Radiological Impact of the Harmony Valley and Nooitgedacht Tailings Storage Facilities Projects

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Revision Table

Revision 0

Section	Page	Changes Made in Revision

List of Acronyms

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

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Credentials: Dr JJ van Blerk

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

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

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

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

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

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

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

Certification

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

Jacobus Josia van Blerk (PhD)

Director: AquiSim Consulting (Pty) Ltd

1 Introduction

1.1 Background

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

Figure 1.1 shows that the South African interests of Harmony are divided into four discrete operations namely; the Free State Operations, West Rand Operations, the Klerksdorp goldfields, and the Kraaipan Greenstone Belt (Kalgold Operations). Through these various operations, Harmony has made significant economic contributions to the provinces of South Africa where they are located, through job creation and stimulation of secondary services and industry.

Mining within the Free State Goldfield dates from the early 1950s when the first shafts consisting of the Harmony Merriespruit, Unisel and Brand shafts became operational. These are among the oldest shafts in the Harmony group, having been operational between 35 and 65 years. Through the acquisition of various other mines in the area, the Free State Operations of Harmony grew to several reporting entities.

Harmony holds an approved Mining Right (MR) and Environmental Management Programme (EMPr), in terms of the Minerals and Petroleum Resources Development Act (Act 28 of 2002, as amended) (MPRDA), for the mining of gold at various operations in the Welkom area (Mining Right Ref: MR84).

Due to the continuous expansion of the Free State Operation, Harmony requires a new deposition site for tailings material generated at the Harmony metallurgical processing plants. This tailings material is currently deposited at the Free State South (FSS) 2 tailings storage facility (TSF), Helena 4 TSF, St. Helena 123 TSF, Dam 23 TSF, Brand D TSF and Target 1&2 TSF. However, the current planned Life of Mine (LOM) of the Free State Operations exceed the available deposition capacity of these TSFs. Harmony is, therefore, proposing to construct the proposed Valley TSF and the Nooitgedacht TSF to cater for this additional capacity. Both these proposed deposition sites are located near Welkom in the Matjhabeng Local Municipality (LM) in the Free State province of South Africa.

The proposed Valley TSF will be used for the deposition of tailings material generated at the Harmony One metallurgical processing plant. Currently, this tailings material is deposited at the FSS2 TSF and the Helena 4 TSF but will reach its capacity by July 2024. The Valley TSF site is located between the Free State North (FSN) 1 TSF and FSN2 TSF and a portion of the footprint of the FSN4 TSF. The proposed Nooitgedacht TSF will be used for the deposition of tailings material generated at the other processing plant. The Nooitgedacht TSF site is located to the south of the FSN1 TSF and the proposed Valley TSF sites.

1.2 Naturally Occurring Radionuclides and Background Radiation

Many radioactive isotopes (or radionuclides) occur naturally throughout the Earth's crust and are present in most rocks, soils, river water, as well as in seawater. Most of these naturally occurring radionuclides are members of four radioactive series identified as the uranium (U-238), actinium (U-235), thorium (Th-232), and neptunium (Np-237)[1] series, named according to the radionuclides that serve as progenitor (or

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

parent) to the series products. Naturally occurring radionuclides that are of particular interest to radiation protection, which are not members of any of the four-decay series, include isotopes of potassium (K-40) and rubidium (Rb-87). These isotopes are of interest because of their presence in environmental media and their contribution to human exposure (Martin, 2006b).

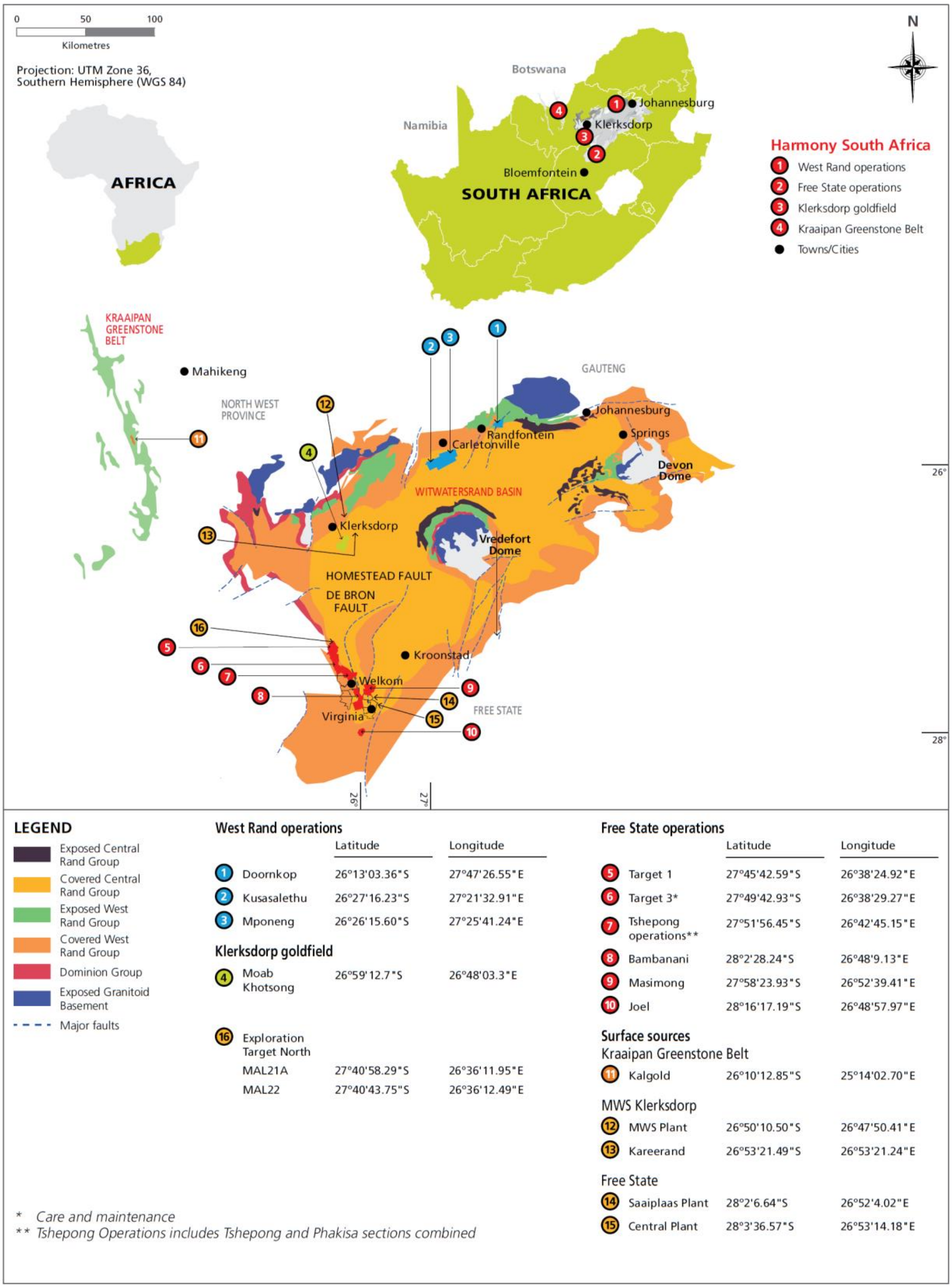

Figure 1.1 Map showing the location of the four discrete Harmony operations in South Africa. The focus of this report is the Projects of Harmony.

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

The annual dose averaged over the population of the world, is about 2.8 mSv in total. As indicated in Figure 1.2, over 85% of this total is from natural sources, with about half coming from radon decay products in the home (2.4 mSv). Medical exposure of patients accounts for 14% of the total (0.4 mSv), whereas all other artificial sources — fallout, consumer products, occupational exposure, and discharges from the nuclear industry — account for less than 1% of the total value. Other natural background radiation sources include cosmic radiation, gamma radiation, and internal radiation in our bodies (IAEA, 2004a).

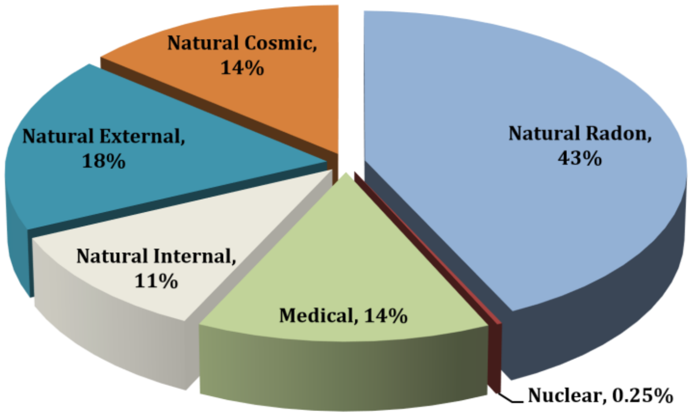

Figure 1.2 Distribution of the background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

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

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

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

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

1.3 Regulatory Context

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

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

Harmony holds nine Certificates of Registrations (CoRs) issued by the NNR to Harmony for their Free State Operations. The area earmarked for the proposed deposition sites falls within the scope of CoR-5 held by FREEGOLD (HARMONY) PROPRIETARY LIMITED previously known as ARMGOLD / HARMONY FREEGOLD JOINT VENTURE (PTY) LIMITED for the Tshepong Operations, the Matjhabeng Operations and Western Holdings Operations (collectively referred to as the Freegold Operations).

Any changes to the scope of the CoR-5 induced by the construction and commissioning of the Valley TSF or the Nooitgedacht TSF as proposed deposition sites for tailings material generated at the metallurgical processing plants (hereafter referred to as the Projects), require an Authorisation Change Request (ACR) to be prepared and submitted to the NNR. The ACR submitted to the NNR requires, amongst others, a quantification of the potential radiological impact of these changes or listed activities on members of the public.

The Projects and the associated upgrade of infrastructure are listed activities that require a full Scoping and Environmental Impact Assessment process to be followed in terms of the National Environmental Management Act, No. 107 of 1998 (NEMA). The Projects trigger activities listed in terms of the NEMA Listing Notice GNR983, 984 and 985 of 2014, as amended, as well as activities listed in terms of the NEM:WA Regulations (GNR921 of November 2013). 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 construction and commissioning of the proposed Valley TSF and Nooitgedacht TSF. EIMS will compile and submit the required documentation in support of separate applications for the Valley TSF and Nooitgedacht TSF for:

- Environmental Authorisation (EA) and Waste Management License (WML) following the National Environmental Management Act – NEMA (Act 107 of 1998)- Listed activity: Listing Notice 2, Activity 15 as well as various Listing Notice 1 and 3 activities as well as the National Environmental Management: Waste Act – NEMWA (Act 59 of 2008)- Activity A14, B7, B10 and B11; and
- Water Use Licence (WUL) following the National Water Act – NWA (Act 36 of 1998). Water uses: Section 21 (c), Section 21 (i) and Section 21 (g). A separate application for a Water Use Licence (WUL) has been lodged with the Department of Water and Sanitation (DWS) for the water use triggers.

One of the key submissions as part of an ACR to the NNR is a Radiological Public Safety Assessment (RPSA), the purpose of which is to assess the potential radiological impact and safety of the proposed changes or listed activities on members of the public. AquiSim Consulting (Pty) Ltd (AquiSim) was consequently commissioned as a Radiation Protection Specialist (RPS) to perform the RPSA for the

Projects in a manner that is consistent with the provision, requirements, and guidelines provided by the NNR, as well as the provisions and requirements of the Environmental, Social and Health Impact Assessment (ESHIA) process in terms of NEMA.

1.4 Purpose of the Report

The Projects represent a scope change of CoR-5 and, therefore, require the preparation and submission of an ACR to the NNR in terms of the NNRA. The purpose of this report is consequently to assess the potential radiological safety of the Projects on members of the public. In addition, the RPSA serves as a basis to quantify the radiological impact of the Projects as input into the ESHIA process prepared by EIMS in terms of NEMA.

1.5 Scope and Structure of the Report

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

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

Figure 1.3 illustrates schematically the conceptual framework used to perform the RPSA of the Projects. It resembles the International Atomic Energy Agency (IAEA) ISAM (Improvement of Safety Assessment Methodologies) methodology developed for the safety assessment of near-surface radioactive waste disposal facilities (IAEA, 2004b). It is inherently systematic and structured and allows for the continual improvement of the assessment or components of the assessment through successive iterations. The assessment framework consists of several interrelated elements that will be followed and presented in a different section of this report. The report has been structured as follows:

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

- Section 8 defines the radiation monitoring plan for the Projects that include the monitoring programme and the proposed monitoring locations.
- Section 10 presents some overall conclusions and recommendations for the improvement of public radiation safety, with safety and impact assessment of the Projects as a basis for the conclusions and recommendations.

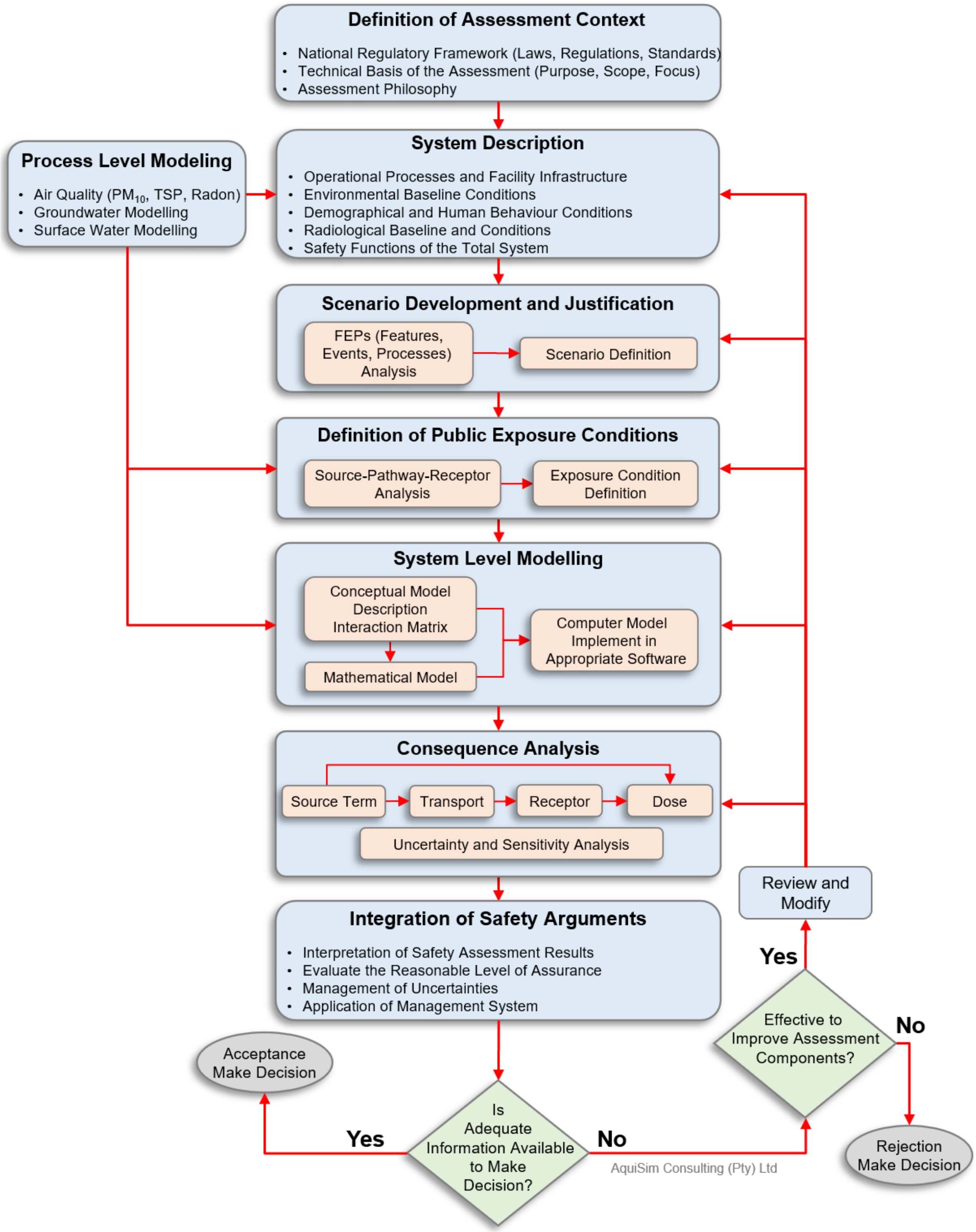

Figure 1.3 Schematic illustration of the conceptual safety assessment framework used to perform the RPSA of the Projects.

2 Assessment Context

2.1 General

The first step in the assessment framework illustrated in Figure 1.3 is the definition of the *assessment context*, which in simple terms defines the *basis* or *context* within which the safety assessment is conducted. Once developed, it serves as a communication tool that provides how stakeholders or target audiences (see Section 2.3.2) are informed of what is included or excluded from the assessment, and justification for the choices made clearly and consistently.

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

2.2 Regulatory Framework

2.2.1 General

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

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

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

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

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

2.2.2 The ICRP System of Radiological Protection

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

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

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

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

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

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

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

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

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

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

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

2.2.4 Safety Standards for the Protection of the Public

To avoid severely inequitable outcomes of the optimisation procedure, restrictions should be imposed on the doses or risks to individuals from a source. The regulatory tools that can be used to achieve a reduction of risks are *dose or risk constraints* and *reference levels*.

In planned exposure situations, the ICRP recommends that public exposure is controlled by the procedures of optimisation below the source-related constraint and using dose limits. In an emergency or existing exposure situation, the ICRP uses the term 'reference level' for the restriction on dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented. The ICRP recommends that any exposure caused by human activity above natural background radiation should be kept as low as reasonably achievable (ALARA) with economic and social factors being taken into account, but below the following individual dose limits (ICRP, 1991):

- The individual dose limit for public exposure in planned exposure situations is 1 mSv in a year.
- In special circumstances, an effective dose of up to 5 mSv in a single year provided that the average dose over five consecutive years does not exceed 1 mSv per year, can be applied.

- Also, the ICRP recommends equivalent dose limits of 15 mSv in a year to the lens of the eye and 50 mSv in a year to the skin.

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

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

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

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

2.2.5 National Radioactive Waste Management Policy and Strategy

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.2.6 Waste Categorisation for Mining and Mineral Processing Facilities

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

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

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

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

2.3 Technical Basis of the AssessmentC

2.3.1 General

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

2.3.2 Stakeholders to the Assessment

A radiological safety assessment is generally undertaken to provide confidence to stakeholders that an operation, facility, or activity does not pose a radiological risk to relevant exposure groups, notably workers or members of the public. Stakeholders, as used here, are groups or individuals with an interest in the radiological safety of an existing or proposed operation. 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 be considered, or consideration as to how the assessment results are to be presented. For this reason, including the list of stakeholders as part of the technical basis in the assessment context is justified.

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

- Regulatory authorities that include the NNR as a statutory body responsible for regulating NORM and that is responsible for monitoring the process to ensure that the operational activities are performed by following relevant regulatory guidance and requirements;
- EIMS as the Independent Environmental Practitioner responsible for the alignment of the Projects with the NEMA and associated ESHIA Regulations;
- Workers at Harmony and more specifically the Freegold Operations that are responsible and involved in the implementation of the Projects;

- Members of the public living near the Freegold Operations and more specifically near the proposed Valley TSF and Nooitgedacht TSF sites, which may potentially be affected by the facilities and activities associated with the Projects (e.g., ward councillors, labour unions, agriculture, and landowners);
- Mining and industry, particularly the mining and mineral processing operations near the Freegold Operations; and
- Officials from the Local, Provincial and National Government Departments that will be responsible for evaluating the applications for environmental authorisation and have to ensure that the environmental investigations are performed by following relevant regulatory guidance and requirements; and
- Technical, scientific, and environmental groups that might have an interest in the approach followed for the assessment and the subsequent results.

2.3.3 Purpose of the Assessment

Any company endeavouring to develop a mining or mineral processing operation must undergo a rigorous permitting effort to convince regulators and public stakeholders that the mining, milling, and associated processing facilities can be developed, operated, decommissioned, and closed without threatening worker and public health, nearby communities, and the environment (Chambers, Lowe and Feasby, 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, 2009b; 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 Projects is twofold:

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

2.3.4 Scope and Focus of the Assessment

2.3.4.1 Natural Background Radiation

The contribution of naturally occurring radionuclides to background radiation was introduced in Section 1.2. Nationally and internationally, the contribution of natural background radiation is not amenable to regulatory control. The focus of this assessment is thus on the radiation exposure contribution induced by

Projects, *above natural background radiation*. This means the background radiation is not included in the comparison of the total effective dose with the regulatory compliance criteria.

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

2.3.4.2 Site-Specific Assessment

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

2.3.4.3 Ionising Radiation Exposure Assessment

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

2.3.4.4 Contaminants of Concern

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

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

Exposure to the isotopes of uranium, thorium and their progeny (i.e. daughter products), has been linked to detrimental health impacts in humans based on their properties of emitting ionizing radiation and the extensive weight of evidence provided by epidemiological studies of radiogenic health effects in humans (Klaassen, 2001). However, not all the radionuclides in these decay series contribute equally to a total effective dose. Radionuclides that pose a significant risk to human health are identified from their dose conversion factors and reported half-lives. Only those radionuclides that can be shown to make a significant contribution to a total effective dose are considered. Table 2.4 lists the radionuclides explicitly considered in the RPSA of the Projects.

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

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

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

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

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

2.3.4.5 Cumulative Effect

The ICRP principles and IAEA safety standards set limits for the protection of human health and the environment from all radiation exposure situations or practices. This implies that limits set for the protection of members of the public are from all potential contributing operations near the Modder East Operation and associated Projects area.

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

2.3.4.6 Worker Safety Assessment

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

2.3.4.7 Assessment of Non-Human Biota

The concept of developing dose limits for non-human biota has been raised by the ICRP in Publication 103 (ICRP, 2008) and Publication 108 (ICRP, 2009a), but no specific guidance about dose limits or an assessment framework for practical application has been developed. A major problem is the complexity and variability of the natural environment. As an example, most of the research to protect the environment and its application is being done in northern European countries, which have a different natural environment than Southern Africa. Radiological impact on non-human biota is, therefore, excluded from the scope of the radiological safety assessment, since it is assumed that if individual humans are shown to be adequately protected, then non-human biota is also be protected, at least at the species level (ICRP, 1991).

2.3.4.8 Human Behavioural Conditions and Age Groups

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

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

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

2.3.5 Spatial Domain of Concern

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

2.3.6 Assessment Timescales

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

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

2.3.7 Assessment Endpoint

2.3.7.1 General

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

2.3.7.2 Radiological Public Safety Assessment Endpoints

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

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

2.3.7.3 ESHIA Criteria

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

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

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

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

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

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

$$ER = C \cdot P$$

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

Table 2.6 Criteria for determining impact consequence

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

Table 2.7 Probability scoring

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

Table 2.8 Determination of environmental risk.

	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

Table 2.9 Significance classes

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).

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

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

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

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

Table 2.10 Criteria for determining prioritisation

	Low (1)	Issue not raised in 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.
	Low (1)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is unlikely that the impact will result in spatial and temporal cumulative change.
	Medium (2)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is probable that the impact will result in spatial and temporal cumulative change.
	High (3)	Considering the potential incremental, interactive, sequential, and synergistic cumulative impacts, it is highly probable/definite that the impact will result in spatial and temporal cumulative change.
	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 value for the final impact priority is represented as a single consolidated priority, determined as the sum of each individual criterion represented in Table 2.11. The impact priority is therefore determined as follows:

$$Priority = PR + CI + LR$$

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

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

Table 2.11 Determination of prioritisation factor

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

Table 2.12 Final environmental significance rating

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

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

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

3.2 Project Location

The Projects area falls within the Matjhabeng Local Municipality (LM) in the Lejweleputswa District Municipality (DM) of the Free State Province of South Africa.

The proposed Valley TSF, which will cover an area of approximately 124 ha, will be located on Farm portions Rietpan 14 (0) and Ouders Gift 48 (0/RE) (see Figure 3.1 and Figure 3.2). The proposed Nooitgedacht TSF, which will cover an area of approximately 895 ha, will be located on Farm portions Mijannie 66 Ptn 0/RE, Goedgedacht 53 Ptn 0, Nooitgedacht 50 Ptn 0, Jacobsdal 37 Ptn 0 and Rheedersdam 31 Ptn 0 (see Figure 3.1 and Figure 3.3).

The area is serviced by the R34, R30, provincial gravel roads and farm roads. Welkom is located 3.7 km southeast and Odendaalsrus is located 3 km northeast of the proposed Valley TSF site. The geographic coordinates at the centre of the site are 27°54'59.44"S, 26°40'22.09"E. Welkom is located 3 km southeast and Odendaalsrus is located 5.2 km north of the proposed Nooitgedacht TSF site. The geographic coordinates at the centre of the site are 27°56'30.11"S and 26°39'43.96"E.

Existing infrastructure includes mine infrastructure such as existing TSFs, electricity transmission lines, telephone lines, fences, and other recent structures.

3.3 Project Description

3.3.1 General

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

Figure 3.1 Locality map showing the Projects is located in the Matjhabeng Local Municipality in the Lejweleputswa District Municipality of the Free State Province of South Africa.

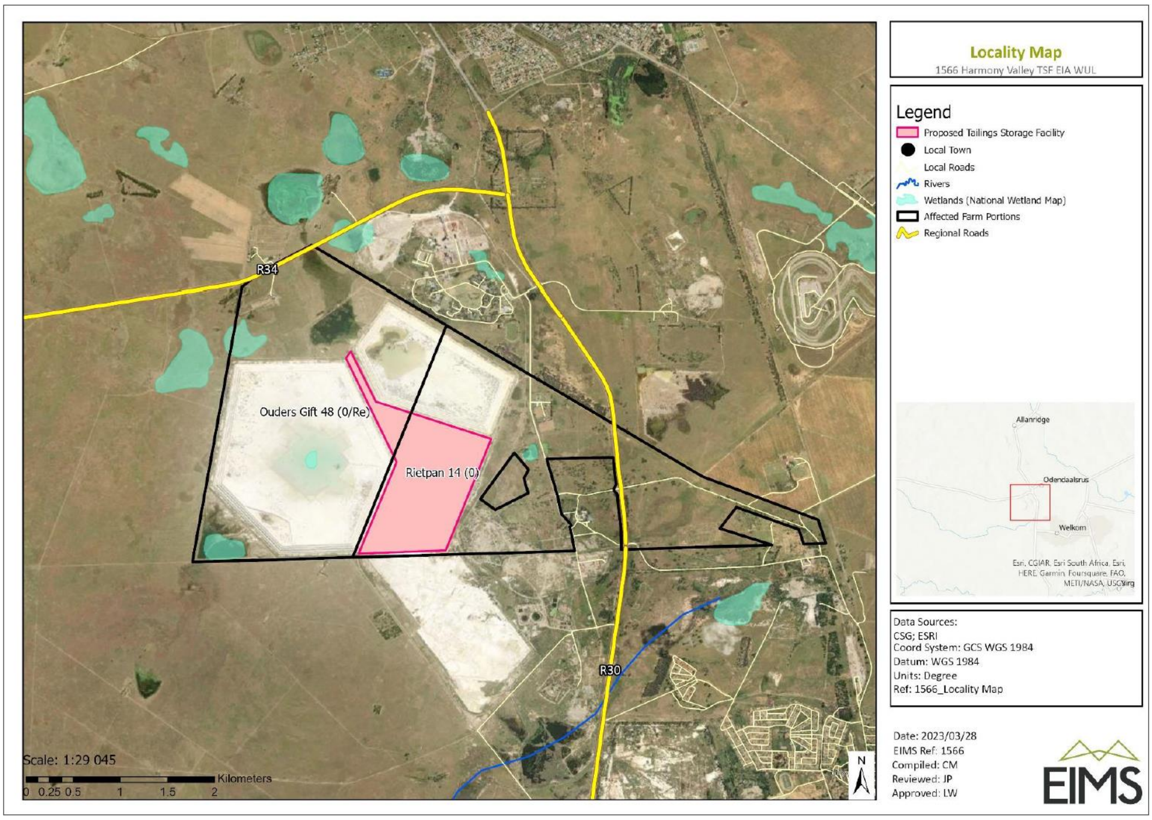

Figure 3.2 Locality map showing the proposed Valley TSF and associated infrastructure (EIMS, 2023b).

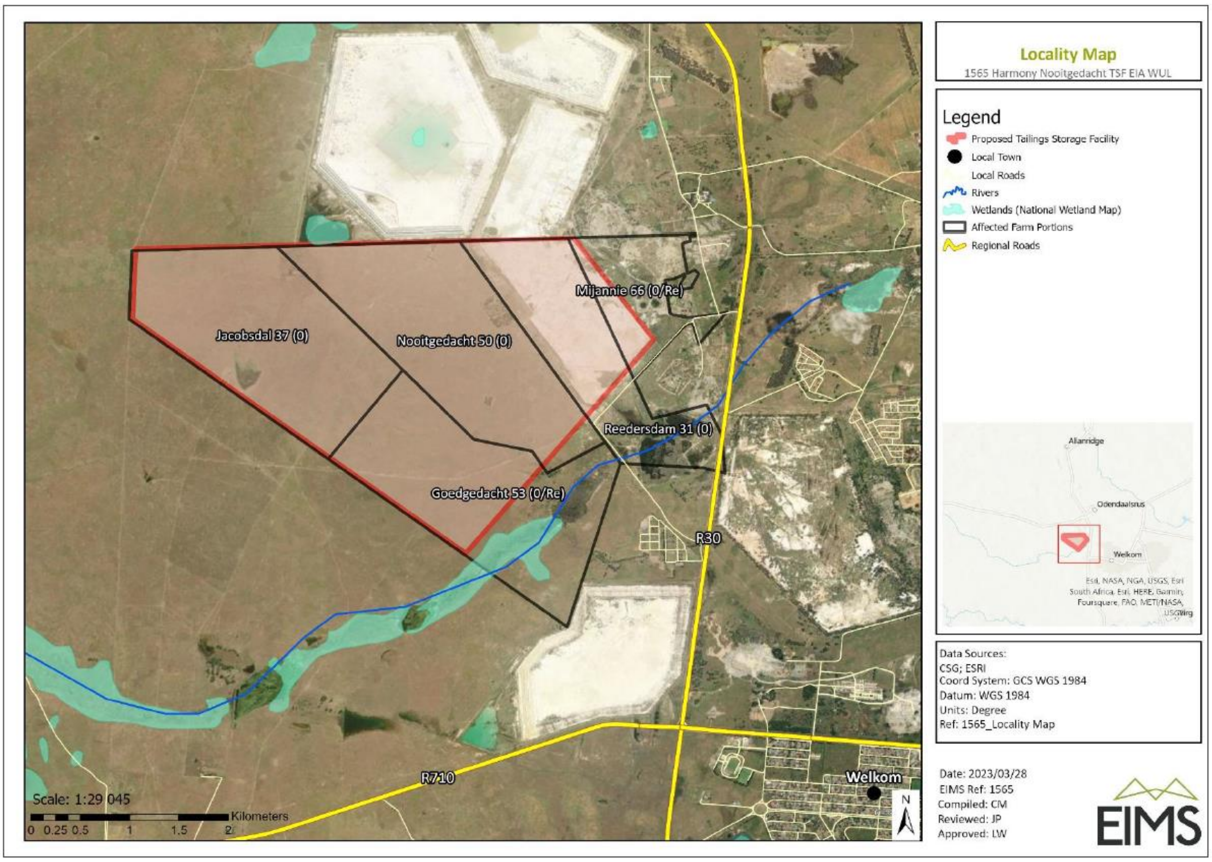

Figure 3.3 Locality map showing the proposed Nooitgedacht TSF and associated infrastructure (EIMS, 2023a).

3.3.2 Need for the Projects

Harmony holds an approved Mining Right (MR) and Environmental Management Programme (EMPr), in terms of the Minerals and Petroleum Resources Development Act (Act 28 of 2002, as amended) (MPRDA), for the mining of gold at various operations in the Welkom area (Mining Right Ref: MR84).

Due to the continuous expansion of the Free State Operation, Harmony requires new deposition sites for tailings material generated at the Harmony metallurgical processing plants. This tailings material is currently deposited at the Free State South (FSS) 2 tailings storage facility (TSF), Helena 4 TSF, St. Helena 123 TSF, Dam 23 TSF, Brand D TSF and Target 1&2 TSF. However, the current planned Life of Mine (LOM) of the Free State Operations exceed the available deposition capacity of these TSFs. Harmony is, therefore, proposing to construct the proposed Valley TSF and the Nooitgedacht TSF to cater for this additional capacity.

The proposed Valley TSF, in particular, will be used for the deposition of tailings material generated at the Harmony One metallurgical processing plant. Currently, this tailings material is deposited at the FSS 2 TSF and the Helena 4 TSF but will reach its capacity by July 2024. Finding an alternative deposition site is, therefore, of paramount importance for the continuous operation of the Harmony One metallurgical processing plant.

3.3.3 Project Alternatives

Since the Projects relate to new TSFs, there are limited feasible and/or reasonable alternatives that can be considered. The following is noted:

- Following a review of possible future tailings deposition sites performed by Golder Environmental in 2008, an option to utilise the space between the FSN 1 and FSN 2 TSFs and a portion of the footprint of the FSN 4 TSF has been identified as the preferred alternative for the Valley TSF (EIMS, 2023b).
- Following a review of possible future tailings deposition sites performed by Golder Environmental in 2008, the Nooitgedacht site located to the south of FSN 1 TSF and the proposed Valley TSF site and a portion of the footprint of the FSN 4 TSF has been identified as the preferred alternative for the Nooitgedacht TSF (EIMS, 2023a).
- The layout and design alternatives to accommodate the total volume of material to be deposited on the TSFs are based on the forecast gold reserves to be processed at the existing Harmony metallurgical processing plants. The total volume is a firm parameter which cannot be downscaled.
- Technological alternatives are limited to the use of a liner system for the TSFs. However, the liner requirements are based on the waste classification of the material and geohydrological modelling and risk assessment.
- Several methods of tailings deposition are possible including the spigotting method, cyclone deposition and the paddocking method. Currently, cyclone deposition is the vastly preferred method of deposition for all the current TSF operations of Harmony. The environmental impacts associated with each deposition method are similar. However, cyclone deposition has higher water recovery rates and is also preferred from a geotechnical perspective.
- Process or activity alternatives imply the investigation of alternative processes, methods, or activities to achieve the same goal for the proposed TSFs. A new deposition site will be required for Harmony One Plant to replace the FSS 2 TSF and St. Helena 4 TSF by July 2024 and for this, there are no feasible

or applicable activity or process alternatives, additional deposition space will be required for the tailings material.

In addition, the current planned LoM of the Free State Operations exceed the available deposition capacity of the current deposition sites and, therefore Harmony proposes to construct the Nooitgedacht TSF to cater for this additional capacity. For this there are no feasible or applicable activity or process alternatives, additional deposition space will be required for the tailings material.

- A new deposition site will be required for Harmony One Plant to replace the FSS 2 TSF and St. Helena 4 TSF by July 2024 and to make provision for the LoM tailings that will be generated. The no-go alternative would mean that the new TSF Projects would not proceed, and this would negatively affect the future viability of the Free State mining operations of Harmony from July 2024 and beyond due to a lack of tailings deposition space.

