Mixed wards	Ward 12	90.03	0.20	3.63	0.07	-	0.79	0.46	0.73	3.37	0.20	0.53	100
	Ward 20	79.45	0.12	2.70	0.03	0.03	0.12	9.49	0.28	7.53	0.03	0.22	100
	Ward 22	56.82	0.32	0.27	0.09	-	0.32	7.46	30.40	3.71	-	0.60	100
	Ward 23	58.85	0.29	6.15	0.17	0.38	0.29	20.97	0.92	11.59	-	0.42	100

Census 2022 shows that the number of households living in formal dwellings or houses on a separate stand has increased in Merafong City from 59.7% in 2011 to 82.9% in 2022. The proportion of households living in any form of informal dwelling declined between 2011 and 2022. In 2016, about a quarter (24.8%) of households in Merafong City reported living in RDP or government-subsidised dwellings. Almost two-thirds (61.3%) of those living in RDP or government-subsidised dwellings have rated the overall quality of the dwellings as good. The Merafong City IDP (2019/2020) indicated the following urban developments are in the pipeline (updated with the status as per the 2025/2026 IDP):

- Ward 12: Elija Barayi Village – west of Carletonville, next to Welverdiend. This development is planned to comprise approximately 8,150 RDP (Reconstruction and Development Programme)/BNG (Breaking New Ground) houses and 2,900 Gap houses. The 2025/2026 IDP indicates that this development is underway, following a phased approach. There are already a community hall and sports facilities. Some houses have already been developed, but the exact number is unclear. The remainder of Phase 1 and Phase 2 is planned for 2024/25. It is not clear how many phases there will be.
- Ward 12: Khutsong South – expansions in the current Khutsong South area. According to the 2025/2026 IDP, multiple housing projects are underway, including Khutsong South Extensions 2, 5, 6, 7, and 8, as well as Portion 123 Wonderfontein. Still, it does not appear that much development has occurred in this area since 2020.
- 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. Later documents (IDP 2025/2026) describe the inclusion of 1,000 RDP/BNG units, 500 Gap market units, and a total of 2,290 planned housing units for low- and middle-income groups. It does not appear that any development has occurred in the area since 2020.

- Ward 22, Ward 23: Wedela Extension 4 – undeveloped area adjacent to Wedela (furthest from mining infrastructure and located where agricultural activities are currently taking place). This development will consider the need for additional business and institutional activities. A strip of multi-use businesses is envisioned, with the design and layout focused on an ‘agri village’ theme. This area has not yet been developed, though a few dwellings exist.
- 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. This expansion is still in the planning phase (no development has commenced yet).

3.4.6.5 Social Infrastructure and Services

Activities that occur in a community vary from community to community. Based on similar studies conducted in other areas over time, people living in areas with high unemployment tend to spend more time outdoors. They socialise outside; children tend to play outside for most of the day, as many households in these areas cannot afford day care. Informal housing tends to be very cold in winter and very hot in summer, and is usually relatively small inside; as such, these residents prefer to be outside. In many low-income areas, makeshift sports fields allow residents to play soccer and other sports. The incidence of food gardens is typically higher in areas with high poverty and unemployment, as many residents lack the means to purchase all their food, and a larger proportion of people have time to tend a food garden.

Census 2011 data, summarised in Table 3.13, shows that more than 90% of households in the area have access to water from a regional or local water scheme operated by the municipality or other water service 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 mainly of farms and smallholdings, has the highest incidence of households accessing water from boreholes (13.5%). Ward 5 (4.4%) and Ward 14 (2.7%) have the highest incidence of households getting their water from water tankers. Between 2011 and 2022, the proportion of households in Merafong City that have access to water from a regional or local water scheme increased, as did the proportion of households that source their water from boreholes. At the provincial and district levels, the proportion of households with access to water through boreholes has declined.

Table 3.14 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 proportions of households without access to piped water. Census 2022 shows that the proportion of households with piped water inside the dwelling in Merafong City increased from 51.0% to 81.9%.

In the 2016 Community Survey, approximately 6.7% of households in Merafong City LM reported not having access to safe drinking water, and about 12.6% rated the overall quality of water services as poor. Approximately 22.2% of households reported experiencing municipal water interruptions in the past three months, and 15.0% reported interruptions lasting more than two days. In Merafong City LM, 40.8% of households that experienced water interruptions reported using water from a water tanker, 22.6% reported using an ‘other’ water source (specification of alternative sources is not provided), and approximately 28% reported using no alternative water source during interruptions. The majority of people (80.9%) who lack access to piped water inside their dwellings or yards have a water source within 200 m.

Table 3.13 Sources of water for households (source: Census 2011, Census 2022) (Equispectives, 2025).

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

Table 3.14 Households that have access to piped water (source: 2 Census 2011, Census 2022) (Equispectives, 2025).

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

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 Section 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, 2020a).

3.5.2 Tailings Material

Of the three TSF complexes, only the Mponeng TSF is currently operational. The Old North Complex TSF has been dormant for several years and has been rehabilitated by establishing vegetation on the surface and side slopes. A section of this TSF is currently being reclaimed. Table 3.15 to Table 3.17 summarise the full-spectrum analysis results available for the three TSF complexes as collected between 2009 and 2022.

Table 3.15 Summary of the full-spectrum analysis results available for the Mponeng tailings material as collected between 2009 and 2022.

Sampling Date	2009	04/12/2014	04/12/2014	04/12/2014	14/04/2022	13/04/2022
Necsa Report No.		RA-15889	RA-15889	RA-15889	RS2022-0840	RS2022-0842
Sampling Point	Mponeng TSF	Mponeng C1	Mponeng C12	Dormant	Mponeng Plant TSF	Mponeng Reef Sample
Radionuclide	Activity Concentration (Bq.kg^{-1})					
U-238	548	442	225	283	219	261
U-234	589	446	227	285	220	263
Ra-226	266	779	245	292	398	422
Pb-210	383	938	360	428		
U-235	26.9	20.4	10.3	13	10.1	12
Th-232	20.9	32.3	26.1	23.4	38.5	33
Ra-228	<MDA	< MDA	< MDA	< MDA	< 28	32.8
Th-228	21	47	37	27	40	24
Gross α		5690	4220	4620	1580	1970
Gross β		266	2320	1480	1680	1870

Table 3.16 Summary of the full-spectrum analysis results available for the Savuka tailings material as collected between 2009 and 2023.

Sampling Date	2009	04/12/2014	04/12/2014	04/12/2014	04/12/2014	13/04/2022
Necsa Report No.		RA-15889	RA-15889	RA-15889	RA-15889	RS2022-0841
Sampling Point	Savuka TSF	Savuka 5A	Savuka 7B	Savuka 7A	Savuka 5B	Savuka Plant TSF
Radionuclide	Activity Concentration (Bq.kg^{-1})					
U-238	442	364	454	516	530	682
U-234	446	367	458	520	534	687
Ra-226	367	411	494	524	555	1240
Pb-210	480	526	613	691	781	-
U-235	20.4	16.8	20.9	23.8	24.4	31.4
Th-232	22.6	28.2	24.3	24	25.3	42.2
Ra-228	<MDA	< MDA	< MDA	43	< MDA	56.3
Th-228	<MDA	26	40		23	54
Gross α		2990	4070	4100	2880	6620
Gross β		2300	2640	2580	2540	4120

Table 3.17 Summary of the full-spectrum analysis results available for the North Shaft tailings material as collected between 2009 and 2023.

Sampling Date	2009	20/09/2023
Necsa Report No.	-	RS2023-2738
Sampling Point	Old North Complex TSF	North Shaft TSF Composite Sample
Radionuclide	Activity Concentration (Bq.kg^{-1})	
U-238	462	759
U-234	466	766
Ra-226	618	0.907
Pb-210	676	918
U-235	21.3	35
Th-232	26.7	30.9
Ra-228	<MDA	0.026
Th-228	24	0.0279
Gross α		3890
Gross β		3010

Assuming the following secular equilibrium between parent radionuclides and their progeny, where radioanalytical 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 3.18 summarises the resulting average activity concentrations for the TSFs derived from the data presented in Table 3.15 to Table 3.17 and the secular equilibrium assumptions.

Table 3.18 Summary of the average activity concentration for the Mponeng Operations TSFs, as derived from the data presented in Table 3.15 to Table 3.17, and the secular equilibrium assumptions.

Radionuclide	Savuka TSF	Mponeng TSF	Old North Complex TSF	Savuka MOD	Mponeng MOD	Tau Tona MOD
	Activity Concentration (Bq.kg^{-1})					
U-238	498	329.7	610.5	67.1	37.8	92.6
U-234	502	338.3	616	67.5	38.1	93.2
Th-230	502	338.3	616	67.5	38.1	93.2
Ra-226	598.5	400.3	692	59.8	54.2	66.5
Pb-210	721.8	488.2	797	59.8	54.2	66.5
Po-210	721.8	488.2	797	84.6	42.1	66.5
U-235	23	15.5	28.2	3.1	1.7	4.2
Pa-231	23	15.5	28.2	3.1	1.7	4.2
Ac-227	23	15.5	28.2	3.1	1.7	4.2
Th-232	27.8	29	28.8	13.0	13.2	8.9
Ra-228	33.3	29	13.4	14.6	14.8	10.9

3.5.3 Radiological Conditions in Marginal Ore Dump

Full-spectrum radioanalysis results are available for the three Marginal Ore Dumps (MODs) associated with the Project for samples collected between 2014 and 2023, a summary of which is presented in Table 3.19.

Table 3.19 Summary of full-spectrum analysis results available for the Marginal Ore Dumps (MODs) associated with the Project for samples collected between 2014 and 2023.

Sampling Date	12/03/2014	17/02/2017	12/05/2022	12/03/2014	17/02/2017	07/12/2023
Necsa Report No.	RA-15021	RS2017-0642	RS20222-1054	RA-15021	RS2017-0642	RS2023-3519
Sampling Point	Mponeng	Mponeng MOD	Mponeng WRD	Savuka	Savuka MOD	Savuka MOD
Radionuclide	Activity Concentration (Bq.kg^{-1})					
U-238	48.9	22.3	42.2	56.7	28.5	116
U-234	49.3	22.5	42.6	57.1	28.5	117
Ra-226	51.2	26.3	85.1	48.9	31.9	98.7
Pb-210	54	< MDA	46	< MDA	77	128
U-235	2.25	1.03	1.94	2.61	1.31	5.34
Th-232	13.1	12.2	14.4	12.5	10.3	16.1
Ra-228	9.4	12	23.1	17.4	< MDA	< 17
Th-228	17	11	26	17	25	21.7
Gross α	1 400	320	260	1 620	300	< 700
Gross β	712	686	617	666	848	686

Sampling Date	17/02/2017	07/12/2023
Necsa Report No.	RS2017-0642	RS2023-3519
Sampling Point	Tau Tona MOD	Tau Tona MOD
Radionuclide	Activity Concentration (Bq.kg^{-1})	
U-238	24.2	161
U-234	24.4	162
Ra-226	31	102
Pb-210	< MDA	< 72
U-235	1.11	7.36
Th-232	5.31	12.4
Ra-228	< MDA	16.5
Th-228	6.9	17.3
Gross α	370	< 690
Gross β	478	631

3.5.4 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 and WRDs. The report used radon exhalation rate measurements from a variety of TSFs and WRDs over 8 years to derive source-characteristic radon diffusion coefficients.

These diffusion coefficients are used with Ra-226 concentrations measured in the tailings material (see Table 3.15 to Table 3.17) to estimate the radon exhalation rate in units of Bq.m^{-2}.s^{-1}. Parc Scientific (2006) presented the data as 'average' and 'maximum' values based on the data's statistical distribution. The derived diffusion coefficients, therefore, also represent average and maximum values and were used in the 2025 Project RPSA to estimate a range of potential radon exhalation from the TSFs and MODs at the Project.

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

Average: Radon exhalation rate ($Bq.m^{-2}.s^{-1}$) = (0.000376 ±0.000043) x Ra-226 ($Bq.kg^{-1}$)

Using these equations, the average and maximum radon exhalation rates estimated from the measured Ra-226 activity concentration in the tailings material of the three TSFs listed in Table 3.15 to Table 3.17 are listed in Table 3.20. In contrast, the average radon exhalation rates estimated in the marginal ore material of the three MODs listed in Table 3.19 are listed in Table 3.21.

Table 3.20 Estimated average and maximum radon exhalation rates for the Project TSFs.

TSF Complex	Activity Concentration ($Bq.kg^{-1}$)	Exhalation Rate ($Bq.m^{-2}.s^{-1}$)	
	Ra-226	Average	Maximum
Mponeng	400.3	0.22	0.24
Old North Complex	692	0.38	0.42
Savuka	598.5	0.33	0.36

Table 3.21 Estimated average and maximum radon exhalation rates for the Project MODs.

MOD Complex	Activity Concentration ($Bq.kg^{-1}$)	Exhalation Rate ($Bq.m^{-2}.s^{-1}$)
	Ra-226	Average
Savuka	59.8	0.02
Mponeng	54.2	0.02
Tau Tona	66.5	0.03

3.5.5 Upcast Ventilation Shafts

Upcast ventilation shafts (or vent shafts) release air that is circulated through the underground workings into the atmosphere. This air is associated with radon gas released from underground working environments, which can expose members of the public living downwind of the release points to radiation. 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 3.22.

Table 3.22 Radon release concentrations from the Project 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 impacts during the post-closure phase. The extent to which members of the public are exposed to ionising radiation induced by the Project may vary depending on operational conditions and the specific point in time (present or future).

Consistent with the assessment framework presented in Figure 1.5, the radiological public impact is evaluated by developing 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. It provides an opportunity to identify and evaluate all potential exposure situations, both current and 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 representation of conceptual models in the definition of exposure conditions. The outcome of the SPR analysis is then used to define and justify 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 by their unique composition (i.e., specific radioactive substances present or emitted) and by characteristics that determine how contaminants may be distributed in the environment.

Secondly, all relevant pathways and routes of exposure associated with the identified sources are evaluated. In this context, *pathways* are the routes by which radionuclides are dispersed or transferred within or between compartments of the environmental system until they reach a point of human interaction with those compartments. An *exposure route* is the pathway by which radiation enters the human body and poses a radiation risk, such as ingestion, inhalation, or external exposure.

Finally, *receptors* are defined and characterised. Receptors are humans who may be exposed to radiation (i.e., a radiation dose) from applicable sources via exposure pathways of concern.

4.3 Source Identification

4.3.1 General

Sources of radiation exposure for the public associated with mining and mineral processing facilities are often inadvertently created. Although the primary sources of radiation exposure are naturally occurring radionuclides, human activities and conditions may increase their concentrations in the accessible environment. Alternatively, the potential for human exposure to naturally occurring radionuclides in products, by-products, residues, and other wastes may increase if these radionuclides are moved from inaccessible locations to locations where humans are exposed to radiation.

To pose a radiological risk to the public and the environment, naturally occurring radionuclides must first be released from radiation sources. 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 the tailings storage facility).
  - Gas-mediated release (e.g., radon gas exhalation).
- Direct gamma radiation.
- Controlled or uncontrolled releases of radionuclides as solids or liquids into the environment.

Controlled releases are human-induced as part of normal operating conditions. In contrast, uncontrolled releases are associated with accidents and incidents that occur outside normal operating conditions (e.g., excessive water erosion, pipeline bursts, releases from storage dams exceeding their capacity, or dam wall failures).

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, and may include naturally occurring radionuclides that could 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 gases and dust may be released from the comminution (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.

- Mine ventilation shafts increase airflow in underground workings, where gases and dust generated underground may be released with the outflowing air.

Radioactivity released from primary sources into the environment may accumulate in environmental compartments (e.g., groundwater, surface water bodies, surface soils, sediments), potentially resulting in *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 results 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 be exposed to radiation from both primary and secondary sources at a mining and mineral processing operation, with expected differences in exposure modes and durations.

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 over the life cycle of the Project.

Primary sources of radiation exposure include existing ventilation shafts, TSFs, WRDs, water management facilities, and pipelines used to transport water and tailings, which are part of the baseline conditions. The Project-specific facilities and activities include the lower Mponeng TSF and the associated water management facilities and pipelines.

The *Assessment Context,* as defined in Section 2, distinguished between an operational and a post-operational period. The nature of mining and mineral processing operations means that some sources present during the operational period will no longer be active after closure. The operational phase, therefore, represents the ‘worst case’ because 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 naturally release radionuclides into the environment and is not, per se, a source of radiation exposure to the public.

4.3.3.2 Tailings Storage Facilities

The tailings storage facilities of concern for the Project are the existing TSFs, as well as the recommencement of deposition on the lower Mponeng TSF.

A TSF can measure a few kilometres in circumference and can be tens of metres high. The surfaces of operational or dormant TSFs are generally susceptible to wind erosion. Rehabilitation efforts on unused sections of an operational TSF can reduce windblown dust formation. TSFs may also be equipped with underdrains, a double high-density polyethene (HDPE) liner to prevent seepage, and a drainage diversion system around the perimeter of the TSF to store and control stormwater and sediment washed off the TSF walls. 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-emitting isotopes, which are dispersed into the atmosphere (solid-mediated release of contaminants, leading to increased 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 in the environment (solid-mediated release of contaminants, resulting in increased radioactivity concentrations in surface soil).
- The radionuclide content of the tailings material, specifically Ra-226, leads to radon emission into the air (gas-mediated release of contaminants), thereby increasing airborne radon concentration.
- Infiltration and subsequent percolation of water through the tailings material induce radionuclide leaching into the underlying geosphere (water-mediated release of contaminants, increasing radioactivity concentrations in groundwater).
- Water erosion of the TSF may induce solid-mediated release of contaminants, thereby increasing radioactivity concentrations in surface soil.

Although not a contaminant in the usual sense, the tailings material's inherent radiological properties may result in continuous gamma-ray emission 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 the solid-, gas-, and water-mediated release of contaminants, in a manner similar to TSFs (see Section 4.3.3.2). However, the radioactivity content of waste rock is generally lower than that of tailings. This makes WRDs 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 increase particulates emissions. Loading and offloading of material, as well as crushing and screening activities, can serve as source activities.

Infiltration and subsequent percolation of water through waste rock may leach water-soluble contaminants and disperse them into the underlying geosphere. Water seeping from the stockpiles may also contain leached radionuclides, which are then transported to the underlying geosphere, from where they can contaminate groundwater and surface water resources. Although the waste rock has been removed, the contamination plume may remain in the unsaturated zone and continue to migrate away from 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. Upcast ventilation shafts are surface points through which 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 results in a quantifiable concentration of airborne radioactivity.
- 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 underground work continues, implying that they will serve as a potential source of radiological exposure only for the mine's operational life.

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

Due to dust control measures in underground working environments, a relatively small volume of particulates is entrained in the upcast ventilation air. In addition, the high moisture levels within the shaft and ventilation system mean that 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 dams) means that the only source contribution is through infiltration, with subsequent leaching of radionuclides into the underlying geosphere (water-mediated release of contaminants, thereby increasing *groundwater activity concentrations*). However, the return water dam will be fitted with a double HDPE liner to prevent seepage. While these dams are within the mining authorisation 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 extensive pipeline infrastructure to transport water and tailings over long distances. Under normal operating conditions, these pipelines do not pose a significant radiation exposure risk. 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, as well as by 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 surface water erosion. During high-rainfall events and over time, surface water erosion of the tailings storage facility results in the transfer of material via 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 in 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 normal operating conditions. For illustrative purposes, two examples can be noted:

- The first example concerns the annual authorised discharge quantities (AADQ) of water to the environment from operations during high rainfall events, or from decanting water from underground workings that is raised due to the cessation of pumping. Water released to the environment under these conditions may introduce a secondary source of radiation exposure for the public.
- The second example concerns the gradual, continuous spillage (or windblown dust) from trucks transporting product or residue along public roads from Point A to Point B during the mining operation. The deposition of these materials along the public road creates an additional source of radiation exposure for the public.

Both examples would require pre-authorisation from the relevant authorities before being included in the environmental management programme. For example, the conditions governing the release of water to the environment are typically specified in the mine's water-use license. From a public radiation protection perspective, the importance is that if such conditions exist within the Project, they *should be defined and included in the radiological public safety assessment as potential sources of radiation exposure*.

4.3.5 Secondary Sources Due to Events Outside Normal Operating Conditions

This category of secondary sources manifests as discrete disruptive events that occur outside the normal operating conditions of a mining and mineral processing operation, resulting in the release of naturally occurring radionuclides into the environment via water- or solid-mediated pathways. Given their nature, these events 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 for 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 specific volume of water under normal operating conditions. This is usually done in accordance with

the regulations published in Government Notice No. 704 on 4 June 1999 (Government Gazette No. 20119), which are intended to protect water resources from mining and related activities. If these facilities do not function as planned or are not designed to contain water, releases to the environment are possible, potentially increasing concentrations in surface soil or surface water. 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 extensive and include features such as underdrains, toe paddocks, and dams to capture seepage and runoff from the facility. However, excessive water erosion may result in tailings being discharged into the environment.

  The most extreme case is when the TSF loses stability, fails, and spills into the environment (e.g., Merriespruit).

The aforementioned cases illustrate disruption events outside the normal operating conditions of a mining and mineral processing operation that may lead to secondary sources of radiation exposure. More examples may be defined on a site and operation-specific basis. It is important to note that the probability of these events occurring is uncertain. Consequently, the event is substantial in both scale and duration. This means the significance of secondary sources from such events is equally uncertain, as public radiation exposure depends on the event's magnitude and characteristics. For example, a pipeline burst lasting a full year will have different radiological consequences than one lasting a day. Similarly, a spillage of tailings material occurring in the open veld will have different implications 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 such discrete, isolated events may occur, the parameter values required 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 consequences of disruptive events are ignored within the broader radiation protection framework implemented in the Project.