3.3.4 Physical Extend of the Projects

The proposed Valley TSF would cover an area of 162.5 ha. The final height is still being determined as part of the engineering design, but will in all likelihood be the same height as the FSN2 TSF, which is around 32 m. A combination of cyclone and spigot deposition methods will be used. Figure 3.4 shows that additional infrastructure includes a Return Water Dam, topsoil stockpile facilities, as well as the normal infrastructure associated with a TSF such as toe drains, underdrains, access roads, pipelines, and solution trenches. The boundary of the expanded Valley TSF and associated infrastructure will be approximately 2 km from the Hestersrus residential area (Odendaalsrus) and about 3 km from the Reederspark residential area (Welkom).

The proposed Nooitgedacht TSF would cover an area of 895 ha. The final height is still being determined as part of the engineering design, but the current design scope of the Nooitgedacht TSF is based on a height of 100 m. A combination of cyclone and spigot deposition methods will be used. Additional infrastructure includes normal infrastructure associated with a TSF such as toe drains, underdrains, access roads, pipelines, and solution trenches. The boundary of the expanded Nooitgedacht TSF and associated infrastructure will be approximately 5.30 km from the Hestersrus residential area (Odendaalsrus) and about 2 km from the Reederspark residential area (Welkom).

3.3.5 Construction and Operation (Valley TSF)[2]

Geotheta was appointed by Harmony Gold to complete the design of the proposed new Valley TSF. Table 3.1 summarises the key parameters of the Valley TSF design (Geotheta, 2023). Figure 3.4 presents a locality map of the Projects TSFs and associated infrastructure.

Table 3.1 Summary of the key design parameters for the proposed Valley TSF (Geotheta, 2023).

Parameter	Unit	Value
Maximum final height	m	36
Footprint area	ha	163.5
Total capacity	tonnes	56.8 million
Maximum rate of rise	$m.year^{-1}$	3.7
Deposition method	-	Cyclone

[2] Note that a detailed design report for the proposed Nooitgedacht TSF was not yet available at the time of writing the report.

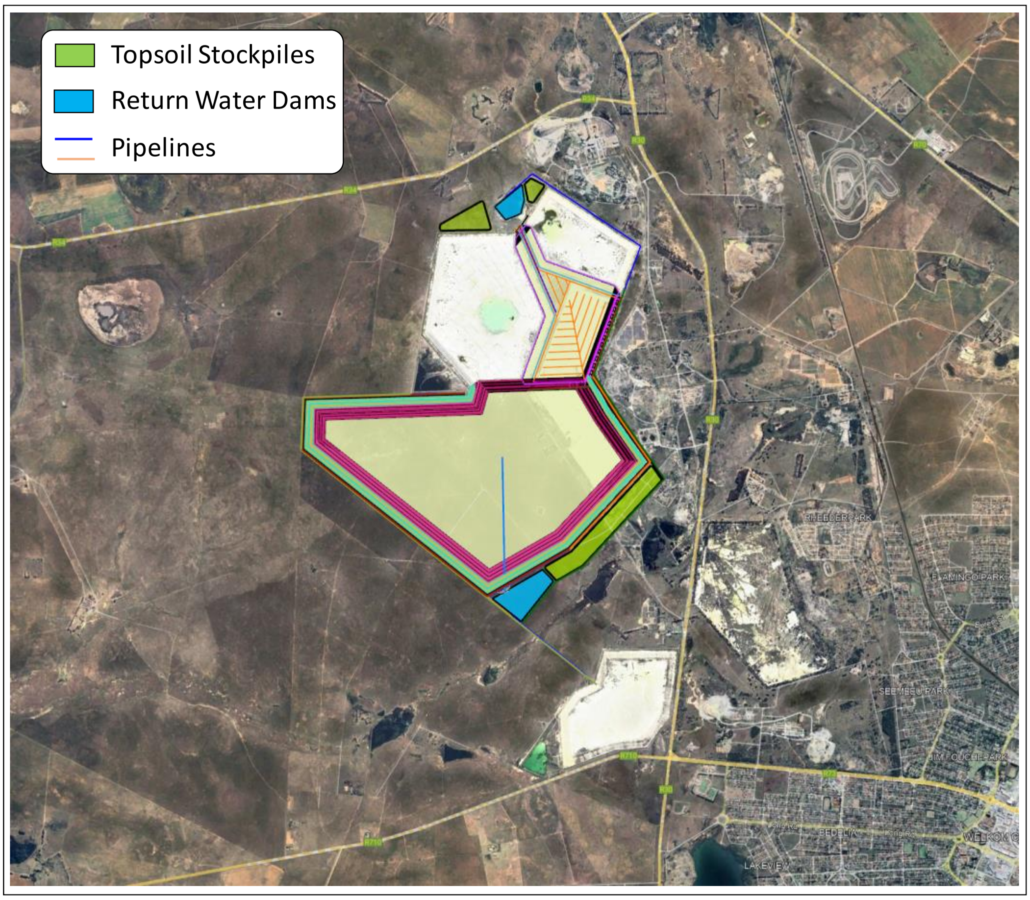

Figure 3.4 Locality map showing the TSF expansion to the north and west of the existing Modder East Operation TSF.

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 Projects area. Within the conceptual assessment framework presented in Figure 1.3, this information would provide input into understanding the potential distribution of radioactivity released from the Projects into the environment (e.g., atmosphere, groundwater, and surface water), the accumulation of radioactivity in the associated environmental media and the subsequent interaction of members of the public with the impacted environmental media.

The environmental baseline conditions observed near the Projects area are described in the relevant scoping reports (EIMS, 2023a; b) and a series of specialist studies that serve as a basis and input into the ESHIA process for the Valley TSF and a separate ESHIA process for the Nooitgedacht TSF (Airshed, 2023; Equispectives, 2023b; MvB Consulting, 2023b). These reports were used and referenced for information on the topography and drainage, geology and hydrogeology, soils, meteorological conditions, as well as the human behavioural and social conditions as appropriate and justified.

3.4.2 Topography

The topography of the location of the proposed TSFs is fairly flat, comprising undulating terrain. An analysis of topographical data indicated a slope of less than 1:10 over most of the Projects area. The elevation on the site is approximately 1,330 meters above means sea level (see Figure 3.5).

3.4.3 Drainage and Catchment

The Projects area falls within the primary catchment (C) and quaternary catchment C43B, which has an area of 723 km^2 and C25B which has an area of 1,895 km^2 both of which are located within the Middle Vaal Water Management Area (WMA) (see Figure 3.6 and Figure 3.7). Two dams are within close proximity to the site. This includes the D-Dam Complex. The proposed TSFs are situated approximately 2 km at its closest from the nearest river/stream (the Mahem Spruit is located southeast of the TSF sites (when considering the more detailed 1:50,000 topographical map data) (see Figure 3.5).

3.4.4 Geological Setting

The Free State Goldfield which forms s triangle between Allanridge, Welkom and Virginia, produces gold from auriferous bearing reefs situated within sediments of the Central Rand Group of the Witwatersrand Supergroup. A detailed description of the geology of the Welkom Goldfields is provided by Minter *et al.*; (1986). The mine geology, from shallow to deep, consists of the following

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

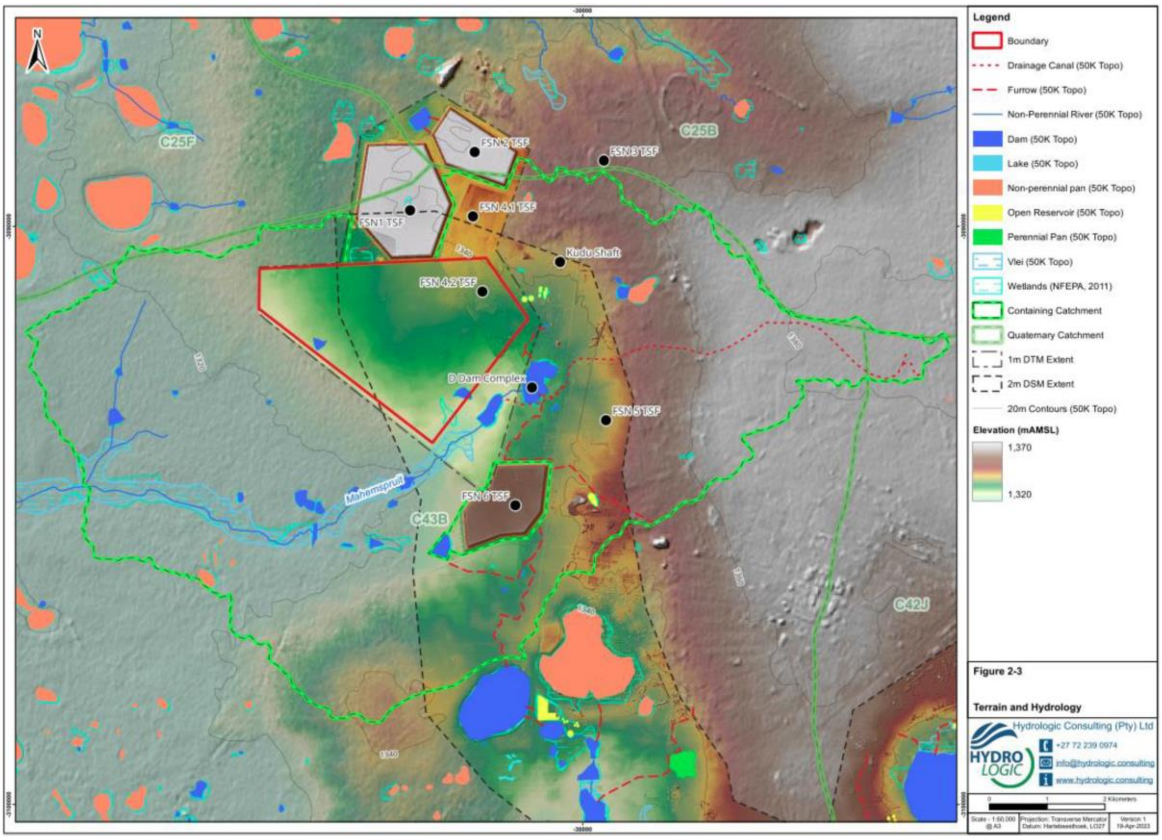

Figure 3.5 Locality map showing the surface water and features and associated elevation of the Projects area (EIMS, 2023a).

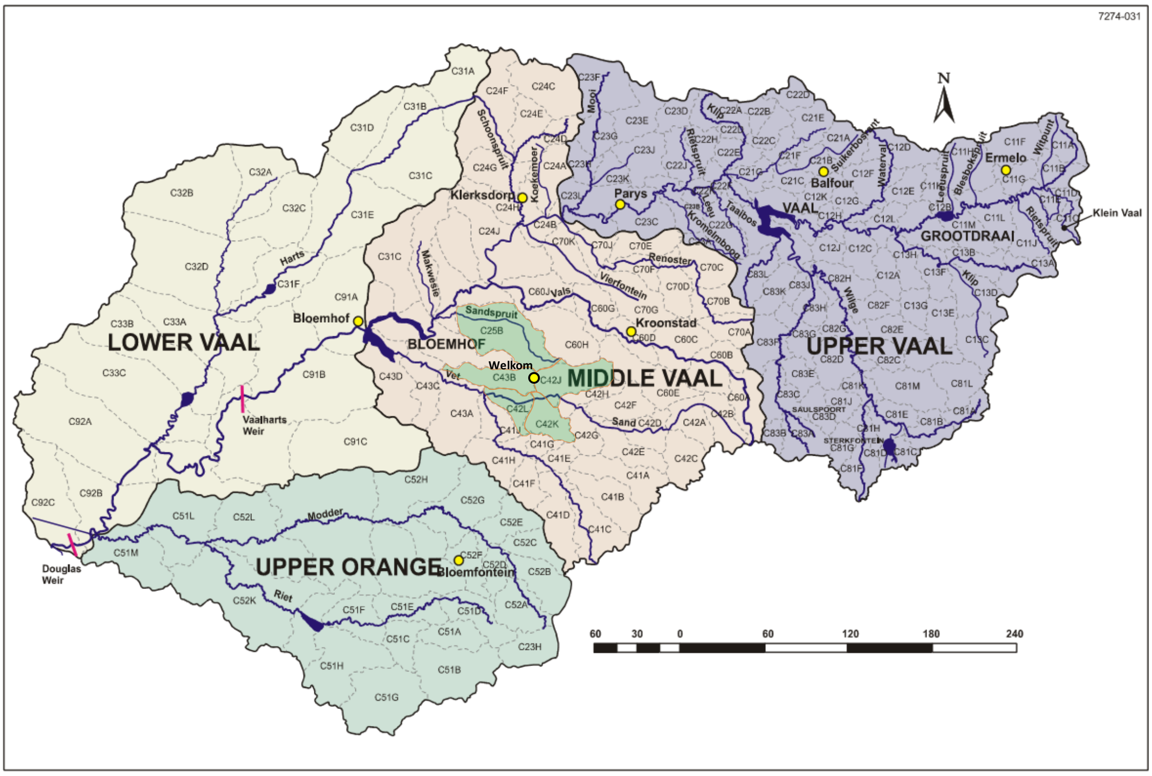

Figure 3.6 **Map showing the Projects is located in the upper catchments of the Vaal Water Management Area (WMA) and more specifically, the C22A Quaternary Catchment (Golder Associates Africa, 2013).**

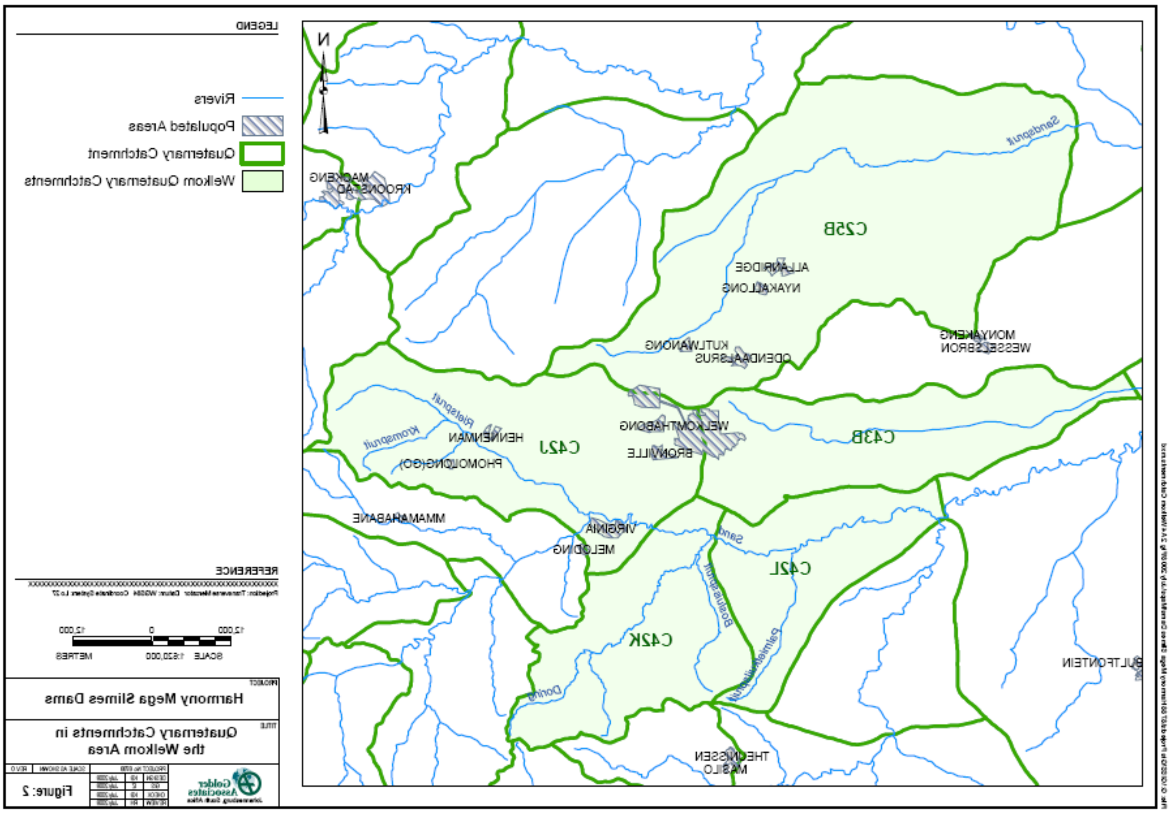

Figure 3.7 **Quaternary Catchments and Rivers associated with the Projects area (Golder Associates Africa, 2008).**

Sediments of the Vryheid Formation of the Ecca Group underlie the study area. The Vryheid Formation (Ecca Group) mainly comprises mudstone, siltstone and fine- to coarse-grained sandstone (pebbly in places). Within the Free State Goldfield, the Ventersdorp Supergroup can be divided into the Pniel sequence, the Platberg Group and the basal Kliprivierberg Group consisting of alternating sediments, amygdaloidal and non-amygdaloidal andesitic lavas, tuffs, and agglomerates (Minter et.al; 1986). Based on prospecting or exploration drilling, the Ventersdorp Supergroup has an average thickness of 1,319m in the area.

The Witwatersrand Supergroup is unconformably overlain by the volcanic and sedimentary rock of the Ventersdorp Supergroup. Within the Free State Goldfield, the Witwatersrand Supergroup, comprising a thick succession of clastic sediments with minor intercalated lava flows, rests on the granites and schist of the Archean Basement. The Central Rand Group of the Witwatersrand Supergroup contains the economic reef horizons mined throughout the basin. The Central Rand Group is dominated by quartzite with minor shale and conglomerate. Several unconformities in the succession are overlain by the economic auriferous paleoplacers (reefs). Figure 3.8 presents the regional geology near the Projects area.

3.4.5 Geohydrological Setting

3.4.5.1 General

The geohydrological setting of the Projects area is described in MvB Consulting (2023b) and includes aspects such as borehole information, aquifer types, groundwater use, aquifer parameters and recharge, groundwater gradients and flow, groundwater quality and aquifer classification. A summary of the relevant information is presented here.

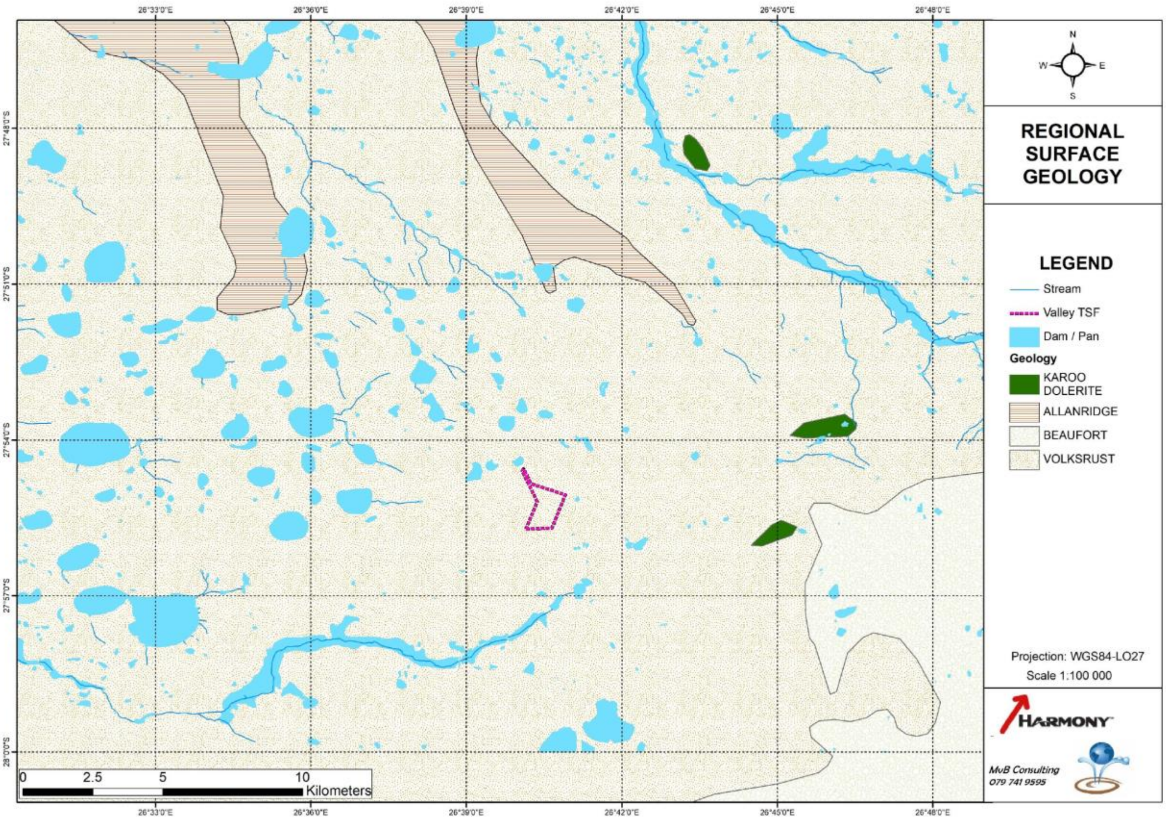

Figure 3.8 The regional geology near the Projects area (MvB Consulting, 2023b).

3.4.5.2 Aquifer Type

The mine infrastructure is situated on interbedded siltstone/sandstone and shale of the Vryheid Formation. Even though the shale and sandstone are not known to contain economic aquifers, groundwater contributes to stream flow and in some instances, high-yielding boreholes have been recorded. The following three aquifers, graphically illustrated in Figure 3.9, underlie the site:

- **Weathered Aquifer (Karoo Formations):** A shallow, weathered aquifer exists in the weathered shale and sandstone at an average depth of 10 m to 20 m below ground level. The most consistent water strike is located at the fresh bedrock/weathering interface. The hydraulic conductivity of the weathered aquifer is typically in the order of 0.1 $m.day^{-1}$. The vertical permeability is in the order of 0.001 $m.day^{-1}$ to 0.00010 $m.day^{-1}$, which is sufficiently low to confine the groundwater in the underlying fractured rock aquifer.
- **Fractured Aquifer (Karoo Formations):** The primary porosity of the Vryheid Formation is very low. Any water-bearing capacity is, therefore, associated with secondary joints, bedding planes and faults. The contact zones of dolerite intrusions are characterised by cooling joints and fractures, which are considered the primary source of groundwater flow within the deeper formations. The hydraulic conductivity of the fractured rock aquifer is typically in the order of 0.001 $m.day^{-1}$ to 0.1 $m.day^{-1}$. The depth of groundwater in this aquifer can be variable due to confining layers in parts of the study area.
- **Witwatersrand/Ventersdorp Aquifer:** The deep brine Witwatersrand aquifer is situated approximately 300 m below the surface. Mining prospecting boreholes indicated this level to be between 170m to 270m (EMP, 2009). This aquifer is thought to be connate (i.e., original formation water) or extremely old (fossil) water and is usually concentrated on geological structures such as fault zones or igneous intrusions (e.g., dykes). The Witwatersrand aquifer has been largely dewatered during the past 40 years of mining and the water levels in the aquifer dropped significantly. Despite the dewatering of the Witwatersrand aquifer, there is no evidence of dewatering of the Karoo aquifers.

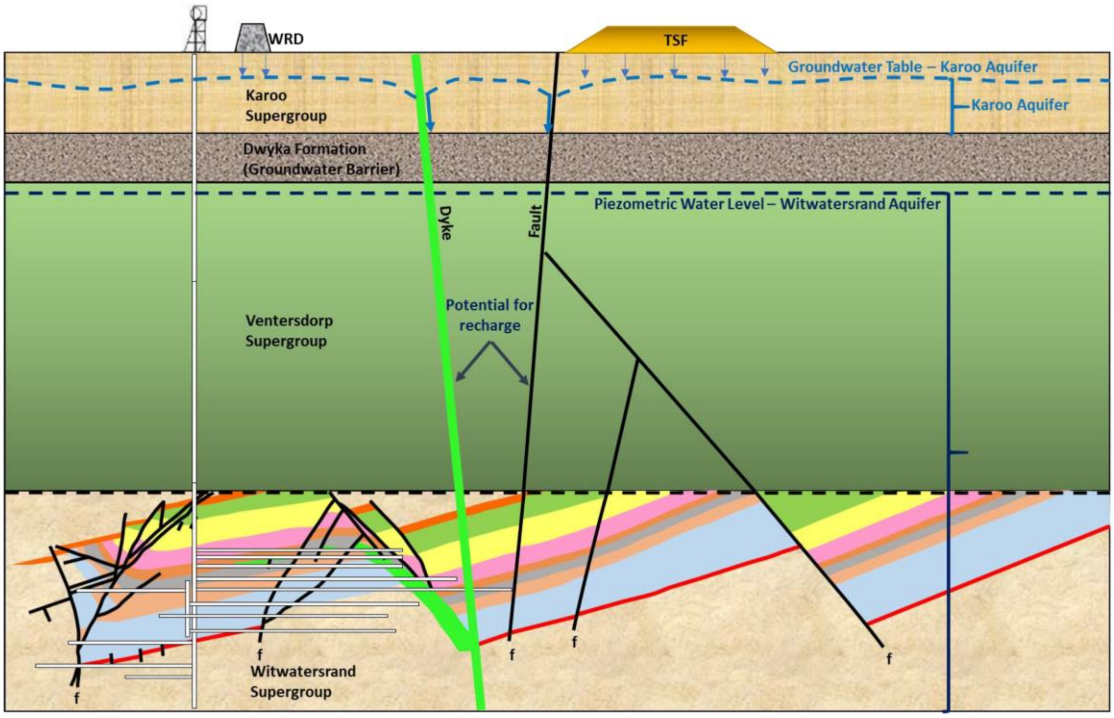

Figure 3.9 Graphical illustration of the aquifers present beneath the Projects area (MvB Consulting, 2023b)

It is, therefore, concluded that:

- There is no or very limited hydraulic connectivity between the Karoo aquifers and the deeper Witwatersrand aquifer, while recharge to the Witwatersrand aquifer is negligible.
- Once the Witwatersrand aquifer is dewatered (or the water level is lowered) it will not recover. The estimated post-mining water level in the Witwatersrand aquifer will therefore be deeper than the pre-mining water level of ~200m below the surface.

3.4.5.3 Groundwater Use

There are no large-scale groundwater supply boreholes within the study area. Farmers are, however, reliant on boreholes for domestic use and stock watering. Windmills have traditionally been utilised in the area. There are no springs recorded. The drilling indicated that groundwater occurrence is predominantly on the contact zones with dolerite intrusions and on the contact between the Karoo sediments and the Ventersdorp lavas. Measured yields vary from 0.1 $L.s^{-1}$ to 22 $L.s^{-1}$.

3.4.5.4 Aquifer Parameters

Test pumping information available from 18 boreholes drilled in the area suggests that the hydraulic conductivity varies between 0.001 $m.day^{-1}$ and 1.8 $m.day^{-1}$. The depth of these boreholes varies between 23 m and 90 m, while the water level measured in these boreholes varies between 0 to 73 m.

Recharge is defined as the process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation or indirectly by way of another formation. According to the Groundwater Assessment Phase II (GRAII), the recharge is approximately 4% of the mean annual precipitation. Groundwater recharge (R) for the area is also 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 540 $mm.year^{-1}$. The recharge rate using the chloride methods equates to 1.6% of MAP or 8.64 $mm.year^{-1}$, which is lower than the GRAII values.

3.4.5.5 Groundwater Flow and Gradients

In most geological terrains, the groundwater mimics the topography and to test if this is the case within the study area the available groundwater levels were plotted against the topography (represented by the borehole collar elevations). The result of this assessment is presented in Figure 3.10. This graph indicates a very good correlation (98%) between the topography and the groundwater level, which suggests that groundwater flow will follow the topographical gradient.

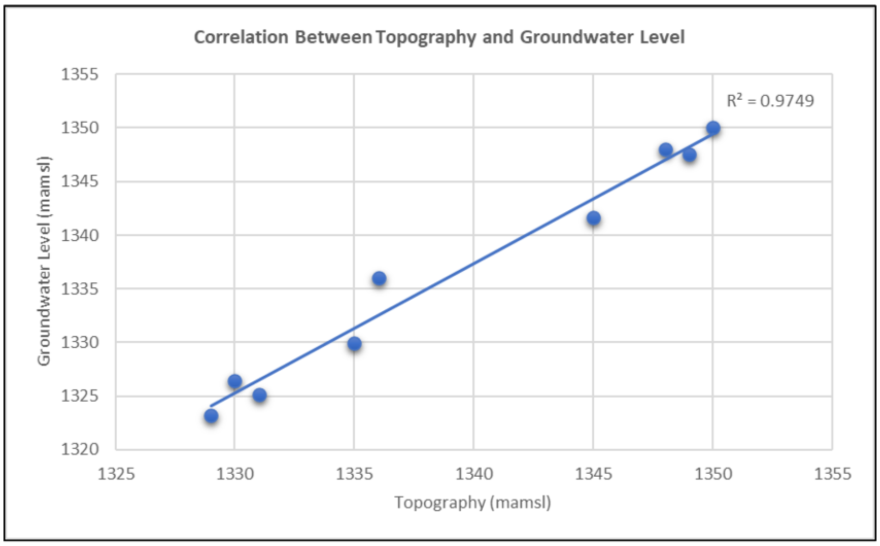

Figure 3.10 Correlation between the topography and the groundwater level near the Projects area (MvB Consulting, 2023b).

Figure 3.11 depicts the groundwater level elevations, which as expected mimic the surface contours. Groundwater flow is perpendicular to the groundwater contours and flows predominantly towards the southwest. The gradient in this direction is in the order of 0.005 (or 0.45%).

Figure 3.12 depicts the simulated sulphate plume from facilities associated with CoR-5 in 2017. It shows that contaminates originating from the FSN 1 TSF, FSN 2 TSF and FSN 4 TSF will migrate in a northwest to a southwesterly direction away from these facilities. Figure 3.13 to Figure 3.15 depicts the simulated sulphate plumes from the proposed Valley TSF after 10, 50 and 100 years without a liner, while Figure 3.16 depicts the plume after 100 years with a liner.

3.4.6 Meteorological Conditions

3.4.6.1 General

The Projects area is located in the summer rainfall region of the Matjhabeng LM in the Lejweleputswa DM of the Free State Province of South Africa. The meteorological characteristics of the area presented and used in the Air Quality Impact Assessment (Airshed, 2023) are based on the weather data for the period January 2019 to December 2021 obtained from the South African Weather Service (SAWS) station at Welkom. The Welkom weather station is located 4 km south of the Projects area.

3.4.6.2 Wind Field

The wind roses comprise 16 spokes, which represent the directions from which winds blew during a specific period. The colours used in the wind roses below, reflect the different categories of wind speeds; the yellow area, for example, represents winds in between 4 and 5 $m.s^{-1}$. The dotted circles provide information regarding the frequency of occurrence of wind speed and direction categories. The frequency with which calms occurred, i.e., periods during which the wind speed was below 1 $m.s^{-1}$ are also indicated.

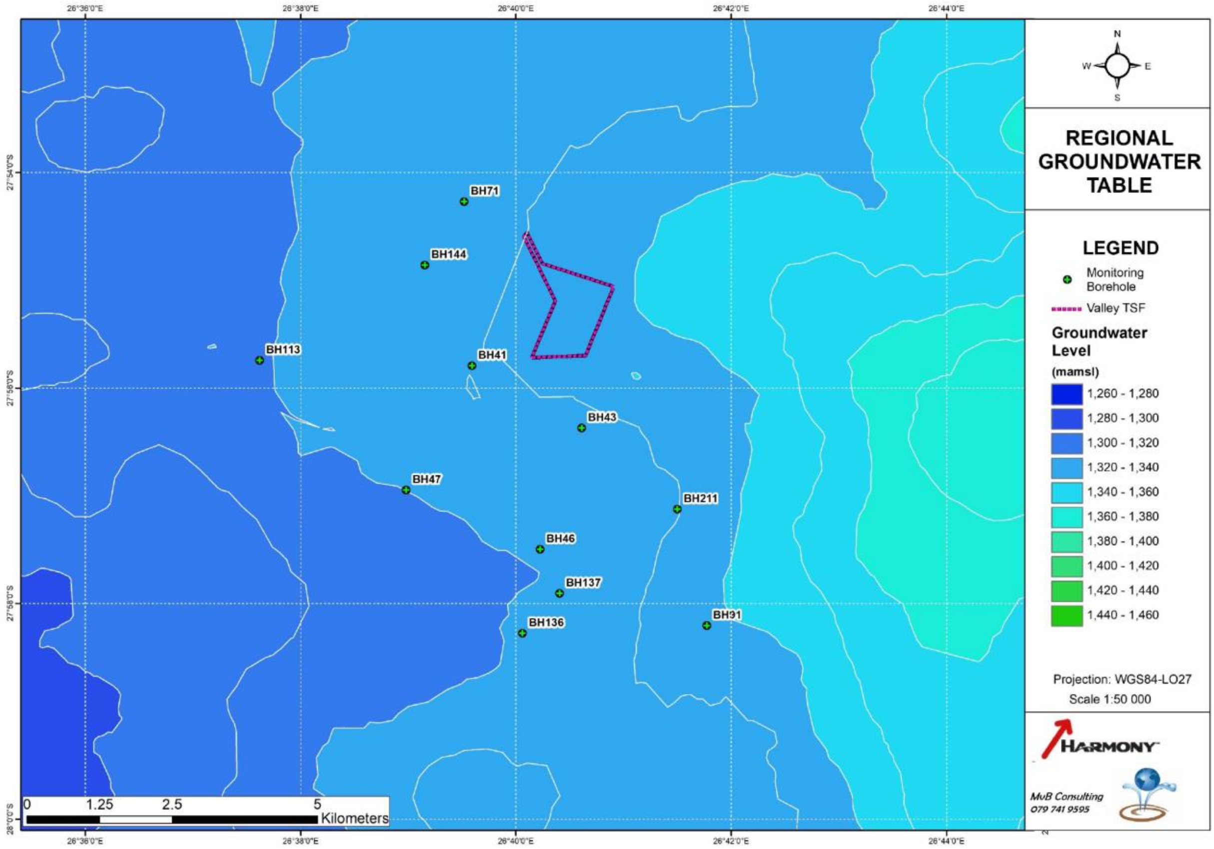

Figure 3.11 **The regional interpolated groundwater gradient near the Projects area (MvB Consulting, 2023b).**

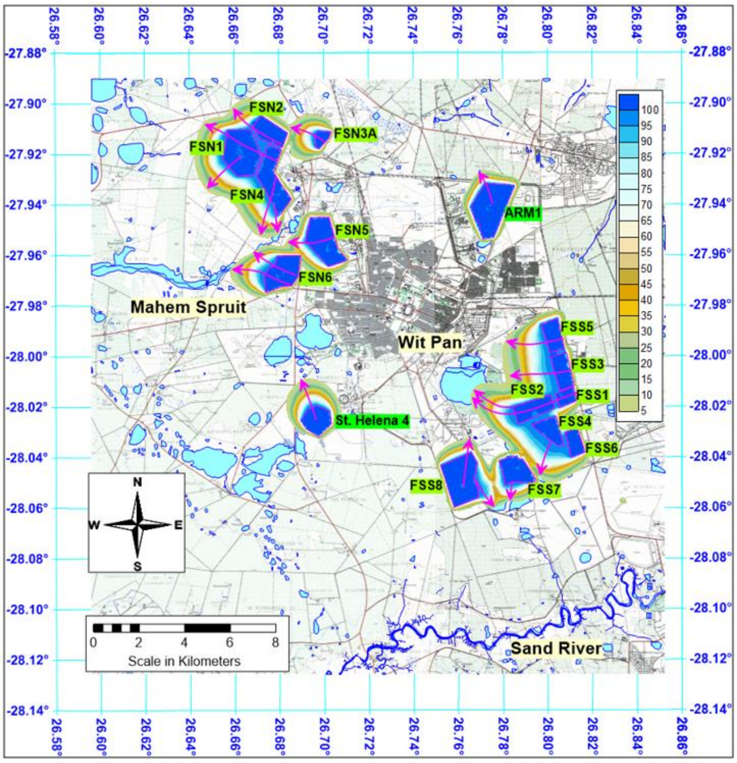

Figure 3.12 **Simulated sulphate plume for CoR 5 in 2017. The contour intervals on the plumes depict the dilution of the plume as a percentage of the input concentration of 100% (AquiSim, 2018c).**

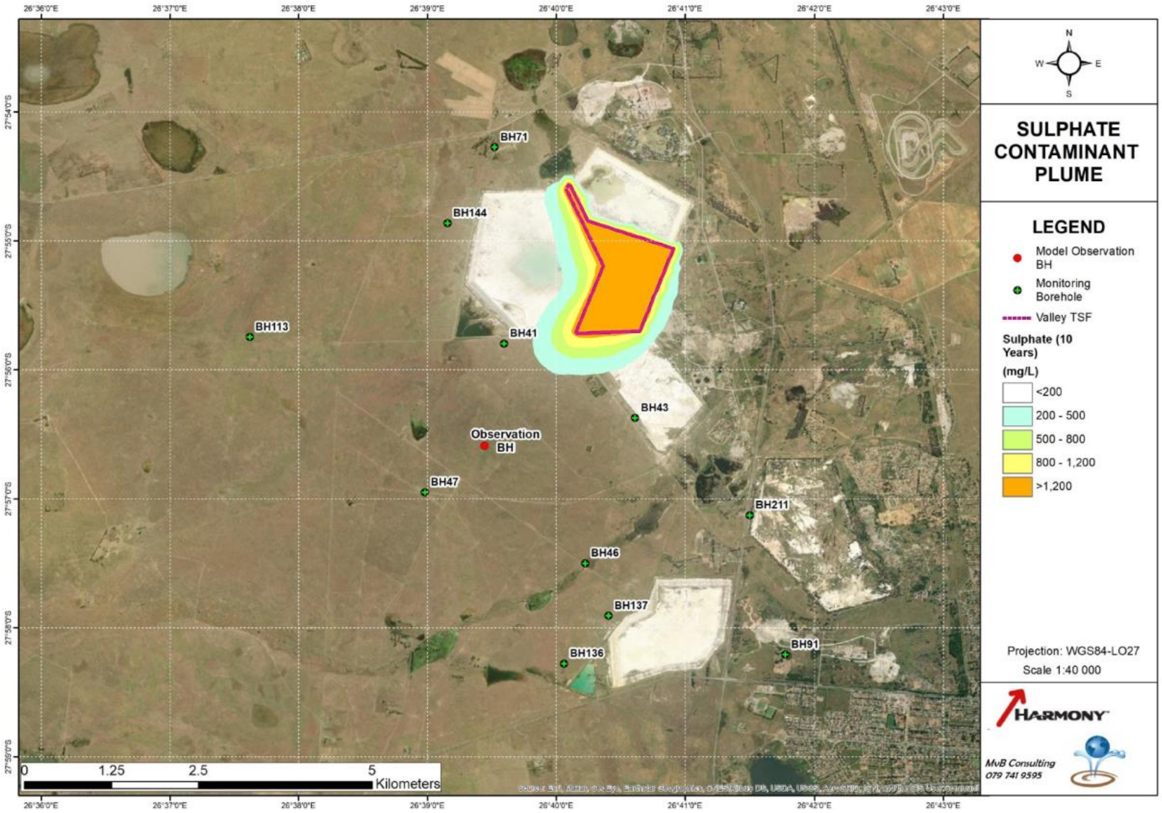

Figure 3.13 The simulated sulphate plume after 10 years without a liner (MvB Consulting, 2023a).

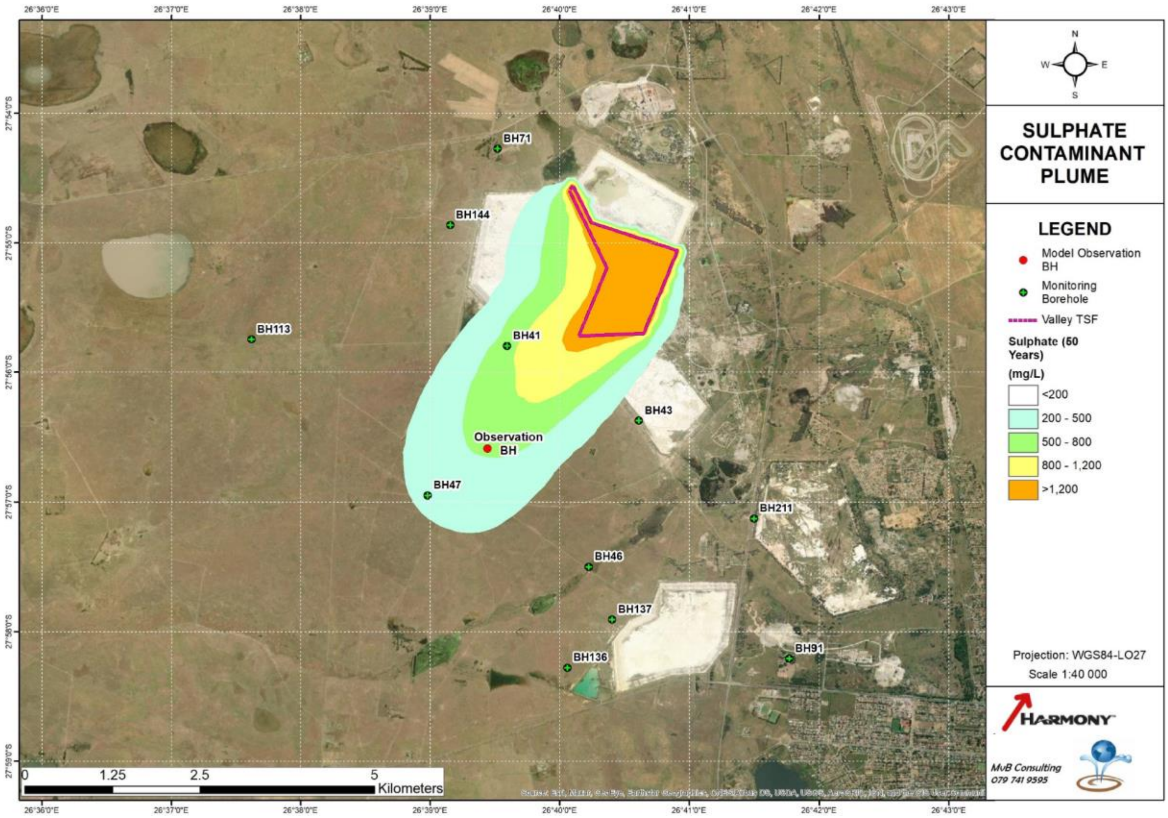

Figure 3.14 The simulated sulphate plume after 50 years without a liner (MvB Consulting, 2023a).

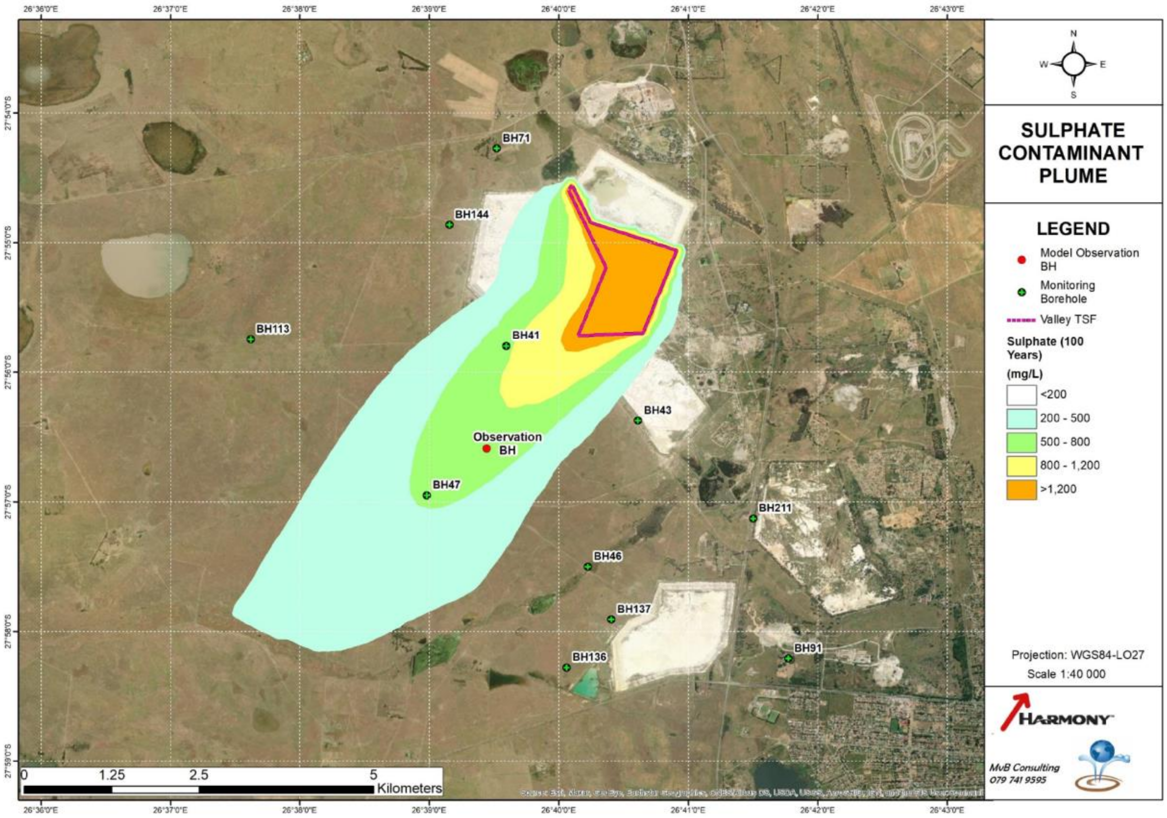

Figure 3.15 The simulated sulphate plume after 100 years without a liner (MvB Consulting, 2023a).

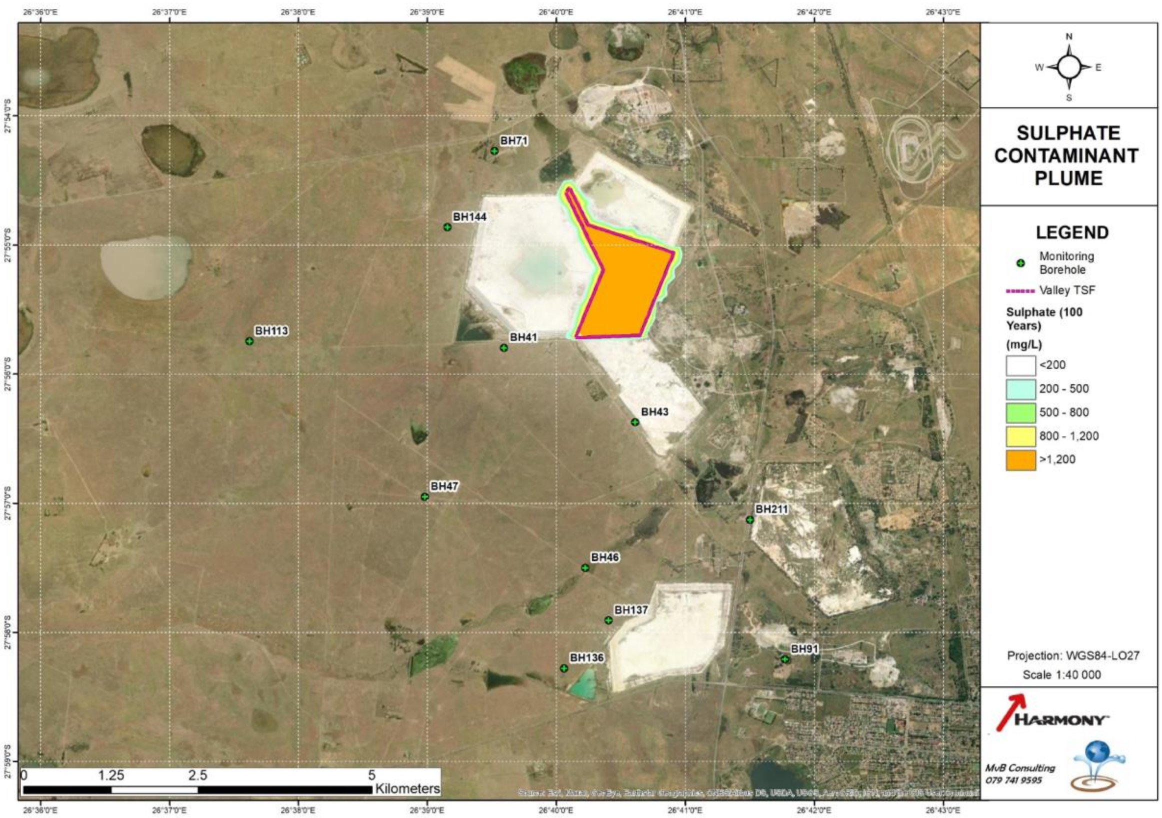

Figure 3.16 The simulated sulphate plume after 100 years with a liner (MvB Consulting, 2023a).

The period wind field and diurnal variability in the wind field are shown in Figure 3.17, while the seasonal variations are shown in Figure 3.18.

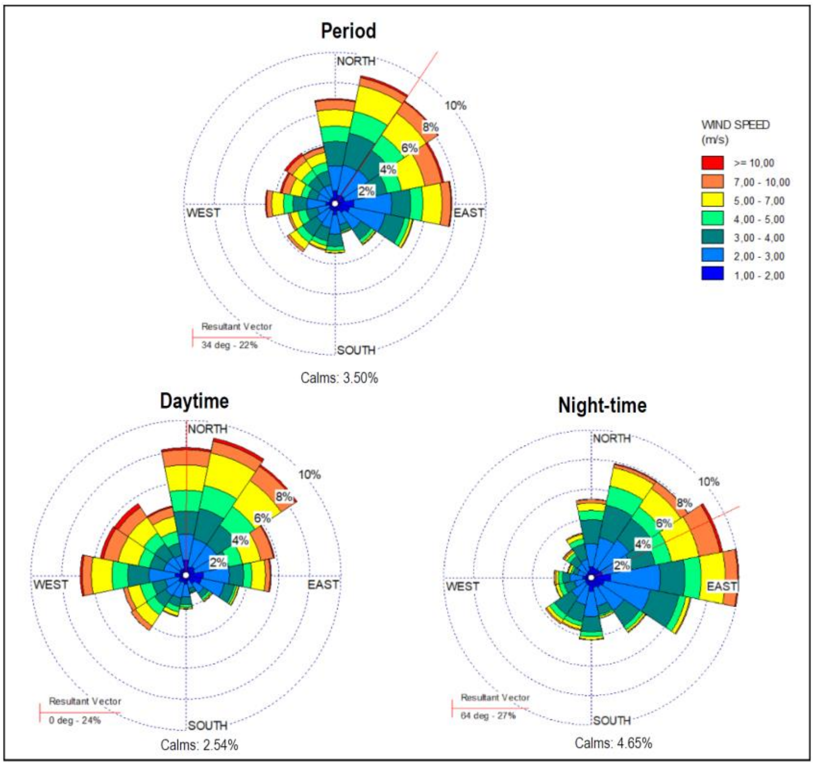

Figure 3.17 Period, day- and night-time wind roses for the Projects area (SAWS Welkom Data, 2019 to 2021) (Airshed, 2023).

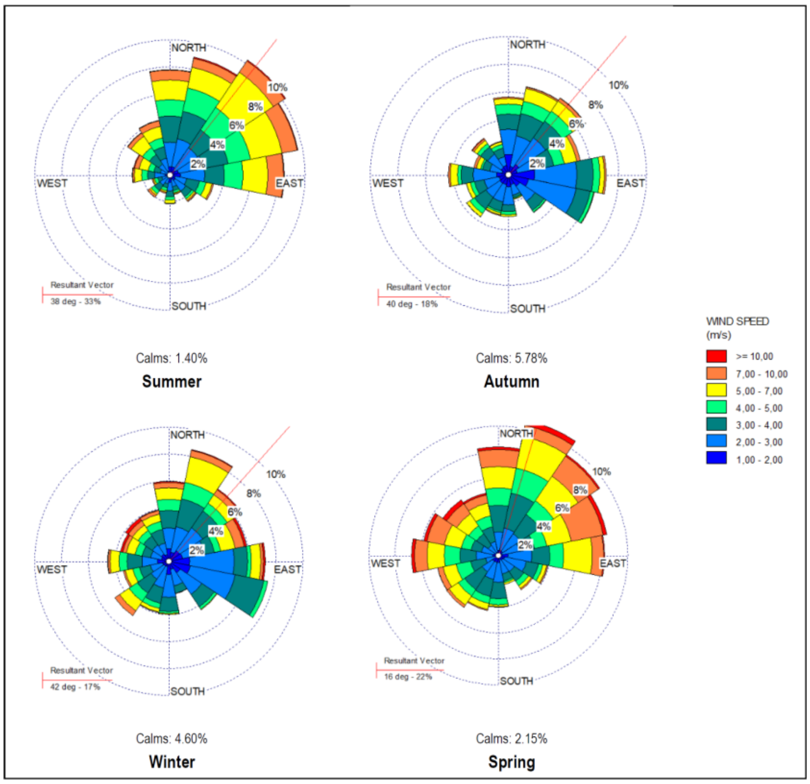

Figure 3.18 Seasonal wind roses for the Projects area (SAWS Welkom Data, 2019 to 2021) (Airshed, 2023).

During the 2019 to 2021 period, the wind field was dominated by winds from the north-northeast and northeast, followed by northerly and easterly winds. During the day (6 AM to 6 PM), the prevailing wind field is from the north to northeast and the west, with less frequent winds from the north-westerly sector, the easterly sector and the southwest. During the night, the wind field shifts to the easterly sector (north-northeast to east-southeast), with very little flow from the westerly sector. Long-term air quality impacts are therefore expected to be the most significant to the south and southwest of the Projects area. The strongest winds (more than 6 $m.s^{-1}$) were also from the north and northeast and occurred mostly during the day, with 15 $m.s^{-1}$ the highest wind speed recorded. The average wind speed over the three years is 3.7 $m.s^{-1}$, with calm conditions occurring for 3.5% of the time (see Figure 3.17).

Seasonally, the wind flow pattern conforms to the period average wind flow pattern. The seasonal wind field shows little seasonal differences in the wind fields. During summer and spring, the dominant winds are from the north-northeast to east, with more frequent westerly winds during spring. Autumn reflects dominant north-easterly and easterly winds, with a similar wind field during winter, but with more frequent north-northeasterly and east-southeasterly winds (see Figure 3.18).

According to the Beaufort wind force scale, wind speeds between 6 and 8 $m.s^{-1}$ equates to a moderate breeze, with wind speeds between 9 and 11 $m.s^{-1}$ referred to as a fresh breeze (https://www.metoffice.gov.uk/guide/weather/marine/beaufort-scale). Wind speeds between 11 and 14 $m.s^{-1}$ are described as a strong breeze with winds between 14 and 17 $m.s^{-1}$ near gale force winds and 17 and 21 $m.s^{-1}$ as gale force winds. Over the 3 years, wind speeds within 14 and 17 $m.s^{-1}$ occurred for 0.03% of the time, and winds between 11 and 14 $m.s^{-1}$ for 0.46%. The likelihood for wind erosion to occur from open and exposed surfaces, with loose fine material, but considering that the TSF surfaces are typically crusted, was estimated when the wind speed exceeds 9 $m.s^{-1}$ (Mian & Yanful, 2003). Wind speeds exceeding 9 $m.s^{-1}$ occurred for 2.27% over the 3 years.

3.4.6.3 Temperature

Air temperature is important from an air quality perspective, both for determining the effect of plume buoyancy (the larger the temperature difference between the emission plume and the ambient air, the higher the plume can rise), as well as for determining the development of the mixing and inversion layers in the atmosphere.

The monthly mean, maximum and minimum temperatures are given in Table 3.2. Temperatures ranged between -6.1°C in July and 40.8°C in January. During the day, temperatures increase to reach the maximum at around 15:00. Ambient air temperature decreases to reach a minimum at around 06:00 i.e., just before sunrise.

Table 3.2 Monthly minimum, average and maximum temperature (°C) for the Projects area (SAWS Welkom Data, 2019 to 2021) (Airshed, 2023).

	Temperature (°C)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum	11.7	10.1	8.1	1.6	-2.8	-4.3	-6.1	-4.8	1.3	3.3	3	10.5
Average	23.2	22.4	20.6	17.6	14.2	10.8	10.6	13.6	18	20.6	22.1	22.7
Maximum	40.8	36.9	33.3	32.8	28.7	26.9	25.6	31	34	37.3	36.7	39

3.4.6.4 Precipitation

Precipitation represents an effective removal mechanism of atmospheric pollutants. Precipitation reduces wind erosion potential by increasing the moisture content of materials. Rain days are defined as days experiencing 0.1 mm or more rainfall.

Rainfall in the region is almost exclusively due to showers and thunderstorms and falls mainly in summer, from October to March. The maximum rainfall occurs during the December-January period. The long-term annual average rainfall (1955 to 1978) for Welkom is given in Table 3.3 (Schulze, 1986). The mean annual precipitation (MAP) is estimated to be 526 mm.year^{-1}

Table 3.3 The long-term average monthly rainfall for Welkom (Airshed, 2023).

Rainfall	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Average (mm)	99	67	67	49	23	8	7	5	17	49	63	56	526
No. of rain days	10	9	9	7	4	2	2	1	2	7	9	10	72

3.4.7 Socio-Economic Baseline Conditions

3.4.7.1 General

The socio-economic baseline conditions relevant to the Projects area are described in Equispectives (2023b). The report focuses on the proposed Nooitgedacht TSF site, but the socio-economic baseline conditions are equally applicable to the Valley TSF site.

Presented here is a summary of the conditions that serve as a basis for human behavioural conditions and their interaction with the environment. Within the conceptual assessment framework presented in Figure 1.3, 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 Projects area is described in Section 3.2 and will not be repeated here.

3.4.7.2 Community Types

Communities can be classified as belonging to one of the following groups (Equispectives, 2023a):

- Formal Residential Structure Communities
  A formal dwelling can be described as "*A structure built according to approved plans, i.e., house on a separate stand, flat or apartment, townhouse, a room in a backyard or rooms or flatlet elsewhere*" (Statistics South Africa, 2012). In some areas there may be a formal as well as an informal dwelling on a stand, creating a community with *mixed dwelling types*.
- Informal Residential Structure Communities
  An informal dwelling can be described as "*A makeshift structure not approved by a local authority and not intended as a permanent dwelling. Typically built with found materials (corrugated iron, cardboard, plastic, etc.), and is contrasted with formal dwelling and traditional dwelling*" (Statistics South Africa, 2012).
- Commercial Agricultural Communities
  Commercial agriculture includes farms where the farmer earns a livelihood from agriculture, such as crop, livestock, or game farming. Areas with smallholdings are categorised according to their character. If the residents of the smallholdings practise agriculture, they are grouped with commercial agriculture, if they just reside in the area or have a business on the smallholding not related to agriculture, the area is classified as formal residential.
- Small-scale Subsistence Farming

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

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

The communities around the Projects area can mostly be described as formal residential areas associated with Welkom and Odendaalsrus (see Figure 3.19), with about two-fifths of households in Ward 35 residing in collective living quarters. Commercial agricultural communities are present to the northwest, west and southwest of the Projects area. Table 3.4 classify the households according to geotypes, which shows that on a ward level, the majority of households live in areas classified as urban.

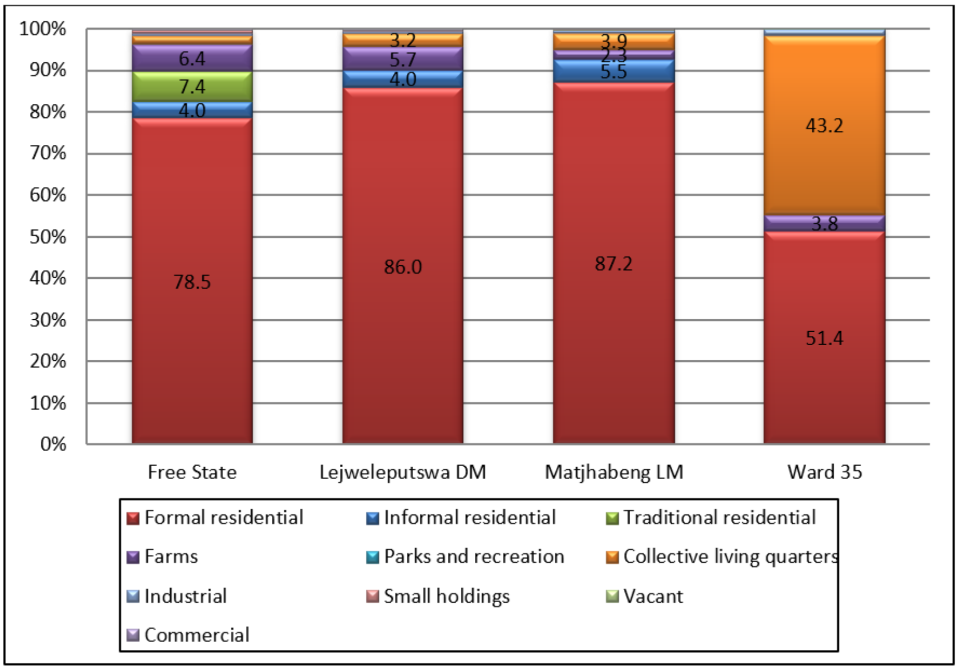

Figure 3.19 Enumeration area types (persons, shown in percentage, source: Census 2011) (Equispectives, 2023b).

Table 3.4 Geotypes (source: Census 2011, households) (Equispectives, 2023b).

Area	Urban	Tribal/Traditional	Farm
Free State Province	84.5	8.8	6.7
Lejweleputswa DM	93.9	0.0	6.1
Matjhabeng LM	97.7	0.0	2.3
Ward 35	94.5	0.0	5.5

3.4.7.3 Demographic and Socio-economic Characteristics

Population and Household Size

According to the Community Survey 2016, the population of South Africa is approximately 55,7 million and has shown an increase of about 7.5% since 2011. The household density for the country is estimated at approximately 3.29 people per household, indicating an average household size of 3-4 people (leaning towards 3) for most households, which is down from the 2011 average household size of 3.58 people per household. Smaller household sizes are in general associated with higher levels of urbanisation.

Table 3.5 shows that the greatest increase in population since 2011 has been on a local level but still lower than the national average. Population density refers to the number of people per square kilometre and the population density on a national level has increased from 42.45 people per km2 in 2011 to 45.63 people per km^2 in 2016. In the study area, the population density has increased since 2011 with the highest density in the Matjabeng LM. Given the steady decline in employment in the gold mining industry (www.mineralscouncil.org.za), it is likely that the population in the area have declined since 2016, rather than increased, but this remains to be confirmed by more recent demographic data of the area.

Table 3.5 Population density and growth estimates (sources: Census 2011, Community Survey 2016) (Equispectives, 2023b).

Area	Size in km^2	Population 2011	Population 2016	Population density 2011	Population density 2016	Growth in population (%)
Free State Province	129,825	2,745,590	2,834,714	21.15	21.83	3.25
Lejweleputswa DM	31,930	627,626	649,964	19.66	20.36	3.56
Matjhabeng LM	5,155	406,461	428,843	78.85	83.19	5.51

Table 3.6 shows that the number of households in the study area has increased on all levels. The proportionate increase in households was greater than the increase in population on all levels and exceeded the growth in households of 12.3% on a national level. The average household size has shown a decrease on all levels, which means there are more households, but with fewer members.

Table 3.6 Household sizes and growth estimates (sources: Census 2011, Community Survey 2016) (Equispectives, 2023b).

Area	Households 2011	Households 2016	Average household size 2011	Average household size 2016	Growth in households (%)
Free State Province	823,316	946,639	3.33	2.99	14.98
Lejweleputswa DM	183,163	219,014	3.43	2.97	19.57
Matjhabeng LM	123,195	149,021	3.30	2.88	20.96

Socio-economic Conditions

Table 3.7 shows that the total dependency ratio in the Matjhabeng LM is lower than on a district or provincial level. The same trend applies to the youth, aged and employment dependency ratios. The employed dependency ratio refers to the proportion of people dependent on the people who are employed, and not only those of working age. The employed dependency ratio for the Matjhabeng LM is lower than on a district and provincial level. In Ward 35, the total dependency and youth dependency ratios are quite low, suggesting a smaller proportion of youth in this ward than at the local or district level.

Table 3.7 Dependency ratios (source: Census 2011) (Equispectives, 2023b).

Area	Total dependency	Youth dependency	Aged dependency	Employed dependency
Free State Province	52.88	44.48	8.39	76.34
Lejweleputswa DM	51.33	43.71	7.61	77.16
Matjhabeng LM	46.93	40.09	6.85	75.46
Ward 35	25.83	21.18	4.65	74.76

Poverty is a complex issue that manifests itself in economic, social, and political ways and to define poverty by a unidimensional measure such as income or expenditure would be an oversimplification of the matter. Poor people themselves describe their experience of poverty as multidimensional. The South

African Multidimensional Poverty Index (SAMPI) (Statistics South Africa, 2014) assess poverty on the dimensions of health, education, standard of living and economic activity using the indicators of child mortality, years of schooling, school attendance, fuel for heating, lighting, and cooking, water access, sanitation, dwelling type, asset ownership and unemployment.

The poverty headcount refers to the proportion of households that can be defined as multi-dimensionally poor by using the SAMPI's poverty cut-offs (Statistics South Africa, 2014). Table 3.8 shows that the poverty headcount has increased on all levels since 2011, indicating an increase in the number of multi-dimensionally poor households.

Table 3.8 Poverty and SAMPI scores (sources: Census 2011 and Community Survey 2016) (Equispectives, 2023b).

Area	Poverty headcount 2011 (%)	Poverty Intensity 2011 (%)	SAMPI 2011	Poverty headcount 2016 (%)	Poverty Intensity 2016 (%)	SAMPI 2016
Free State Province	5.5	42.2	0.023	5.5	41.7	0.023
Lejweleputswa DM	5.6	42.8	0.024	4.8	42.2	0.020
Matjhabeng LM	5.5	43.0	0.024	4.3	41.8	0.018

The intensity of poverty experienced refers to the average proportion of indicators in which poor households are deprived (Statistics South Africa, 2014). The intensity of poverty has increased slightly on all levels. The intensity of poverty and the poverty headcount is used to calculate the SAMPI score. A higher score indicates a very poor community that is deprived of many indicators. The SAMPI score in the Matjhabeng LM area has decreased, suggesting an improvement in some aspects relating to poverty in this area.

Figure 3.20 shows the education profiles for the areas under investigation for those aged 20 years or older. Ward 35 has the highest proportion of people who have completed Grade 12 or higher.

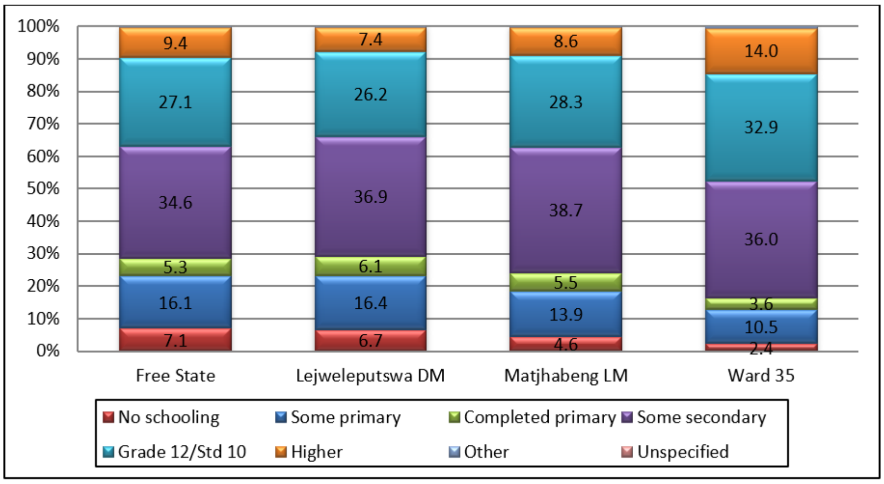

Figure 3.20 Education profiles (those aged 20 years or older, shown in percentage, source: Census 2011) (Equispectives, 2023b).

Figure 3.21 shows that Ward 35 has the highest proportion of people of economically active age (aged between 15 years and 65 years) that are employed. Since 2010 employment in the gold mining industry showed a steady decline from 157 019 in 2010 to 93 841 in 2022 (www.mineralscouncil.org.za). As such the proportion of unemployed people in the area are likely to have increased since 2011.

Figure 3.22 shows that the majority of the employed people in the areas under investigation work in the formal sector. Ward 35 has the highest proportion of people working in the formal sector.

Figure 3.23 shows that Ward 35 has the highest average household income, indicating more employed people than on the local, district or provincial level.

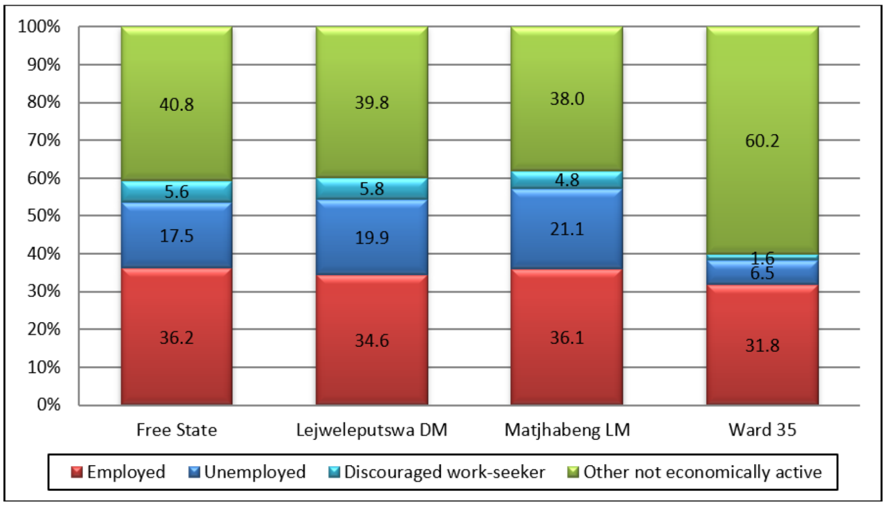

Figure 3.21 Labour status (those aged between 15 - 65 years, shown in percentage, source: Census 2011) (Equispectives, 2023b).