The approach for such disruptive events is described in detail in the NNR-approved Radiation Management Plan, which outlines procedures (e.g., physical security, radiation function, emergency preparedness, occurrence reporting). For emergency preparedness, the emergency response plan is initiated as soon as an accident or incident is identified, with an emphasis on keeping radiation doses as low as reasonably achievable (ALARA).

As outlined in the radiation function procedure, specific actions must be taken on the day the incident or accident is identified, and additional actions must be taken as soon as possible thereafter. 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 taken to protect workers and members of the public; and exposures that have occurred and are expected.
- Initiate the cleanup process, taking into account the extent of contamination, the potential radiological impact on workers and the public, and appropriate interim mitigation measures to contain risks.

- 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 for the emergency preparedness procedure, they do 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, potential secondary sources of radiation exposure arising from events outside normal operating conditions will not be explicitly considered in the Project. However, recommendations will be made, as appropriate, to ensure they are adequately 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 lead to doses from ingestion of contaminated soil and food, as well as from external radiation.
- 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 different pathways into the environment, and how interactions among 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 atmospheric and groundwater, with surface water contributing to a lesser extent. 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 stems from the presence of naturally occurring radionuclides in the particulates and gases released into the atmosphere by 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 highest near the source and to decrease with distance from the source, depending on meteorological conditions, the physical characteristics of the contaminants, and the facilities from which they are released.

The sources identified in Section 4.3 relevant to the atmospheric pathway include the existing TSFs, WRDs, and ventilation shafts that contribute to baseline conditions, as well as the proposed Mponeng Lower TSF. Using emission estimates from these sources, modelled airborne concentrations of PM_{10} and 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, 2026). These results confirm that airborne particulates concentrations and radon gas concentrations are highest near the source and decrease with distance. 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.

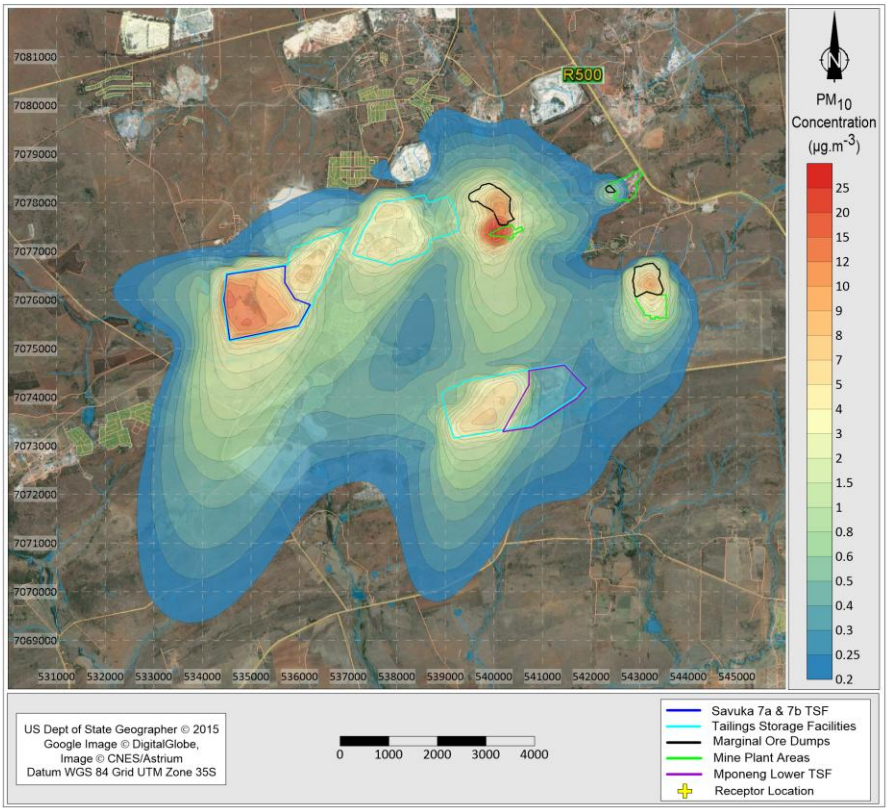

Figure 4.1 The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to the current baseline conditions from existing surface infrastructure.

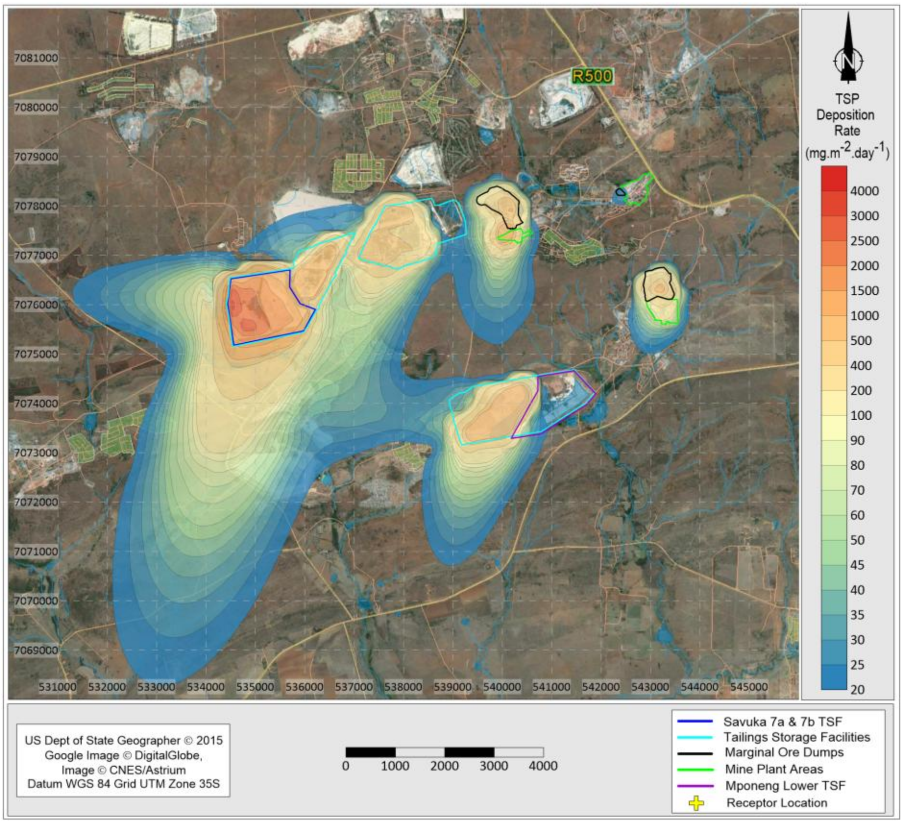

Figure 4.2 The simulated annual average TSP deposition rate (in units of mg.m^{-2}.day^{-1}) attributed to the current baseline conditions from existing surface infrastructure.

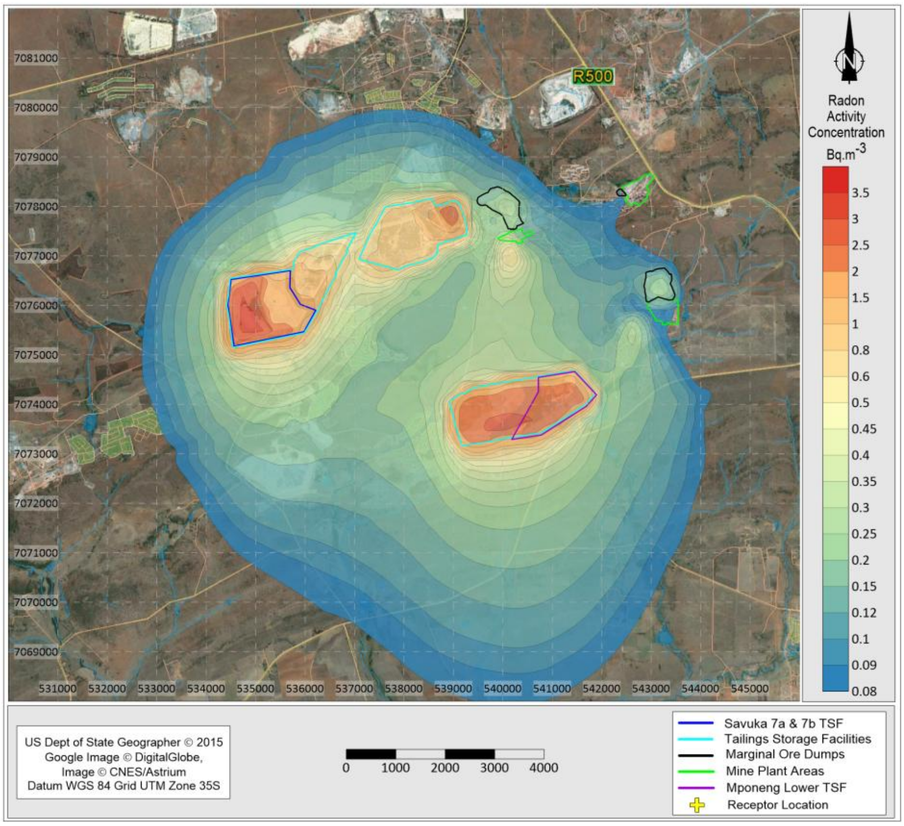

Figure 4.3 The simulated annual average radon concentration (in units of Bq.m^{-3}) attributed to the current baseline conditions from existing surface infrastructure.

4.4.2.3 Depositioning at the Lower Mponeng TSF

Figure 4.4 shows a graphical representation of PM_{10} deposition concentrations at the lower Mponeng TSF under 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 deposition concentrations at the lower Mponeng TSF and the current baseline conditions. Figure 4.4 to Figure 4.6 clearly illustrate the effect of the proposed deposition at the lower Mponeng TSF relative to baseline conditions.

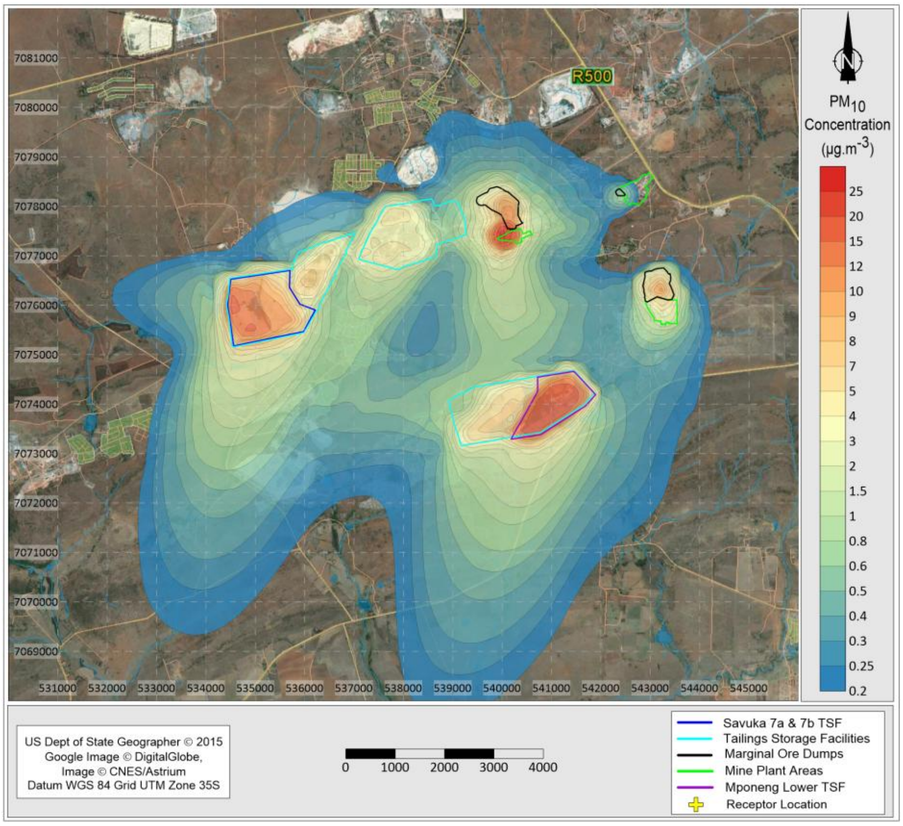

Figure 4.4 The simulated annual average airborne PM_{10} concentrations (in units of µg.m^{-3}) for the deposition at the lower Mponeng TSF and the current baseline conditions.

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 dust emissions containing 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 surface soils, thereby increasing soil concentrations. Depending on prevailing atmospheric conditions, contaminants deposited on the soil may be resuspended, further distributing them into the air. Exposure to soil concentration also contributes to an external gamma radiation dose (groundshine). Similarly, airborne contaminants may be deposited onto the surface water bodies, contributing to the surface water pathway (see Section 4.4.4).

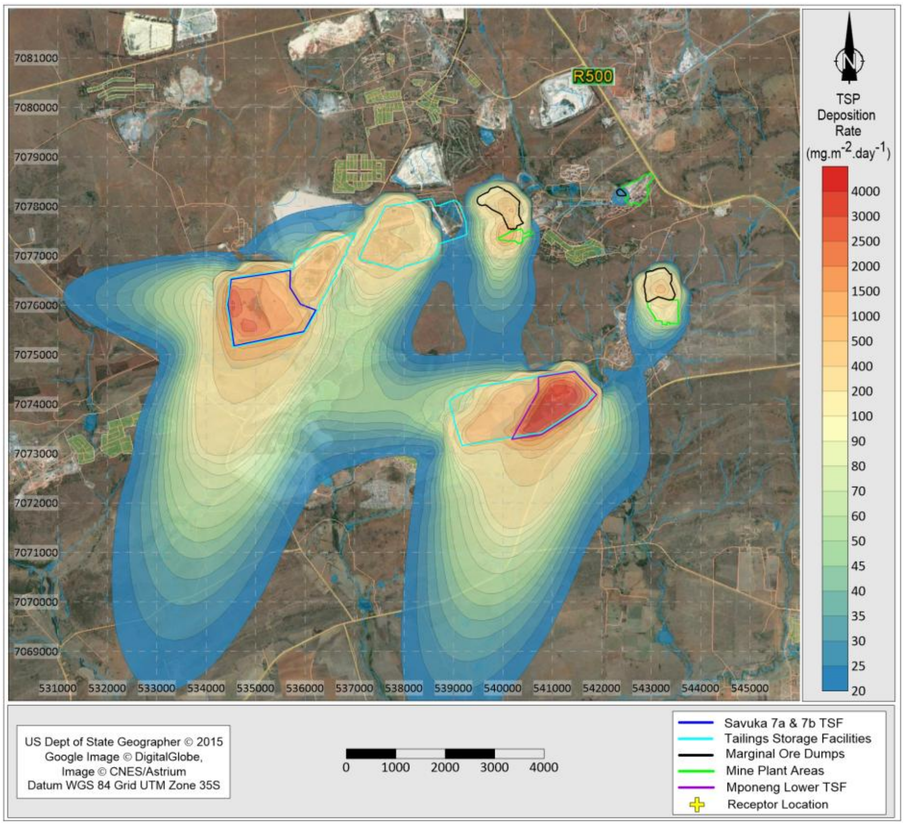

Figure 4.5 **The simulated annual average TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) for the deposition at the lower Mponeng TSF and the current baseline conditions.**

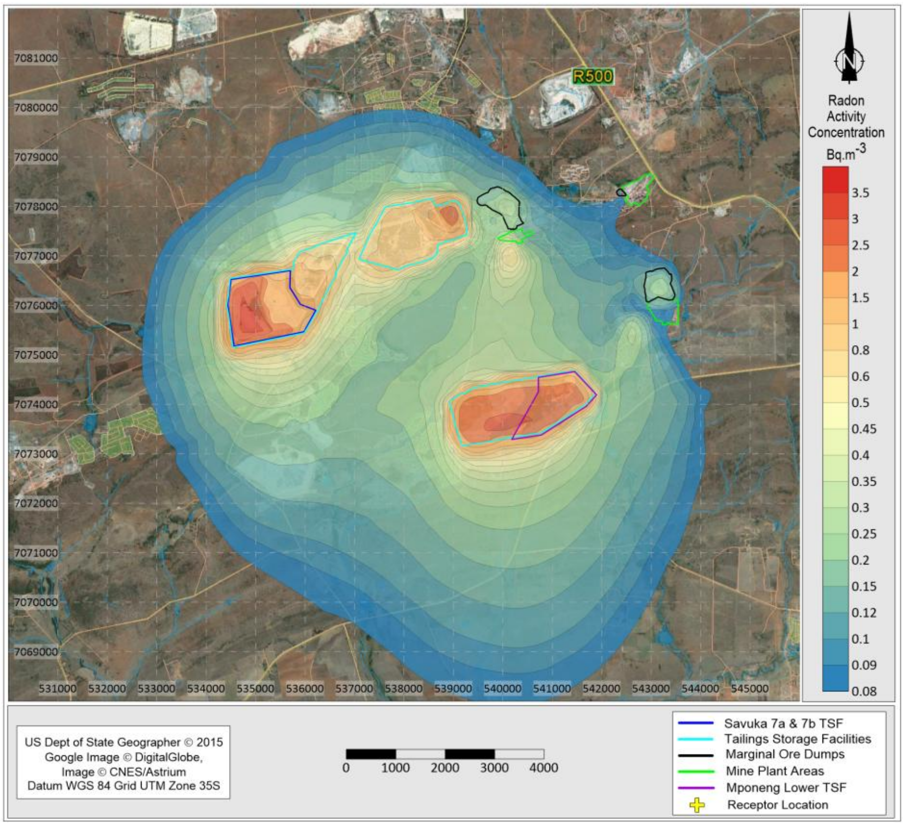

Figure 4.6 **The simulated annual average radon concentration (in units of $Bq.m^{-3}$) for the deposition at the lower Mponeng TSF and the current baseline conditions.**

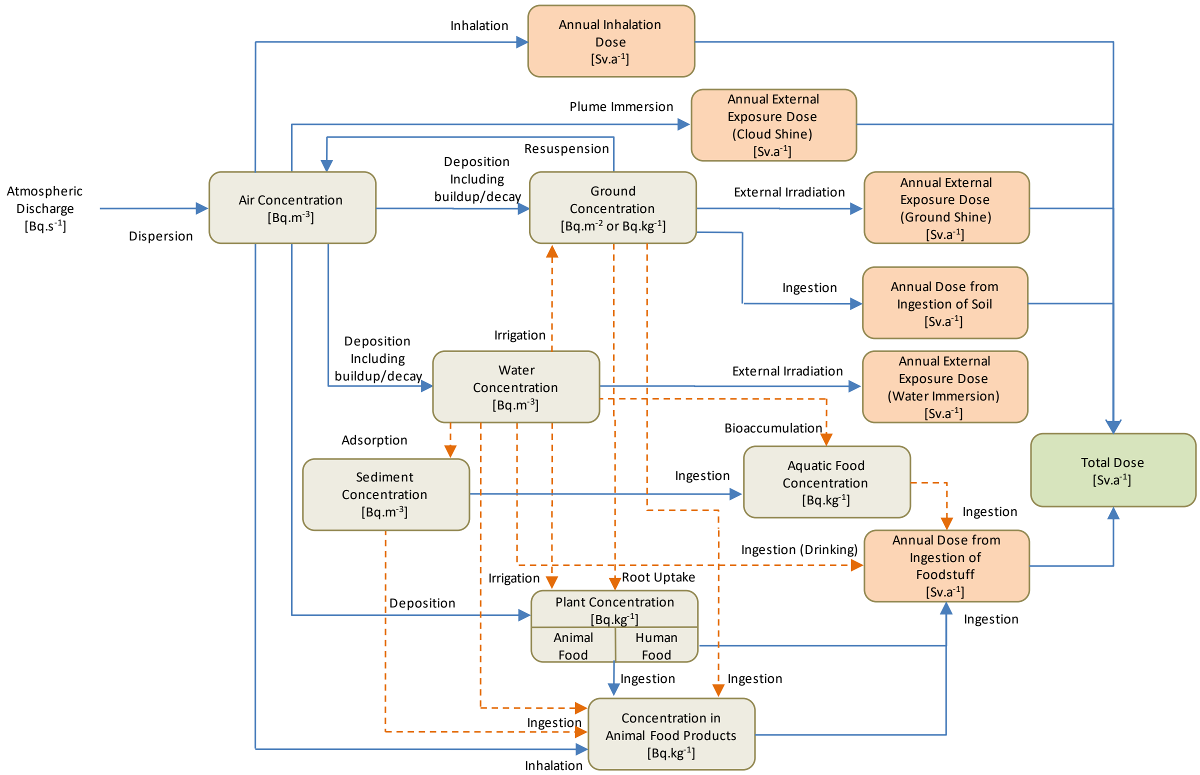

Figure 4.7 Features, processes, and associated exposure modes to consider when calculating the contribution of the atmospheric pathway to the total dose.

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, conversely, biological decay of crops containing radionuclides may increase soil concentration).
- Transfer (through translocation) of the deposited contaminants to the plant structure.

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

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

4.4.3 Groundwater Pathway

The primary sources of radiation exposure (see Section 4.3) for the groundwater pathway are linked to existing TSFs and their associated water management facilities in the area. Section 3.4.4 provides a summary of the hydrogeological conditions in the Project area, as documented by MvB Consulting (2025) and GCS (2024). A detailed characterisation of the hydrogeological flow regime of the Mponeng Operations is also provided in Aquisim (2020b).

The Mponeng Operations are divided into three water management areas: the North Boundary Dam, Varkenslaagte, and Aquatic Dam sub-catchments. These three sub-catchments are separated by topographic features that span the lease area and represent the three major “outflow” points for 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 of the Mooi River. However, it is stopped at the Turffontein Dolomite Compartment, where mining activities have dewatered the area. 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 radiation sources, the near-surface unconsolidated aquifer is particularly important. Any contaminants released from the sources can seep into the underlying aquifer, potentially increasing radionuclide concentrations in groundwater. Given the local groundwater gradient toward low-lying areas that coincide with surface water bodies, radionuclides released from sources into the underlying aquifer are expected to contribute to surface-water concentrations. This, together with groundwater abstraction toward the contaminant plume, may contribute to radiological impacts via aquatic pathways.

Water discharging from the North Boundary Dam sub-catchment joins the Wonderfontein Spruit and flows into the Mooi River and eventually the Vaal River. Water from these rivers is used for irrigation and domestic purposes. Groundwater in the southern sub-catchment (Aquatic Dam) flows southward and eventually drains into the lower Elandsfontein Spruit basin.

GCS (2014) demonstrated that a contaminant plume emanates from the primary sources in each of the three sub-catchments (see Figure 4.8 and Figure 4.9). Through groundwater flow and mass transport processes (e.g., advection, dispersion, and diffusion), radionuclides introduced into groundwater from these source areas may migrate to various discharge points (e.g., surface water streams, rivers, dams, springs, or boreholes). These processes can therefore result in increased radionuclide concentrations in surface water at these discharge points.

However, it should be considered that the contaminant plumes shown in Figure 4.8 and Figure 4.9 are representative of sulphate, which is very soluble and easily remains in solution. The movement of radionuclides may be retarded relative to other contaminants due to geochemical reactions and solubility constraints. Consequently, the radionuclides may take tens to thousands of years to migrate to groundwater discharge points such as boreholes (e.g. monitoring, drinking or irrigation boreholes), fountains, and surface water bodies.

The flow diagram in Figure 4.10 can be used to quantify the groundwater pathway's contribution to the total effective dose. Depending on radionuclide concentrations in groundwater and on human habits and behavioural characteristics, various secondary pathways can contribute to the total effective dose, as illustrated in Figure 4.10. These pathways are similar to those described for the atmospheric path, except that, rather than deposition of airborne contaminants onto crops or soils, irrigation with water increases radionuclide concentrations in crops or soils.

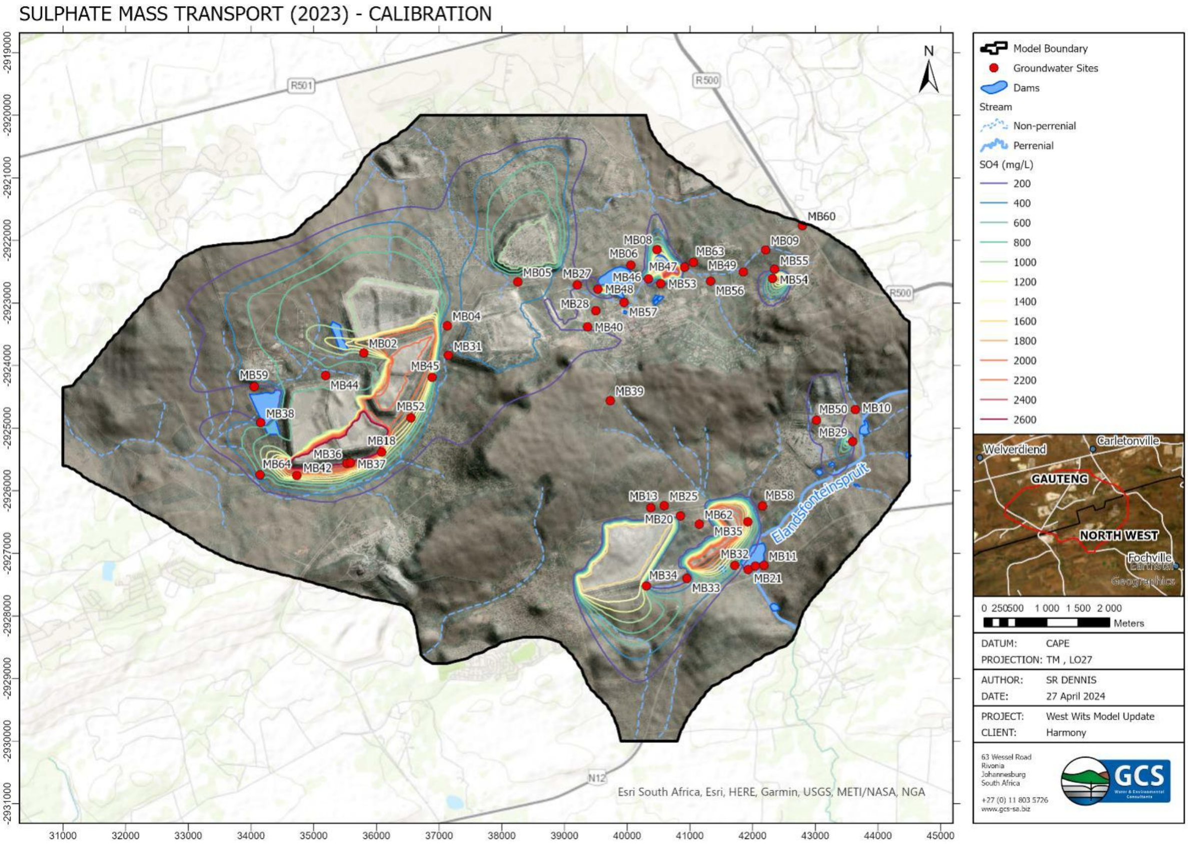

Figure 4.8 The calibrated SO_4 concentration plume for 2023 as reported in GCS (2024).

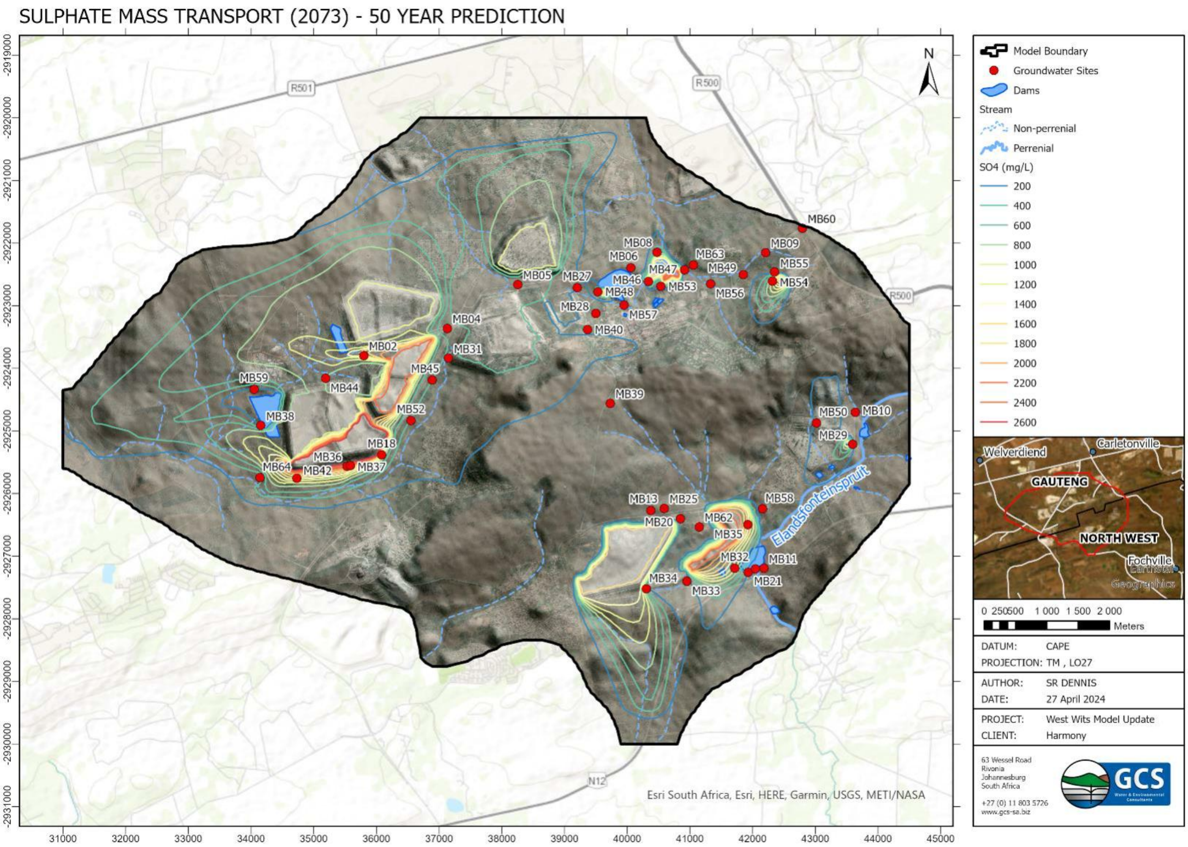

Figure 4.9 The calibrated SO_4 concentration plume after 50 years as reported in GCS (2024).

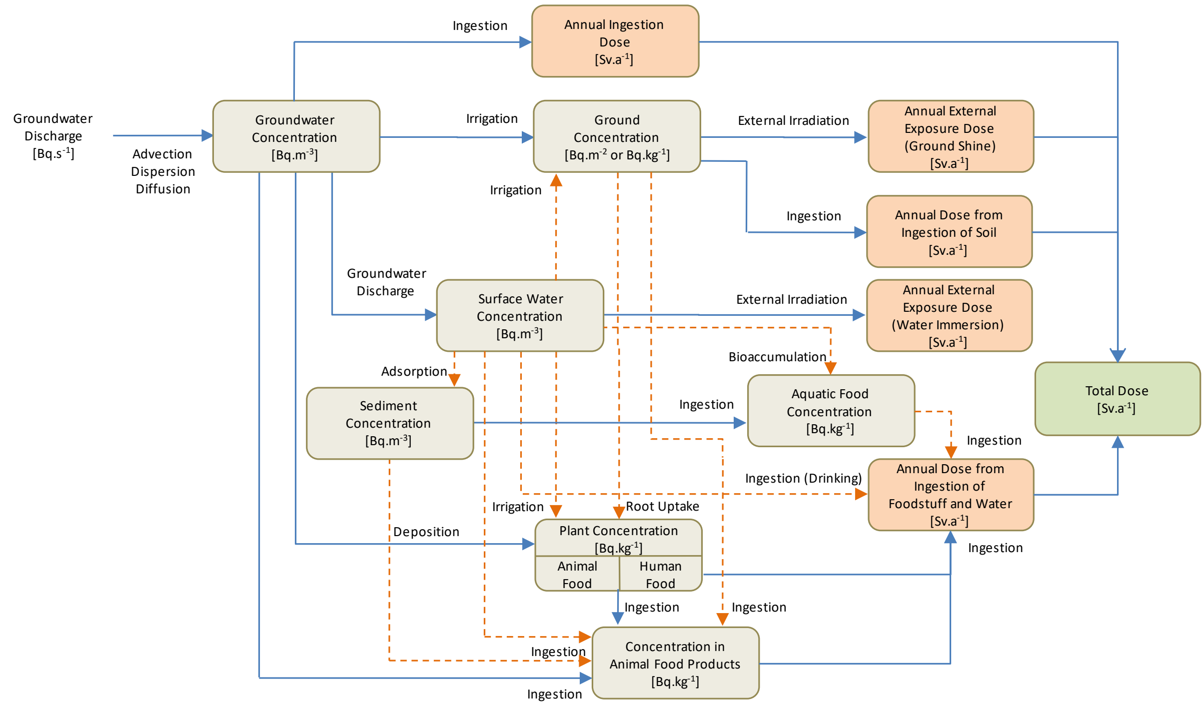

Figure 4.10 Features, processes, and associated exposure modes to consider when calculating the groundwater pathway's contribution to the total dose.

4.4.4 Surface Water Pathway

Under normal conditions, the surface water pathway extends the groundwater pathway and, to a lesser extent, the atmospheric pathway. However, the controlled or uncontrolled release of contaminated water or mine residue may directly increase radiation exposure through 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 that are illustrated in Figure 4.11 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 volatilisation (if any).

The distribution of radionuclides into surface water is thus much faster than in groundwater, and large volumes of surface water and sediment can 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.

Section 3.4.2 and Section 3.4.4 summarise 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.

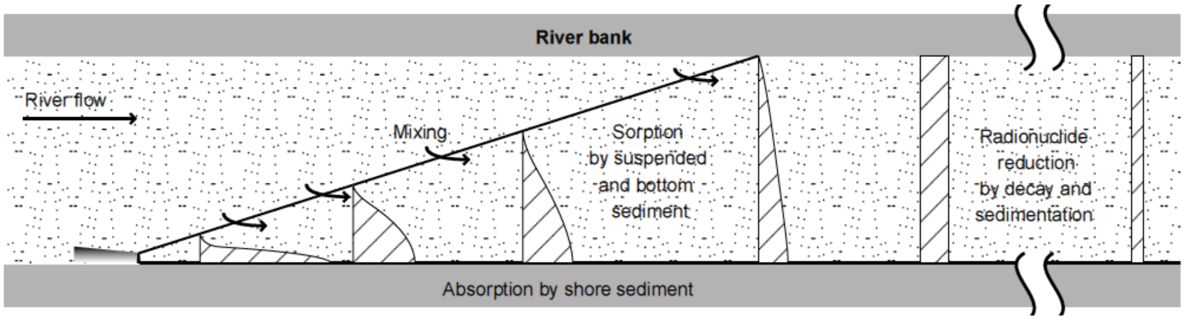

Figure 4.11 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001**).**

The flow diagram in Figure 4.12 can be used to calculate the contribution of the surface-water pathway to the total effective dose. Deposition of airborne radionuclides onto surface water bodies may increase radionuclide concentrations 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 radionuclide concentrations in surface water and on human habits and behavioural characteristics, various secondary pathways can contribute to the total effective dose, as illustrated in Figure 4.12. These pathways are similar to those described for the atmospheric pathway, except that, rather than deposition of airborne contaminants onto crops or soils, irrigation with contaminated water increases radionuclide concentrations in crops or soils.

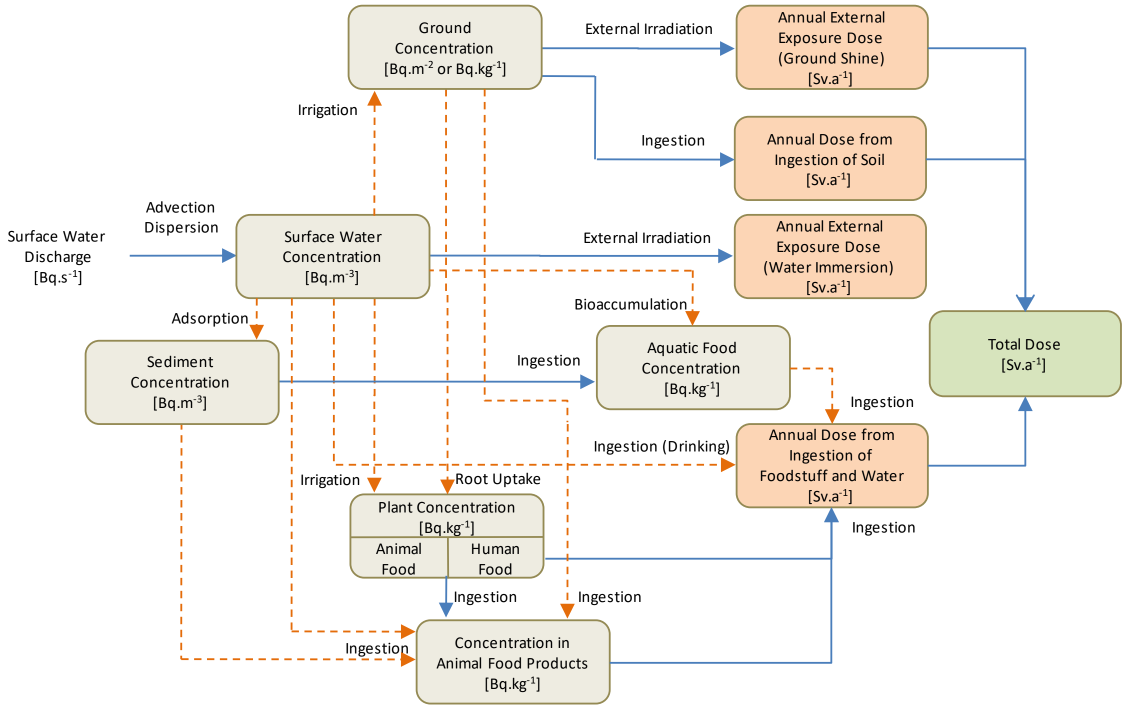

Figure 4.12 Features, processes, and associated exposure modes to consider when calculating the contribution of the surface water pathway to the total dose.

Direct exposure to contaminated surface water (e.g., swimming) also contributes to an external gamma radiation dose (water immersion). Adsorption of contaminants onto sediments results in their transfer and accumulation (buildup) within the sediments (sediment concentration). Contaminants in surface water can be transferred to aquatic animals such as fish (bioaccumulation) and can also be ingested from contaminated sediments.

4.4.5 External Gamma Radiation

Although not a contaminant in the usual sense, the inherent radiological properties of certain primary radiation sources can result in continuous gamma-ray emission, exposing 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, 2006b).

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 environmental contamination releases (secondary sources) is expected to be limited.

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, locations, ages, or other characteristics could lead them to receive a higher dose than the rest of the potentially exposed population.

The information presented in Section 3.4.6 indicates that the communities closest to the Project include the residents of Deelkraal, Elandsridge, Wedela, Southdene, and Northdene. Agricultural activities are present in the northwest, west and southwest of the Project area.

Radiological impact on receptors can occur only if a complete Source-Pathway-Receptor linkage exists. Section 4.4.2 demonstrates that the atmospheric pathway can transport radionuclides from the Project into the off-site environment. The spatial distribution of airborne particulates and contaminants can indicate whether members of the public may be affected. The dispersion modelling results, presented in Figure 4.1 to Figure 4.6, indicate that airborne particulate concentrations are highest near the sources and decrease rapidly with distance from the sources. The spatial distributions of airborne particulates and contaminants indicate that areas around the Project area, particularly in a southwesterly and southerly direction, are potentially the most impacted (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. However, 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 extends the groundwater pathway and, to a lesser extent, the atmospheric pathway. However, the contributions from both pathways are typically limited, particularly over the relevant timescales. A greater contribution is expected from both controlled and uncontrolled releases to surface water bodies. However, the Project operate in a closed water-balance system, and releases, whether controlled or uncontrolled, are limited.

Based on the synopsis above, conservative receptor locations cover most residential areas. The air quality-sensitive receptors identified in Airshed (2026) for the air quality impact assessment are shown in Figure 4.13, along with descriptions and coordinates of the locations listed in Table 4.1.

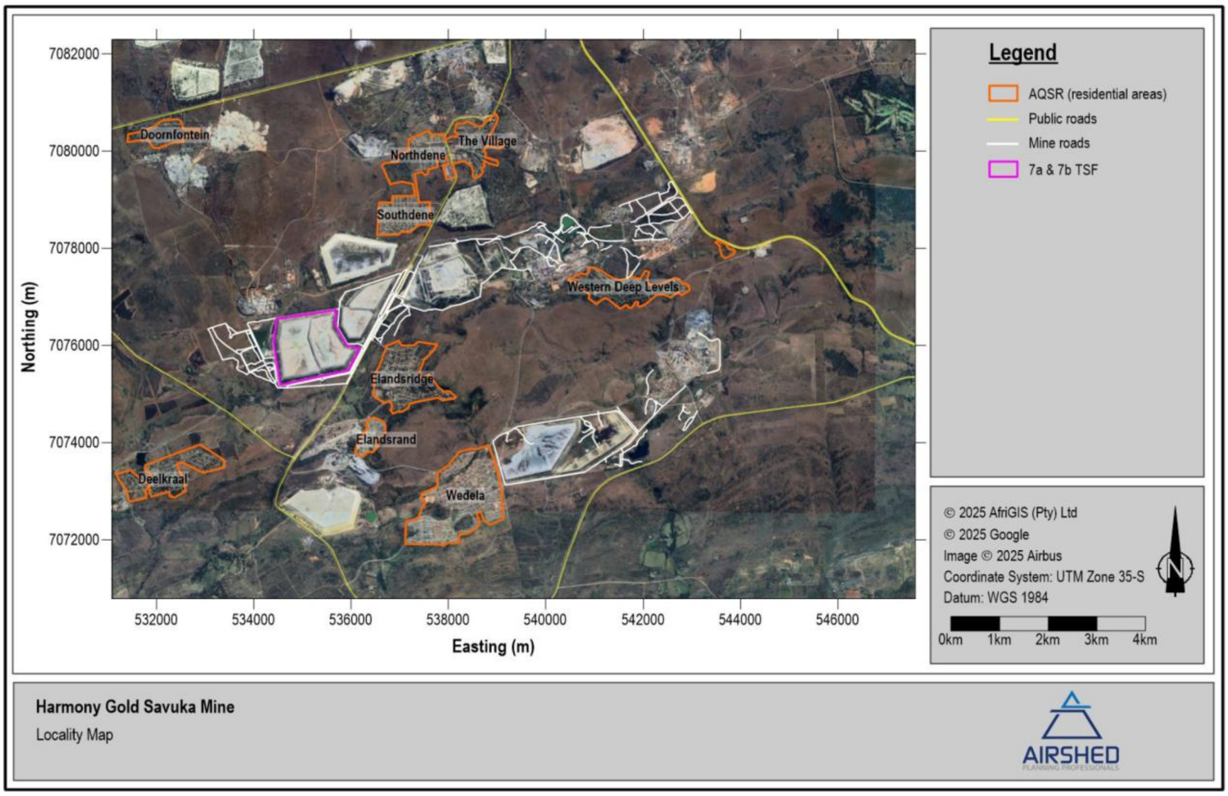

Figure 4.13 **Location map and Air Quality Sensitive Receptors identified in Airshed (2026) for the air quality impact assessment (see Table 4.1 for description and the coordinates).**

Table 4.1 **Description and coordinates of the Air Quality Sensitive Receptors identified in Airshed (2026) for the air quality impact assessment (see Figure 4.13).**

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*. Ideas, words, and figures represent a conceptual model, whereas a mathematical model is expressed as 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 natural sciences, the term conceptual model is used in diverse ways. Its interpretation and use often depend on the field and the application purpose. Various definitions of conceptual models can thus be found in the scientific and technical literature. These definitions share a 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 is a representation and simplification of reality as observed or analysed by the observer or analyst.