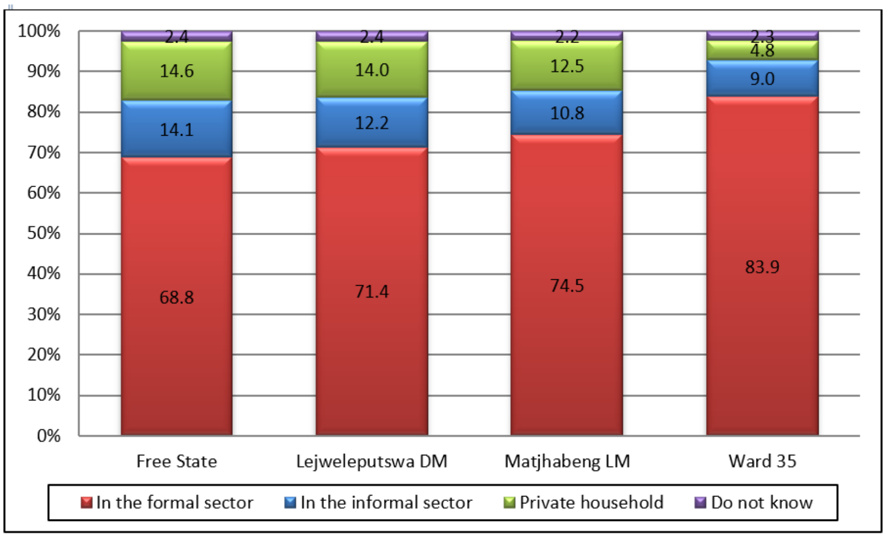

Figure 3.22: Employment sector (those aged between 15 - 65 years, shown in percentage, source: Census 2011) (Equispectives, 2023b).

Population Composition, Age, and Gender

Figure 3.24 shows that in all the areas under investigation, the majority of the population belongs to the Black population group. In Ward 35 almost a fifth of people belong to the White population group.

Table 3.9 shows that the average age is very similar on a local, district and provincial level, with a much higher average age on a ward level. Figure 3.25 shows that the age distribution of the areas under investigation shows that the population on a ward level tend to be older than on the local, district or provincial level, with a greater proportion of people aged between 35 years to 64 years.

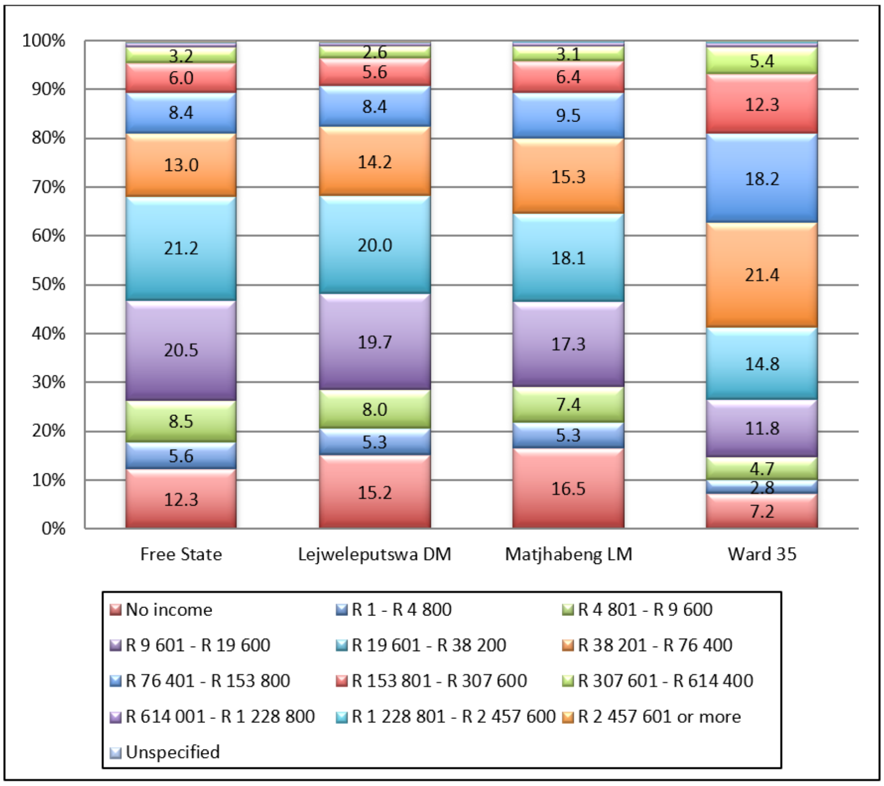

Figure 3.23 Annual household income (shown in percentage, source: Census 2011) (Equispectives, 2023b).

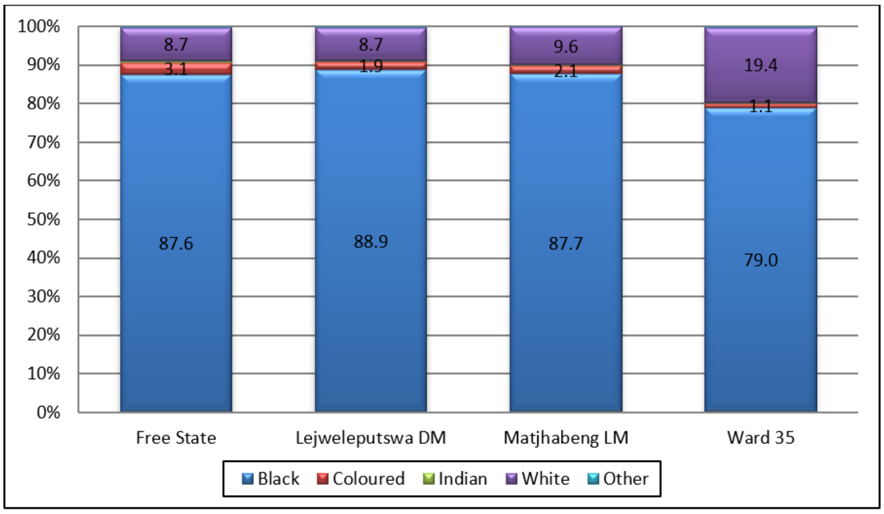

Figure 3.24 Population distribution (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Table 3.9 Average age (source: Census 2011) (Equispectives, 2023b).

Area	Average Age (in years)
Free State Province	28.38
Lejweleputswa DM	28.52
Matjhabeng LM	28.89
Ward 35	33.90

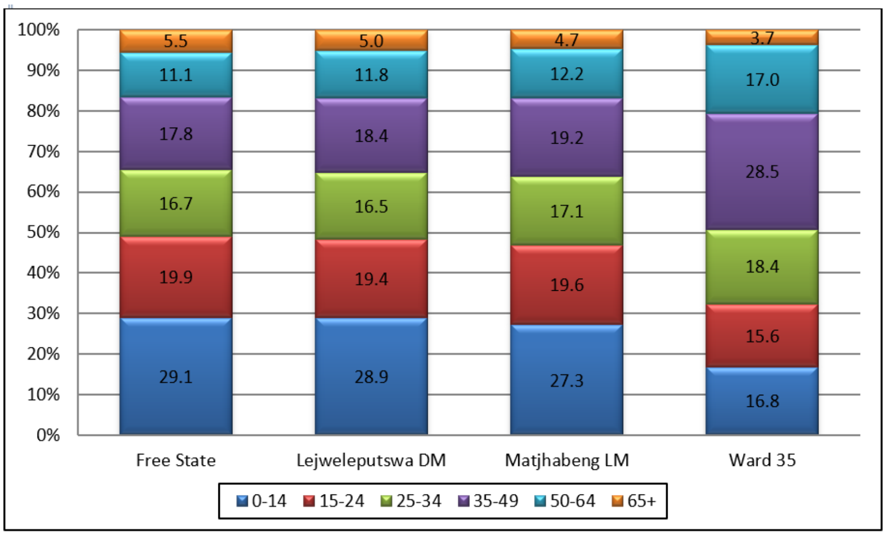

Figure 3.25 Age distribution (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Figure 3.26 shows that the gender distribution on provincial, district and local levels is balanced, but on a ward level, there is a strong bias towards males. A higher incidence of males is usually found in mining areas.

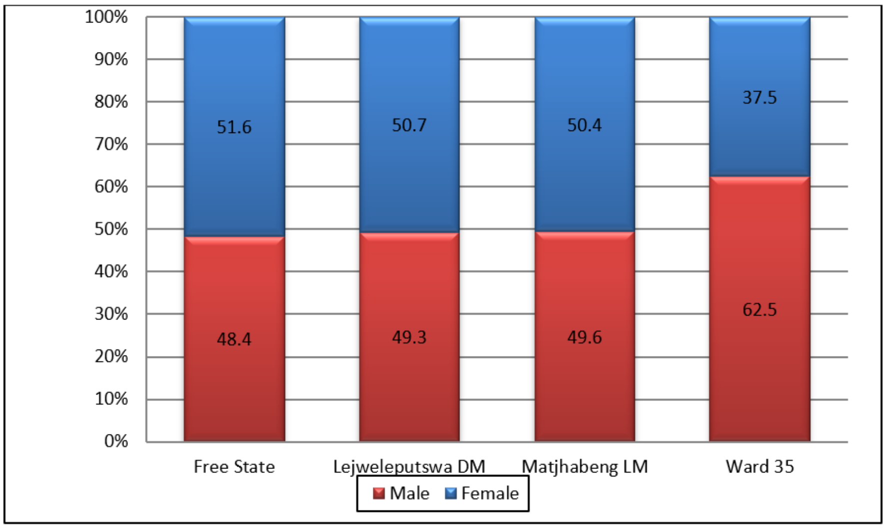

Figure 3.26 Gender distribution (shown in percentage, source: Census 2011) (Equispectives, 2023b).

3.4.7.4 Household Structures

Figure 3.27 shows that most of the dwellings in the area are houses or brick/concrete block structures that are on a separate yard, stand or farm. Although there are informal dwellings in Ward 35, it is a lower proportion than on the local, district or provincial level.

Figure 3.28 shows that Ward 35 has the largest proportion of households that are renting their dwellings, with about a third of the households renting their dwellings.

Figure 3.29 shows that the household sizes on a ward level in the Matjhabeng LM tend to be smaller than on the local, district or provincial level, with approximately 50% or more of households on the ward level consisting of one or two people, compared to just over 40% on local, district and provincial level. This is very typical in mining areas where there are migrant workers.

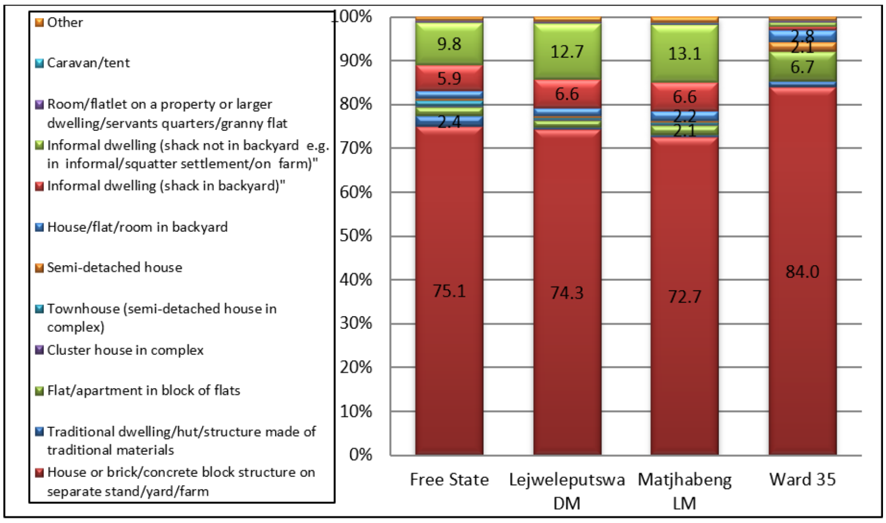

Figure 3.27 **Dwelling types (shown in percentage, source: Census 2011) (Equispectives, 2023b).**

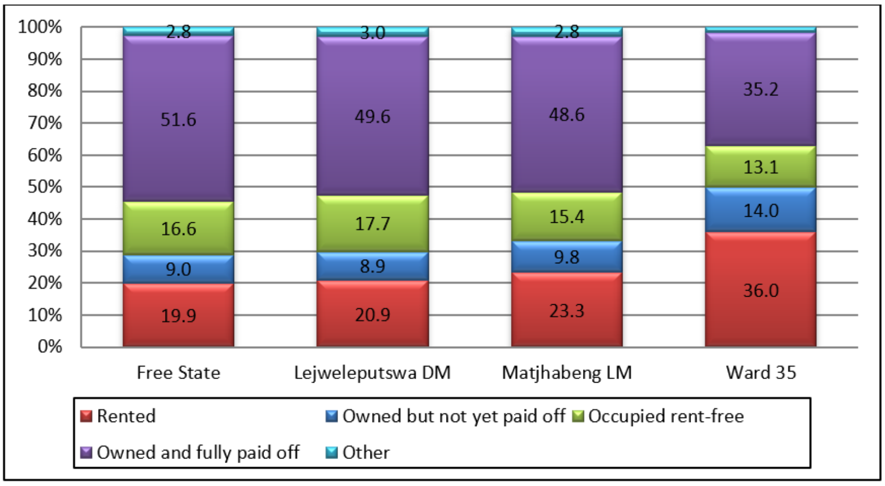

Figure 3.28 **Tenure status (shown in percentage, source: Census 2011) (Equispectives, 2023b).**

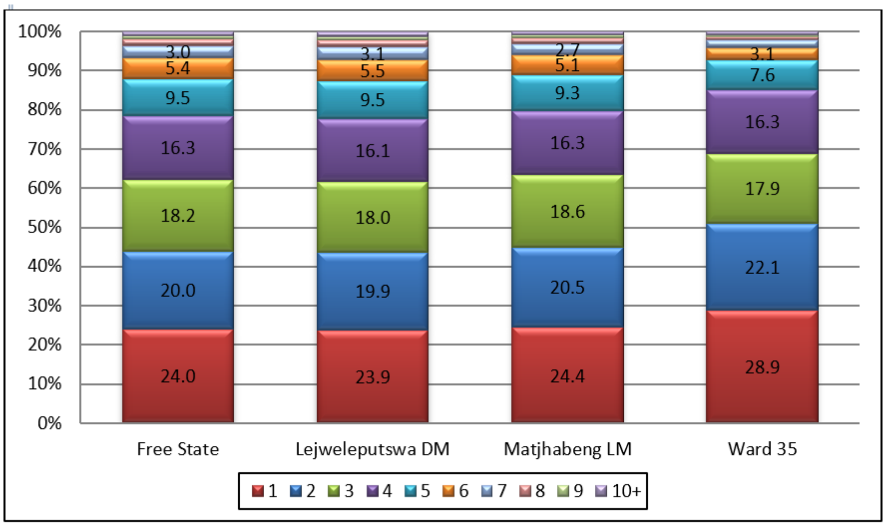

Figure 3.29 **Household size (shown in percentage, source: Census 2011) (Equispectives, 2023b).**

3.4.7.5 Social Infrastructure and Services

Figure 3.30 shows that Ward 35 has the lowest incidence of households that have access to water from a local or a regional water scheme, but the highest incidence of households that get their water from another source. Census 2011 does not specify what the 'other' water sources include.

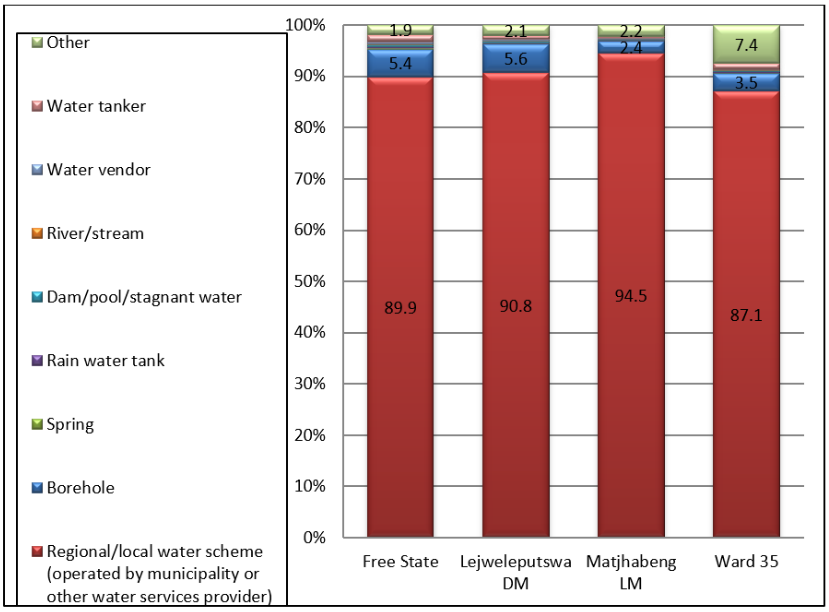

Figure 3.30 Water source (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Access to piped water, electricity and sanitation relates to the domain of Living Environment Deprivation as identified by Noble et al (2006). Figure 3.31 shows that just over three-quarters of households in Ward 35 have access to piped water inside the dwelling. This is much higher than on the local, district and provincial levels.

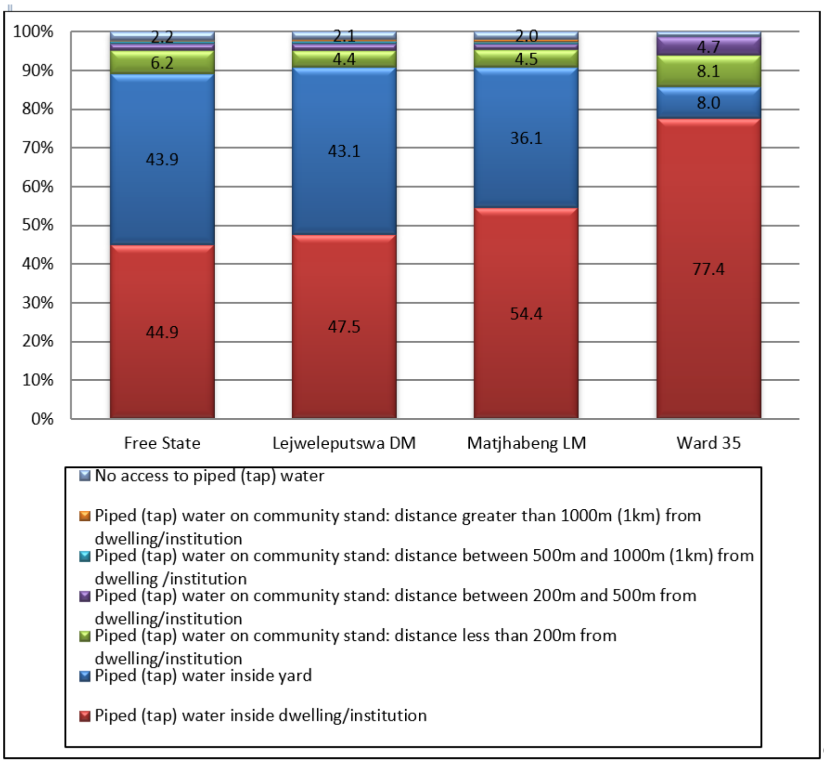

Figure 3.31 Piped water (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Figure 3.32 shows that the majority of households in Ward 35 have access to sanitation services, with the bulk of the households in the ward having access to flush toilets that are connected to a sewerage system.

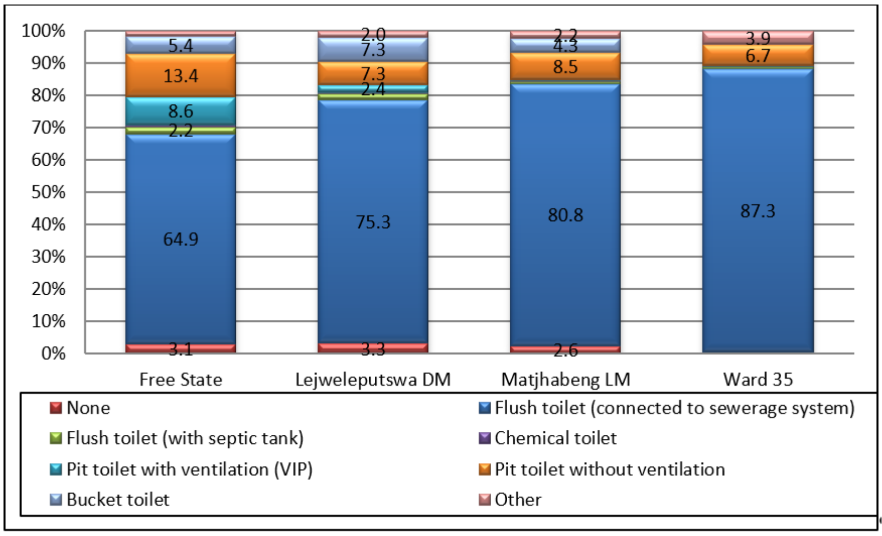

Figure 3.32 Sanitation (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Electricity is seen as the preferred lighting source (Noble et al, 2006) and the lack thereof should thus be considered a deprivation. Even though electricity as an energy source may be available, the choice of energy for cooking may be dependent on other factors such as cost. Figure 3.33 shows that almost 90% of households have access to electricity as an energy source for lighting, with candles as the second most used source.

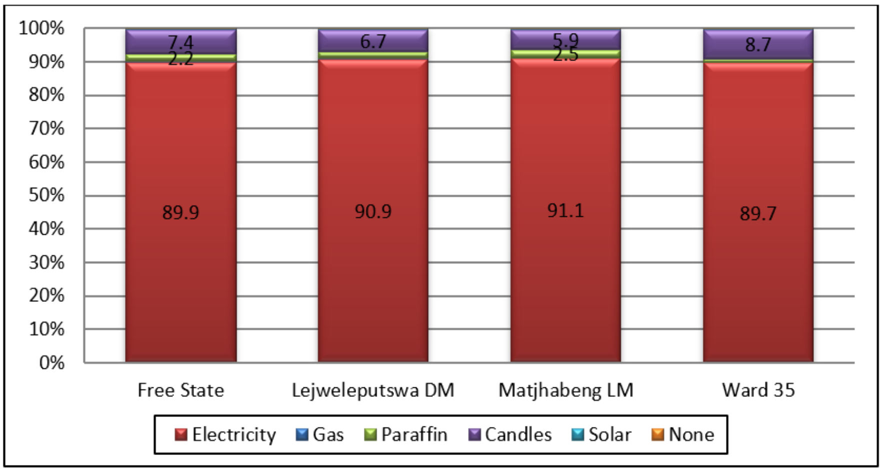

Figure 3.33 Energy source for lighting (shown in percentage, source: Census 2011) (Equispectives, 2023b).

Figure 3.34 shows that the incidence of households that have their refuse removed at least once a week by a local authority or private company in Ward 35 is lower than on the municipal level, with a larger proportion than on the local, district or provincial level that indicated that there refuse is removed less frequently than once a week.

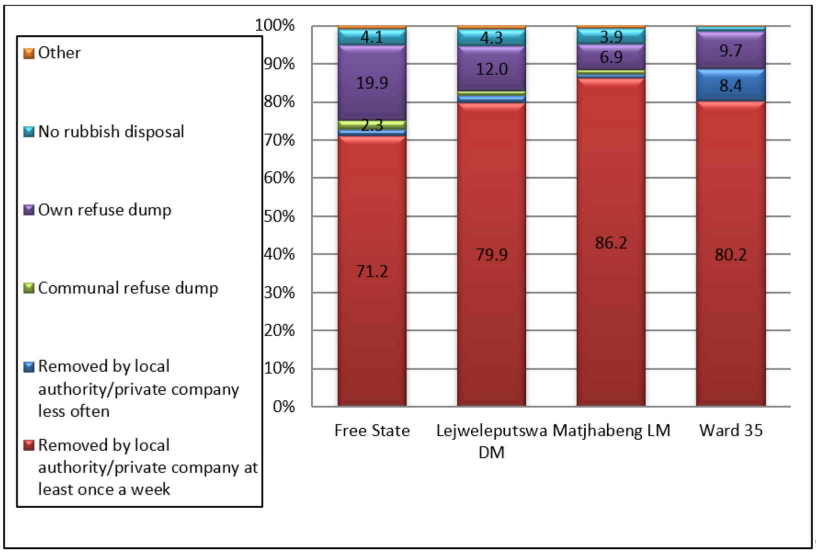

Figure 3.34 Refuse removal (shown in percentage, source: Census 2011) (Equispectives, 2023b).

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 Projects. Radionuclide concentrations in the relevant residue material (i.e., tailings and waste rock materials) are presented in Section 3.5.2, while the radon exhalation rates for the existing TSFs, WRDs and ventilation shafts are presented in 3.5.3. The data presented here were sources from the 2018 Free State Operation RPSA, which is the most recent NNR-approved assessment available for the Harmony Free State Operations (AquiSim, 2018b).

3.5.2 Tailings and Waste Rock Material

The TSFs that are of relevance to the Projects area are FSN1 TSF, FSN2 TSF, FSN3A TSF, FSN 5 TSF and FSN 6 TSF (see Figure ??). Full-spectrum analysis results are not available for all these TSFs. Table 3.10 summarises the available radioanalysis results for tailings samples. The average values can be used for FSN 3A TSF and FSN 5 TSF, as well as

Table 3.10 Full-spectrum radioanalysis results of tailings samples as derived for the 2018 Free State Operations RPSA (AquiSim, 2018b).

Radionuclide	FSN 1	FSN 2	FSN 4	FSN 6	Average
	Activity Concentration (Bq.kg^{-1})				
U-238	476	754	199	327	439
U-234	480	760	201	330	443
Th-230	480	760	201	330	443
Ra-226	208	475	715	324	431
Pb-210	208	475	715	324	431
Po-210	162	409	513	261	336
Th-232	24.7	31.3	29.4	33.3	30
Ra-228	24.7	31.3	29.4	33.3	30
Th-228	31	27	15	21	24
U-235	21.9	34.7	9.16	15.1	20
Pa-231	21.9	34.7	9.16	15.1	20
Ac-227	21.9	34.7	9.16	15.1	20

Ra-223	21.9	34.7	9.16	15.1	20

The WRDs that are relevant to the Projects area are Nyala WRD, Freddies 3 WRD, Kudu WRD, Eland WRD, Sable WRD, ARM7 WRD and ARM7 WRD (see Figure ??). Full-spectrum analysis results are not available for all these WRDs. Table 3.11 summarises the available radioanalysis results for waste rock samples. The average values can be used for Nyala WRD and Eland WRD.

Table 3.11 Full-spectrum radioanalysis results of waste rock samples as derived for the 2018 Free State Operations RPSA (AquiSim, 2018b).

Radionuclide	Tshepong	Sable	Kudu	ARM 6	ARM 7	Average
	Bq.kg^{-1}					
U-238	111.3	34	70.5	33.2	40.5	58
U-234	112.3	34	70.5	33.4	40.7	58
Th-230	112.3	34	70.5	33.4	40.7	58
Ra-226	138	49.9	141	46.9	52	86
Pb-210	118.9	62.2	243	45.3	52.3	104
Po-210	118.9	62.2	243	45.3	52.3	104
Th-232	22.7	15.7	33	15.3	14.8	20
Ra-228	27	15.7	49.2	10	16.9	24
Th-228	29.4	20.2	43.9	18.2	19.5	26
U-235	5.1	1.6	3.3	1.5	1.9	3
Pa-231	5.1	1.6	3.3	1.5	1.9	3
Ac-227	5.1	1.6	3.3	1.5	1.9	3
Ra-223	5.1	1.6	3.3	1.5	1.9	3

Note that where radioanalysis data was lacking, the radionuclide concentration was estimated assuming secular equilibrium between parent radionuclides and their progeny. The following assumptions were consequently applied to 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.

3.5.3 Radon Exhalation Rates

Several methods exist for estimating the radon release characteristics of source materials. Table 3.12 presents a summary of the results using a closed diffusion-tube measurement method to estimate the rate of radon release from the tailings samples (Strydom, 2008).

Table 3.12 Radon generation and transport properties for tailings material from relevant TSFs in the Projects area (Strydom, 2008).

Tailings Storage Facility	Production Rate	Calculated Ra-226 (Bq.kg^{-1})	Emanation Fraction	Exhalation Rate (Bq.m^{-2}.s^{-1})
FSN 1 TSF	3.41	15	0.235	0.0154
FSN 2 TSF	11.42	49	0.235	0.0274
FSN 4 TSF	5.11	22	0.235	0.0104
FSN 6 TSF	5.93	25	0.235	0.00483
			Average	0.01450

Another method that can be used to estimate radon exhalation rates for TSFs and WRDs, is to use correlation coefficients derived from measured data collected from similar materials. Parc Scientific (2006) summarised radon exhalation rates measured from residue storage facilities in the South African gold mining industry and reported coefficients, derived from regression lines fitted through these data points, which can be used to estimate radon exhalation rates from TSFs and WRDs. These diffusion coefficients are used with concentrations of Ra-226 measured in the tailings material or waste rock to estimate the radon exhalation rate in units of $Bq.m^{-2}.s^{-1}$. Parc Scientific (2006) presented the measured data as 'average' and 'maximum' values based on the statistical distribution of the data. The derived diffusion coefficients therefore also represent average and maximum values. The equations and coefficients used for deriving radon exhalation rates for TSFs are as follows (Parc Scientific, 2006):

Average: Radon exhalation rate ($Bq.m^{-2}.s^{-1}$) = (0.000554 ±0.000014) x Ra-226 ($Bq.kg^{-1}$)

Maximum: Radon exhalation rate ($Bq.m^{-2}.s^{-1}$) = (0.000609 ±0.000017) x Ra-226 ($Bq.kg^{-1}$)

Table 3.13 presents the average and maximum radon exhalation rates, estimated from the measured radium concentration in the tailings material listed in Table 3.10.

Table 3.13 Radon source term characteristics for TSFs associated with the Projects (AquiSim, 2018b).

TSF Name	Surface Area (ha)	Ra-226 ($Bq.kg^{-1}$)	Rn Exhalation Rate ($Bq.m^{-2}.s^{-1}$)		
			Average	Maximum	Table 3.12
FSN 1	278	208	0.08	0.13	0.0154
FSN 2	122	475	0.183	0.297	0.0274
FSN 3B	37	637	**0.245**	0.399	-
FSN 4	230	715	0.275	0.448	0.0104
FSN 5	230	473	**0.182**	0.296	-
FSN 6	121	324	0.125	0.203	0.0048
Average			0.182	0.296	0.0145

Radon exhalation rates from waste rock can be estimated using a similar method. The equation and coefficients that can be used for this are (Parc Scientific, 2006):

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

Table 3.14 presents the average and maximum radon exhalation rates, estimated from the measured radium concentration in the waste rock from the WRDs listed in Table 3.11.

Table 3.14 Radon source term characteristics for WRDs as derived for the 2018 Free State Operations RPSA (AquiSim, 2018b).

WRD Name	Ra-226 ($Bq.kg^{-1}$)	Rn Exhalation Rate ($Bq.m^{-2}.s^{-1}$)
Tshepong	138	0.0578
Sable	49.9	0.0209
Kudu	141	0.059
ARM 6	46.9	0.0196
ARM 7	52	0.0218
Average	85.6	0.0358

There are a few upcast ventilation shafts in the Projects area that may contribute to the airborne radon gas concentration. These include Nyala Shaft, Freddie's No. 3 Shaft and Eland Shaft (see Figure??). To estimate the radon release rate for Vent Shafts the measured radon activity concentrations must be scaled with the volume of air expelled from the shafts. Table 3.15 summarises the average flow rate values available from Airshed (2017), as well as the measured average radon activity concentrations in each Vent

Shaft. It should be kept in mind that both the flow rate and radon activity concentration of expelled air can vary greatly over time. Using average values, therefore, represents the best estimate of radon emission rates for the Vent Shafts.

Table 3.15 Radon source term characteristics for Vent Shafts as derived for the 2018 Free State Operations RPSA (AquiSim, 2018b).

Vent Shaft	The range for Monitoring Data Used	Average Measured Radon Activity Conc.	Average Vent Shaft Air Flow Rate	Average Radon Activity Release Rate
		$Bq.m^{-3}$	$m^3.s^{-1}$	$Bq.s^{-1}$
Nyala Shaft	2010 to 2017	4,226	313	1,322,738
Freddie's 3 Shaft	2014 to 2017	779	279	217,341
Eland Shaft	2009 to 2016	2,622	364	954,408

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 Projects, with due consideration of the impact that may occur during the post-closure phase. How members of the public are exposed to ionising radiation induced by the Projects may be different depending on the operational conditions and the specific point in time (either present or future).

Consistent with the assessment framework presented in Figure 1.3, the radiological public impact is evaluated through the development of site-specific public exposure conditions. As used here, an exposure condition is defined as follows:

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

The purpose of this section is to use the current understanding of the Projects and their 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 1.3). The SPR analysis approach is inherently systematic, traceable, and transparent, and provides the opportunity to identify and evaluate all possible exposure situations that may exist both now and in the future.

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

4.2 Key Concepts Used in the SPR Analysis Approach

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

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

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

4.3 Source Identification

4.3.1 General

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

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

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

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

4.3.2 Primary and Secondary Sources of Radiation Exposure

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

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

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

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

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

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

4.3.3 Primary Sources Associated with the Projects

4.3.3.1 General

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

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

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

4.3.3.2 Tailings Storage Facilities

The tailings storage facilities of concern for the Projects are the existing TSFs, as well as the proposed Valley TSF and Nooitgedacht TSF.

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

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

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

4.3.3.3 Waste Rock Dumps

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

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

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

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

4.3.3.4 Ventilation Shaft

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

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

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

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

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

4.3.3.5 Water Management Facilities

The nature of these water management facilities (e.g., return water dam) is such that the only contribution as a source is through water infiltration and subsequent leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing *groundwater activity concentrations*). However, the return water dam is fitted with a double HDPE liner to prevent seepage. While these dams are within the mining authorization of the Projects, 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 Projects make use of an extensive pipeline surface infrastructure to transfer water and tailings material over vast distances. Under normal operating conditions, these pipelines do not serve as a significant source of radiation exposure. It is only under accident and incident conditions (e.g., pipeline bursts) that these pipelines may serve as a potential secondary source of radiation exposure (see Section 4.3.4).

4.3.4 Secondary Sources Associated with the Projects

4.3.4.1 General

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

4.3.4.2 Natural Processes and Events

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

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

4.3.4.3 Normal Operating Conditions

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

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

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

4.3.5 Secondary Sources Due to Events Outside Normal Operating Conditions

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

- *Pipelines* are used to transfer water or tailings materials between components of the operation. If implemented, operated, and maintained as designed and planned (i.e., under *normal operating conditions*), pipelines do not serve as a primary or secondary source of radiation exposure to members of the public. However, a pipeline burst could occur, during which solid-mediated release of contaminants may result in either an increase in *surface soil activity concentrations* or if the spillage occurred at or near a surface water crossing, in an increase in s*urface water activity concentrations.* Under these conditions, the pipelines may induce secondary sources of radiation exposure.