As in other scientific fields, conceptual models are widely used in radiological public safety assessments. The use of conceptual models in the development of exposure conditions is shown in Figure 1.5 and Figure 4.14.

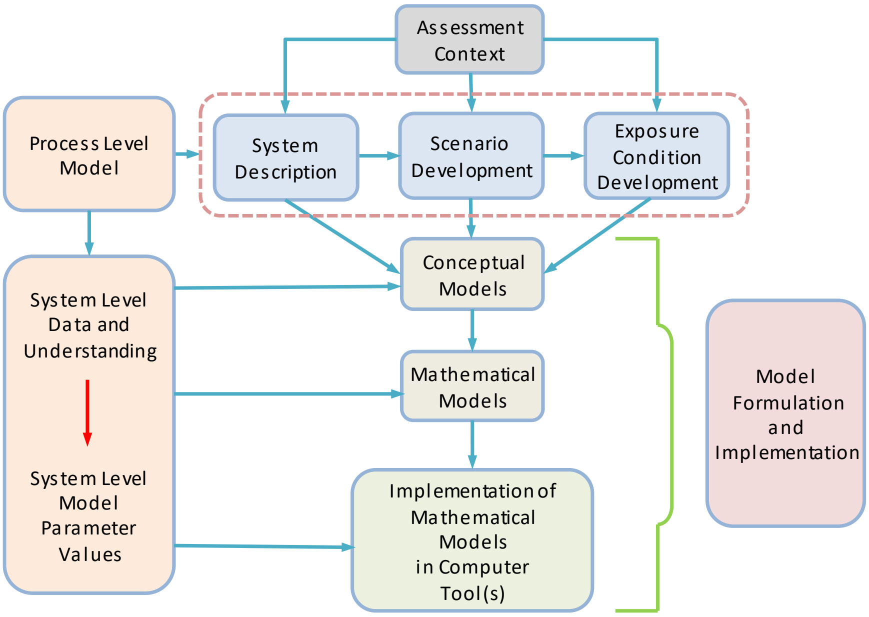

Figure 4.14 The model development process relative to other elements of the assessment framework presented in Figure 1.5.

4.6.2 Conceptual Models for Environmental Pathway Analysis

Three environmental pathways are essential to radiological public safety assessments of mining and mineral processing operations: the atmospheric, groundwater, and surface-water pathways. 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, 2026; GCS, 2024; HydroLogic, 2025; MvB Consulting, 2025). Conceptual models developed as part of these Process Level studies will not be repeated here.

4.6.3 Representation of Conceptual Models for Exposure Conditions

The conceptual model for developing exposure conditions is a schematic representation of reality, designed to improve 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, each contribution contributes to overall confidence in the assessment process.

Two methods are used to represent the concept of exposure conditions: 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 listed along the main 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 4.15, with the atmospheric (radioactive dust concentration) and topsoil layer as diagonal elements. Deposition is the exchange between the atmosphere and surface soil, and some of the deposited dust may be resuspended back into the atmosphere.

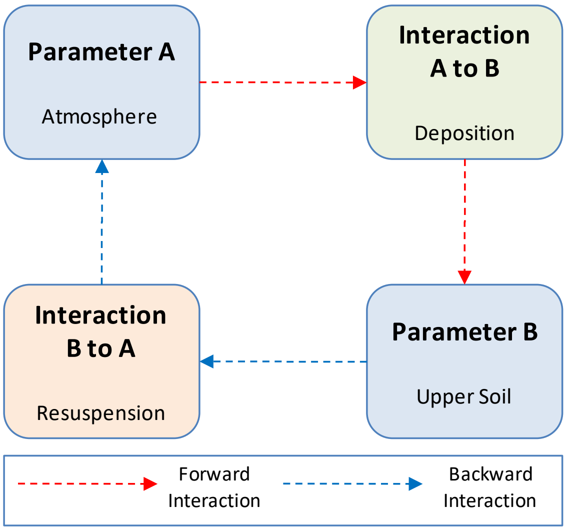

Figure 4.15 A simple 2x2 Interaction Matrix, showing the interaction between features, events, and processes in a safety assessment.

It is thus clear that the system's elements can be included in the Interaction Matrix and analysed in detail by creating one or more sub-matrices. This approach suggests that a specific theme, such as the migration pathway of radionuclides from sources to receptors, can be represented by the elements along the main diagonal. The off-diagonal elements represent interactions among events and processes that cause or influence the migration of radionuclides from one diagonal element (system feature) to another along the identified pathway. Those above the diagonal represent the influence on the forward motion, while those below influence the backward moment. This is illustrated in Figure 4.16, which shows 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.

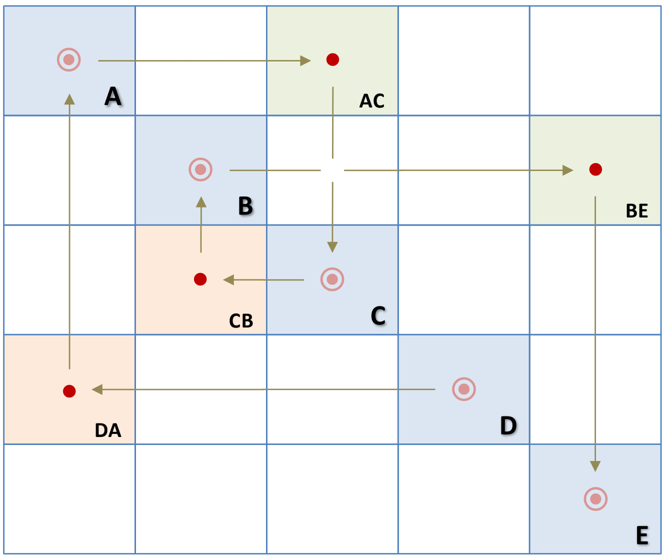

Figure 4.16 Principle of a radionuclide migration path through the Interaction Matrix.

Figure 4.17 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.

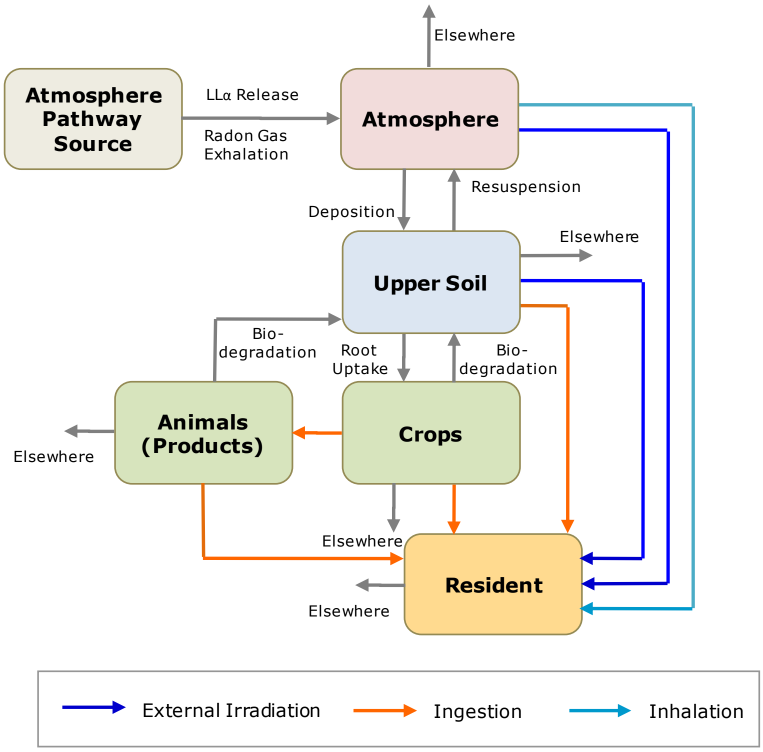

Figure 4.17 **A flow diagram is a conceptual model of a specific exposure condition, illustrating exposure pathways and relationships among the system's compartments.**

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 of this might vary. The release mechanisms (source terms) for the groundwater pathway, for example, tend to be slow. Releases from the atmospheric pathway sources are much faster. Direct releases to the surface-water pathway (e.g., overflow from a water-management facility) are often event-specific and may have an impact for only 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 through the release of particulate matter and radon gas. The dispersion is localised around the surface infrastructure of the Project and dissipates with distance away from the sources. This impact via the atmospheric pathway will persist as long as the sources remain at the site.

The release mechanisms of groundwater pathway sources and the subsequent dispersion into and through the environment differ from those of atmospheric pathways. The groundwater pathway is slow, primarily due to radionuclide adsorption onto porous media, with radiological impact potentially occurring only in the far future. The migration path extends through the unsaturated zone (vertically downward) before following the groundwater flow path to the lower-lying areas.

The release mechanisms for surface water pathway sources are the discharge of contaminated water into 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 significant only 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 primarily consist of residential areas, including densely populated low-cost housing areas. Given their proximity to surface infrastructure and the availability of social and land-use data, these population groups may receive higher radiological doses 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 with commercial 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 required across the phases of mining and mineral processing operations.
- Exposure conditions may vary with site-specific operational conditions.
- Different radiation sources (e.g., point or diffuse) may yield different exposure conditions for receptors.
- The importance of environmental (e.g., atmospheric, surface water, or groundwater) or direct exposure pathways depends on the characteristics of sources and human behaviour.
- 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 radiation receptor at a mining and mineral processing operation is an impossible task, particularly for evaluating radiological consequences. For this reason, the approach is to revert to a limited set of exposure conditions that capture the environment's diversity and complexity.

While the SPR analysis approach systematically derives exposure conditions, expert judgment may still be needed to combine information on sources, pathways, and receptors into well-defined, justified exposure conditions. 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, therefore, is on defining exposure conditions that are representative of a wide range of individuals and human behavioural conditions.
- In doing so, the emphasis is also on defining exposure conditions representative of the group of individuals with the highest exposure. This does not imply that other exposed groups are less important.
- Where possible, actual conditions are considered to derive exposure conditions that are representative and realistic.

Where justified, a set of alternative, hypothetical exposure conditions is defined. These hypothetical conditions tend to be more conservative, allowing a wide range of conditions to 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 2025 GCTI Operations RPSA (Aquisim, 2025b), 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.

Additional exposure conditions can be defined that are relevant to the area. The key criterion for assessing whether the discrete set of exposure conditions is representative of the radiological public safety assessment is whether potential radiation-exposure receptors can be associated with at least one of these conditions. The potential radiation exposure for nearby industry workers, for example, will be lower than that for 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 the Mohaleshoek informal settlement. This may include formal and informal residential structures. One can assume that residents of residential areas may have a household garden to supplement their daily food. However, it is reasonable to expect that informal settlements may be more dependent on these food sources 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 protein intake (eggs, milk, and meat). However, in formal areas, residents generally have access to plots large enough to meet their total annual food requirements, whereas in informal areas, they do not.

The primary contributor to the total effective dose in residential areas was shown to come from atmospheric (i.e., ambient air) and associated secondary pathways. No evidence was presented to suggest that any 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 indicate that surface water could 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 include external gamma radiation, internal exposure from ingestion of contaminated soil, crops, and animal products, and internal exposure from 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 comprise members of the public across all age groups.
- The exposure group maintains a small household garden consisting of fruits, vegetables (leafy and root), and cereal (mealies), which fulfils 50% of their annual requirements for these foods.
- The exposure group keeps animals such as chickens, goats, and cattle. These serve as sources of protein, including eggs, milk, and meat. For the assessment, it is conservatively assumed to account for 50% of their daily protein intake.

- Food preparation (e.g., peeling, boiling) may reduce radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in all food produced in the area remain constant regardless of the preparation method.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.2 lists the age-group-specific indoor and outdoor occupancy factors used 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 4.18 and Figure 4.19 using a flow diagram and an Interaction Matrix, respectively.

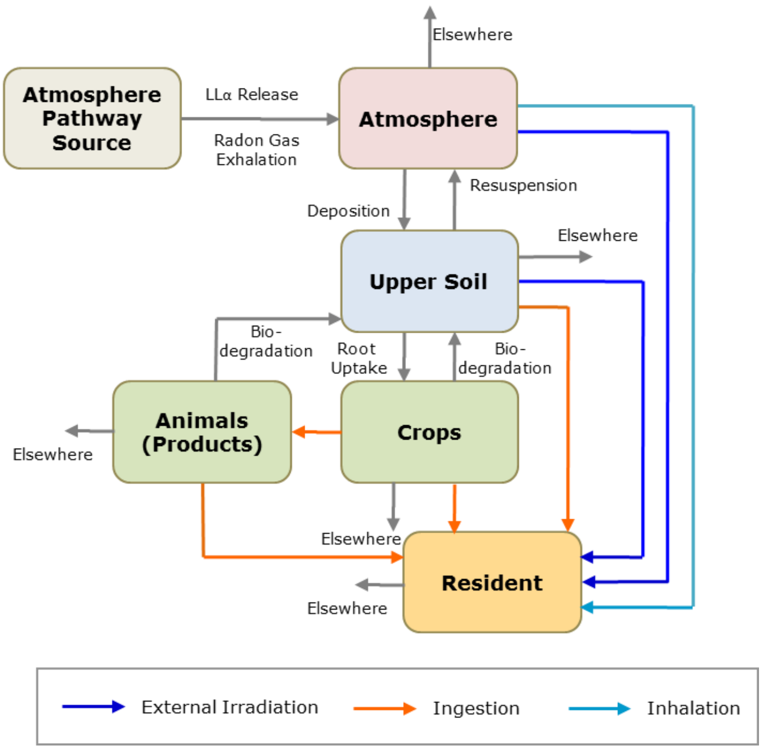

Figure 4.18 Conceptual flow diagram of the exposure pathways associated with a Residential Area Exposure Condition.

Radon gas and LLα released from atmospheric pathway sources are dispersed into the environment, thereby increasing airborne radionuclide concentrations. Some airborne radionuclides are deposited on soil surfaces and on crops (fruits, vegetables, and cereals), thereby increasing radionuclide concentrations in both soil and crops. Root uptake processes transfer radionuclides from the soil to 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 from radionuclides deposited on the upper soil layer (groundshine).

Note that, as illustrated in Figure 4.18 and Figure 4.19, biodegradation of crop material may also increase the upper soil concentration, while resuspension of deposited dust may contribute to the airborne activity concentration. Also illustrated in Figure 4.18 and Figure 4.19 is the transfer of radioactivity released from 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	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				Biodegradation Excrement		Animals	Ingestion	
				Irrigation Tilling Ploughing	Plant crops Food preparation	Feed	Resident	Excrement
J								Elsewhere

Figure 4.19 Conceptual Interaction Matrix of the exposure pathways associated with Residential Area Exposure Condition.

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 within a radius of the Project. This means that the exposure condition applies to any farming activity under the conditions and assumptions outlined below.

The main contributors to the total effective dose are atmospheric, groundwater, and associated secondary pathways. This resulted in contributions from external gamma radiation, internal exposure from ingestion of contaminated water, soil, and crops, and internal exposure from 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) comprise members of the public across all age groups.
- The exposure group maintains a commercial farm system consisting of fruits, vegetables, and cereals (maize). It is conservatively assumed that the farm accounts for 100% of its annual consumption rate.

- The exposure group keeps animals such as chickens, sheep, and cattle. These serve as sources of protein, including eggs, milk, and meat. For the assessment, it is conservatively assumed that it accounted for 100% of their annual consumption rate.
- Food preparation (e.g., peeling, boiling) may reduce radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in all food produced in the area remain constant regardless of the preparation method.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.2 lists the age-group-specific indoor and outdoor occupancy factors used for the assessment.

The conceptual model for the Commercial Agricultural Exposure Condition is presented in Figure 4.20 and Figure 4.21 using a flow diagram and an Interaction Matrix, respectively.

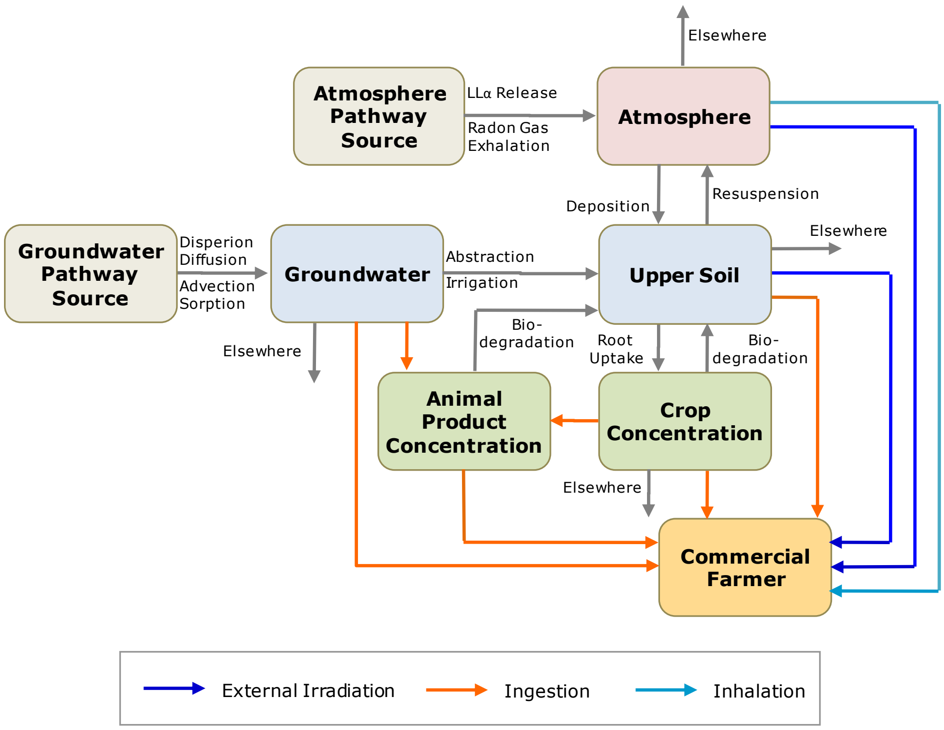

Figure 4.20 Conceptual flow diagram of the exposure pathways associated with the Commercial Agricultural Exposure Condition.

Radon gas and LLα released from atmospheric pathway sources are dispersed into the environment, contributing to airborne radionuclide concentrations. Some airborne radionuclides are deposited on crops (fruits, vegetables, and cereals), thereby increasing radionuclide concentrations in crops and the upper soil layer. Root uptake processes transfer radionuclides from the soil to crops.

Radionuclides leached from groundwater pathway sources enter the underlying aquifer, where they are dispersed into groundwater and surface water environments. Members of the public practising agriculture use groundwater abstracted from a borehole for domestic consumption and to maintain a commercial farming system (i.e., irrigation and water supply) comprising crops, poultry, and cattle. Radionuclides in water are deposited on crops, thereby increasing radionuclide concentrations in the crops and the upper soil layer. Root uptake processes transfer radionuclides from the soil to crops. Products such as meat, milk, and eggs from animals that consume contaminated water or crops may contain elevated radionuclide concentrations.

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 arise from exposure to LLα in the atmosphere (cloud immersion) and from radionuclides deposited in the upper soil layer (groundshine).

Note that, as illustrated in Figure 4.20 and Figure 4.21, biodegradation of crop material may also increase radionuclide concentrations in the upper soil layer, whereas resuspension of deposited dust may increase airborne radioactivity. Also illustrated in Figure 4.20 and Figure 4.21 is the transfer of radioactivity released from 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						Biodegradation Excrement		Animals	Ingestion	
					Abstract	Irrigation Tilling Ploughing	Plant crops Food preparation	Feed	Commercial Farmer	Excrement
J										Elsewhere

Figure 4.21 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 for calculating 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 for agricultural purposes cannot be excluded with confidence. In principle, groundwater abstracted from a borehole may be contaminated by leachate from facilities associated with the Project (e.g., TSF or RWD). However, the leaching and subsequent lateral migration of radionuclides are slow processes. 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, for illustrative purposes only. Consequently, a simplified one-dimensional numerical groundwater model is presented, 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 comprises several compartments that must be considered holistically to assess its potential contribution to the total effective dose. Figure 5.1 depicts the relevant compartments and their interactions. 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 potential radionuclide concentrations in groundwater and the resulting ingestion dose, hypothetical conditions, complemented by site-specific conditions, are used to illustrate the relative insignificance of the groundwater pathway over a brief period (e.g., the operational period).

5.2.2 Parameter Values

As a conservative assumption, the average activity concentrations listed in Table 3.18 for the CoR-03 tailings material generated at the Mponeng Operations were used as the initial activity concentrations. Table 5.1 summarises additional parameter values used for the leaching analysis. Note that these parameter values are selected conservatively.