- *Water management facilities,* whether lined or unlined, are engineered, designed, and built to contain a certain volume of water under normal operating conditions. This is normally done in line with regulations published in Government Notice No. 704 on 4 June 1999 (Government Gazette No. 20119) aimed at protecting water resources from mining and related activities. If these facilities do not function as planned or are designed to contain water, releases to the environment are possible, which may increase *surface soil* or *surface water activity concentrations.* Under these conditions, water management facilities may induce secondary sources of radiation exposure.
- *Tailings storage facilities* are designed and built based on engineered and geotechnical principles to contain the total volume of tailings material that will be generated during the Life of Mine. These facilities are large and include features such as underdrains, toe paddocks, and dams to capture seepage and runoff that may occur from the facility. However, excessive water erosion may lead to the discharge of tailings material into the environment.

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

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

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

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

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

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

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

4.4 Pathways

4.4.1 General

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

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

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

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

4.4.2 Atmospheric Pathway

4.4.2.1 General

The significance of the atmospheric pathway is due to the presence of naturally occurring radionuclides in the particulates and gases released into the atmosphere from the activities and features associated with the Projects. 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 these gases by members of the public;
- The release and distribution of dust particulates containing radionuclides (associated with the PM_{10} particulates and (generally referred to as Long-Lived Alpha particles or LLα) into the atmosphere and the subsequent inhalation of the dust by members of the public; and
- The deposition of airborne dust particulates containing radionuclides (associated with the Total Suspended Particulates or TSP) onto the ground, and the subsequent interaction of members of the public with the deposited dust on the soil surface or crops.

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

The sources identified in Section 4.3 that are relevant to the atmospheric pathway include the existing TSFs, WRDs and ventilation shafts that contribute to the baseline conditions, as well as the proposed Valley TSF and Nooitgedacht TSF. Using emission estimates from these sources, modelled airborne concentrations of PM_{10}, radon and rates of dust fallout, were determined for the area of concern as part of an air quality impact assessment performed for the Projects (Airshed, 2023). These results confirm that airborne particulate, as well as radon gas concentrations, are highest close to the source and decrease with distance from the sources. The general direction of air dispersion of the particulates and radon gas dispersion is predominantly in a southwesterly direction.

4.4.2.2 Baseline Conditions

The baseline conditions reflect the contribution of the existing surface infrastructure. Figure 4.1 shows a graphical representation of the PM_{10} concentrations in air attributed to the existing TSFs, WRDs and ventilation shafts (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.

4.4.2.3 Valley TSF

Figure 4.4 shows a graphical representation of the PM_{10} concentrations in air attributed to the proposed Valley TSF in addition to the existing TSFs, WRDs and ventilation shafts (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 4.5, while Figure 4.6 presents the estimated airborne radon concentration attributed to the proposed Valley TSF in addition to the baseline conditions. Figure 4.4 to Figure 4.6 clearly illustrate the effect of the proposed Valley TSF relative to the baseline conditions.

4.4.2.4 Nooitgedacht TSF

Figure 4.7 shows a graphical representation of the PM_{10} concentrations in air attributed to the proposed Nooitgedacht TSF in addition to the existing TSFs, WRDs and ventilation shafts (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 4.8, while Figure 4.9 presents the estimated airborne radon concentration attributed to the proposed Nooitgedacht TSF in addition to the baseline conditions. Figure 4.7 to Figure 4.9 clearly illustrate the effect of the proposed Nooitgedacht TSF relative to the baseline conditions.

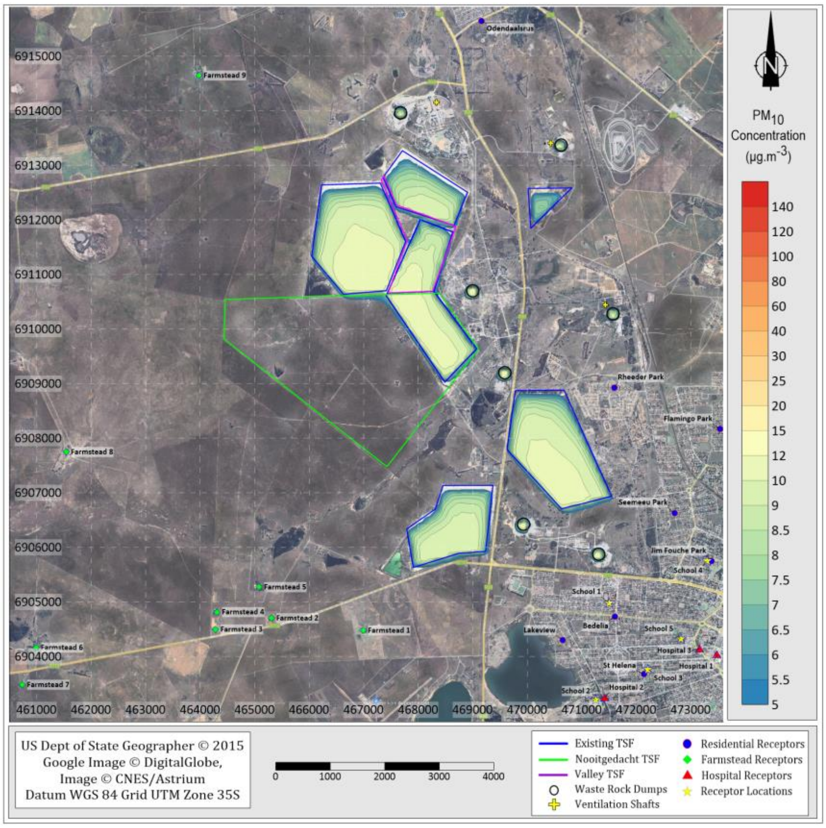

Figure 4.1 The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to the current baseline conditions from existing surface infrastructure.

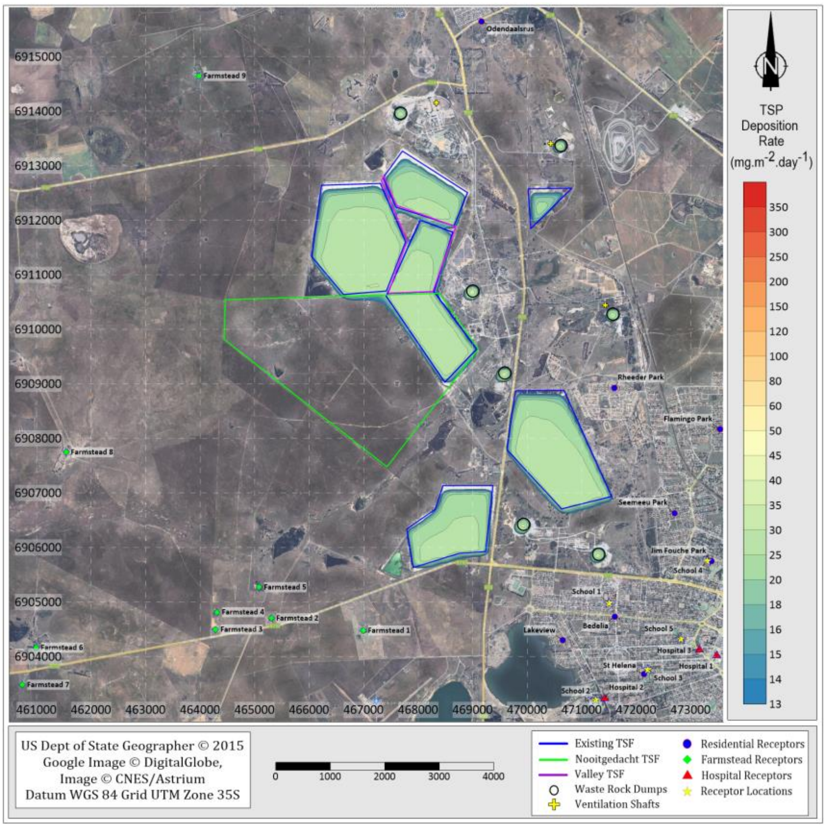

Figure 4.2 **The simulated annual average TSP deposition rate (in units of mg.m^{-2}.day^{-1}) attributed to the current baseline conditions from existing surface infrastructure.**

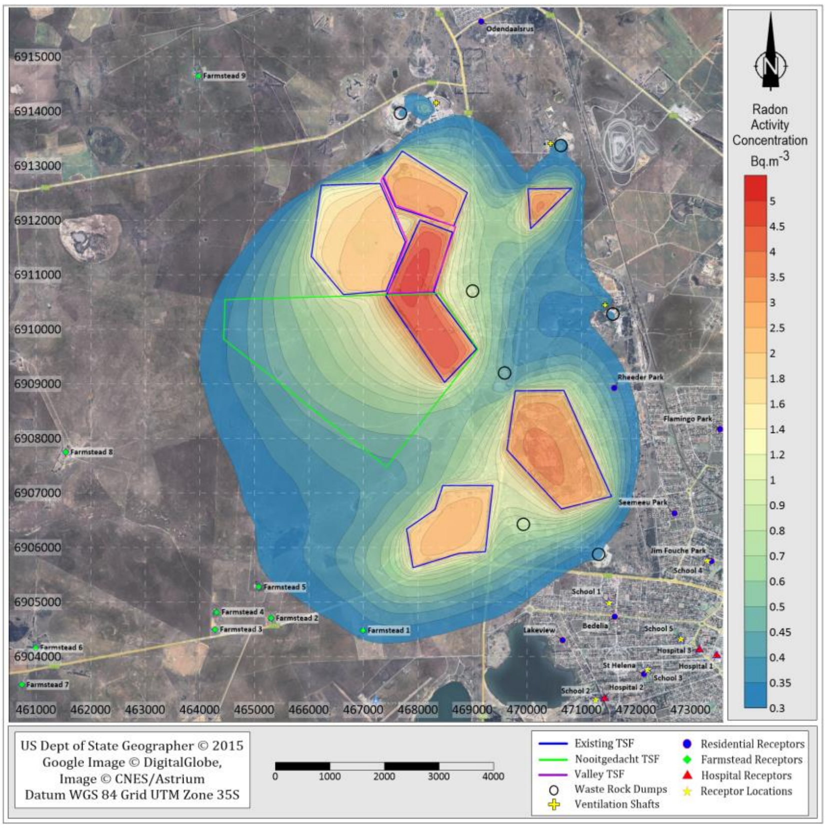

Figure 4.3 **The simulated annual average radon concentration (in units of Bq.m^{-3}) attributed to the current baseline conditions from existing surface infrastructure.**

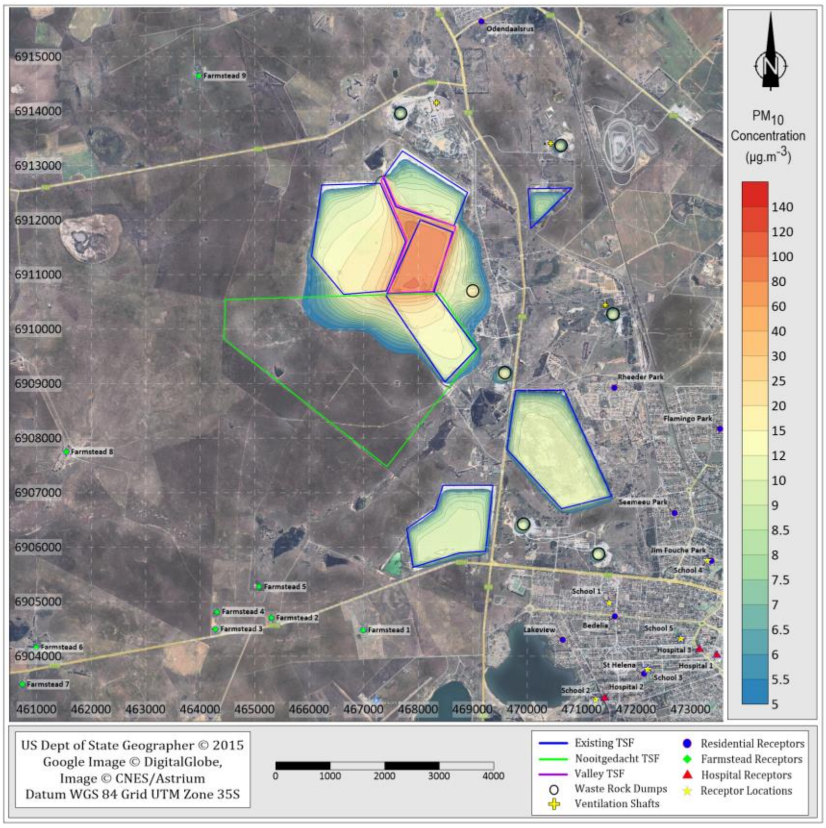

Figure 4.4 The simulated annual average airborne PM_{10} concentrations (in units of µg.m^{-3}) attributed to the proposed Valley TSF and the current baseline conditions.

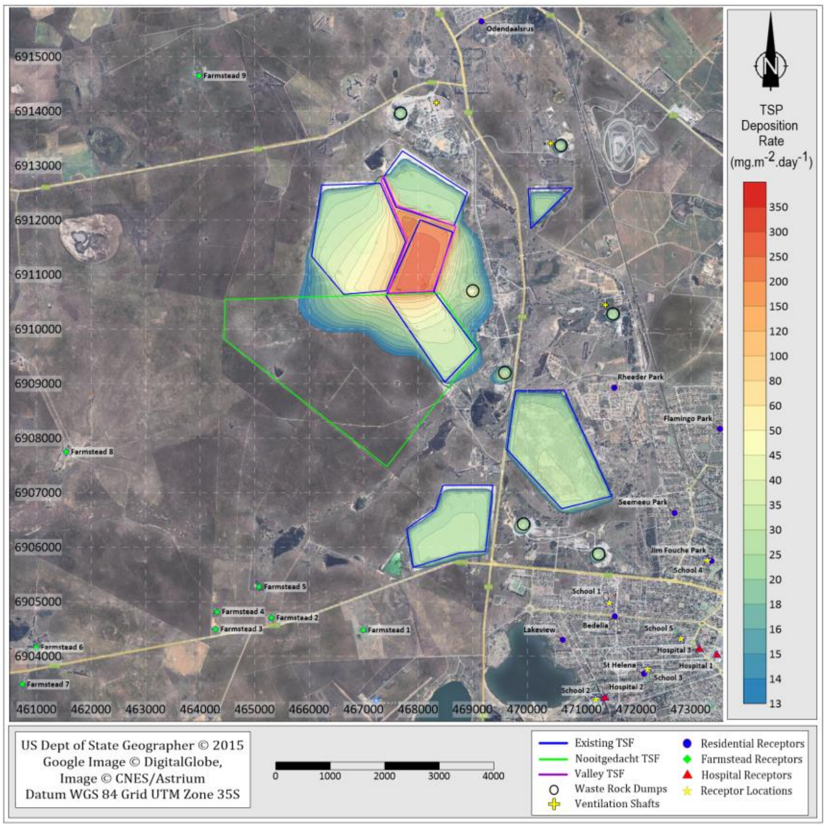

Figure 4.5 The simulated annual average TSP deposition rate (in units of mg.m^{-2}.day^{-1}) attributed to the proposed Valley TSF and the current baseline conditions.

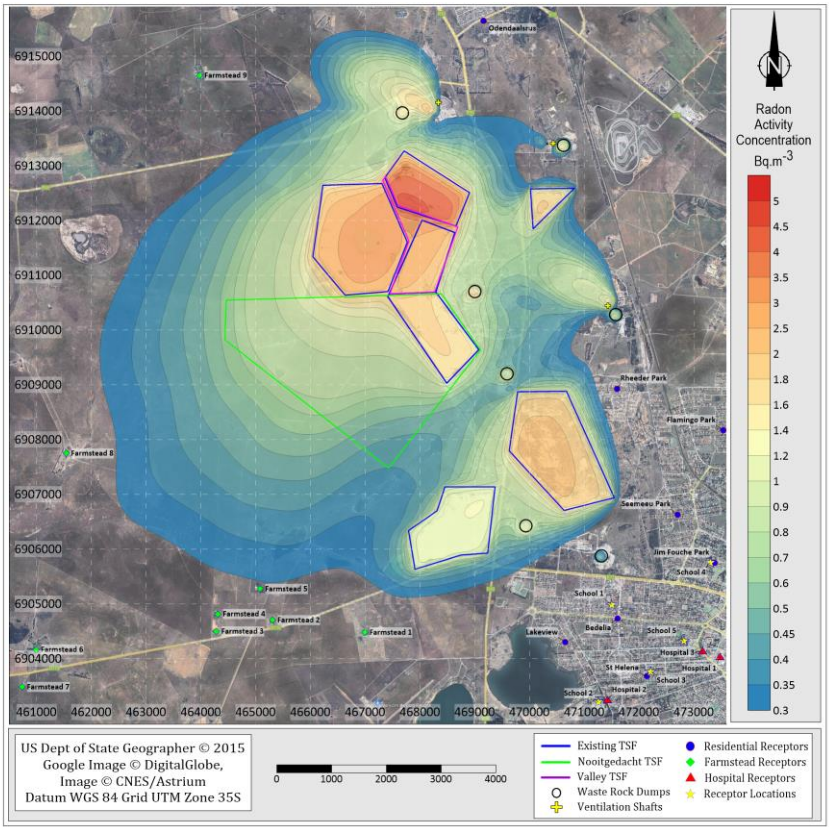

Figure 4.6 **The simulated annual average radon concentration (in units of Bq.m^{-3}) attributed to the proposed Valley TSF and the current baseline conditions.**

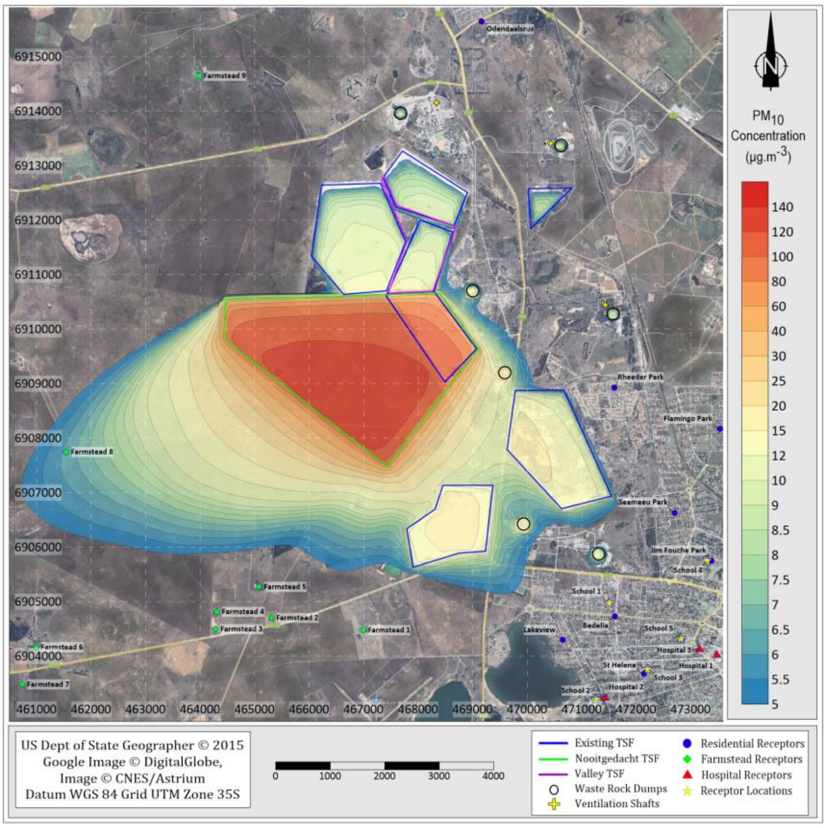

Figure 4.7 **The simulated annual average airborne PM_{10} concentrations (in units of µg.m^{-3}) attributed to the proposed Nooitgedacht TSF and the current baseline conditions.**

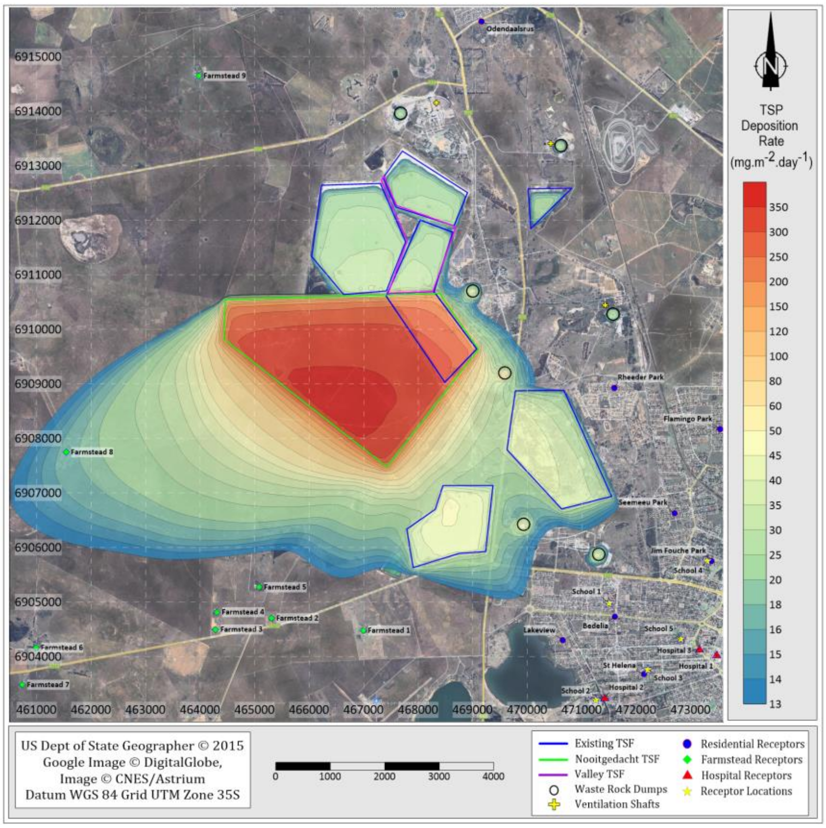

Figure 4.8 **The simulated annual average TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to the proposed Nooitgedacht TSF and the current baseline conditions.**

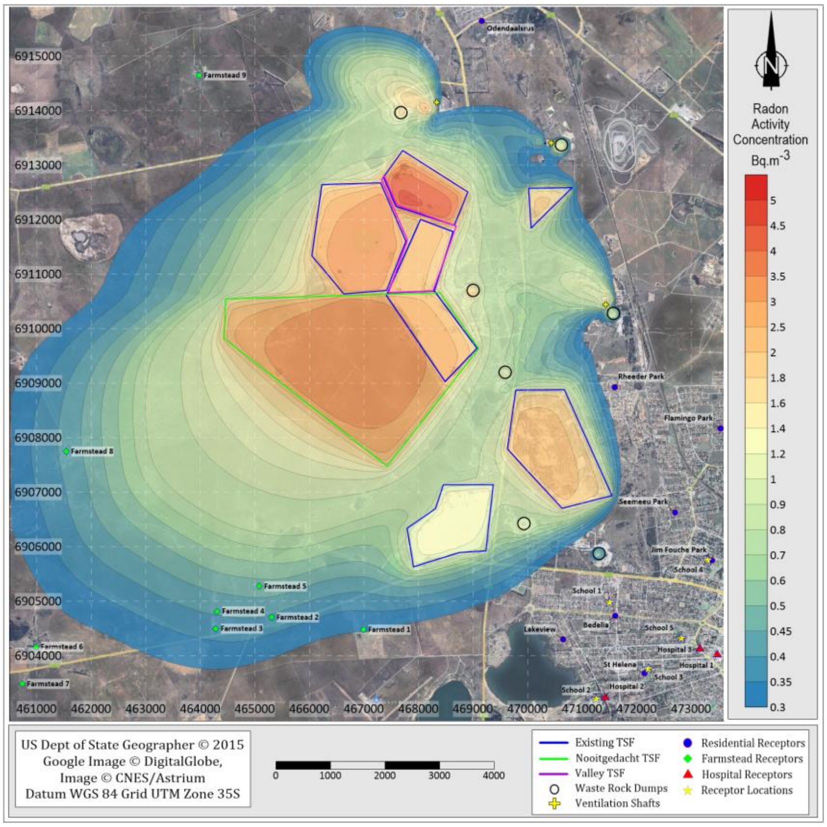

Figure 4.9 **The simulated annual average radon concentration (in units of $Bq.m^{-3}$) attributed to the proposed Nooitgedacht TSF and the current baseline conditions.**

4.4.2.5 Valley TSF and Nooitgedacht TSF

Figure 4.7 shows a graphical representation of the PM_{10} concentrations in air attributed to both the proposed Valley TSF and the Nooitgedacht TSF in addition to the existing TSFs, WRDs and ventilation shafts (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 4.8, while Figure 4.9 presents the estimated airborne radon concentration attributed to the proposed Valley TSF and the Nooitgedacht TSF in addition to the baseline conditions. Figure 4.7 to Figure 4.9 clearly illustrate the effect of the proposed Nooitgedacht TSF relative to the baseline conditions.

4.4.2.6 Contribution of the Atmospheric Pathway to Radiological Impact

The flow diagram in Figure 4.13 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 Projects can be attributed to the emissions of dust that contain long-lived alpha-emitting radionuclides (LLα) and radon gas. Note that the airborne contaminant plume will contribute to the external gamma radiation dose (plume immersion) and inhalation of the airborne radioactivity contributes to the inhalation dose.

As shown in Figure 4.13, airborne contaminants may be deposited onto the surface soils, resulting in a soil concentration. Depending on the prevailing atmospheric conditions, the contaminants deposited onto the soil may go into re-suspension, resulting in the further distribution of airborne contaminants. Exposure to the soil concentration also contributes to an external gamma radiation dose (ground shine). Similarly, airborne contaminants may be deposited onto the surface water bodies, contributing to the surface water pathway (see Section 4.4.4).

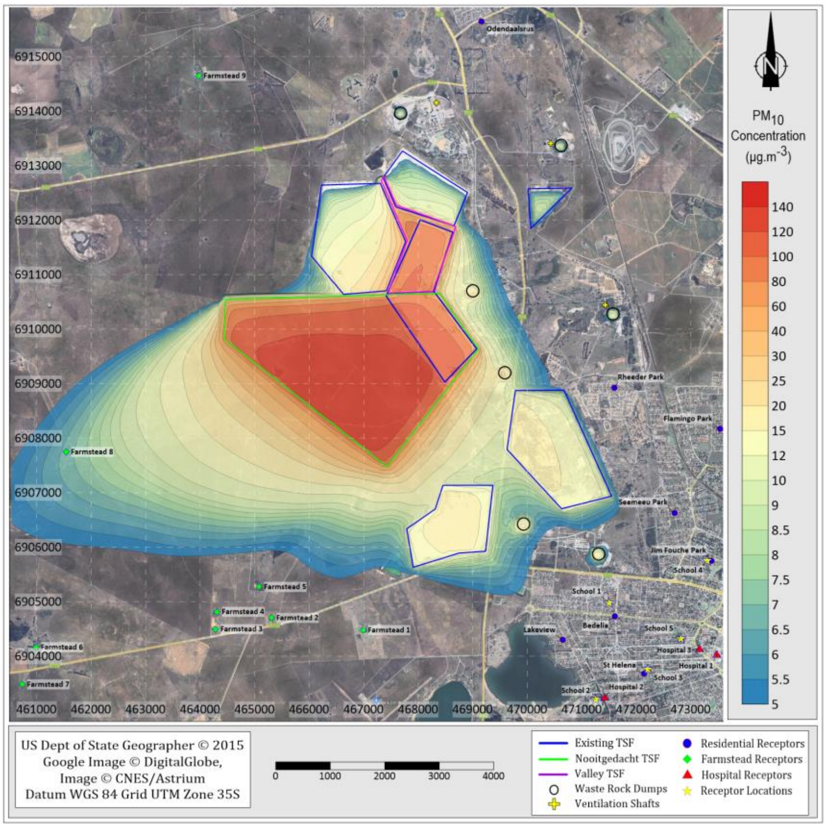

Figure 4.10 The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to the Valley TSF, Nooitgedacht TSF and the current baseline conditions.

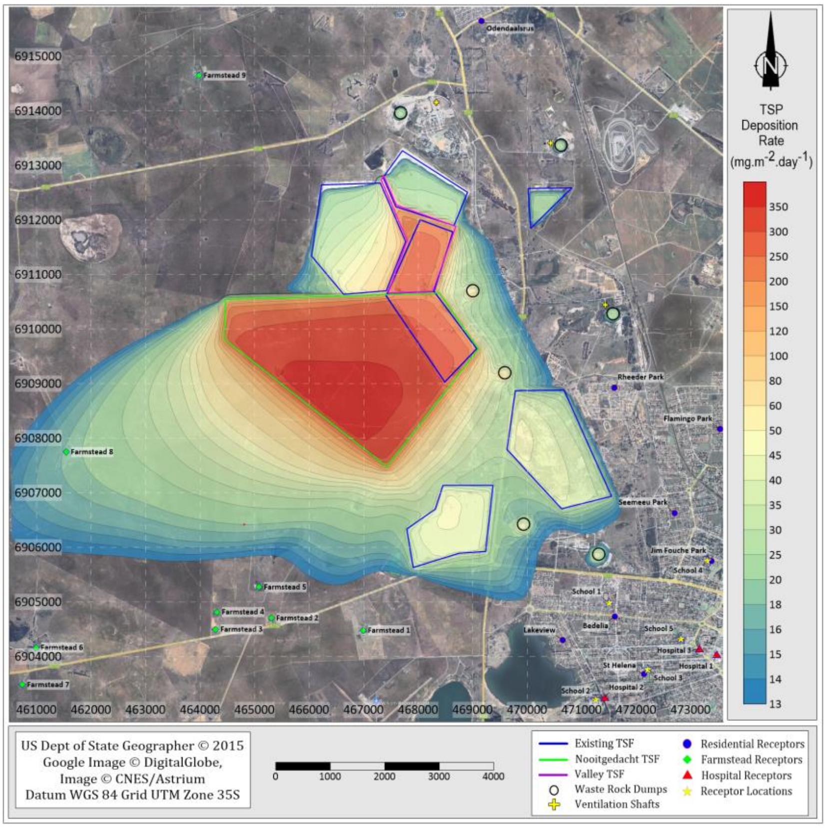

Figure 4.11 **The simulated annual average TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to the Valley TSF, Nooitgedacht TSF and the current baseline conditions.**

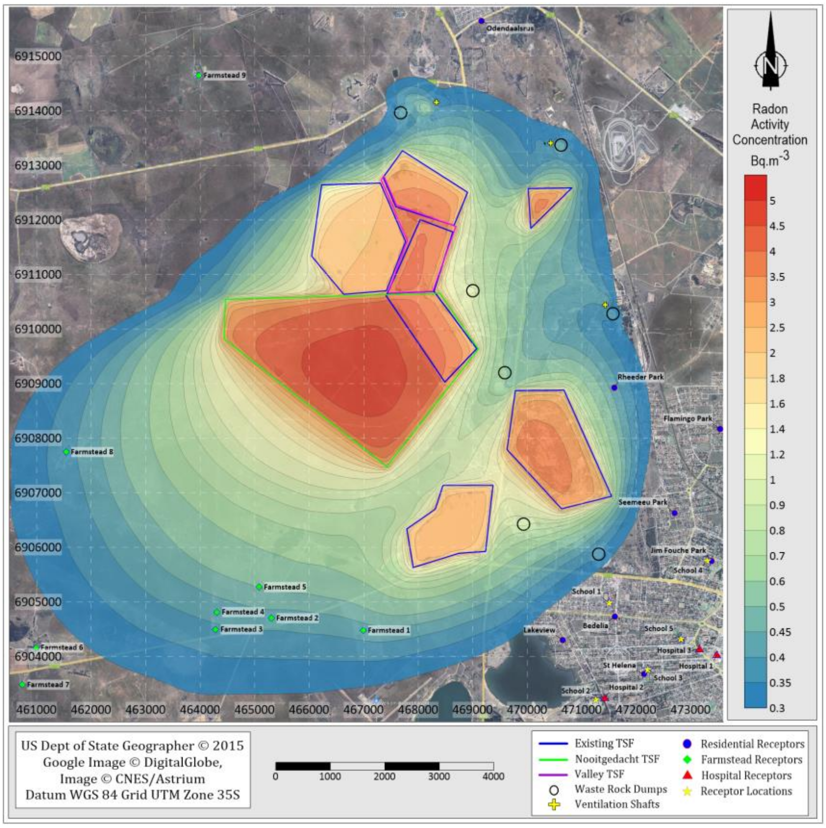

Figure 4.12 **The simulated annual average radon concentration (in units of $Bq.m^{-3}$) attributed to the Valley TSF, Nooitgedacht TSF and the current baseline conditions.**

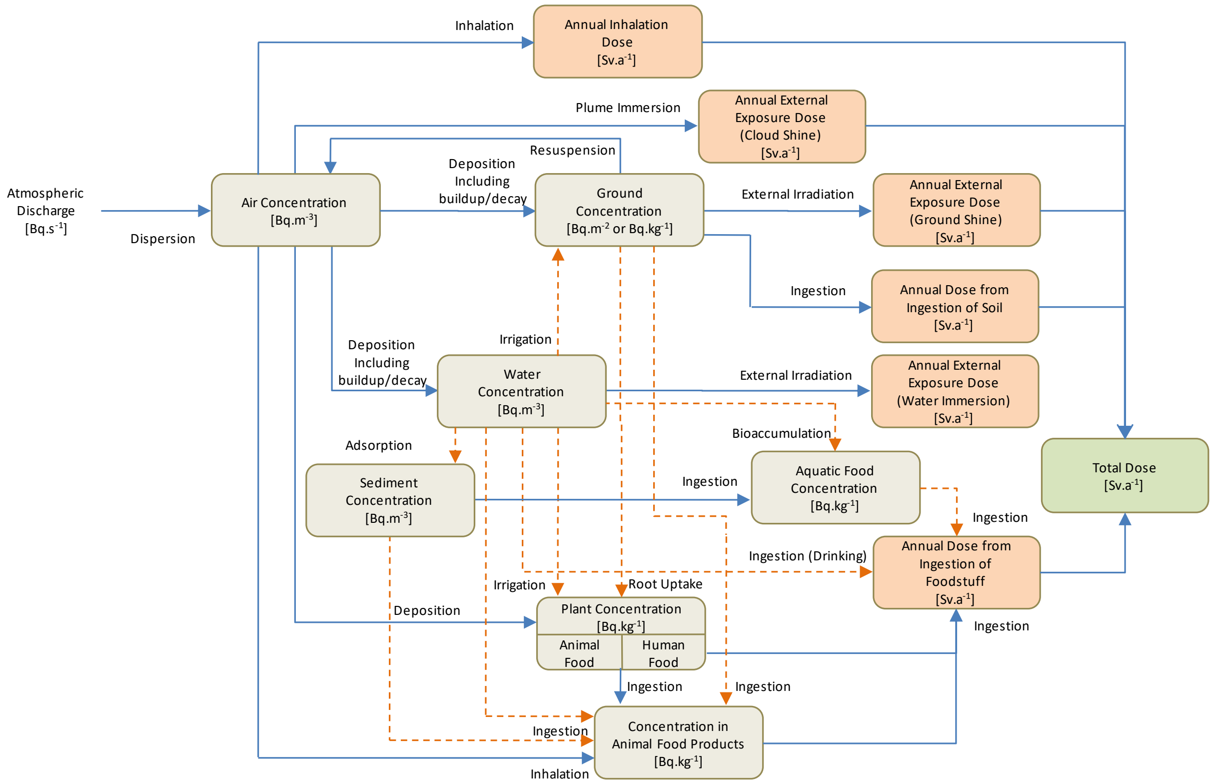

Figure 4.13 Features, processes and associated exposure modes that should be considered to calculate the contribution of the atmospheric pathway to a total dose.

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

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

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

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

4.4.3 Groundwater Pathway

The primary sources of radiation exposure (see Section 4.3) for the groundwater pathway are associated with existing TSFs in the area, as well as the proposed Valley TSF and Nooitgedacht TSF as a contribution to the existing TSFs. In addition, the proposed return water dams may contribute to a source of radiation exposure. Section 3.4.5 provides a summary overview of the hydrogeological conditions in the Projects area (MvB Consulting, 2023a; b; c). A detailed characterisation of the hydrogeological flow regime of the Free State Operation of Harmony is presented in (AquiSim, 2018c).

Consistent with the observed groundwater levels, the simulated groundwater levels suggest that the general direction of flow is consistent with the topography, resulting in groundwater flow towards the low-lying areas in a northwest, west and southwesterly direction in the direction of Bakkenpan, Dankbaar pan, Brakpan and the Mahem Spruit (see Figure 3.11 and Figure 3.12).

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

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

The flow diagram in Figure 4.14 can be used to calculate the contribution of the groundwater pathway to a quantitative total effective dose. Depending on the radionuclide concentration of the groundwater as well as human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.14. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation of water contributes to the concentrations of radionuclides in crops or soil.

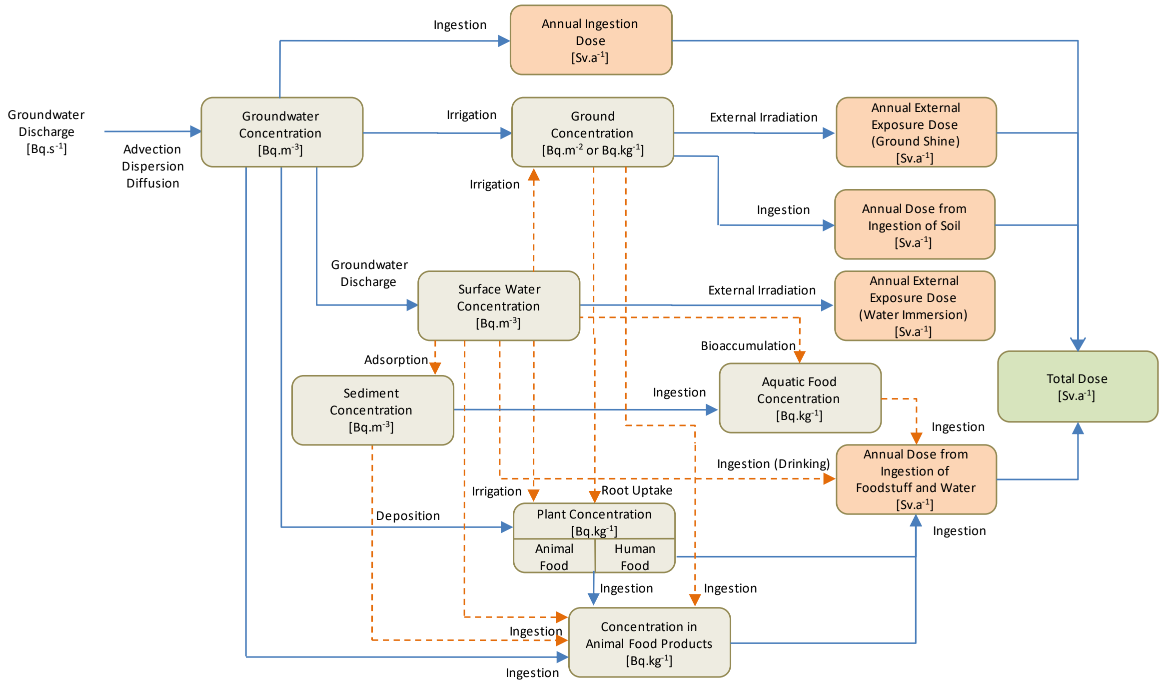

Figure 4.14 Features, processes and associated exposure modes that should be considered to calculate the contribution of the groundwater pathway to a total dose.

4.4.4 Surface Water Pathway

Under normal conditions, the surface water pathway is an extension of the groundwater pathway and to a lesser extent the atmospheric pathway. However, the controlled or uncontrolled release of contaminated water or mine residue material may serve as a direct source of radiation exposure associated with the surface water pathway. Once discharged into the surface watercourse, radionuclides are subject to a series of physical and chemical processes that affect their transport from the point of discharge. These processes illustrated in Figure 4.15, include the following (IAEA, 2001):

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

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

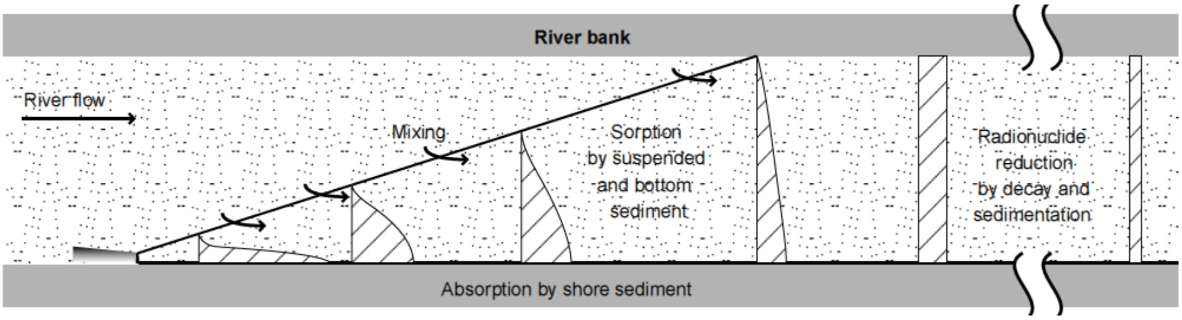

Figure 4.15 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001**).**

Section 3.4.3 and Section 3.4.5 provide a summary overview of the hydrological conditions in the Projects area. The surface water drainage lines follow the topography to low-lying areas associated with the Mahem Spruit towards the south and southwest of the Projects area as the receiving water bodies.

The flow diagram in Figure 4.16 can be used to calculate the contribution of the surface water pathway to a total effective dose. Deposition of airborne radionuclides onto surface water bodies may contribute to the concentration of radionuclides in surface water. Factors that will influence the migration of radionuclides in surface water include surface water/groundwater interaction (e.g., discharge rates), mean annual flow rates, seasonal variation, and adsorption of radionuclides onto sediments. Depending on the radionuclide concentration of the surface water as well as the human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.16. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation with contaminated water contributes to radionuclide concentrations in crops or soil.

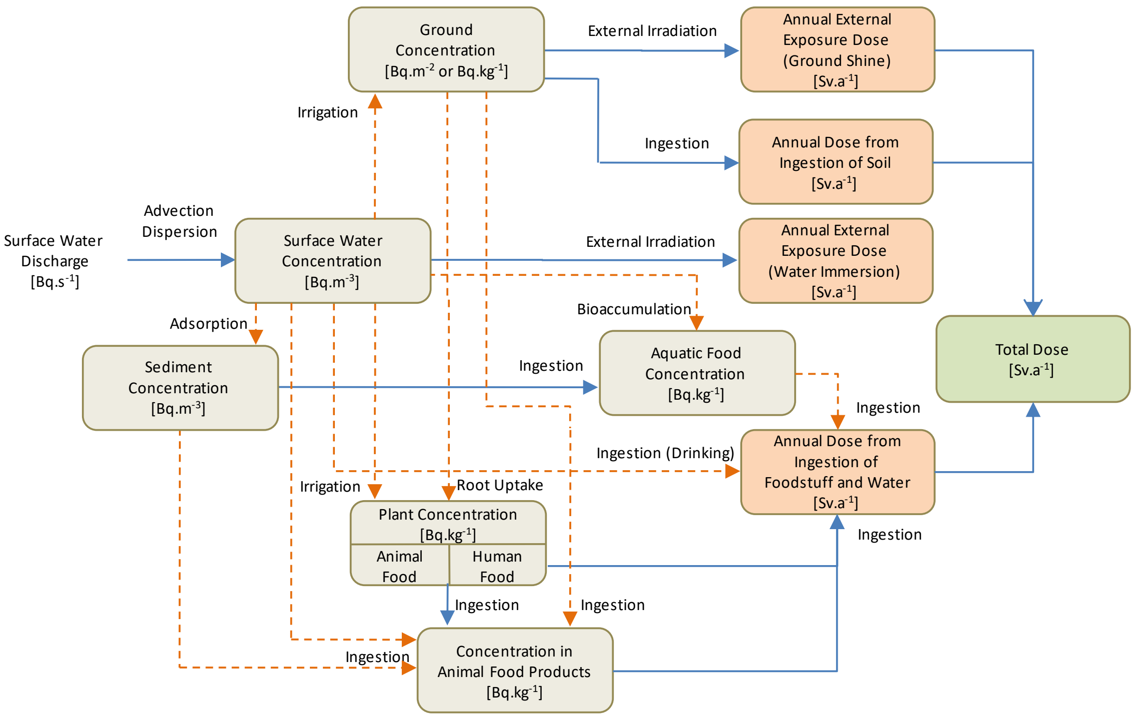

Figure 4.16 Features, processes and associated exposure modes that should be considered to calculate the contribution of the surface water pathway to a total dose.

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

4.4.5 External Gamma Radiation

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

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

4.5 Receptors

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

The information presented in Section 3.4.7 indicates that the communities closest to the Projects include the residents in residential areas of Odendaalsrus (e.g., Hestersrus and Ross Kent South) and Welkom (Rheederpark, Flamingo Park, Phomolong Village and Jabulani). Farmsteads associated with agricultural activities are present to the north of the Projects area, but predominantly towards the south and southwest of the area along the Mahem Spruit.

A radiological impact on receptors can only occur if a complete Source-Pathway-Receptor linkage exists. It was demonstrated in Section 4.4.2 that the atmospheric pathway has the potential to transport radionuclides from the Projects into the off-site environment. The spatial distributions of airborne particulates and contaminants can be used as a basis to determine whether members of the public could potentially be affected. The dispersion modelling results presented in Figure 4.1 to Figure 4.12 indicate that airborne particulate concentrations are highest close to the source and decrease rapidly with distance away from the sources. The spatial distributions of airborne particulates and contaminants indicate that areas around the Projects area, and in particular in a southwesterly direction, are potentially the highest impacted areas, with a component to the south as well (for PM_{10}, TSP and radon gas).

As far as the groundwater pathway is concerned, indications are that any potential off-site transfer of radionuclides would be towards the low-lying areas associated with the Mahem Spruit but that the impact during the operational phase of the Projects 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 Mahem Spruit, albeit in the far future.

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

With the synopsis presented above as a basis, conservative receptor locations include the residential areas of Odendaalsrus and Welkom, as well as agricultural activities and areas in a southwesterly direction. The receptor locations selected for the assessment and shown in Figure 4.1 to Figure 4.12 are the same locations identified in the air quality impact assessment (Airshed, 2023). They consist of 9 farmsteads, 8 residential locations, 5 schools and 3 hospitals.

4.6 Conceptual Model Development

4.6.1 General

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

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

As applied in other fields of science, conceptual models are extensively used in radiological public safety assessments. The use of conceptual models in the development of exposure conditions is captured in Figure 1.3 and Figure 4.17.

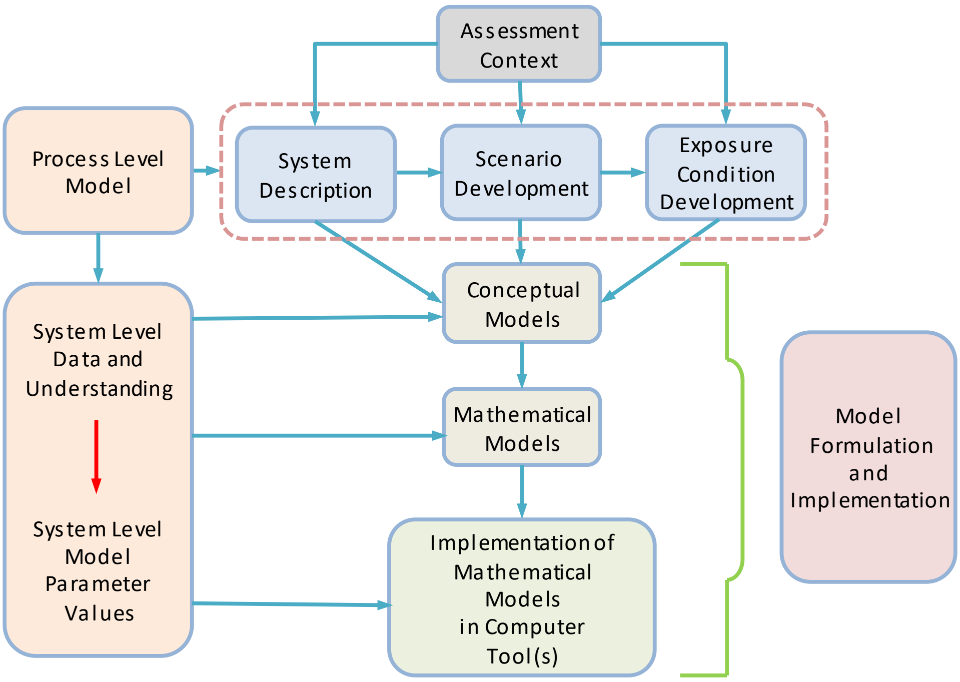

Figure 4.17 The model development process relative to other elements of the assessment framework presented in Figure 1.3.

4.6.2 Conceptual Models for Environmental Pathway Analysis

Three environmental pathways tend to be of importance in radiological public safety assessments of mining and mineral processing operations, namely the atmospheric pathway, the groundwater pathway, and the surface water pathway. To a lesser extent, external gamma radiation may also contribute to a 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 Projects (MvB Consulting, 2023b). Conceptual models developed as part of these studies that were performed on a Process Level, will not be repeated here.

4.6.3 Representation of Conceptual Models for Exposure Conditions

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

Two methods are used to represent the exposure conditions conceptually: a process flow diagram and an RES Matrix or Interaction Matrix (Kozak and Zhou, 1998). In an Interaction matrix, the main variables or parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. A simple example of a 2x2 matrix is illustrated in Figure 4.18, with the atmospheric (radioactive dust concentration) and topsoil layer as diagonal elements. Deposition represents an interaction between the atmosphere and the surface soil, while some of the deposited dust may be re-suspended back into the atmosphere.

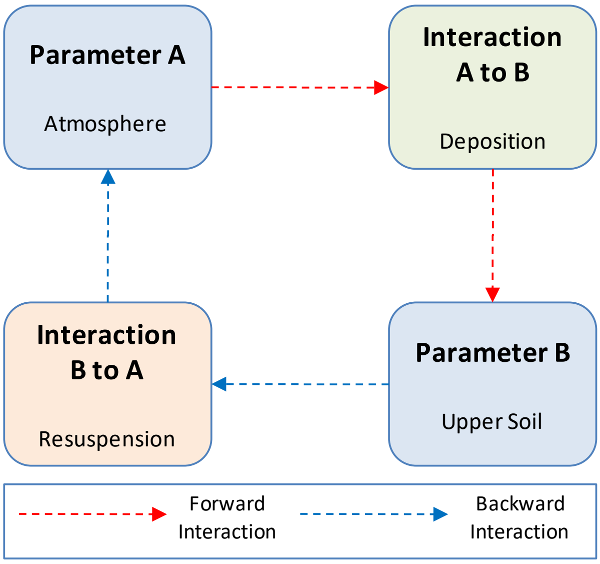

Figure 4.18 A simple 2x2 Interaction Matrix, showing the interaction between features, events, and processes in a safety assessment.

It is thus clear that the different elements of the system can be included in the Interaction Matrix and analysed in detail by creating one or more sub-matrices. This approach suggests that the elements on the main diagonal can be represented by a specific theme, such as the migration pathway of radionuclides from the sources to receptors. The off-diagonal elements represent the interaction of events and processes that cause or influence the migration of the radionuclides from one diagonal element (system feature) to another along the identified pathway. Those above the diagonal represent the influence on forwarding motion, while those below influence the backward moment. This is illustrated in Figure 4.19, which represents a 5x5 matrix and the potential migration pathway of radionuclides from element D, through various interactions between diagonal and off-diagonal elements, to element E.

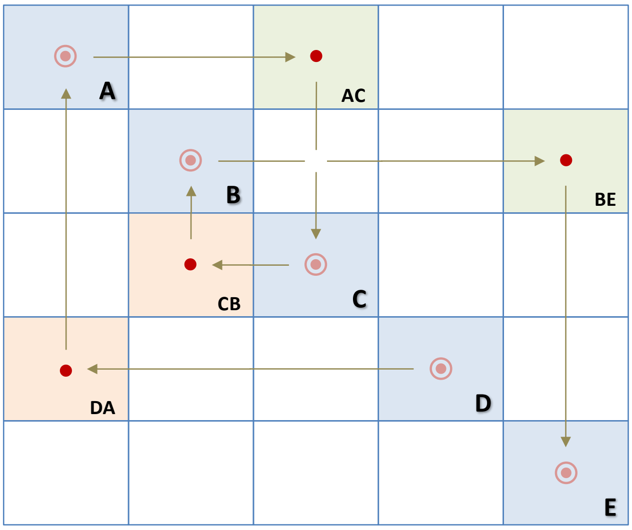

Figure 4.19 Principle of a radionuclide migration path through the Interaction Matrix.

Figure 4.20 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.

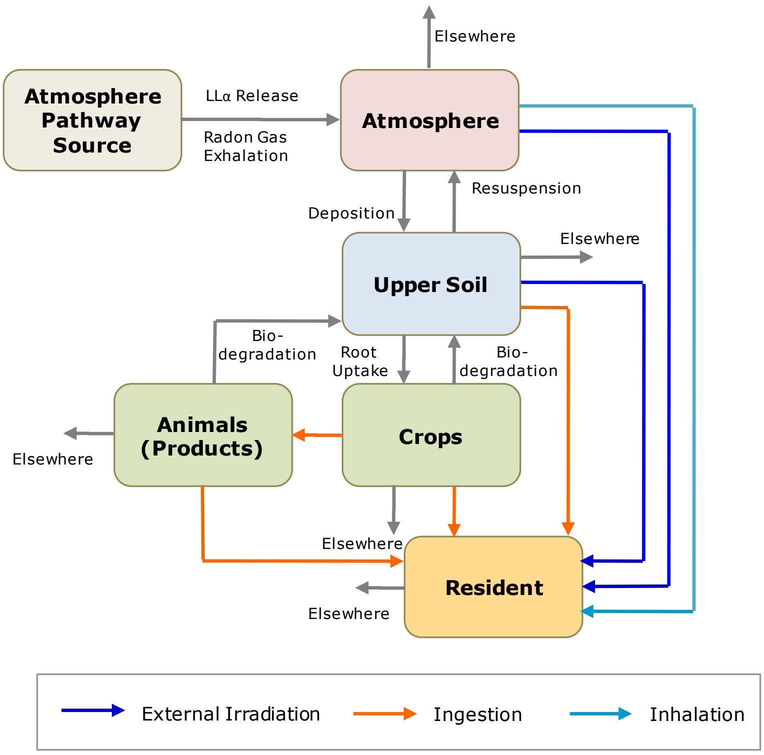

Figure 4.20 A flow diagram is an example of a conceptual model for a specific exposure condition, showing the exposure pathways and the relationship between the different compartments of the system.

4.7 Public Exposure Conditions for the Projects

4.7.1 General

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

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

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

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

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

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

4.7.2 Criteria Used to Define the Discrete Set of Exposure Conditions

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

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

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

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

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

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

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

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

With due consideration of the sources, pathways and receptors described above and consistent with the exposure groups defined for the 2018 Free State Operations RPSA (AquiSim, 2018a), the following two public exposure conditions can be defined to evaluate the potential radiological impact of the Projects to members of the public under normal operating conditions:

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

More exposure conditions can be defined that would be relevant to the area. The key point of judgment on whether the discrete set of exposure conditions is representative of the radiological public safety assessment is whether potential receptors of radiation exposure can relate to at least one of these exposure conditions. The potential radiation exposure to nearby industry workers, for example, will be less than those 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 Hestersrus (Odendaalsrus) and Rheeders Park (Welkom). This may include formal and informal residential structures.

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

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

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

- The exposure groups consist of members of the public from all age groups.
- The exposure group maintain a small household garden consisting of fruits, vegetables (leafy and root) and cereal (mealies), which fulfil 50% of their annual requirement of fruit, vegetables, and cereal.
- The exposure group keep animals in the form of chickens, goats, and cattle. These serve as a source of protein in the form of eggs, milk, and meat. For the assessment, it is conservatively assumed that it contributes to 50 % of their daily rate of protein consumption.
- Food preparation (e.g., peeling, boiling) may contribute to a reduction in radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in any food produced in the area remain the same irrespective of preparation methods used.
- Consistent with RG-002 guidelines (NNR, 2013a), Table 4.1 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.
- As a conservative assumption, the rate of incidental soil ingestion is maintained at 100% of the value published in RG-002 (NNR, 2013a).

Table 4.1 Age group specific indoor and outdoor occupancy factors (NNR, 2013a).

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 4.21 and Figure 4.22 using a flow diagram and Interaction Matrix, respectively.

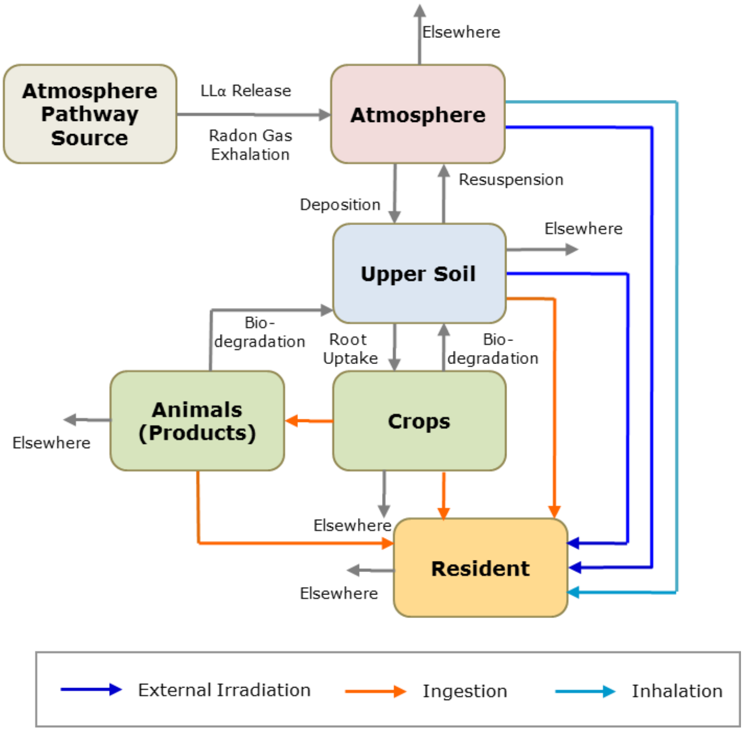

Figure 4.21 Conceptual flow diagram of the exposure pathways associated with a Residential Area Exposure Condition.

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

Exposure routes associated with the Residential Area Exposure Condition include radon gas and LLα inhalation, as well as ingestion of contaminated crops (fruits, vegetables, and cereal) and animal products (meat, eggs, and milk). Inadvertent soil ingestion is also assumed. Contributions to the total effective dose from external gamma radiation are also expected from airborne LLα (cloud immersion) and radionuclides deposited on the upper soil layer (ground shine).

Note that, as illustrated in Figure 4.21 and Figure 4.22, biodegradation of crop material may also contribute to the upper soil concentration, while resuspension of deposited dust may contribute to the airborne activity concentration. Also illustrated in Figure 4.21 and Figure 4.22, is the transfer of some of the radioactivity released from the atmospheric pathway sources, to "elsewhere" through processes such as dispersion, leaching, washing, weathering and excrement. "Elsewhere" as used here refers to a place where humans will not be affected by the radionuclides of concern.

4.7.5 Commercial Agricultural Exposure Condition

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

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

Figure 4.22 Conceptual Interaction Matrix of the exposure pathways associated with Residential Area Exposure Condition.

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

- The exposure groups (farmers and farm workers) consist of members of the public from all age groups.
- The exposure group maintain a commercial farm system consisting of fruits, vegetables, and cereal (mealies). It is conservatively assumed that the farm contributes 100% to its annual consumption rate.
- The exposure group keep animals in the form of chickens, sheep, and cattle. These serve as a source of protein in the form of eggs, milk, and meat. For the assessment, it is conservatively assumed that it contributed 100% to their annual consumption rate.
- Food preparation (e.g., peeling, boiling) may contribute to a reduction in radioactivity concentrations in fruits and vegetables. However, for this assessment, it is assumed that radionuclide concentrations in any food produced in the area remain the same irrespective of preparation methods used.
- Consistent with RG-002 guidelines (NNR, 2013a), Table 4.1 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.

The conceptual model for the Commercial Agricultural Exposure Condition is presented in Figure 4.23 and Figure 4.24 using a flow diagram and Interaction Matrix, respectively.

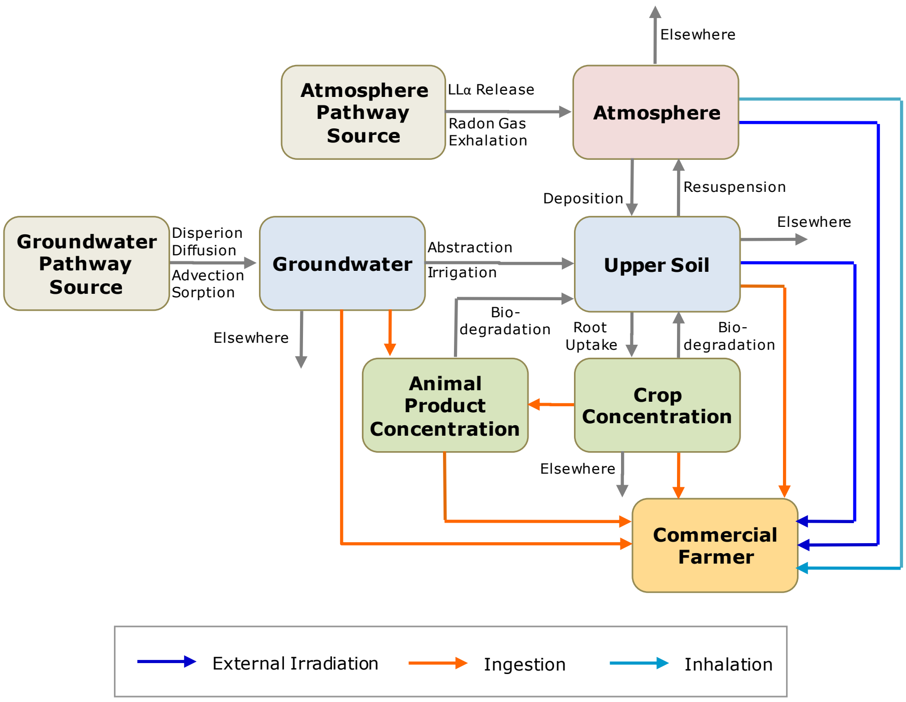

Figure 4.23 Conceptual flow diagram of the exposure pathways associated with the Commercial Agricultural Exposure Condition.

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

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

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

Note that, as illustrated in Figure 4.23 and Figure 4.24, biodegradation of crop material may also contribute to the concentration of radionuclides in the upper layer of soil, while resuspension of deposited dust may contribute to airborne radioactivity. Also illustrated in Figure 4.23 and Figure 4.24, is the transfer of some of the radioactivity released from the atmospheric pathway sources, to “elsewhere” through processes such as dispersion, leaching, washing, weathering and excrement. “Elsewhere” as used here refers to a place where humans will not be affected by the radionuclides of concern.

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

Figure 4.24 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 Projects in Section 4.7. Consistent with the safety assessment framework and technical approaches therein (see Figure 1.3), the assessment results are then interpreted in terms of the total annual effective dose as compliance criteria (boundary conditions) as defined in the *Assessment Context* (see Section 2). The methodological approach used to calculate the total effective dose is described in Appendix B.

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

5.2 Contribution from Groundwater Pathway

5.2.1 General

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

Although little information is available to evaluate this scenario, some assumptions can be made to assess the radiological consequences, albeit for illustrative purposes. Consequently, presented here is a simplified one-dimensional numerical groundwater model using a compartmental modelling approach to represent the migration and fate of contaminants in the environment with the TSF as the source of contamination. The conceptual representation of the *System Level* compartmental model implemented in Ecolego (Version 8) is presented in Appendix D.

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

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

5.2.2 Parameter Values

As a conservative assumption, the average activity concentrations listed in Table 3.10 for tailings material generated at the Harmony Operations were used as the initial activity concentrations, while Table 5.1 summarises a few additional parameter values assumed for the leaching analysis. Note that these parameter values are selected to be conservative.

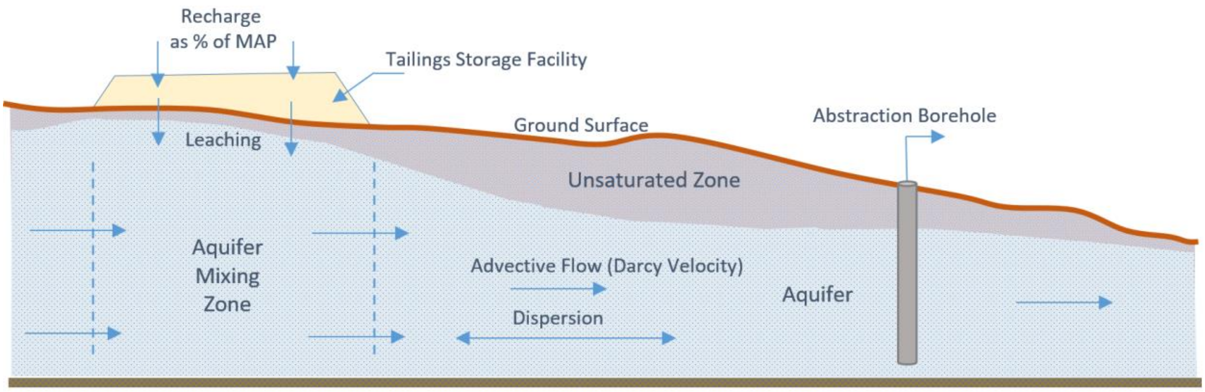

Figure 5.1 Conceptual representation of the model compartment included in the System Level modelling of the groundwater pathway (Not to Scale).

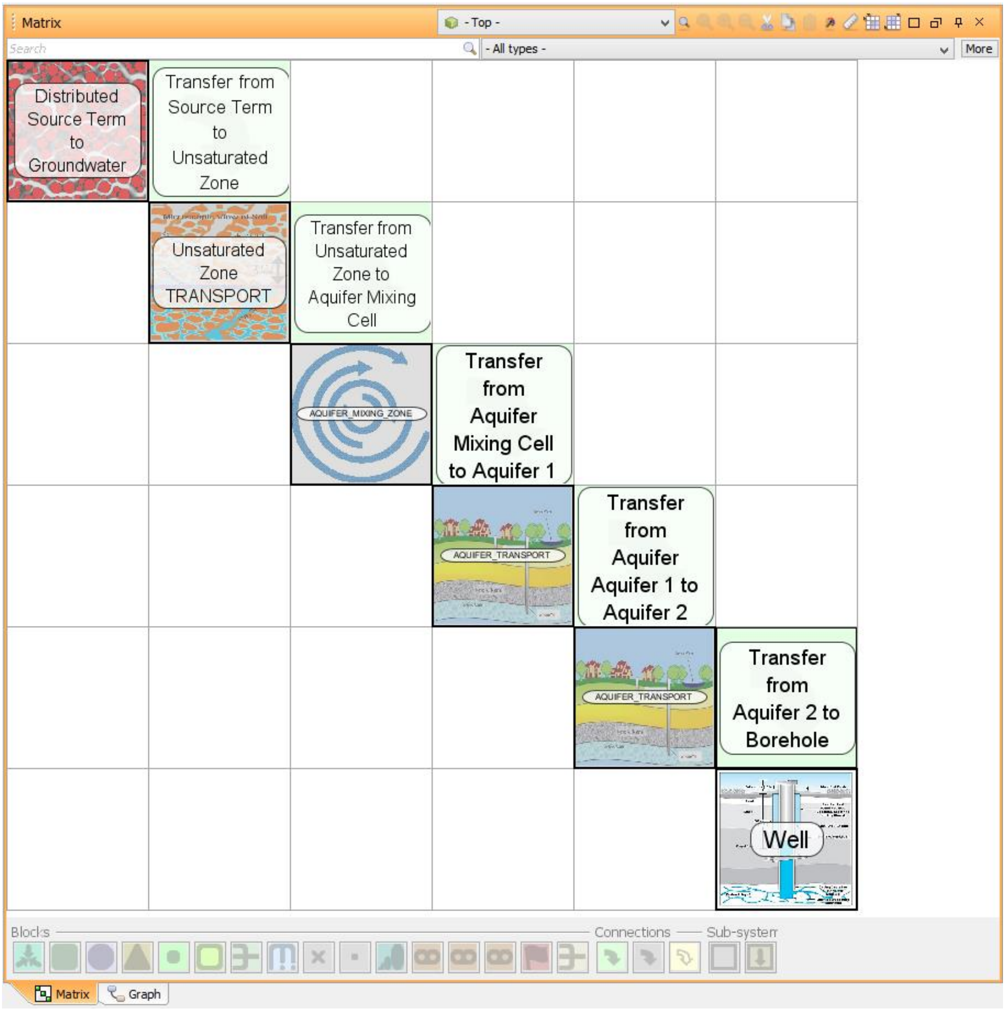

Figure 5.2 Screen capture of the model implementation in Ecolego used to evaluate the contribution of the groundwater pathway for the Projects.

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

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

Parameter		Units	Valley TSF	Nooitgedacht TSF	Combined TSF Complex
Mean Annual Precipitation (MAP)		[mm]	606		
Recharge (Infiltration) Rate Through TSF as % of MAP	< 50 years	[m.year^{-1}]	9.09E-02 (15% of MAP)		
	50 to 75 years		6.06E-02 (10% of MAP)		
	75 to 100 years		3.03E-02 (5% of MAP)		
	> 100 years		1.82E-02 (3% of MAP)		
Volumetric Moisture Content		[m^3.m^{-3}]	3.0E-01		
The density of Tailings Material		[kg.m^{-3}]	1.700E+03		
Average Height		[m]	32	100	60
Average Area		[m^2]	1.2400E+06	8.950E+06	1.375E+06
Assumed Length and Width (√Area)		[m]	1.2248E+03	2.992E+03	3.708E+03
Volume		[m^3]	3.968E+07	8.950E+08	8.250E+08

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

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

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

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

Table 5.3 lists additional aquifer parameters needed for the calculations. The unsaturated zone underneath the TSF is conservatively assumed to be only 5 m thick, with a dry bulk density of 1,400 kg.m^{-3} and a volumetric moisture content of 0.3 m^3.m^{-3}. A thicker unsaturated zone will retard the migration of radionuclides to the point of abstraction even further. Here the hydraulic gradient is in the order of 0.29%, while the hydraulic conductivity in the weathered aquifer can be set at 1.6E-01 m.day^{-1}, which equates to a relatively low Darcy velocity of 0.17 m.year^{-1} (or 4.68E-02 m.day^{-1}). With an effective porosity of 1%, the advective flow velocity is in the order of 17 m.year^{-1} for the area as listed in Table 5.1, which correlates well with the plume migration distance in 50 years quoted in AquiSim (2018c) (see Figure 3.12).