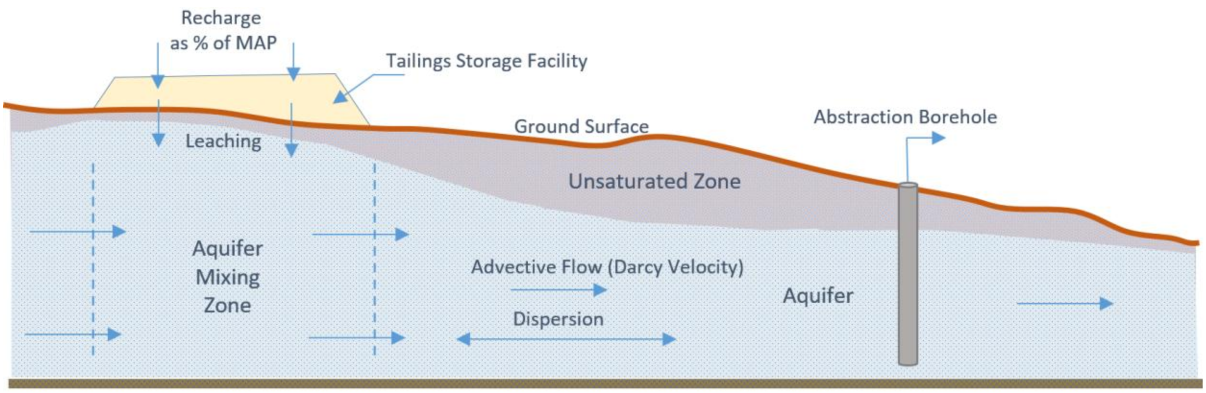

Figure 5.1 Conceptual representation of the model compartment included in the System Level modelling of the groundwater pathway (Not to Scale).

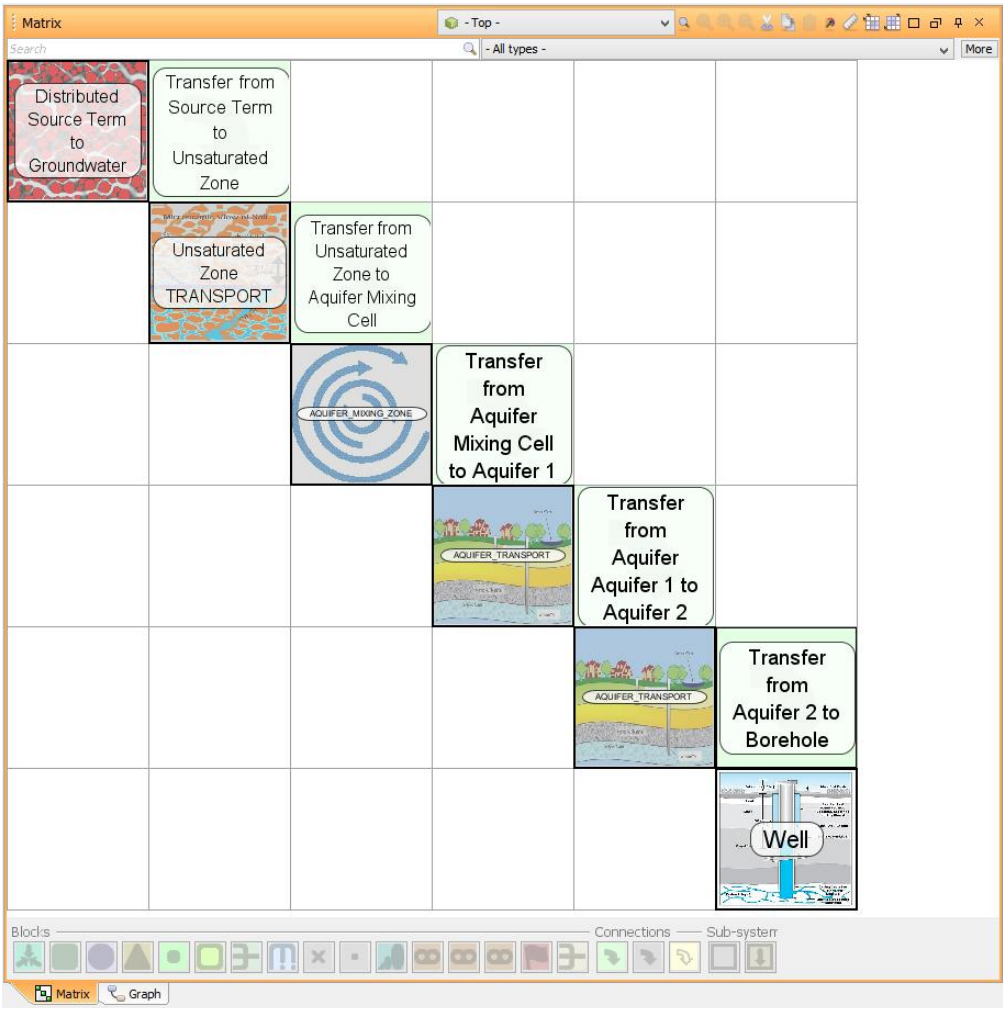

Figure 5.2 Screen capture of the model implementation in AFRY ISM used to evaluate the contribution of the groundwater pathway for the Project.

It was assumed that the recharge (or infiltration) rate of water through the TSF decreases from the assumed 50-year operational period 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 that the TSF will remain at the surface for 1 million years, the duration used in the simulations.

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

Parameter			Units	Mponeng TSF
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}]	2.63E+03
Average Height			[m]	60
Average Area			[m^2]	2.32E+06
Assumed Length and Width (√Area)			[m]	1.52E+03
Volume			[m^3]	1.39E+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 highly conservative, assuming minimal absorption to retard radionuclide migration 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 analysis presented here uses 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), along with the literature ranges for different soil types reported by the Argonne National Laboratory (Yu *et al.*, 1993). The comparison shows that reported distribution coefficient values 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 beneath 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.

5.2.3 Results

The Mponeng TSF drains towards the Elandsfontein Spruit, which is about 1,000 m south of the TSF. Results from the calibrated groundwater flow model suggest that the *maximum* flow velocity in the underlying aquifer is in the order of 1.2 m.day^{-1} near the TSF towards the Elandsfontein Spruit, which equates to a Darcy velocity of 8.77 m.year^{-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		30
Hydraulic Conductivity	m.day^{-1}	1.2
Effective Porosity	-	0.02
Hydraulic Gradient		0.02
Darcy Velocity	m.day^{-1}	2.40E-02
Actual Velocity		1.20E+00
Longitudinal dispersivity (α_L)	m	30
Dry Bulk Density	kg.m^{-3}	1,800
Distance to Borehole	m	500
Borehole Fraction in Contaminant Plume	-	1

Figure 5.3 presents the resulting nuclide-specific activity concentrations in groundwater abstracted from the borehole, showing 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 5.4 translate to water ingestion doses shown in Figure 5.3. It illustrates that, under the assumed conditions, the potential contribution from the groundwater pathway at a point 500 m from the Mponeng TSF is detectable only after thousands of years and may be at doses of approximately 50 µSv.year^{-1} or lower. Water ingestion doses above 10 µSv.year^{-1} are detectable only after 3,000 years.

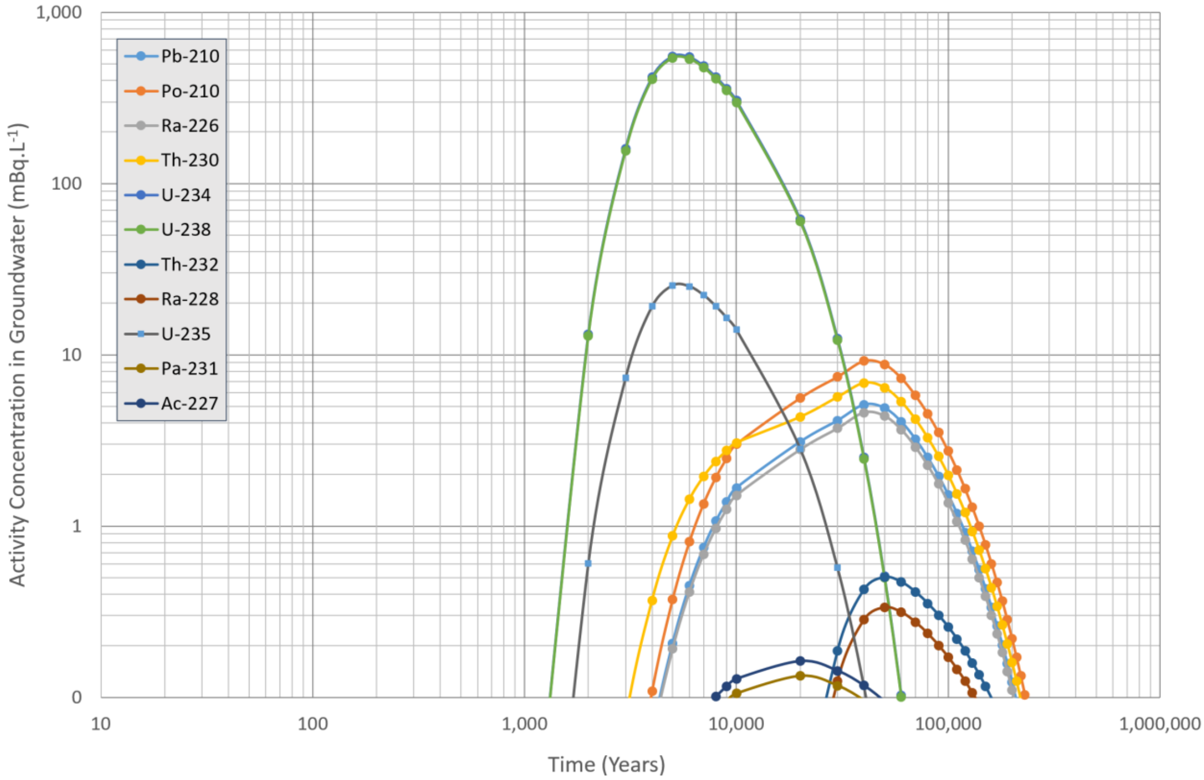

Figure 5.3 The simulated activity concentration in groundwater abstracted from a borehole 500 m from the Mponeng TSF.

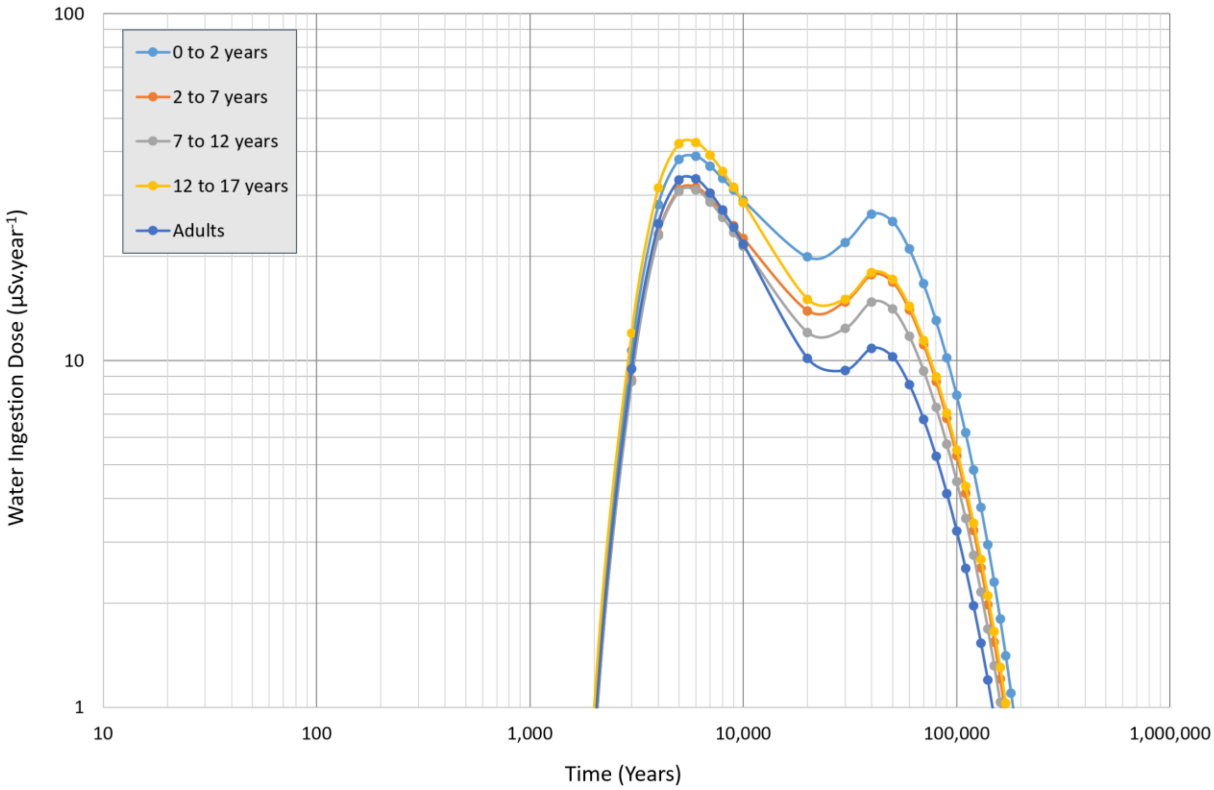

Figure 5.4 The simulated water ingestion dose to the different age groups 500 m from the Mponeng TSF, using the activity concentrations in Figure 5.3.

The results presented in Figure 5.3 to Figure 5.4 suggest that a contribution from the groundwater pathway is possible only during the post-closure period and unlikely over the next 1,000 years, and then only at doses below 70 µSv.year^{-1}. This applies to the current Mponeng TSF and the deposition on the lower Mponeng TSF.

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 practical dose calculations for the public exposure conditions defined for the Project in Section 4.7. Given the nature of these exposure conditions and the potential contributions of different environmental pathways to the total effective dose, the results presented here focus on 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.

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, so the radioactivity concentrations of the dust released by each source differ accordingly. 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 3.18 were used for the Mponeng Operations TSFs, for which no full-spectrum analysis is currently available.

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 results in nuclide-specific airborne activity concentrations (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 residen residential areas such as Deelkraal, Elandsrand, Wedela, the mine villages and residences, as well as the Mohaleshoek informal settlement, 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 accounts for 50% of their annual consumption of cereal, fruit, and vegetables, as well as animal products such as eggs, milk, and meat.

The primary contributor to the total effective dose in informal residential areas was shown to originate from atmospheric (i.e., ambient air) 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) reared in the yard (50% annual consumption rate).
- Inadvertent ingestion of contaminated soil.
- External exposure to radionuclides deposited in the upper soil layer (ground shine) and external exposure to airborne LLα (cloud shine).

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

5.3.3.2 Results

The results are presented graphically as dose isopleths overlain on a map of the Project and the surrounding area. The dose isopleths in Figure 5.5 represent the total effective dose for the 12 to 17-year age group under Baseline Conditions. Based on the dose estimate, the 12 to 17-year age group was shown to receive the highest total effective dose (see Figure 5.7). Figure 5.6 presents the total effective dose for the 12 to 17-year age group for deposition at the lower Mponeng TSF and under current baseline conditions.

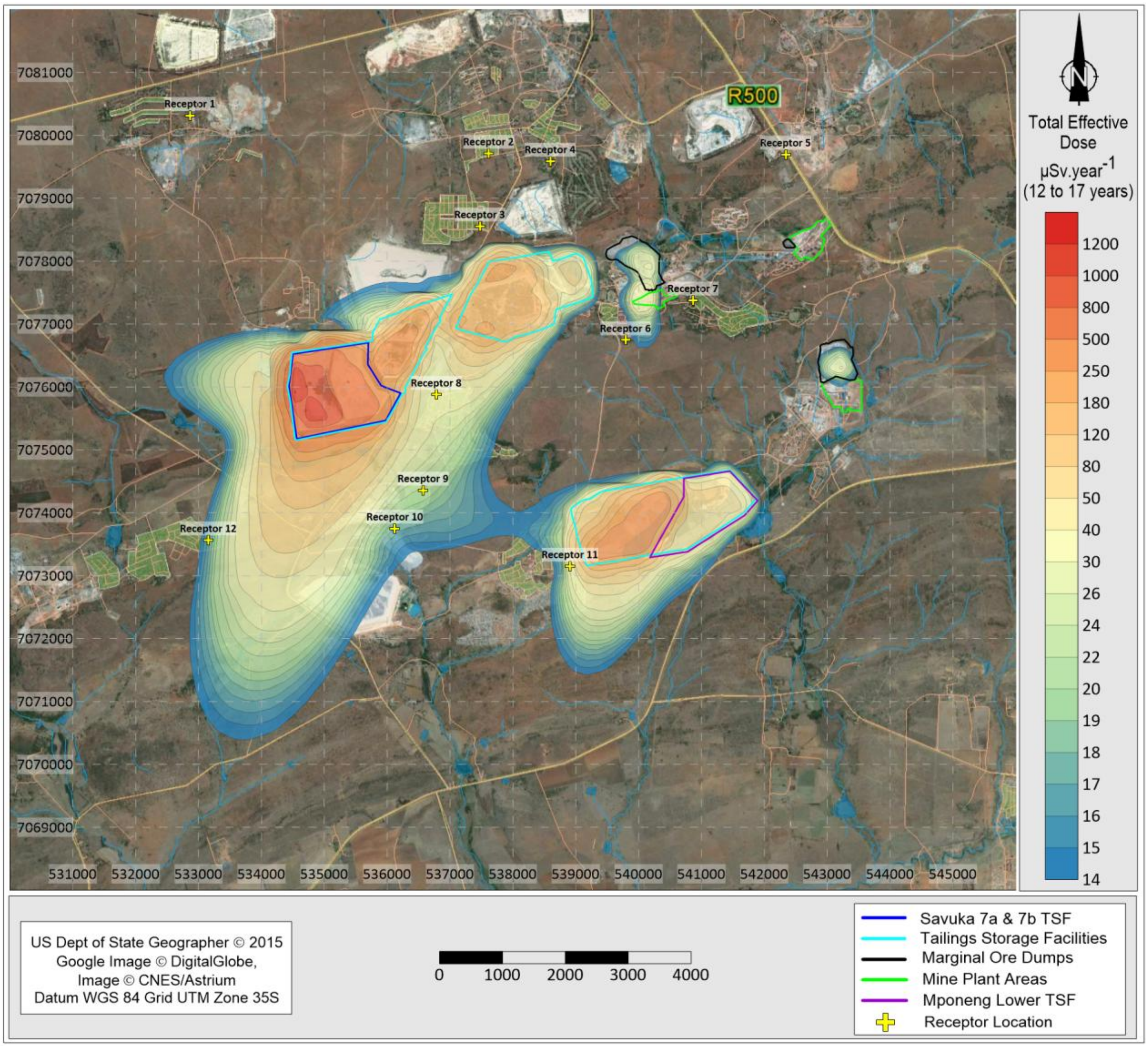

Figure 5.5 **Dose isopleths showing the total effective dose (12 to17 years of age, in µSv.year^{-1}) for the Residential Area Exposure Condition, attributable to the baseline conditions.**

5.3.3.3 Interpretation of Results

The dose isopleth results presented in Figure 5.5 show that the effect of the baseline condition on residential areas is minimal and does not extend into residential areas at doses greater than 1 to 40 µSv.year^{-1}. Figure 5.6 shows that the contribution from deposition at the lower Mponeng TSF is also minimal, resulting in an insignificant increase in the total effective dose. However, it still does not reach residential areas at doses below 40 µSv.year^{-1}.

To put the dose isopleth result into perspective, the total effective dose results at several receptor locations in residential areas are presented in Figure 5.7 and Figure 5.8 (see Figure 5.5 for the locations). These locations correspond to the locations identified in the air quality impact assessment (Airshed, 2026). The results are for all age group categories listed in Table B 1.

The results indicate 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 value at Elandsridge. With the height extension included, the dose in this area remains below 40 µSv.year^{-1}.