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	5
Aquifer Thickness		30
Hydraulic Conductivity	$m.day^{-1}$	1.60E-01
Effective Porosity	-	0.01
Hydraulic Gradient		2.93E-03
Darcy Velocity	$m.day^{-1}$	4.68E-04
Actual Velocity		4.68E-02
Longitudinal dispersivity (α_L)	m	30
Dry Bulk Density	$kg.m^{-3}$	1,800
Distance to Borehole	m	300
Borehole Fraction in Contaminant Plume	-	1

5.2.3 Results

5.2.3.1 Valley TSF (Alone)

Figure 5.3 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 100,000 years (the Th-232 decay chain only becomes visible after 1,000,000 years). If one assumes the RG-002 (NNR, 2013a) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.3 translate to water ingestion doses shown in Figure 5.4. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a point 300 m from the TSF is only visible in hundreds of thousands of years, and potentially at doses that are below 130 $\mu Sv.year^{-1}$.

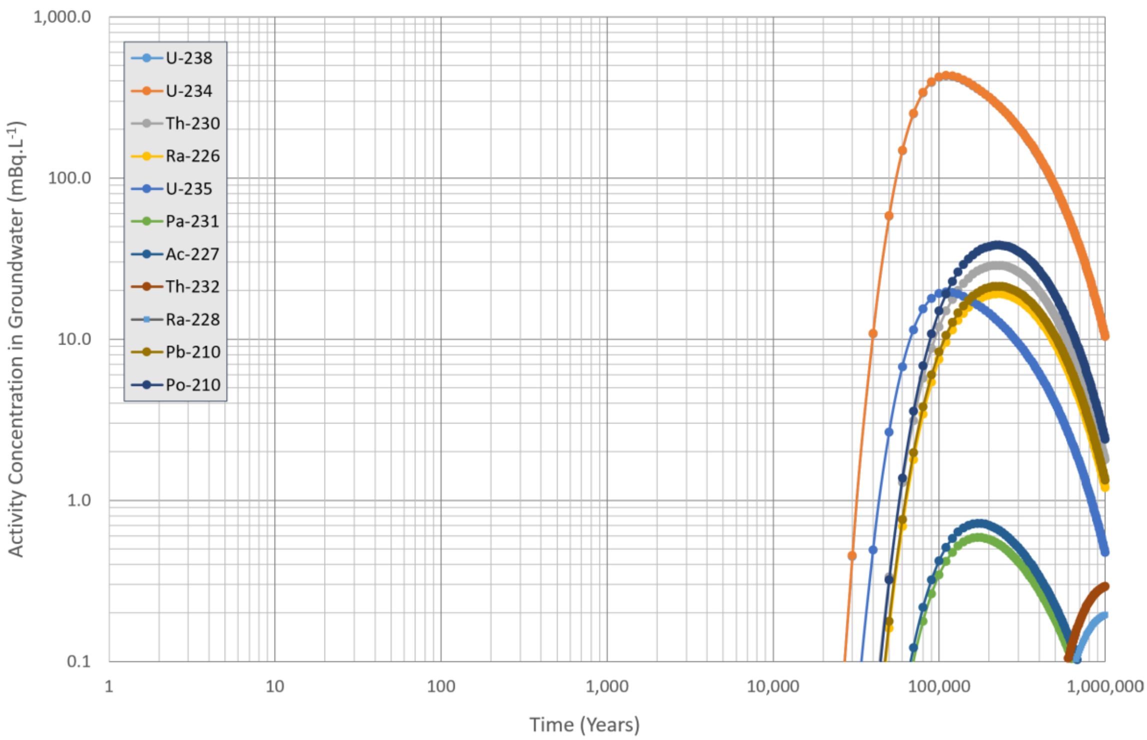

Figure 5.3 The simulated activity concentration in groundwater abstracted from a borehole 300 m from the proposed Valley TSF.

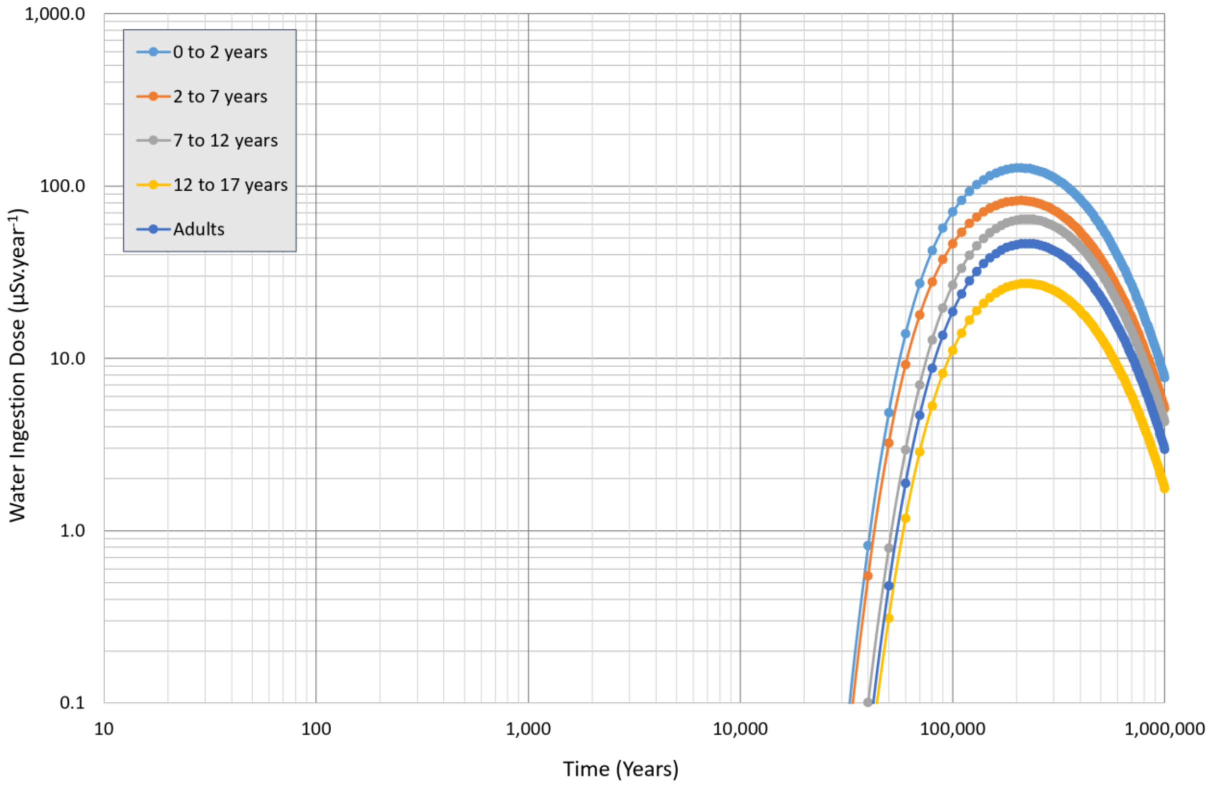

Figure 5.4 The simulated water ingestion dose to the different age groups 300 m from the proposed Valley TSF, using the activity concentrations in Figure 5.3.

5.2.3.2 Nooitgedacht TSF (Alone)

Figure 5.5 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 110,000 years (the Th-232 decay chain only becomes visible after 1,000,000 years). If one assumes the RG-002 (NNR, 2013a) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.5 translate to water ingestion doses shown in Figure 5.6. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a point 300 m from the TSF is only visible in hundreds of thousands of years, and potentially at doses that are below 170 µSv.year^{-1}.

5.2.3.3 Combined TSF Complex

Figure 5.7 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 120,000 years (the Th-232 decay chain only becomes visible after 1,000,000 years). If one assumes the RG-002 (NNR, 2013a) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.7 translate to water ingestion doses shown in Figure 5.8. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a point 300 m from the TSF is only visible in hundreds of thousands of years, and potentially at doses that are below 180 µSv.year^{-1}.

5.2.3.4 Discussion

The results presented in Figure 5.3 to Figure 5.8 suggest that a contribution from the groundwater pathway is only possible during the post-closure period and unlikely within the next 1,000 years and then only at doses of less than 200 µSv.year^{-1}. This applies to the proposed Valley TSF and Nooitgedacht TSF, as well as a combined TSF complex that includes the existing TSFs.

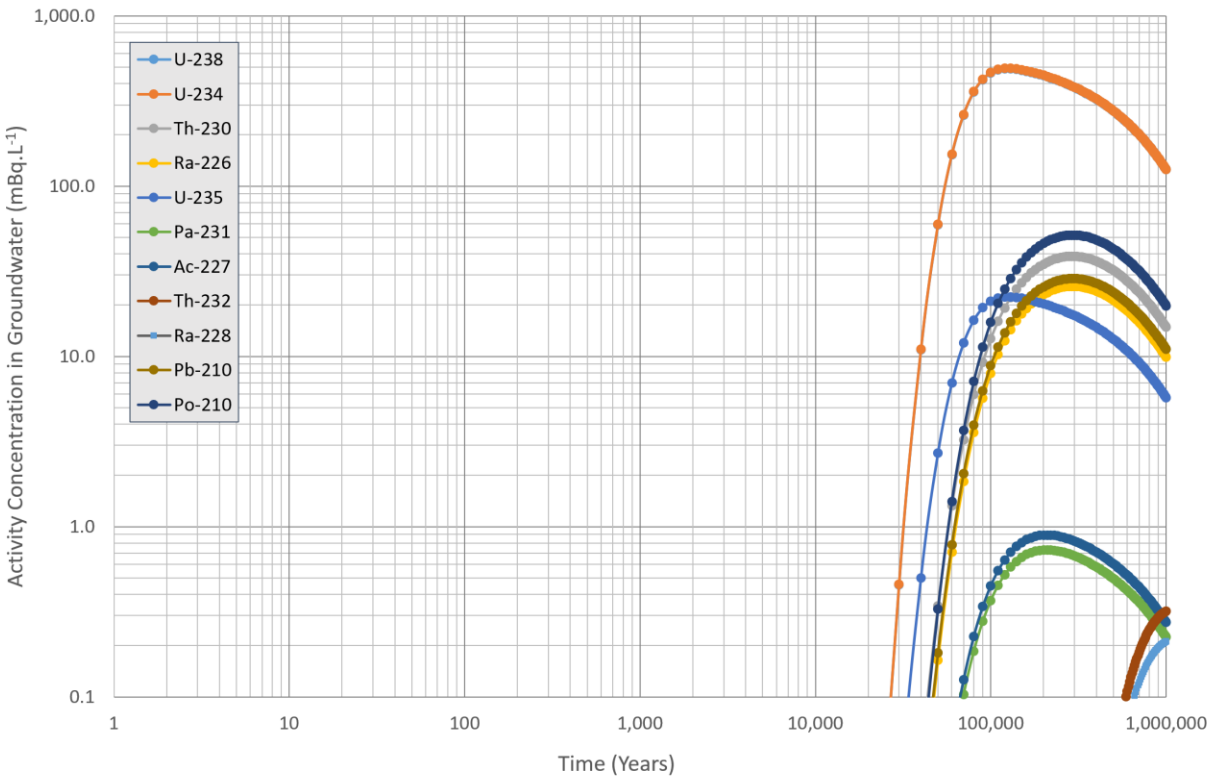

Figure 5.5 **The simulated activity concentration in groundwater abstracted from a borehole 300 m from the proposed Nooitgedacht TSF.**

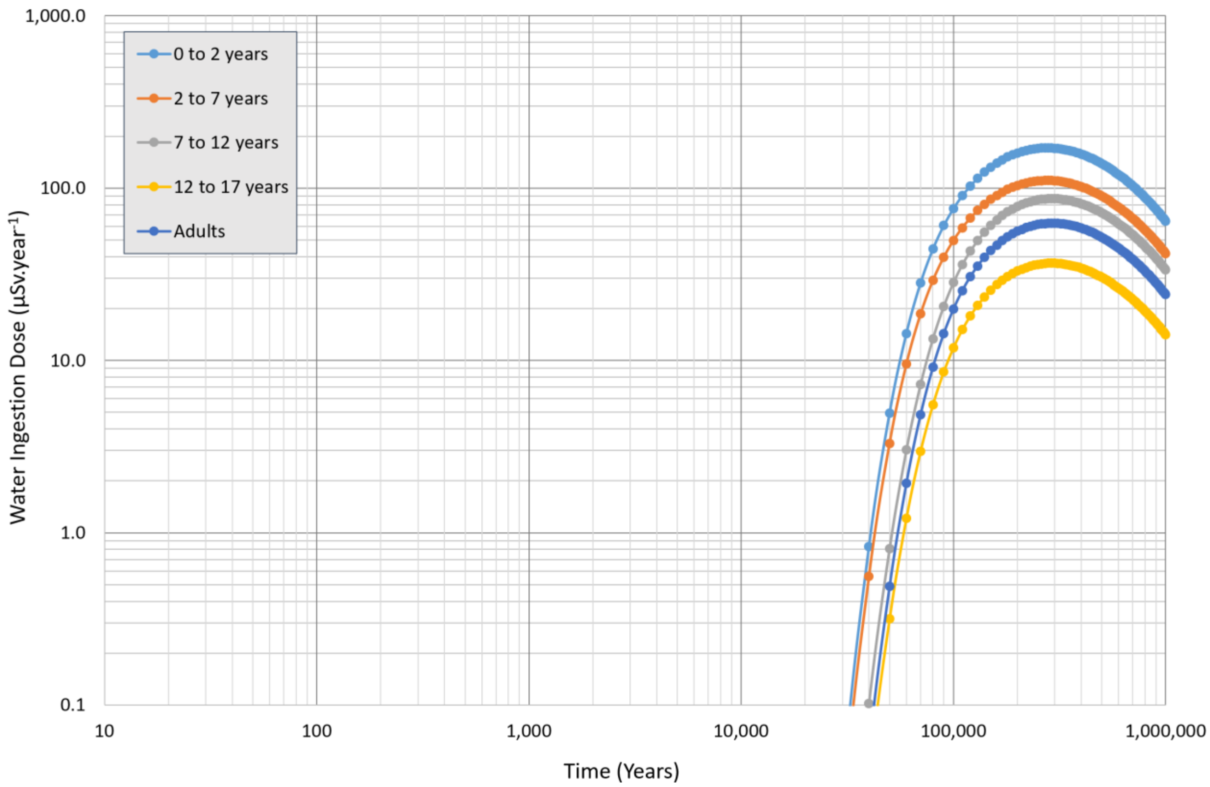

Figure 5.6 **The simulated water ingestion dose to the different age groups 300 m from the proposed Nooitgedacht TSF, using the activity concentrations in Figure 5.3.**

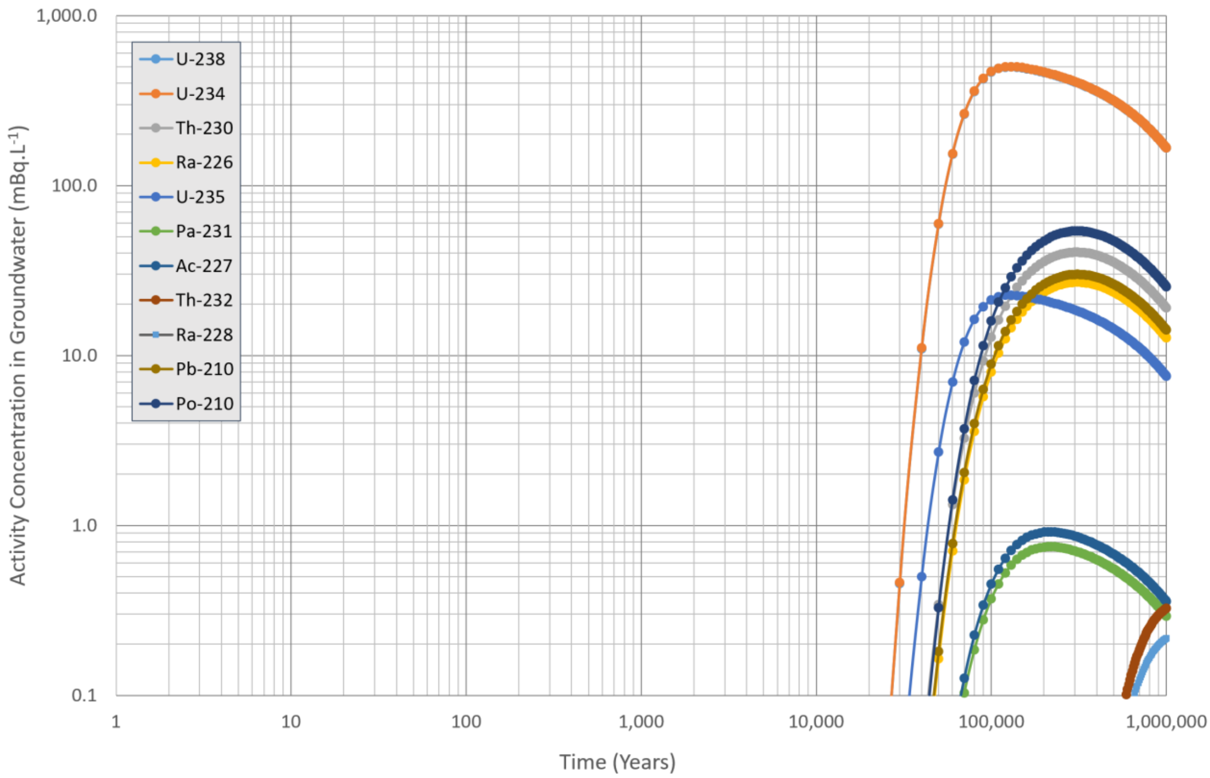

Figure 5.7 The simulated activity concentration in groundwater abstracted from a borehole 300 m from the Combined TSF Complex.

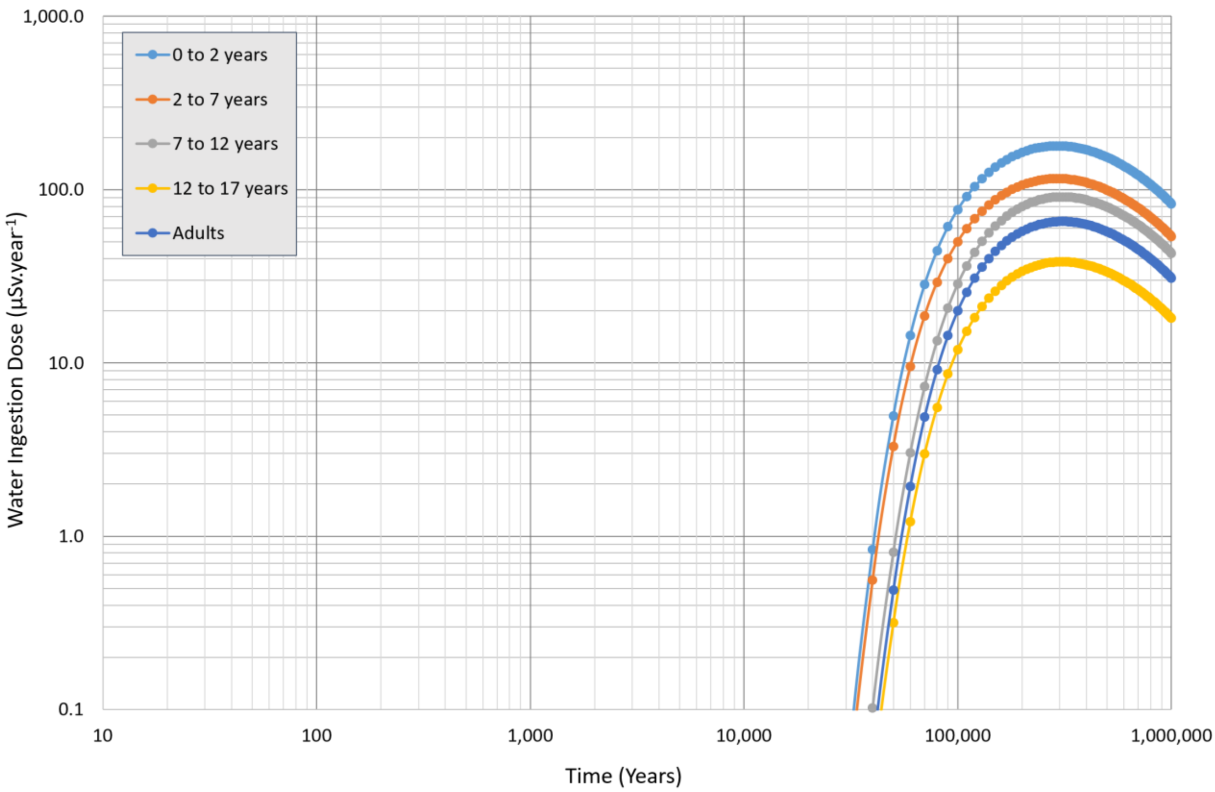

Figure 5.8 The simulated water ingestion dose to the different age groups 300 m from the Combined TSF Complex, using the activity concentrations in Figure 5.3.

5.3 Total Effective Dose Calculation for Exposure Conditions

5.3.1 General

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

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 as rates as defined for each exposure condition.

5.3.2 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2 represent the consolidated concentrations from all atmospheric pathway sources of concern. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well. The radioanalysis results available for the Projects are presented in Section 3.5.2. As a conservative assumption, the average activity concentrations listed in Table 3.10 were used for the proposed Valley TSF and Nooitgedacht TSF, as well as for FSN 3A TSF and FSN 5 TSF for which no full-spectrum analysis is available at present.

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

The radon exhalation rate for the TSFs, WRDs and ventilation shafts is presented in Section 3.5.3 (see Table 3.13 to Table 3.15). The average values in Table 3.13 were used for the proposed Valley TSF and Nooitgedacht TSF.

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 Projects. This includes residential areas and suburbs such as Odendaalsrus (Hestersrus, Ross Ken South, Mimosa Park, Philippi) and Welkom (Phomolong Villiage, Flamingo Park, Rheerderspark, Jim Fouche Park, Bedelia), but are equally relevant to other residential areas that might be affected. It is conservatively assumed that these residents maintain a household garden that contributes to 50% of their annual consumption rate of cereal, fruit, and vegetables, as well as animal products that include eggs, milk, and meat.

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

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

A dust deposition period of 75 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative.

5.3.3.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Projects and surrounding area. Based on the dose estimate, the 12 to 17 years age group was shown to receive the highest total effective dose. The dose isopleths in Figure 5.9 represent the total effective dose for the age group 12 to 17 years for the Baseline Conditions.

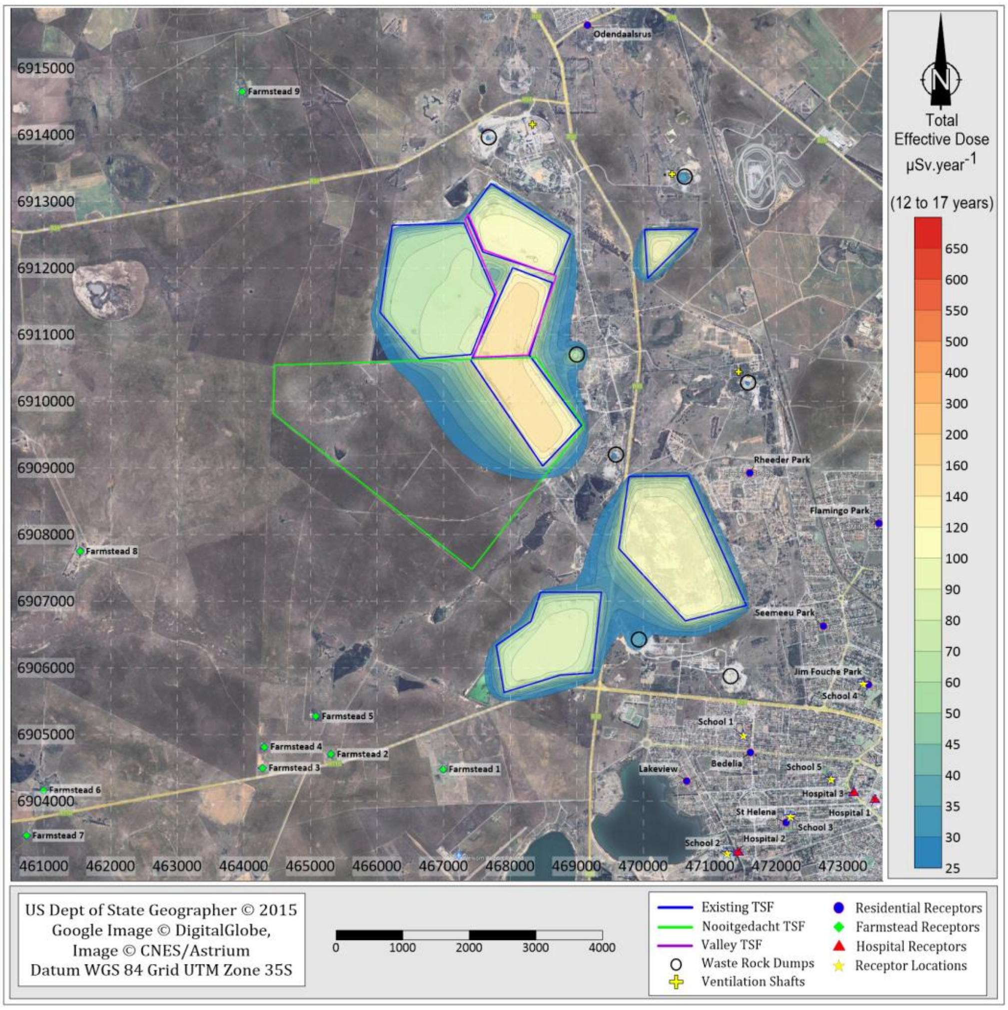

Figure 5.9 **Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Residential Area Exposure Condition attributed to the baseline conditions.**

Figure 5.10 and Figure 5.11 present the total effective dose for the age group 12 to 17 years attributed to the Valley TSF and the Nooitgedacht TSF, respectively, in addition to the Valley Baseline Conditions, while Figure 5.12 presents the total effective dose attributed to both the Valley TSF and the Nooitgedacht TSF in addition to the Valley Baseline Conditions.

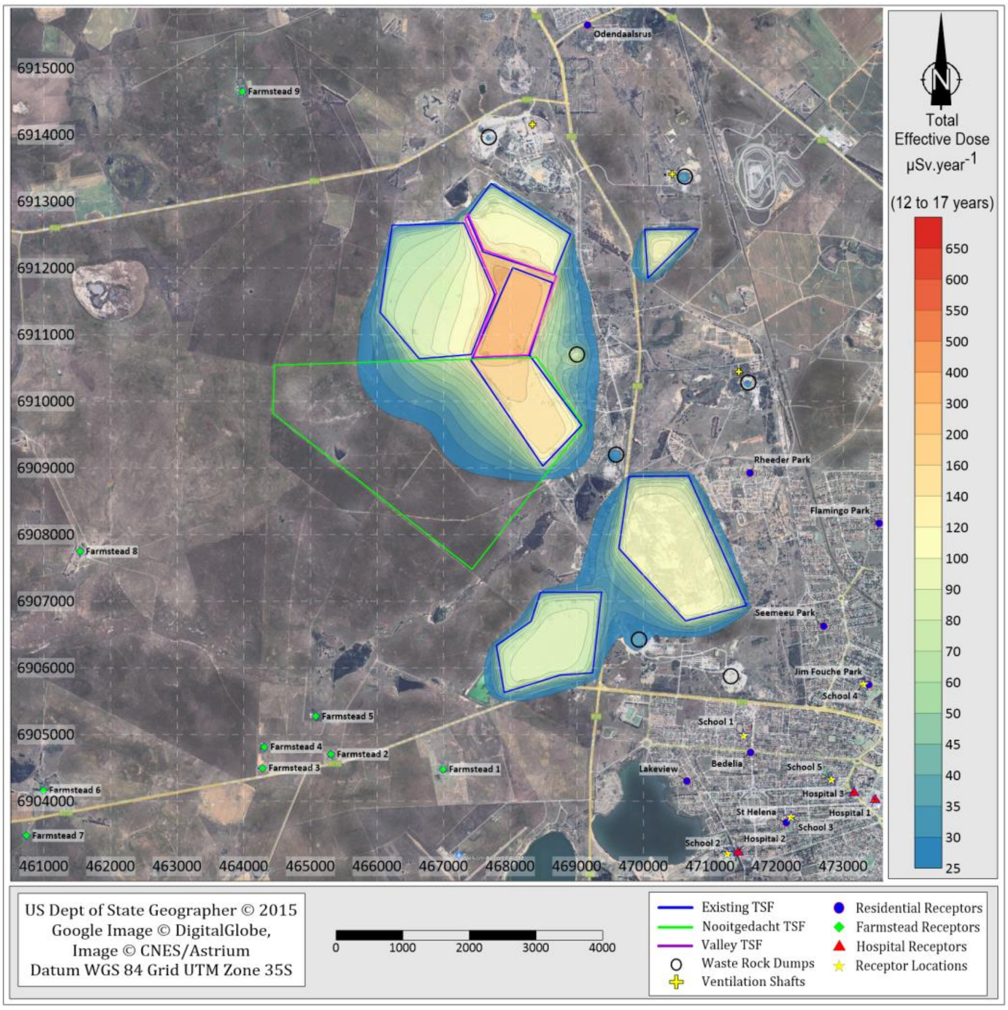

Figure 5.10 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Residential Area Exposure Condition attributed to the Valley TSF in addition to the baseline conditions.

5.3.3.3 Interpretation of Results

The dose isopleth results presented in Figure 5.9 to Figure 5.12 show that the effect of the baseline condition on the residential areas is minimal and does not reach residential areas at doses more than 10 to 20 μSv.year^{-1}. Figure 5.10 shows that the contribution of the proposed Valley TSF is also minimal and results in an increase of the total effective dose in the order of 10 μSv.year^{-1}. However, it still does not reach residential areas in doses of more than 10 to 20 μSv.year^{-1}.

Figure 5.11 and Figure 5.12 show that the contribution of the proposed Nooitgedacht TSF is more significant, mainly because of the difference in physical dimensions between the two TSFs. However, the resulting total effective dose, even as a contribution of both TSFs, is still relatively low in residential areas.

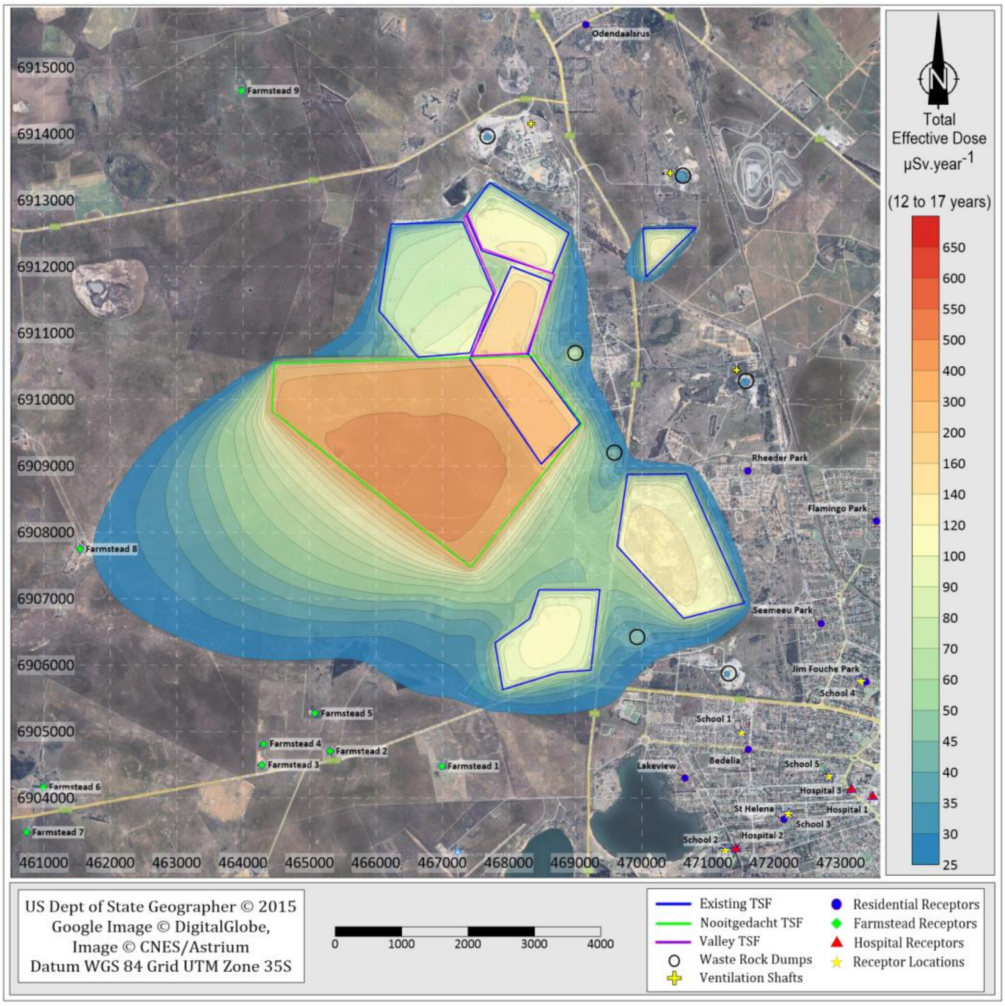

Figure 5.11 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of µSv.year^{-1}) of the Residential Area Exposure Condition attributed to the Nooitgedacht TSF in addition to the baseline conditions.

To put the dose isopleth result into perspective, the total effective dose results at several receptor locations in residential areas are presented in Figure 5.13 to Figure 5.16 (see Figure 5.9 to Figure 5.12 for location). These locations correspond to the locations identified in the air quality impact assessment (Airshed, 2023). In addition to residential locations, it also includes some schools and hospitals located in the residential areas. The results are for all the age group categories listed in Table B 1.

The results suggest that at the selected locations for the Residential Area Exposure Condition, the total effective dose is well below 20 µSv.year^{-1}. There is very little difference between the contribution under baseline conditions and the contribution from the Valley TSF. The contribution from the Nooitgedacht TSF is more significant but still results in total effective doses of less than 20 µSv.year^{-1}.

Figure 5.13 to Figure 5.16 suggest that the main contributor to the total effective dose is from radon gas inhalation, with more significant contributions from dust inhalation, as well as soil, crop, and animal product ingestion as a result of releases from the Nooitgedacht TSF. External gamma radiation (product of cloud and ground shine) is insignificant.

Note that these results are in direct correlation with the air quality impact assessment results for PM_{10}, TSP and radon gas concentrations as calculated as part of the air quality impact assessment (Airshed, 2023).