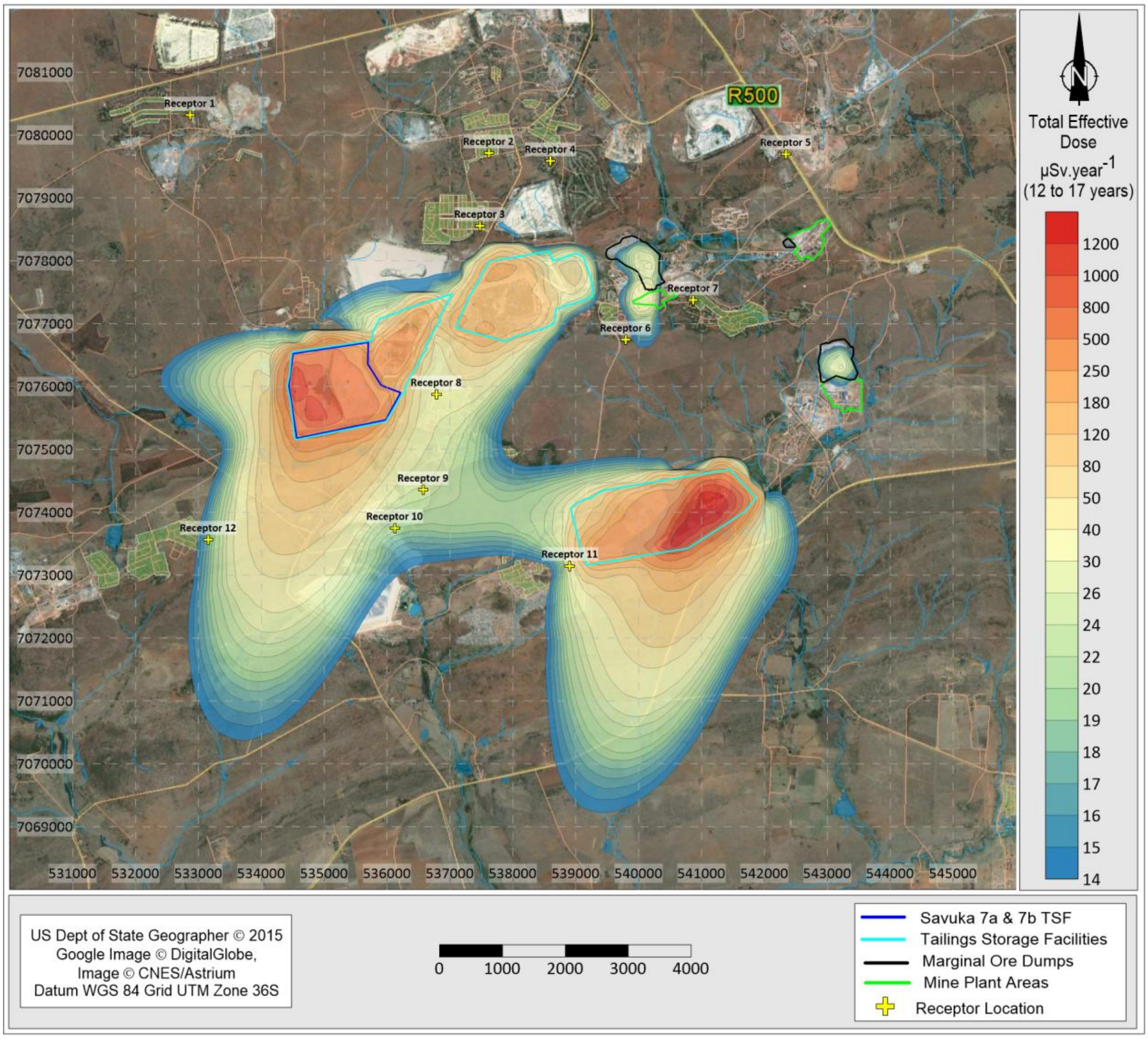

Figure 5.6 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) for the Residential Area Exposure Condition attributed to deposition at the lower Mponeng TSF and under current baseline conditions.

Figure 5.7 and Figure 5.8 suggest that for some locations, the primary 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 primary contributor to the total effective dose. External gamma radiation (from cloud and groundshine) 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, 2026).

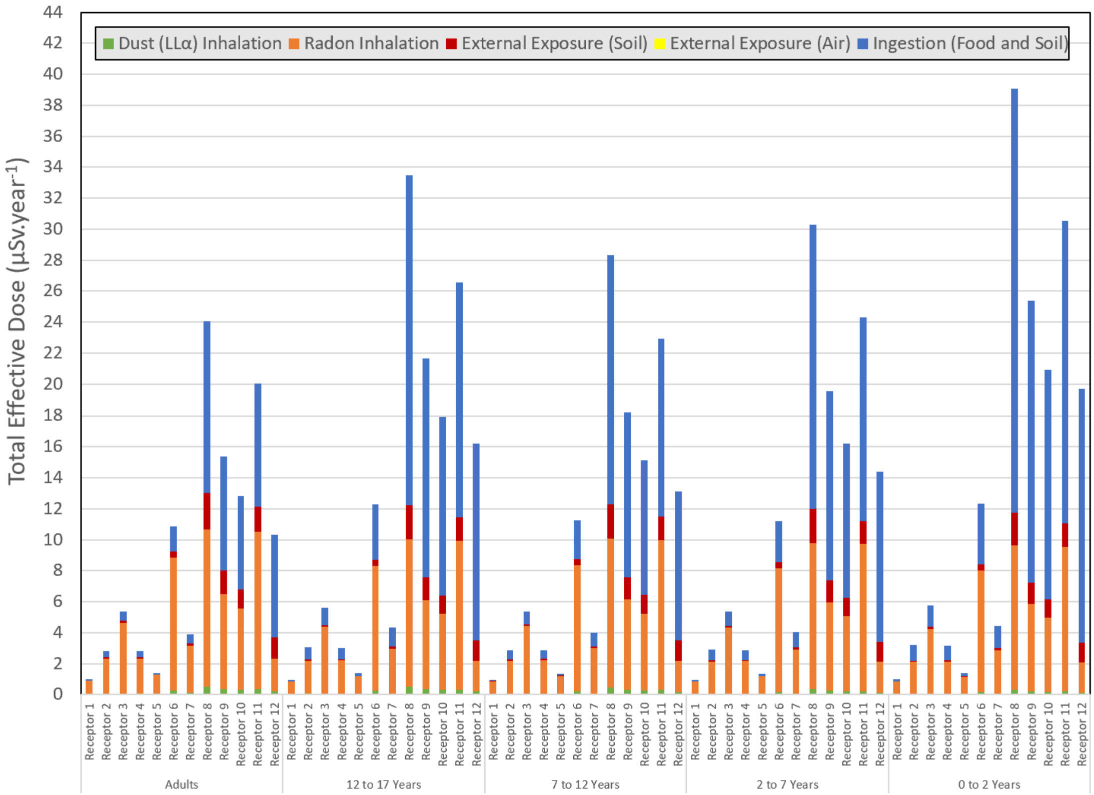

Figure 5.7 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.5 for locations).

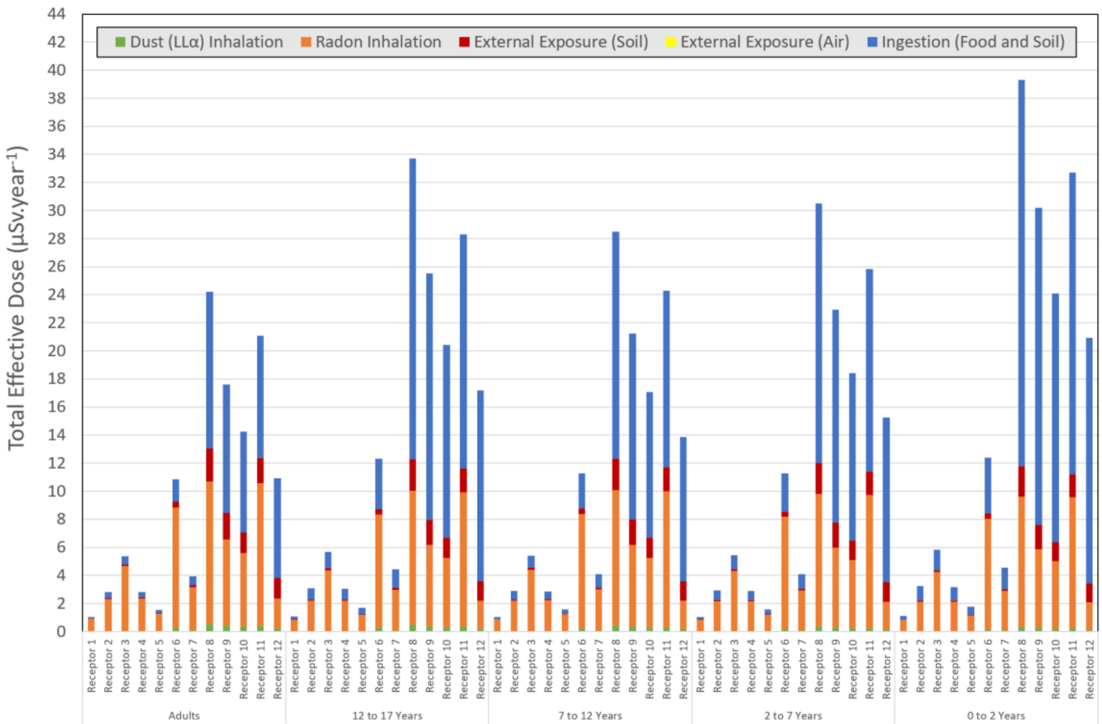

Figure 5.8 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to deposition at the lower Mponeng TSF, in addition to the baseline conditions (see Figure 5.5 for locations).

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 within a radius of 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 depend on the land for annual consumption of cereals, fruits, and vegetables, as well as animal products such as eggs, milk, and meat.

The main contributors to the total effective dose for the Commercial Agricultural Exposure Condition are atmospheric, groundwater, and associated secondary pathways. Groundwater sustains the farm system through irrigation and supplies water for livestock. 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) from 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 graphically as dose isopleths overlain on a map of the Project and the surrounding area. The dose isopleths in Figure 5.9 represent the total effective dose for the 12 to 17-year age group under 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 5.11). Figure 5.10 presents the total effective dose for the age group 12 to 17 years, attributed to deposition at the lower Mponeng TSF, along with baseline conditions (see also Figure 5.12).

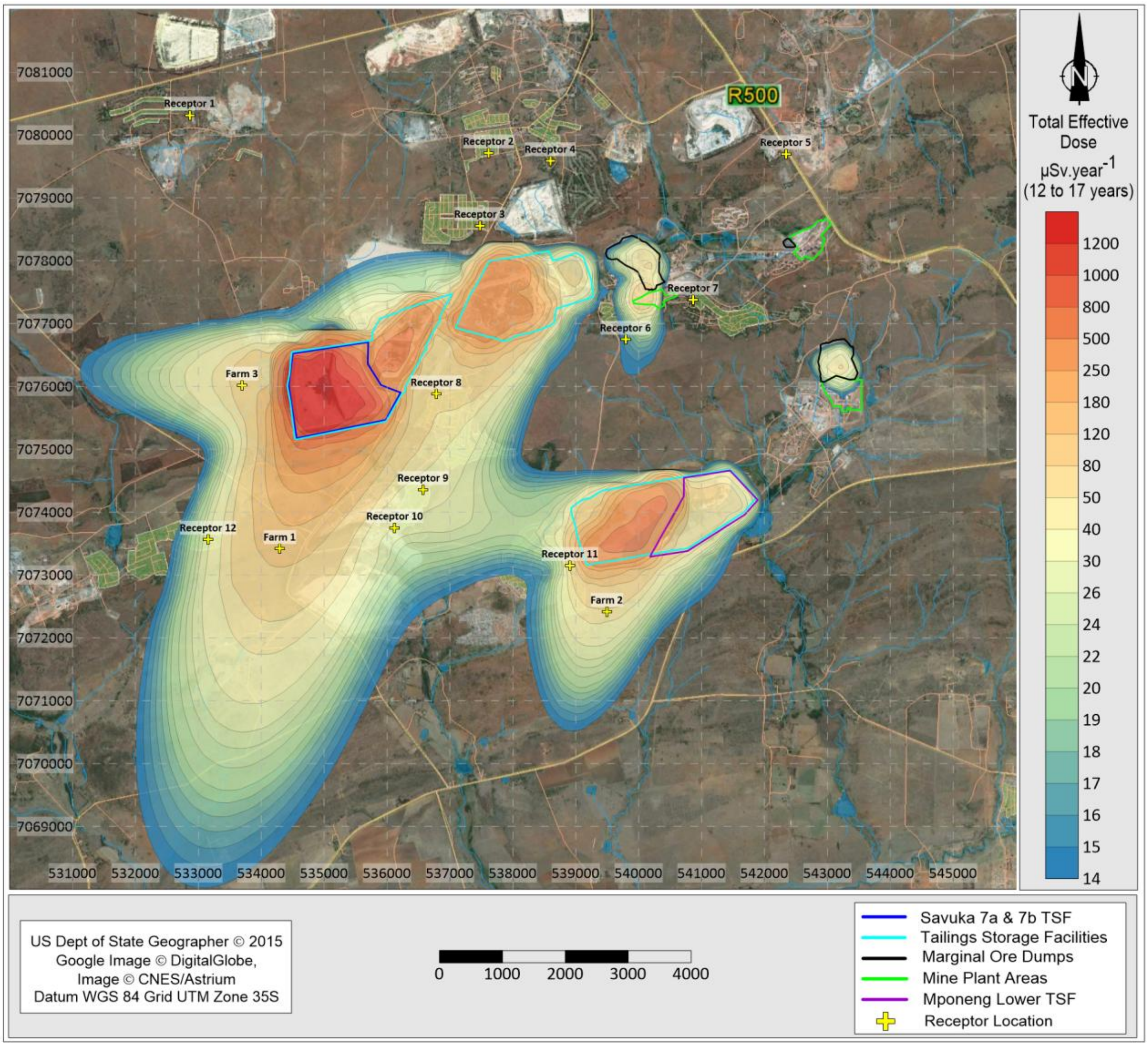

Figure 5.9 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the baseline conditions.

5.3.4.3 Interpretation of Results

As expected, the radiological impact of the Commercial Agricultural Exposure Condition is greater than that of the Residential Area Exposure Conditions because it includes more exposure pathways at higher ingestion rates. The effect is more pronounced near the TSFs and decreases with increasing distance from them. The dispersion is almost predominantly towards the west and southwest. The impact of deposition at the lower Mponeng TSF is noticeable, but not expected to increase the public dose above the dose constraint of 250 μSv.year^{-1}.

To put the dose isopleth result into perspective, the total effective dose results at several receptor locations are presented in Figure 5.11 and Figure 5.12 (see Figure 5.9 for locations). Some of these locations correspond to the locations identified in the air quality impact assessment (Airshed, 2026). 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 age group categories listed in Table B 1.

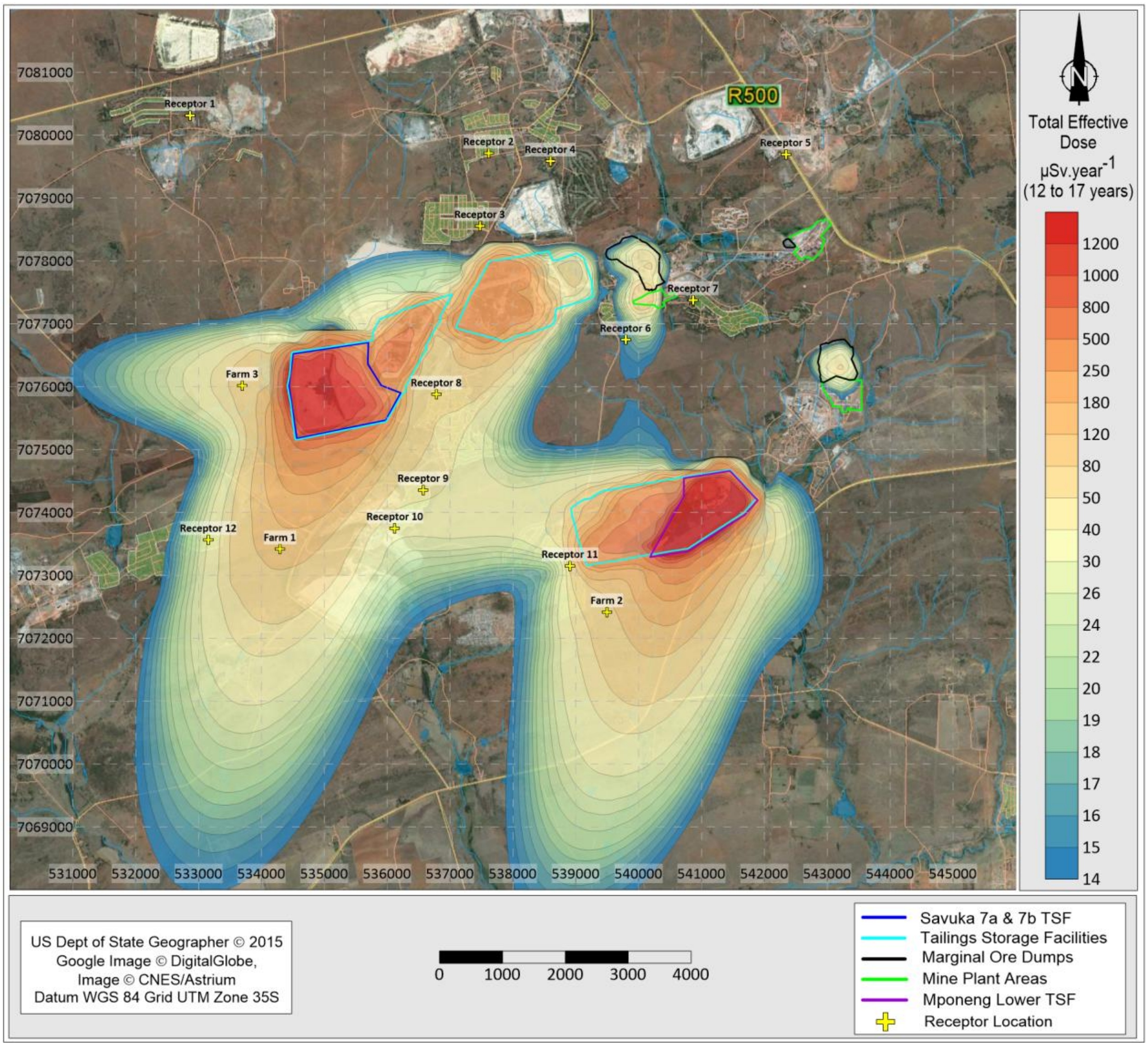

Figure 5.10 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to deposition at the lower Mponeng TSF, in addition to the baseline conditions.

Figure 5.11 and Figure 5.12, compared to Figure 5.7 and Figure 5.8, confirm that the total effective dose is higher than for the Residential Area Exposure Condition. As with the Residential Area Exposure Condition, in some locations, the primary contributor to the total effective dose is ingestion, followed by radon inhalation. At others, it is the other way around, with radon inhalation the primary contributor to the total effective dose. External gamma radiation (from cloud and groundshine) is insignificant. It also shows that the redepositioning of tailings at the lower Mponeng TSF has a marginal impact on the total effective dose.

What is also evident from Figure 5.9 to Figure 5.12 is that the impact of deposition at the lower Mponeng TSF is more significant than that of the other TSFs. This is reflected to some extent in the total effective dose of the Farm 2 location, which is in the direction of dispersion from the Mponeng 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, 2026).

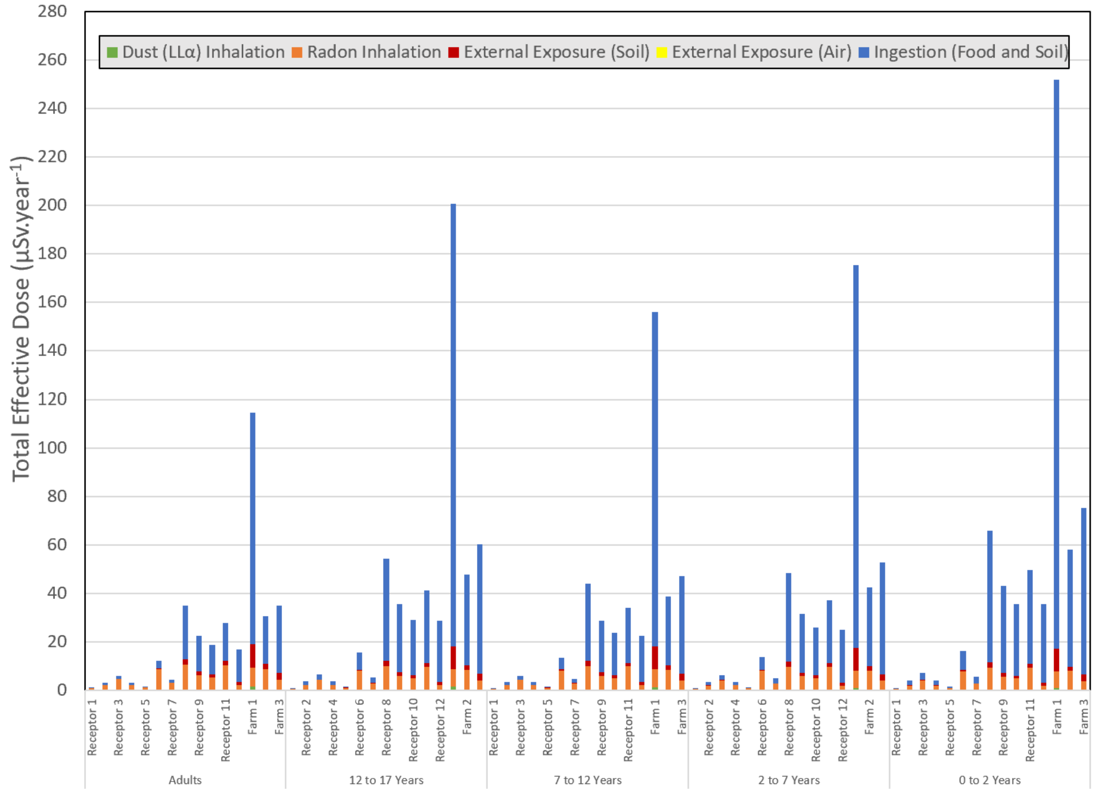

Figure 5.11 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.9 for locations).**

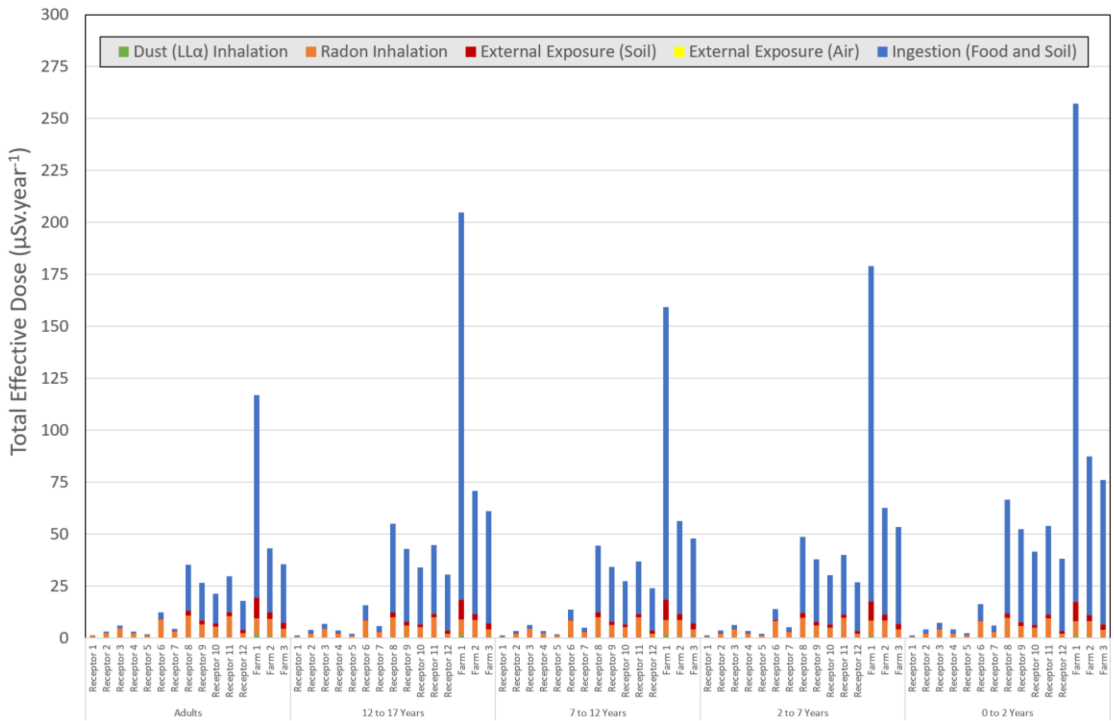

Figure 5.12 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to deposition at the lower Mponeng TSF, in addition to the baseline conditions (see Figure 5.9 for locations).**

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 means that uncertainties exist in both the assumed conditions 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

At the local scale, the assessment calculated the total effective dose to the public from all relevant exposure pathways 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 regional scale, it can be noted that the results presented in Section 5 represent only the contribution of the Project to the total effective dose to members of the public, in addition to the current baseline conditions. National safety standards and associated regulatory compliance criteria make it clear that members of the public should be protected from *all* contributing sources or operations. Under 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 specify a dose constraint of 0.25 mSv.year^{-1} (or 250 µSv.year^{-1}) for each operation with 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 all contributing sources across all applicable CoRs, the dose limit is applicable; for facility-specific assessments, the dose constraint is more appropriate, particularly for addressing multiple contributions. However, the question remains: "*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 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 total effective dose would remain below the 1,000 µSv.year^{-1} dose limit.

6.3 Variations in Public Exposure Conditions

6.3.1 General

The public exposure conditions evaluated as part of the Project were defined using a systematic Source–Pathway–Receptor analysis approach (see Section 4). An attempt was made to be comprehensive while limiting the number of exposure conditions to a select 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 conservative.

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 both cautious, realistic, and comprehensive in defining 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 area residents because it is likely limited to inhalation and external exposure and occurs for shorter periods. In addition, the Commercial Agricultural Exposure Condition is highly conservative and assumes that the exposure group depends 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 defined and evaluated in the Project were considered comprehensive and representative of a wide range of site-specific conditions. It was also argued that variations are expected but will have a lower radiological impact than those considered in the assessment.

For example, the Source–Pathway–Receptor analysis suggests that an alternative public exposure condition is that induced by accidents and incidents, 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) explains that these conditions are best addressed as part of the emergency response and other programs within the radiation management plan.

6.3.3.2 Tailings Spillage

Several factors determine the potential level of public radiation exposure, making it difficult, if not impossible, to provide a general assessment, especially given the Project's widespread and diverse nature. 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.
- How long has the potential contamination been left unaddressed before remedial action is initiated for the area, and is there any possibility that members of the public could access the contaminated area?

It is thus clear that each spillage event would be different and would have 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 for 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 duration of exposure, may be exposed 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 Mponeng tailings material as a function of the exposure period. The total effective dose is predominantly determined by the Ra-226 concentration in the tailings material and, consequently, by the radon inhalation dose.

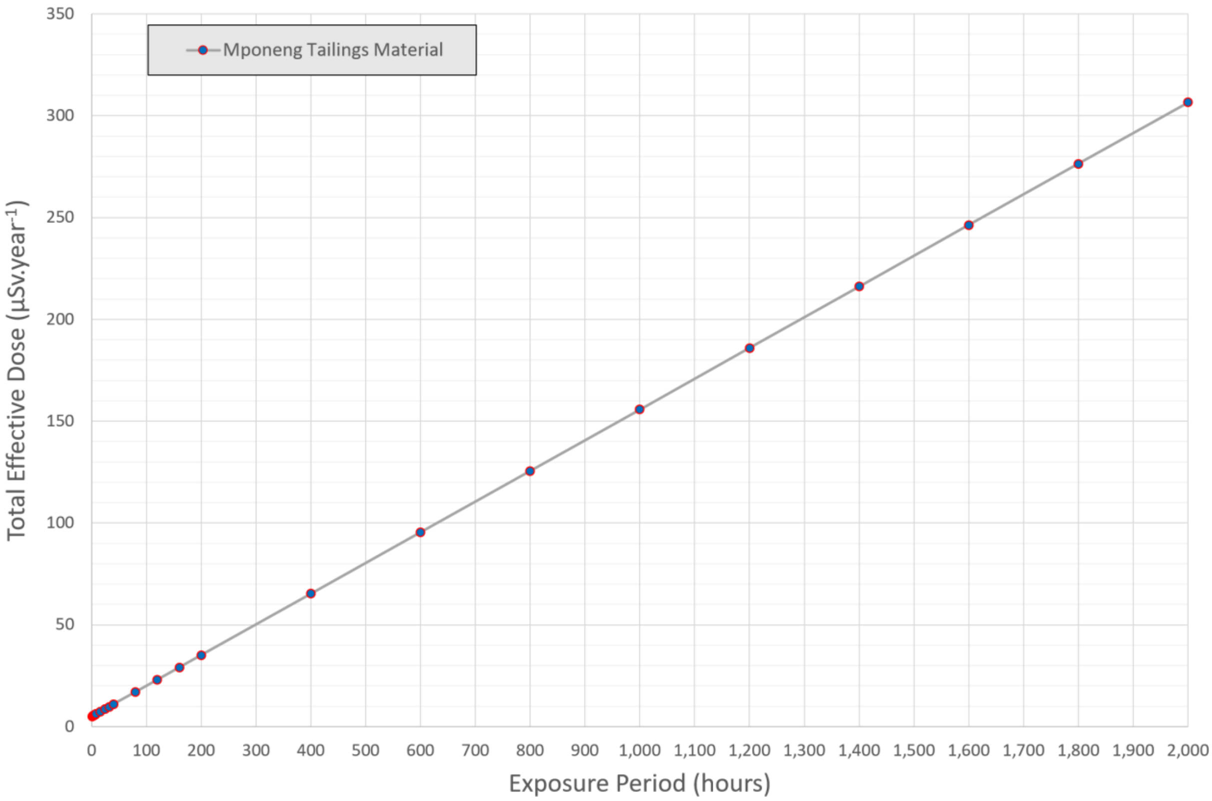

Figure 6.1 Total effective dose for the Mponeng TSF tailings material as a function of the exposure period.

From Figure 6.1, it is clear that for the assumed Mponeng TSF tailings material, an exposure period of 2,000 hours will still result in a total effective dose of approximately 310 μSv.year^{-1}. To keep the annual dose below 250 μSv.year^{-1}, the exposure period should not exceed 1,600 hours.

Note that these results should be interpreted with caution, as 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, the results emphasise 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 from surface impoundment overflows are possible. As with tailings spills, several factors determine the potential level of radiation exposure to the public, making it difficult, if not impossible, to provide a general assessment. For a water spillage, the situation is even more uncertain, as water will disperse horizontally downgradient and infiltrate vertically under 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 with literature values, some of these values are high and conservative. This means that using more realistic values in the definition and use will reduce the calculated ingestion doses. Since most of the calculated ingestion doses across the different exposure conditions are relatively low, lower consumption rates will further reduce them (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 significantly increase the grain ingestion dose. 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, assuming 100% grain consumption, along with all other ingestion pathways, is unrealistic given the amount of food a person can consume in a year. Under these conditions, the consumption rates of other products must be reduced substantially to be realistic, given the amount of food that humans across 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 considered realistic given the history of the Project. The dose assessment models assumed a buildup of activity on the soil surface over this period, thereby influencing 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, ingestion doses may increase by more than threefold, accompanied by greater uncertainty.

7 Impact Assessment for the Project

7.1 General

The purpose of this section is to present the radiological impact assessment rating for the redepositioning of tailings at the lower Mponeng 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 distinguishes between the different phases of the Project (i.e., operation and post-closure) and the contributions 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 potential radiological impacts on the public differ. Where required, mitigation measures are proposed for activities across the Project phases, followed by an impact rating of 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 from all three environmental pathways (i.e., surface water, groundwater, and atmosphere). However, due to the slow-moving nature of any radionuclide-contaminant plume originating from the facilities through the groundwater system, the potential radiological impact through the groundwater pathway will only occur during 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 TSFs.
- Exhalation and dispersion of radon gas from the redepositioning of tailings at the lower Mponeng TSF.

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

Table 7.1 Summary of the activities and the impact of the activities during the operational phase of the redepositioning of tailings at the lower Mponeng 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.
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. Airborne dust (PM10) and deposited dust (TSP) contribute to the total effective dose via inhalation, ingestion, and external radiation exposure.

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 these gases are continuously exhaled from this facility into the atmosphere.

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

7.2.3.2 Management/Mitigation Measures

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

The total effective dose from radon gas released from tailings material at the TSF areas is well below regulatory compliance criteria, indicating 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 wet area at a TSF (i.e., the 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 radon exhalation from the TSF is to install a covering layer. This will increase the diffusion length, allowing radon progeny to decay before release from the tailings surface.

7.2.3.3 Impact Rating

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

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. These particulate matter containing radionuclides are dispersed into the environment through the atmospheric pathways. The emission and subsequent dispersion of particulate matter into the atmosphere result in airborne radionuclide concentrations associated with PM10, and soil radionuclide concentrations following TSP deposition. 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, cro, and animal products, and external gamma radiation from cloud and ground shine.

7.2.4.2 Management/Mitigation Measures

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

Table 7.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng 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 Sa redepositioning of tailings at the lower Mponeng 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, but at a 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 redepositioning of tailings at the lower Mponeng 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, but at a 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.			

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 exact locations is less than 13% (on average) of the public exposure dose constraint of 250 µSv.year^{-1}.

From a dose-optimisation perspective, the following mitigation measures can be implemented. These measures, which are in line with the measures proposed in the air quality impact assessment (Airshed, 2026), 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 redepositioning of tailings at the lower Mponeng 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 of a significant rating on the emission and dispersion of particulate matter containing radionuclides during the operational phase.

7.3 Post-Closure Phase

7.3.1 General

Before the actual closure of the redepositioning of tailings at the lower Mponeng 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 activities to be performed and how the associated radiological impacts during the decommissioning and closure phases will be managed.

7.3.2 Activities

Considering that a decommissioning plan of the redepositioning of tailings at the lower Mponeng 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).
- Leaching and migration of radionuclides from the remaining facilities (e.g., TSF).

7.3.3 Implementation of the Decommissioning Plan

7.3.3.1 Impact Description

The implementation of the NNR-approved decommissioning plan will have a positive impact by demolishing, decontaminating (to the extent possible), and removing surface infrastructure containing or contaminated with radionuclides, and demonstrating compliance with clearance criteria.

Generally, this would involve conducting a gamma radiation survey, supplemented by full-spectrum radioanalysis of soil samples collected at the infrastructure sites, followed by appropriate rehabilitation and cleanup operations to obtain conditional or unconditional clearance from the regulatory authority. However, for the TSF that would remain at the surface during the post-closure period, cleanup is limited to areas outside the TSF footprint that may have become contaminated during or as a result of operational activities. These areas outside the TSF footprint can still be rehabilitated and cleaned up for conditional or unconditional clearance.

Table 7.3 Impact significant rating for the particulate matter emission and dispersion that contains radionuclides during the operational phase of the redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a significant time and cost to reduce 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 $\mu Sv.year^{-1}$			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a significant time and cost to reduce 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 $\mu Sv.year^{-1}$			
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.			

Table 7.4 summarises the activities associated with the post-closure phase that may affect receptors.

Table 7.4 Summary of the activities and the impact of the activities during the post-closure phase of the redepositioning of tailings at the lower Mponeng TSF.

Interaction	Impact
Implementation of the decommissioning plan	The execution of the decommissioning plan involves a site-wide program to demolish, decontaminate, and remove all surface infrastructure that may contain or be contaminated with radionuclides. These areas, along with any other contaminated areas, will be rehabilitated and cleaned to achieve regulatory clearance.
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. Airborne dust (PM10) and deposited dust (TSP) contribute to the total effective dose via inhalation, ingestion, and external radiation exposure.
Leaching and migration of radionuclides from the TSF	Radionuclides will leach from the TSF into the underlying aquifer and then migrate with the general groundwater flow. Abstraction and use of contaminated water contribute to the total effective dose through ingestion and potential external radiation exposure.

7.3.3.2 Impact Rating

Table 7.5 presents the impact significance 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 facilities (e.g., TSFs) will remain at the surface and continue to pose a radiation exposure risk to 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 particulate matter into the atmosphere result in airborne radionuclide concentrations associated with PM_{10}, and soil radionuclide concentrations following TSP deposition. 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 from cloudshine and groundshine.

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

7.3.4.2 Management/Mitigation Measures

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

Table 7.5 Impact significant rating for the implementation of the decommissioning plan of the redepositioning of tailings at the lower Mponeng TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan for the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					16
Nature	1	Likely to result in a positive impact	16		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The practical implementation of the decommissioning plan will have irreversible effects that will persist 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}			
Post Mitigation					
Nature	1	Likely to result in a positive impact	-2.5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have irreversible effects that persist 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.			

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

From a dose optimisation perspective, the following mitigation measures, in line with the measures proposed by the air quality impact assessment (Airshed, 2026), 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 significance rating for the exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a significant time and cost to reduce 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 redepositioning of tailings at the lower Mponeng 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 or cost to mitigate 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.			

7.3.5 Leaching and Migration of Contaminants from the Redepositioning at the Lower Mponeng 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. Complex geochemical and hydrological processes govern the rate of leaching, which is generally slow. Once in the underlying strata, migration of these radionuclides is equally slow along the groundwater flow path.

Abstraction of groundwater for personal or agricultural use may result in radiological impacts on receptors through direct ingestion of water or through secondary pathways via ingestion of crops and animal products. 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 is first to ensure that radiation exposure is below the regulatory compliance criteria (i.e., the dose constraint) and, secondly, to optimise radiation protection by applying the ALARA principle.

The total effective dose from groundwater ingestion attributable to the TSF was hypothetically estimated to be below regulatory compliance criteria (i.e., the dose limit), indicating 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 cutoff trenches or pump-and-treat systems, may also be effective in the short- to medium-term. However, the timescales of concern are beyond the period of active institutional control.

Table 7.7 presents the impact significance rating for radionuclide leaching and migration 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 contributions from all relevant exposure pathways, including surface water, groundwater, and the atmosphere, 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 contributions from all relevant exposure routes for each pathway. These include radon gas inhalation, dust inhalation, external gamma radiation (groundshine and cloudshine), and ingestion of 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.

Thirdly, the radiological safety assessment process considers the cumulative contribution from all relevant sources of radiation exposure associated with the redepositioning of tailings at the lower Mponeng TSF, including those from existing TSFs in the area. This means that the radiological impact assessment includes the cumulative impact of these sources, 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 redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng 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 $\mu Sv.year^{-1}$			
Reversibility	3	The impact is reversible only by incurring significant time and cost to reduce radionuclide migration 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 $\mu Sv.year^{-1}$			
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 $\mu Sv.year^{-1}$			
Reversibility	2	The impact is reversible only by incurring significant time and cost to reduce radionuclide migration 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 $\mu Sv.year^{-1}$			
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.			

Finally, at the regional scale, the assessment context accounts for cumulative impacts from all contributing operations (or practices) in the area, which may increase the total effective dose to members of the public. This is important because the public dose limit of 1,000 $\mu Sv.year^{-1}$ is derived 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. It 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 broader radiation management plan, the purpose of the public Radiation Protection Programme (RPP) is to implement measures to ensure that members of the public are protected from potential exposure to ionising radiation arising fromhe Project. The regulatory authority's definition of the public RPP is based on the outcome of the comprehensive radiological public safety assessment. It 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, to the extent possible, include soil, surface water, and groundwater samples, as well as an airborne environmental radon survey of the area using RGMs.

In addition to these sampling and analysis, it is proposed that a full gamma radiation and dose rate survey be conducted on a grid basis 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 determined by the gamma radiation survey.

8.3 Monitoring Programme

The Projects TSFs fall within the scope of CoR-3, which has an approved public Radiation Protection Programme (RPP) that provides for environmental monitoring and analysis to ensure that members of the public are adequately protected from environmental releases. The responsibility for implementing and executing the monitoring programme lies with the Radiation Protection Function (RP Function), which may include legally appointed personnel: a Radiation Protection Monitor (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.

Full-spectrum analysis is suitable for detailed dose analysis but is an expensive procedure with long lead times; therefore, less frequent intervals are proposed. Total uranium and thorium analyses are relatively inexpensive and have fast turnaround times. These results will monitor variations in activity concentration over the monitoring period.

Significant variations in activity concentration over short periods are not expected in groundwater, unlike in surface water. Therefore, a less frequent sampling schedule is proposed for groundwater. The same principle applies to the sediment samples from the exact 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 radon gas for 2 to 3 months, after which they are replaced with new RGMs for the next monitoring period.

The dust-fallout samples are collected quarterly but are used to produce an annual sample for total U and Th analysis. This is because the volume of material collected in a dust bucket is insufficient for quarterly analysis.

8.4 Proposed Monitoring Points

Most proposed monitoring points coincide with the environmental pathways monitoring programme (e.g., soil, 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 align with the existing surface water monitoring points 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, using the same principles.
- The groundwater monitoring points should coincide with the existing ones. 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 (2026).
- The environmental radon monitoring locations need not coincide with specific locations. The principle is that it should be widespread across the mining rights area, aligned with the dominant wind direction at the receptor locations, and complemented by the background monitoring locations. The exact location is often determined by the availability of a secure location, which can 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 to evaluate whether members of the public living near the Project will be exposed to levels of ionising radiation above the regulatory compliance criteria for public protection, and to assess the associated radiological impact as input into the ESHIA/EIA process. A systematic approach was followed, including the definition of the regulatory framework and the technical basis for the assessment; a system description; the systematic definition of public exposure conditions; the analysis of the consequences of those conditions; and the radiological impact assessment.

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

9.2 Conclusions

Following a systematic Source-Pathway-Receptor analysis, two public exposure conditions were derived for the area: 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 may reduce radiation exposure.

Given that the Project has not been implemented yet, the radiological assessment is prospective based on available information and reports generated as part of the ESHIA/EIA process. The results and conclusion are presented here for the conditions and parameter values assumed in the assessment. These may change in future iterations as site-specific data and information become available and are used.

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

- The contribution from the groundwater pathway was evaluated, with the Project TSFs being the primary contributing source. It was shown that the potential radiological impact is only visible over thousands of years, with a maximum total effective dose of less than 100 μSv.year^{-1}, indicating that it cannot be considered a contributing pathway for the Commercial Agricultural Exposure Condition during the operational phase of the Project.
- The most significant contribution from the atmospheric pathway is inhalation of airborne radon. This is due to the presence of Ra-226 in the source material.
- 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, despite the proximity of the receptor locations to surface infrastructure, the doses remain below the dose constraint for all age groups, with a maximum contribution from the atmospheric pathway of less than 250 μSv.year^{-1}.

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 μSv.year^{-1}.

These total effective dose assessment results were used to determine the radiological impact rating during the different phases of the Project. Table 9.1 summarises the radiological impact, a significance rating for the operational phase of the redepositioning of tailings at the lower Mponeng TSF, while Table 9.2 summarises the radiological impact significance rating for the post-closure phase of the redepositioning of tailings at the lower Mponeng TSF.

Table 9.1 Summary of the radiological impact significant rating for the operational phase of the redepositioning of tailings at the lower Mponeng 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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a 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 redepositioning of tailings at the lower Mponeng 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, but at a 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 redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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.			-2.5
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		
Reversibility	2	The impact is reversible, but at a significant time and cost to reduce wind erosion from the TSF.			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
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 redepositioning of tailings at the lower Mponeng 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, but at a significant time and cost to reduce 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 redepositioning of tailings at the lower Mponeng TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan for the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					16
Nature	1	Likely to result in a positive impact	16		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The practical implementation of the decommissioning plan will have irreversible impacts that will persist 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}			
Post Mitigation					
Nature	1	Likely to result in a positive impact	-2.5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The practical implementation of the decommissioning plan will have irreversible impacts that persist 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			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
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.			
Impact	Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the redepositioning of tailings at the lower Mponeng TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-5		
Extent	2	The extent of potential impact for the redepositioning of tailings at the lower Mponeng 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, but at a significant time and cost to reduce 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 redepositioning of tailings at the lower Mponeng 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 or cost to mitigate 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 redepositioning of tailings at the lower Mponeng 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			

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
		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 radionuclide migration 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 radionuclide migration 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.			

9.3 Recommendations

The proposed radiological monitoring programme for the Project includes recommendations for monitoring surface water, groundwater, sediment, environmental radon, and dust fallout, including the frequency and type of analyses. Most proposed monitoring points coincide with the environmental pathways monitoring programme (e.g., soil, surface water, and groundwater), which is consistent with the current Public Radiation Protection Programme (PRPP). Considering the surface infrastructure that will be developed for the Project, the following was noted:

- The surface water monitoring locations should align with the existing surface water monitoring points 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 align with the existing ones. 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 (2026).

- The environmental radon monitoring locations need not coincide with specific locations. The principle is to apply it across the mining rights area, in the dominant wind direction where receptors are located, and to complement it with monitoring locations in the background. The exact location is often determined by the availability of a secure location, which can improve the recovery rate of RGMs.

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APPENDIX A:
RADIONUCLIDE AND ELEMENT-DEPENDENT DATA

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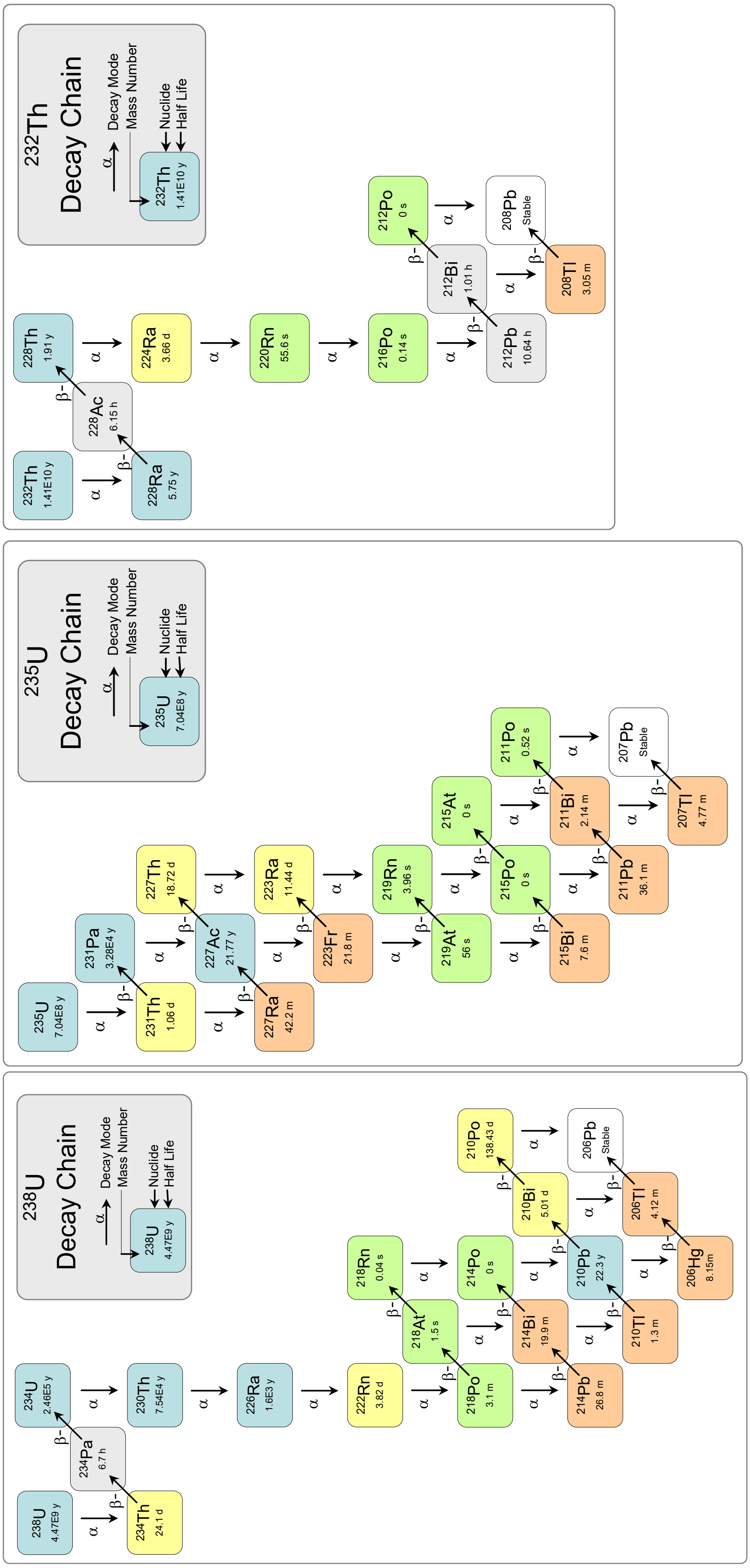

Figure A 1 **Schematic illustrations of the U-238, U-235, and Th-232 decay chains.**

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 the amount of energy that ionising radiation deposits in a given mass of matter, such as human tissue. Types of ionising radiation differ in how they interact with biological materials. Hence, equal amounts of energy 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 to account for the relative effectiveness of the radiation in causing biological harm and other parameters related 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 total annual effective radiation dose 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 ICRP Publication 72 (ICRP, 1996) and the IAEA Safety Standards Series (IAEA, 2011). The dose conversion factors published in RG-002 distinguish between age groups, with ranges corresponding to those 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 enter the body through the skin, resulting in external radiation exposure. For external exposures, the radiation of concern is sufficiently penetrating to traverse the body's overlying tissues 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 via inhalation or ingestion, where radiation is emitted within 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 radionuclide concentrations in environmental media to the effective radiation doses to organs and tissues.

Effective external dose conversion factors are published in the EPA Federal Guidance Document No. 12 (Eckerman and Ryman, 1993). The dose from external exposure is a function of radiation intensity and is assumed to be uniform across the body. The dose estimate is independent of the person's age, and the conversion factors are 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 proportional 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 to 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 the 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 1:1 ratio of Pb-212 to Bi-212 concentration is proposed, but no data are available for outdoor exposure.

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, making them applicable to 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 expressed as a percentage of the annual ingestion rate for adults, as 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 soil can increase over time due to continued deposition of airborne radionuclides. The approach used to estimate activity concentrations in soil (Csoil) is presented in Appendix D. The rate at which different age groups inadvertently consume soil annually is obtained from RG-002.

Ingestion of Contaminated Crops

Soil contaminated with radionuclides can contaminate crops 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

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

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

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

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 themselves, which is represented by the term $C_{soil}(CF_{crop} + (1 - f_{prep})\ S_{crop})$.

- External contamination of the crop due to the deposition of airborne dust, represented by the term $Int_{crop}\, f_{growth}\, Dep_{rate}$.
- 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 radionuclide uptake from the soil via roots and excludes the effects of radionuclide deposition on plant surfaces via resuspension, 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 they are listed alongside values from other literature sources. Where data for a specific nuclide are unavailable from RG-002, values from Staven *et al.* (2003) will be used. Values for the other parameters are 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 rates for different animal products are 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 are summarised in Table C 8 of 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 apply to all poultry types. 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 concentrations in air, multiplied by appropriate dose coefficients and the exposure period to 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, 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 by 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 concentrations in water, multiplied by appropriate dose conversion coefficients and the exposure duration 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: by deposition of airborne radionuclides onto the soil surface and by transfer of radionuclides in irrigation water into the soil. 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 radionuclides will be adsorbed onto soil particles, while bioturbation 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 soil root zone density. 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 rates 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 root zone density. $\lambda_{BioT,DZ}$ (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

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

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

Equation 26

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

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

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

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

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

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, it 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 into the environment occurs via 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 bulk medium's diffusion coefficient.

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 with the diffusion coefficient. 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 the 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}. Within a material, it is proportional to its porosity and moisture saturation. In different materials, the radon diffusion length can vary from low values (~0.2) to approximately 1.4 m in 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, at which it reaches its maximum value. Any thickness greater than 4 m approaches 1. To simplify the calculation, it is conservatively assumed that the facility will be at least 5 meters in length. A thinner layer will only reduce the radon exhalation rate. Alternatively, a much thicker layer (>10 m) will not significantly increase the radon exhalation rate calculated assuming a 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 meters), 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 in porous materials. 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 (aside from their radioactive properties), and physicochemical processes govern their diffusion. It is therefore assumed that the diffusion coefficients for the two isotopes are equal, $D_R = D_T$. 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 thoron exhalation rate from the radon exhalation rate (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 Lawrence (2005), who reported that the emanation fraction for thoron is approximately 10% lower than that 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 concentration using the Ra-228/Ra-226 activity ratio.

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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 The adult ingestion rates define ingestion rates for different age groups.

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 the 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.

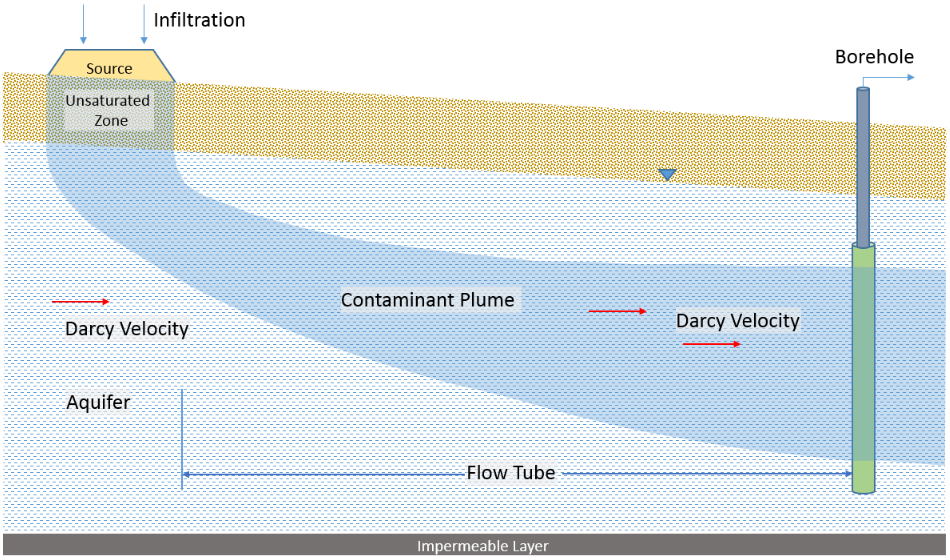

Figure D 1 Schematic representation of the groundwater system to calculate the migration of radionuclides through a deep (thick) aquifer system and a relatively small lateral extent source term, with an abstraction borehole as a receptor.

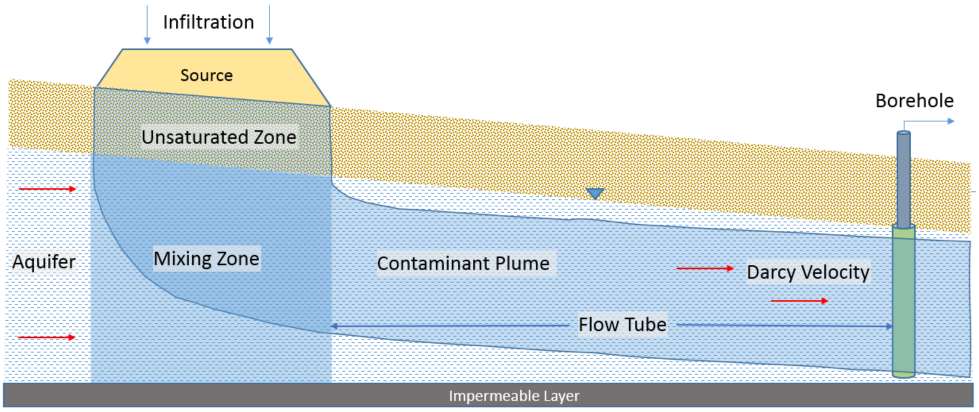

Figure D 2 Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with an abstraction borehole as a receptor.

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 occurs, after which the radionuclides migrate with groundwater flow toward the downstream borehole or surface water body.

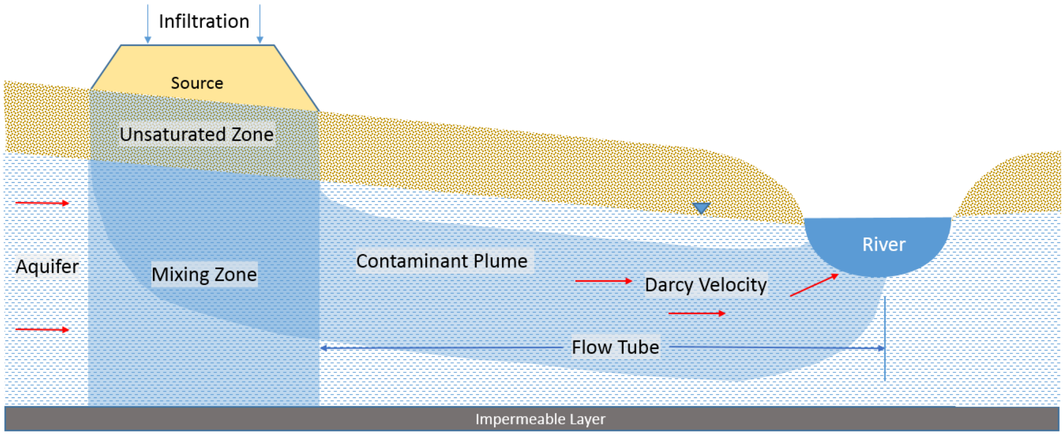

Figure D 3 **Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with a river as a receptor.**

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.

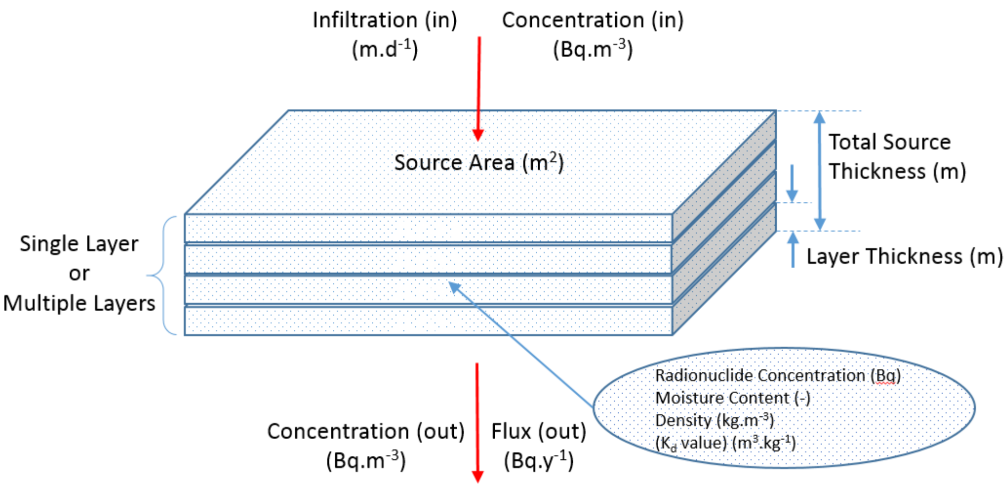

Figure D 4 **Conceptual representation and associated parameter values for the source term model.**

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 the 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 they pertain to unsaturated zone parameter values.

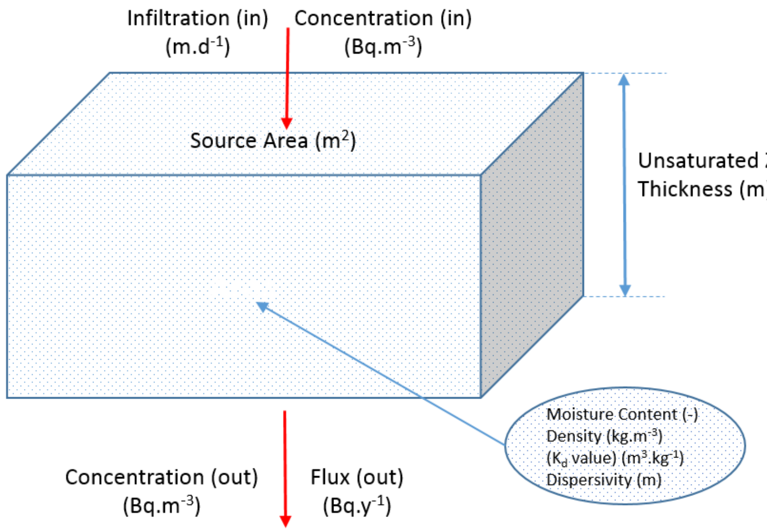

Figure D 5 **Conceptual representation and associated parameter values for the unsaturated zone model.**

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 a single compartment of known thickness represents the mixing zone. 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).

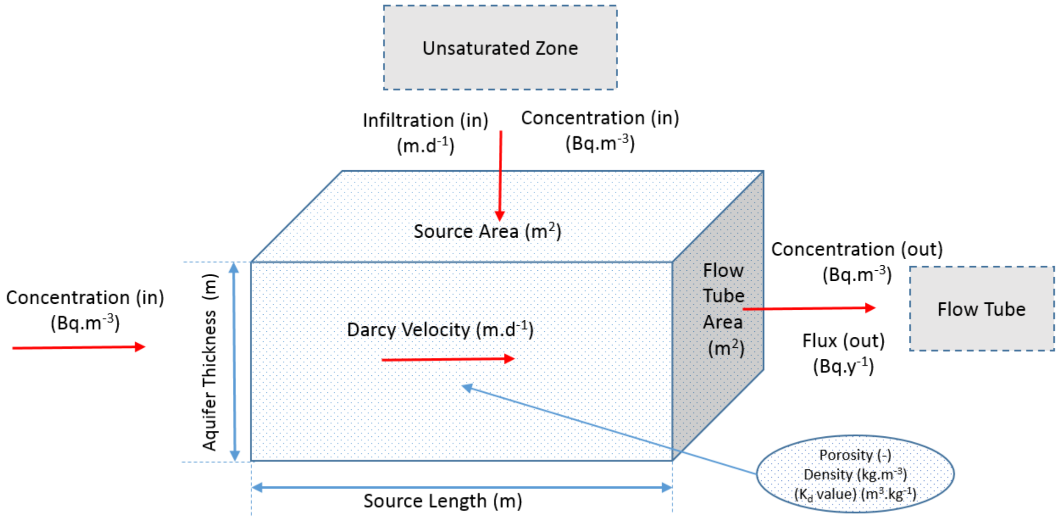

Figure D 6 Conceptual representation and associated parameter values for the aquifer mixing zone model.

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 aquifer dry bulk density (kg.m^{-3}), the radioelement specific distribution coefficient or the aquifer K_d-value (m^3.kg^{-1}), 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 they pertain to aquifer parameter values.

The concentration of water abstracted from the borehole is taken, for simplicity, as the sum of the flow-tube concentration (Bq.m-3) multiplied by the fraction of the borehole intersected by the plume, and the background concentration (Bq.m-3) multiplied by the fraction intersected by uncontaminated water. As a conservative assumption, the entire screen is assumed to intersect the contaminant plume.

Figure D 8 is a simplified representation of the borehole abstraction module and the most important parameters.

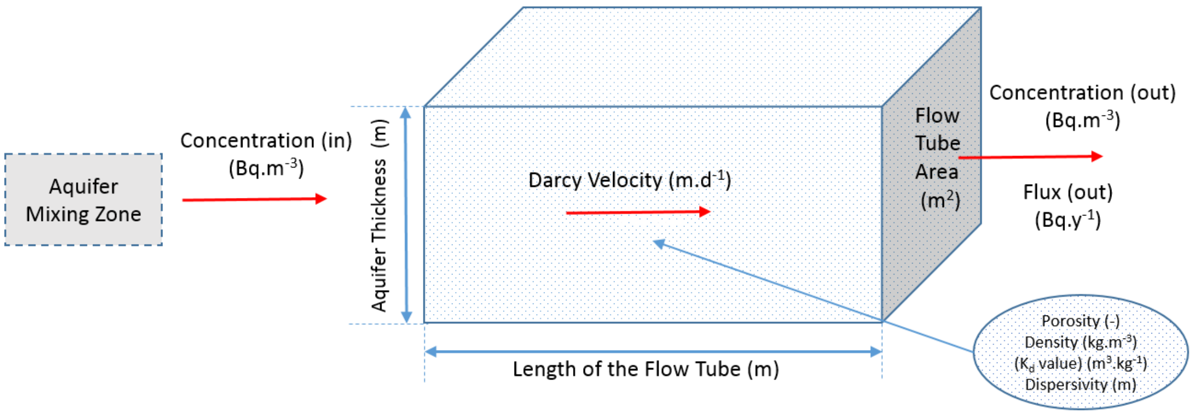

Figure D 7 Conceptual representation and associated parameter values for the aquifer (saturated zone) model.

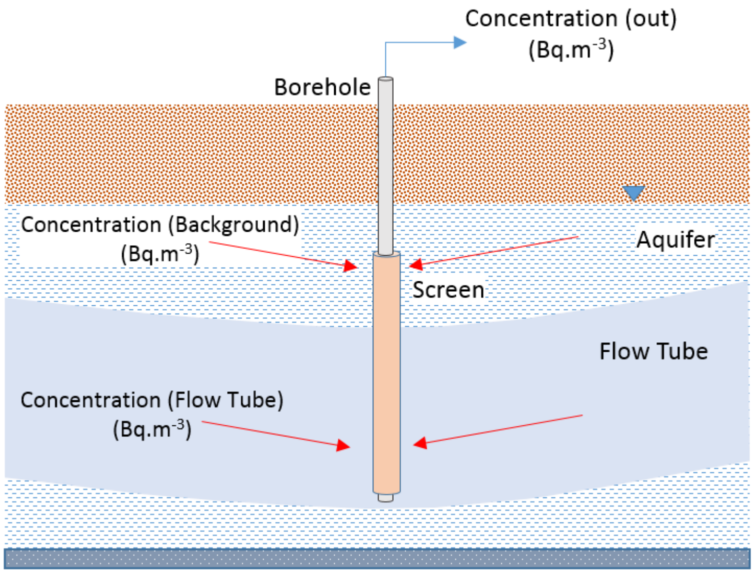

Figure D 8 Conceptual representation and associated parameter values for the borehole abstraction model.