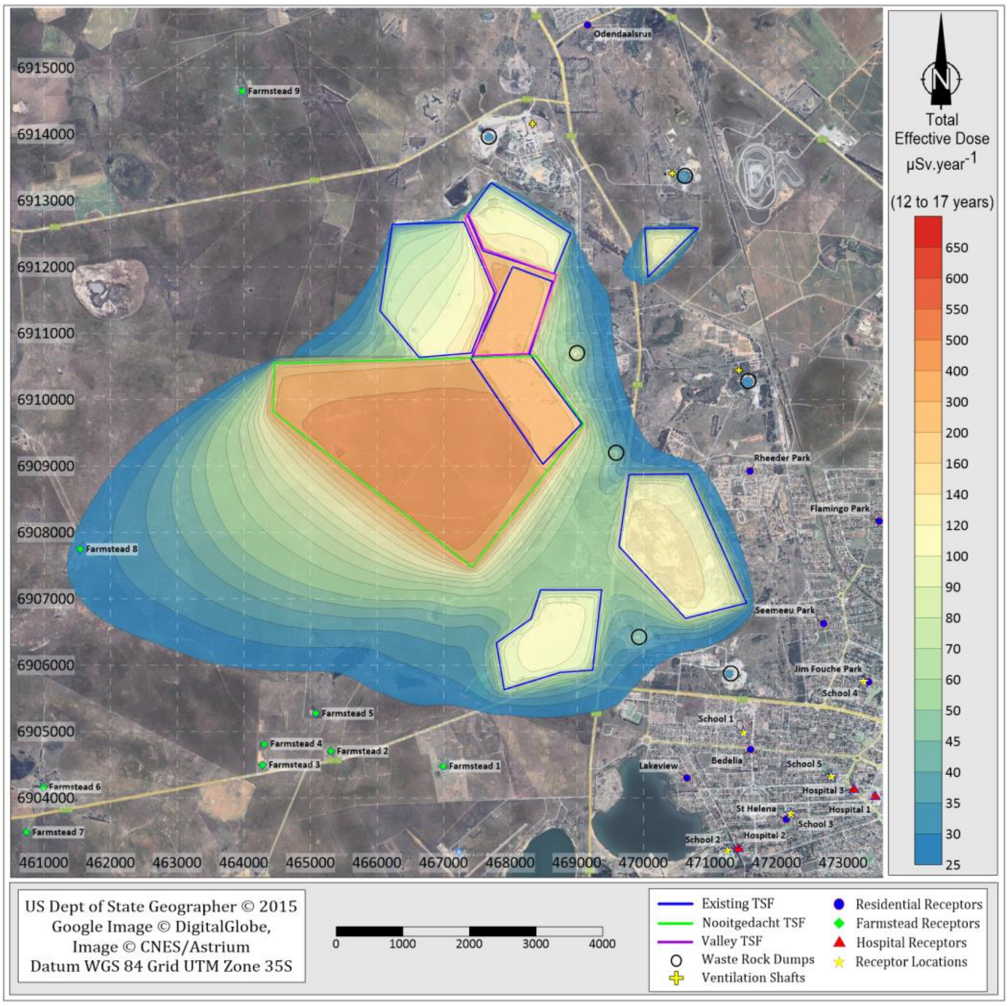

Figure 5.12 **Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year-1) of the Residential Area Exposure Condition attributed to the Valley TSF and Nooitgedacht TSF in addition to the baseline conditions.**

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 Projects, which is mainly in a southwesterly direction. However, the exposure condition is equally relevant to agricultural activities practices anywhere near the Projects This means that this exposure condition relates to any farming activity for the conditions and assumptions included in the definition of the Commercial Agricultural Exposure Condition.

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

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

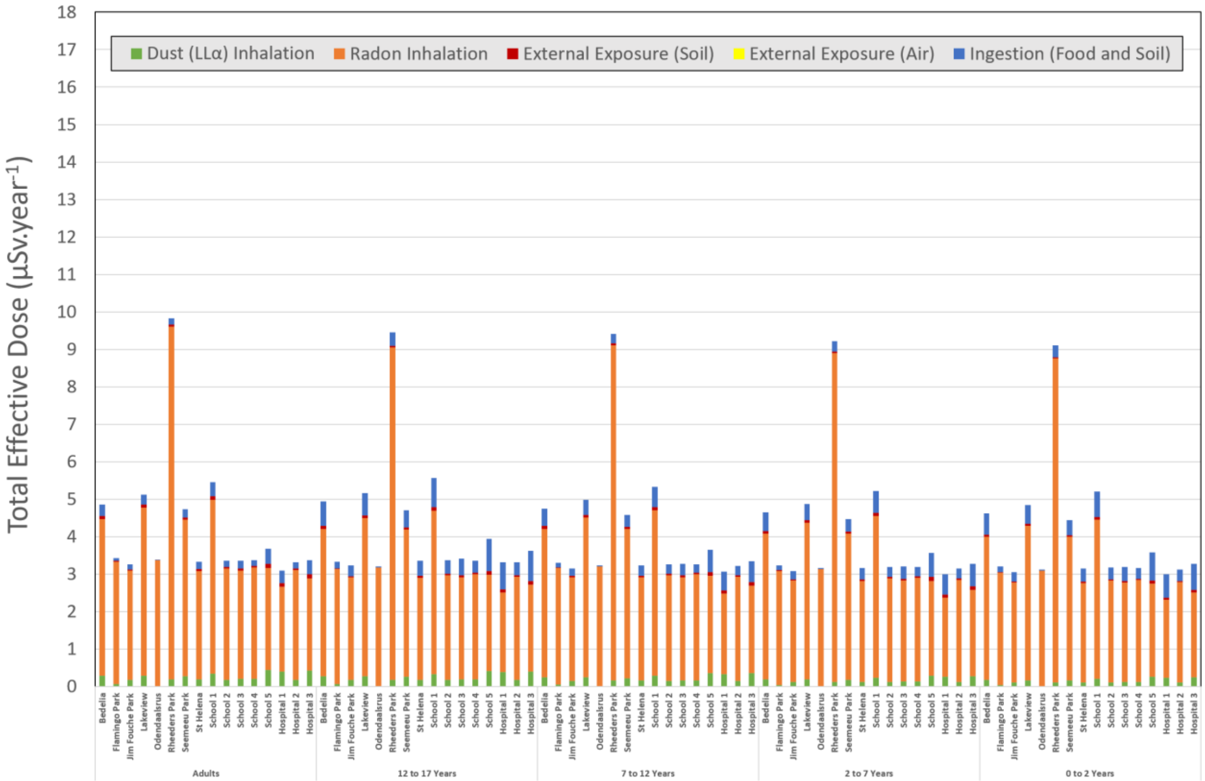

Figure 5.13 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.9 to Figure 5.12 for locations).

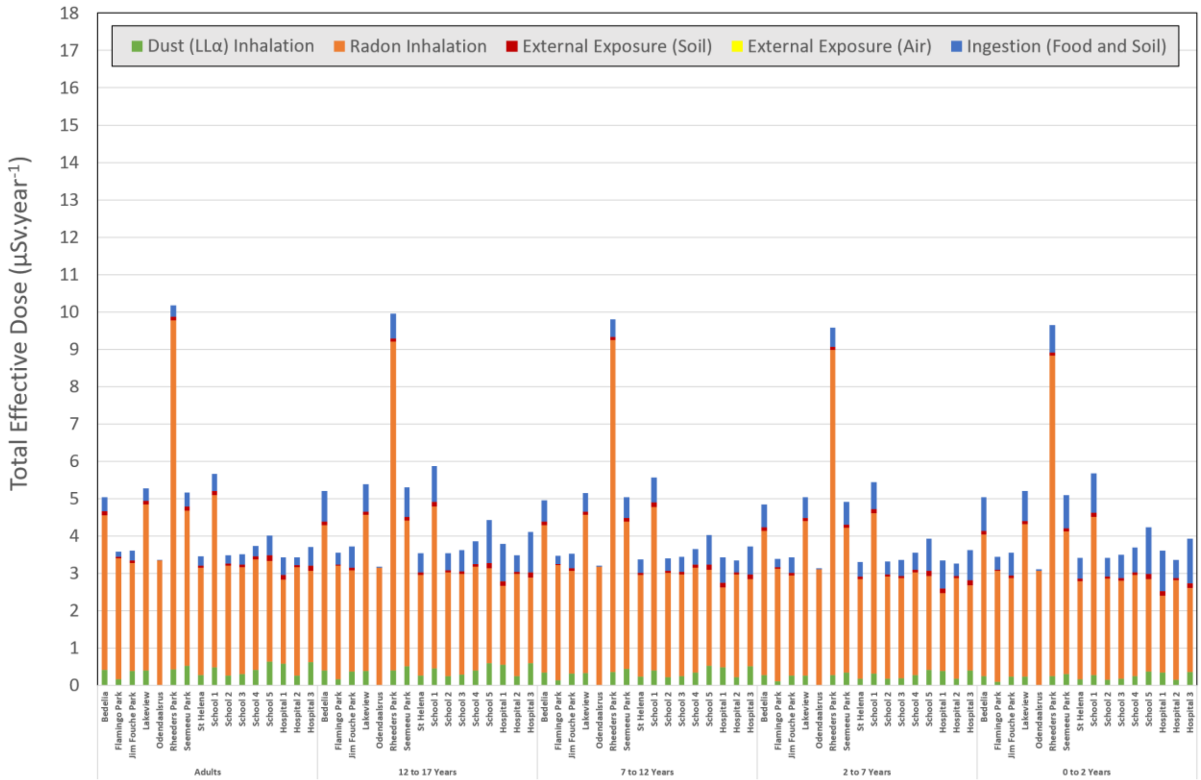

Figure 5.14 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the Valley TSF in addition to the baseline conditions (see Figure 5.9 to Figure 5.12 for locations).

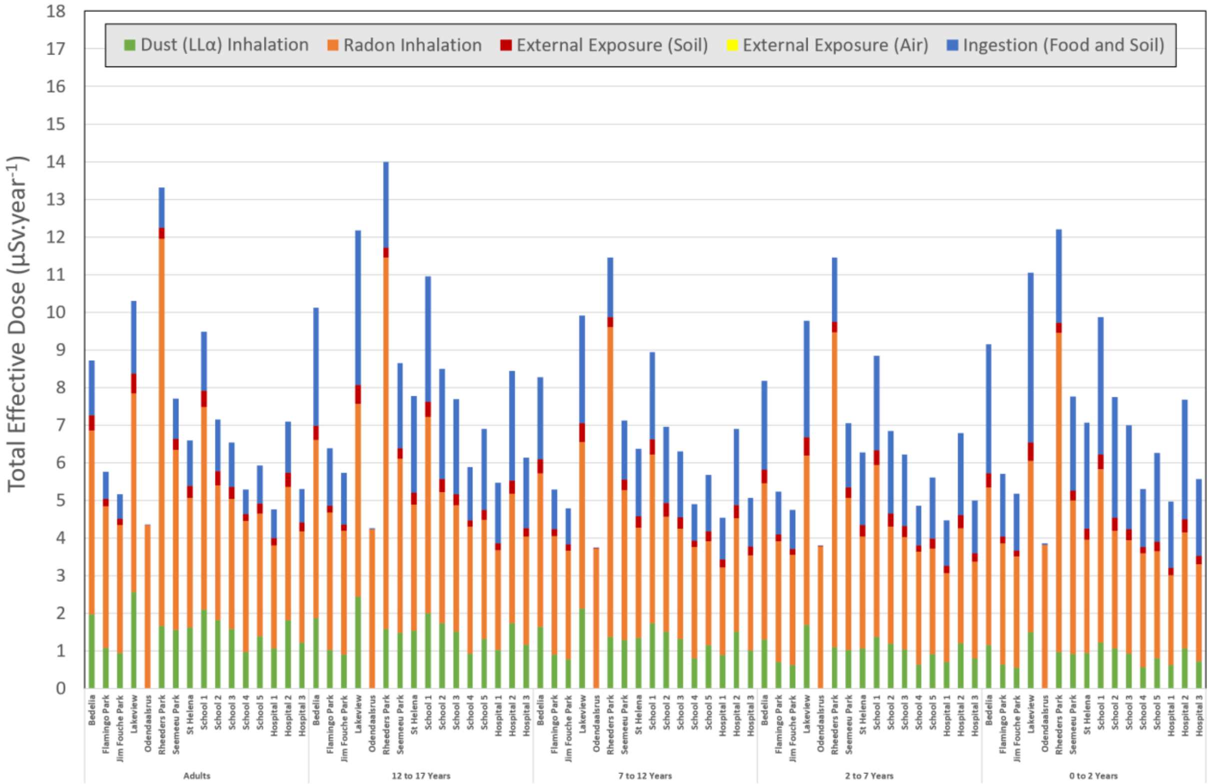

Figure 5.15 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the Nooitgedacht TSF in addition to the baseline conditions (see Figure 5.9 to Figure 5.12 for locations).

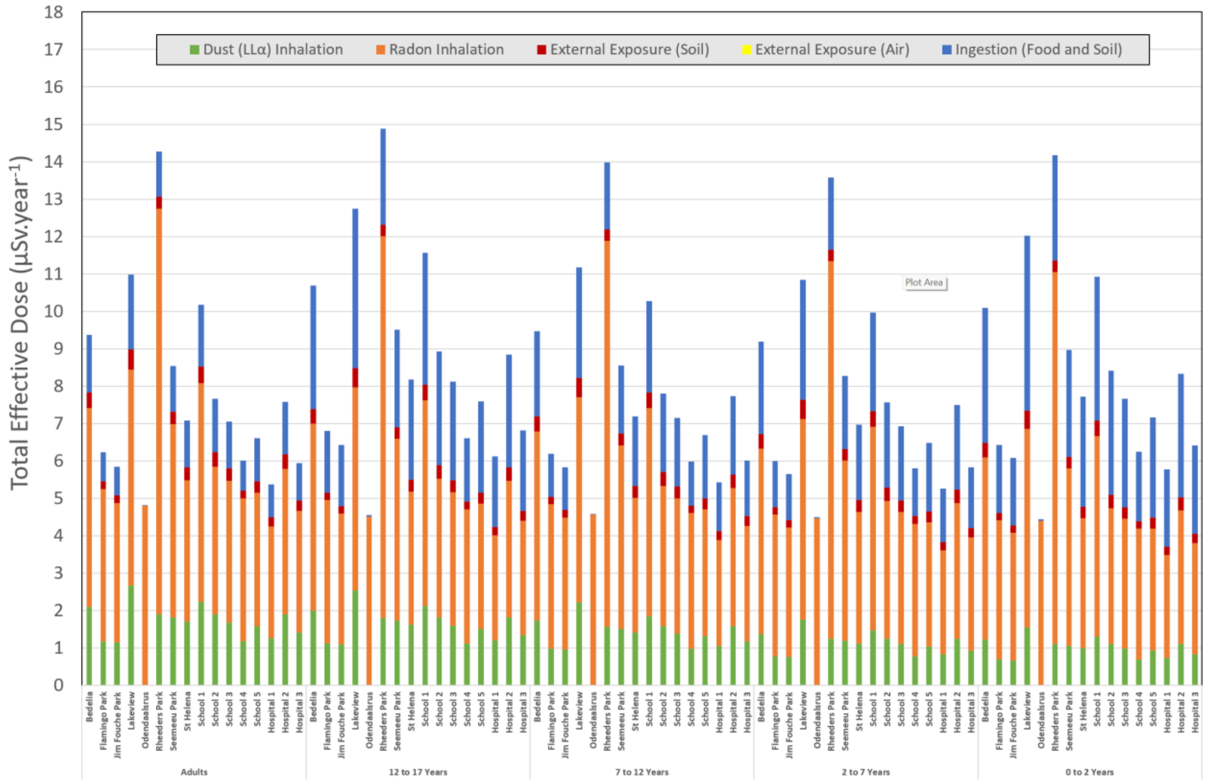

Figure 5.16 Total effective doses to different age groups at the Residential Area Exposure Condition receptor locations attributed to the Valley TSF and Nooitgedacht TSF in addition to the baseline conditions (see Figure 5.9 to Figure 5.12 for locations).

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

A dust deposition period of 75 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.

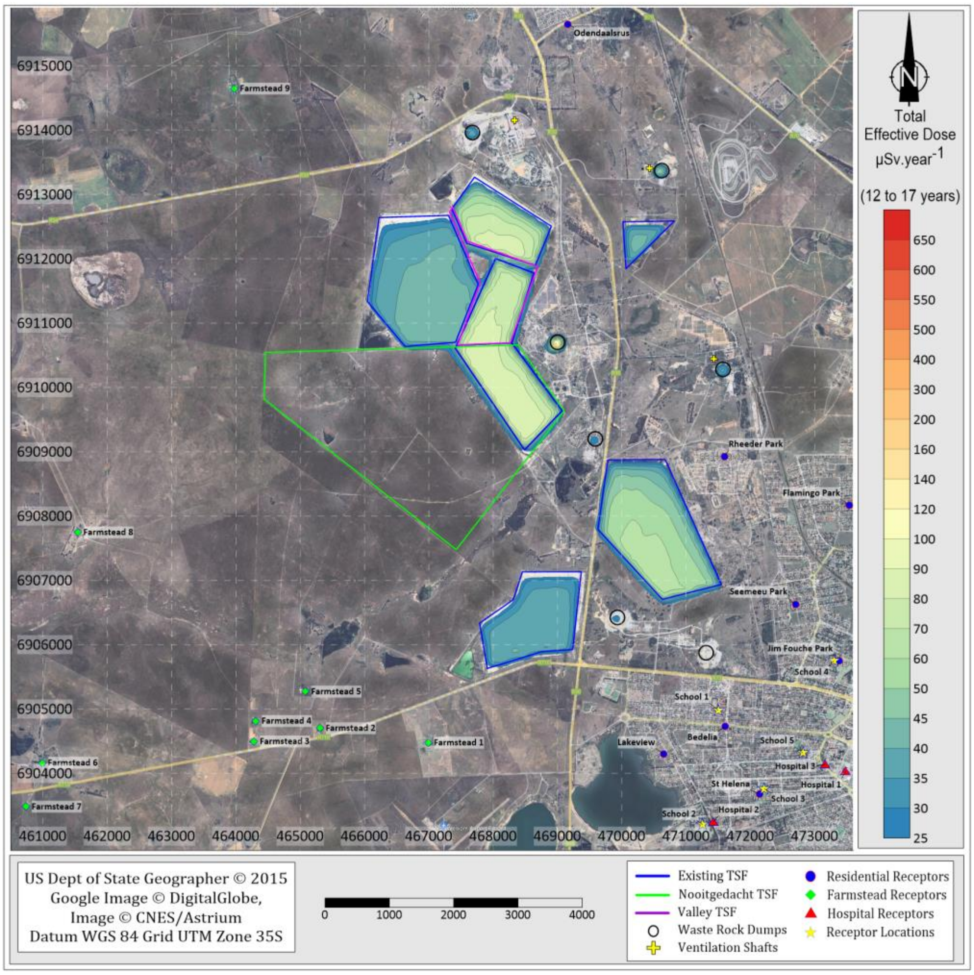

Figure 5.17 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the baseline conditions.

5.3.4.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Projects and surrounding area. Based on the dose estimate, the 12 to 17 years age group was shown to receive the highest total effective dose. The dose isopleths in Figure 5.17 represent the total effective dose for the age group 12 to 17 years for the baseline conditions. The maximum total effective dose at a distance of approximately 500 m from the TSF boundaries is in the order of 10 μSv.year^{-1} (see Figure 5.17).

Figure 5.18 and Figure 5.19 present the total effective dose for the age group 12 to 17 years attributed to the Valley TSF and the Nooitgedacht TSF, respectively, in addition to the Valley Baseline Conditions, while Figure 5.20 presents the total effective dose attributed to both the Valley TSF and the Nooitgedacht TSF in addition to the Valley Baseline Conditions.

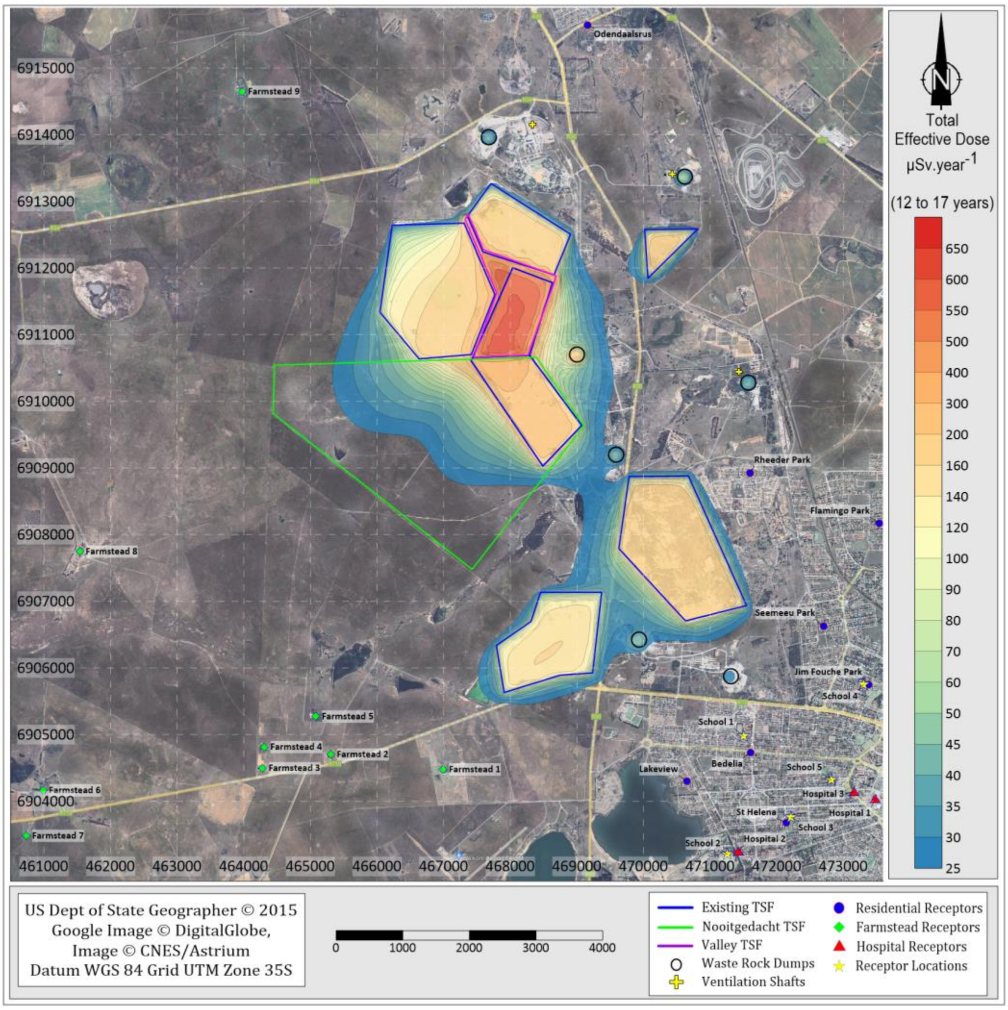

Figure 5.18 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the Valley TSF in addition to the baseline conditions.

The maximum total effective dose at a distance of approximately 500 m from the TSF boundaries for the Valley TSF in addition to the baseline conditions is in the order of 60 μSv.year^{-1}, (see Figure 5.18) which increases to about 110 μSv.year^{-1} 500 m from the Nooitgedacht TSF boundary (see Figure 5.19). For the

Valley TSF and Nooitgedacht TSF in addition to the baseline conditions, the total effective dose at a distance of approximately 500 m from the Nooitgedacht TSF boundary in a southwesterly direction increases to about 150 μSv.year^{-1} (see Figure 5.20).

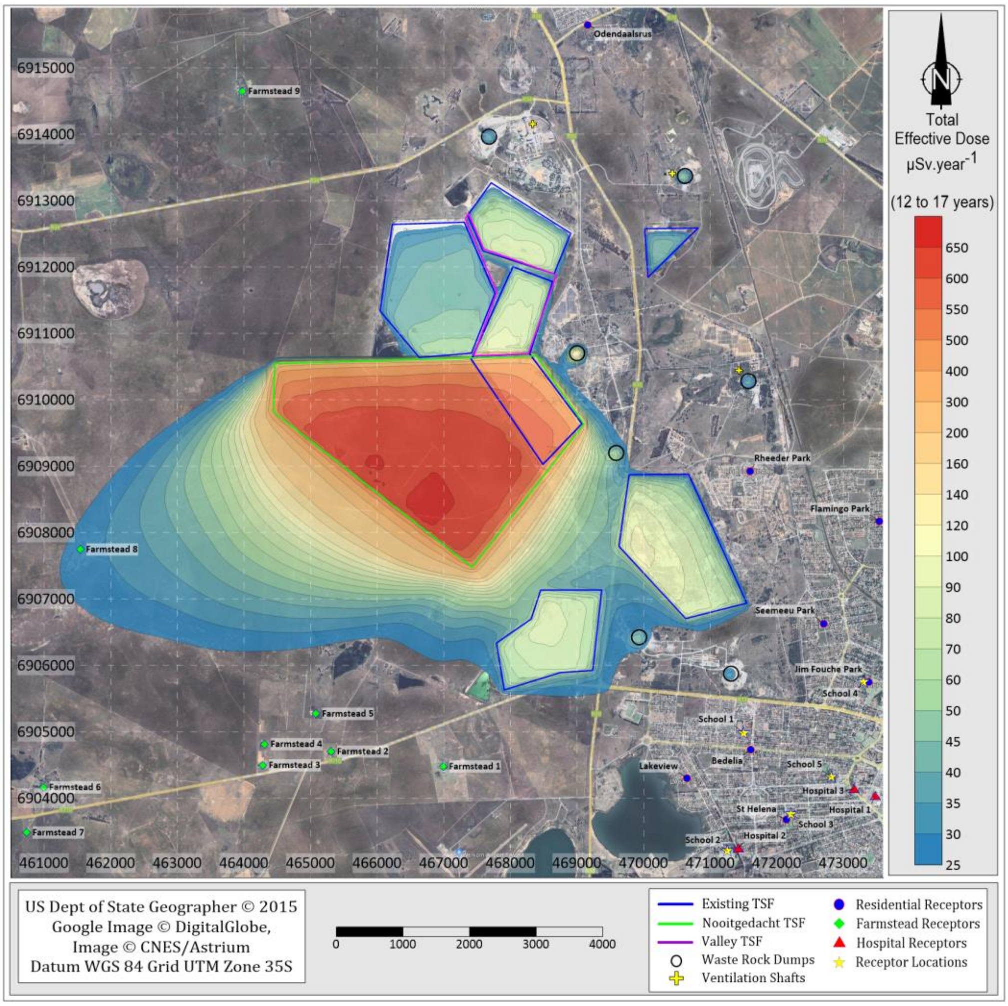

Figure 5.19 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of μSv.year^{-1}) of the Commercial Agricultural Exposure Condition attributed to the Nooitgedacht TSF in addition to the baseline conditions.

5.3.4.3 Interpretation of Results

The dose isopleth results presented in Figure 5.17 show that the effect of the baseline condition on potential agricultural areas is still minimal and does not reach these areas (in a southwesterly direction outside the Nooitgedacht TSF boundary) at doses more than 5 to10 μSv.year^{-1}. Figure 5.18 shows that the contribution of the proposed Valley TSF is also minimal and results in an increase of the total effective dose in the order of 10 μSv.year^{-1}. However, it still does not reach agricultural land in doses of more than 10 to 20 μSv.year^{-1}.

Figure 5.19 and Figure 5.20 show that the contribution of the proposed Nooitgedacht TSF is more significant, mainly because of the difference in physical dimensions between the two TSFs. However, the resulting total effective dose, even as a contribution of both TSFs, is still relatively low in agricultural areas (less than 40 μSv.year^{-1}).

To put the dose isopleth result into perspective, the total effective dose results at several farmstead receptor locations are presented in Figure 5.21 to Figure 5.24 (see Figure 5.17 to Figure 5.20 for locations). These locations correspond to the locations identified in the air quality impact assessment (Airshed, 2023). The results are for all the age group categories listed in Table B 1.

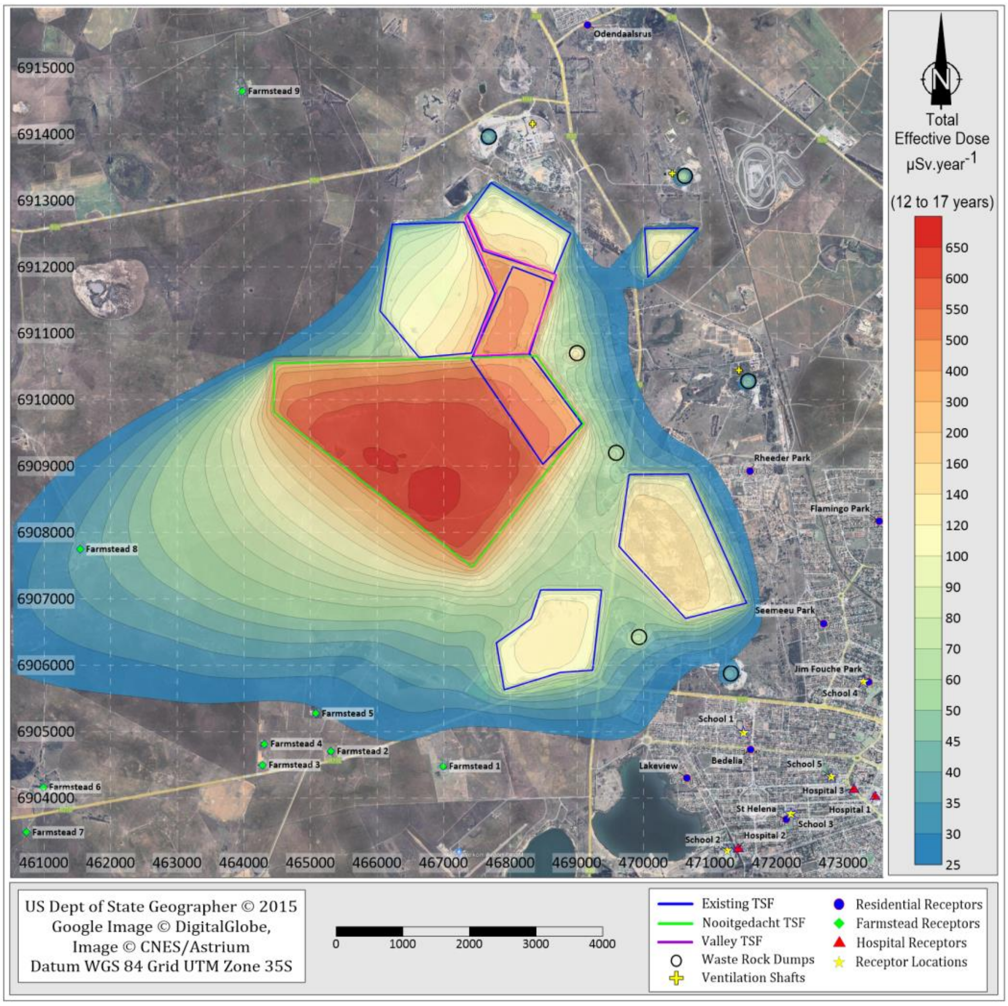

Figure 5.20 Dose isopleths representing the total effective dose (12 to 17 years age group, in units of $\mu Sv.year^{-1}$) of the Commercial Agricultural Exposure Condition attributed to the Valley TSF and Nooitgedacht TSF in addition to the baseline conditions.

The results suggest that at the selected locations for the Commercial Agricultural Exposure Condition, the total effective dose is still below 40 $\mu Sv.year^{-1}$. There is very little difference between the contribution under baseline conditions and the contribution from the Valley TSF. The contribution from the Nooitgedacht TSF is more significant but still results in total effective doses of less than 40 $\mu Sv.year^{-1}$.

Figure 5.21 to Figure 5.24 suggest that the main contributor to the total effective dose is from radon gas inhalation, with more significant contributions from dust inhalation, as well as soil, crop, and animal product ingestion as a result of releases from the Nooitgedacht TSF. External gamma radiation (product of cloud and ground shine) is insignificant. As expected with higher ingestion rates of crops and animal products, the contribution of the ingestion route is more significant than for the Residential Area Exposure Condition.

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, 2023).

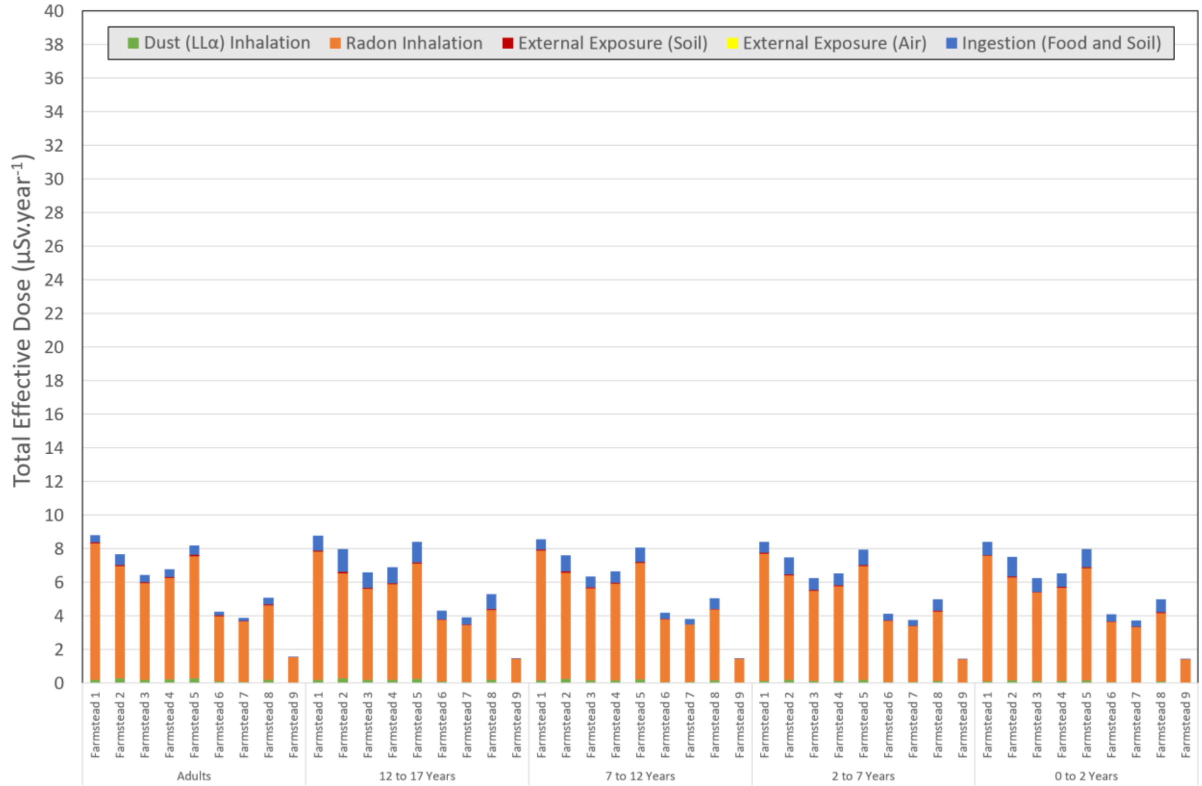

Figure 5.21 Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the baseline conditions (see Figure 5.17 to Figure 5.20 for locations).

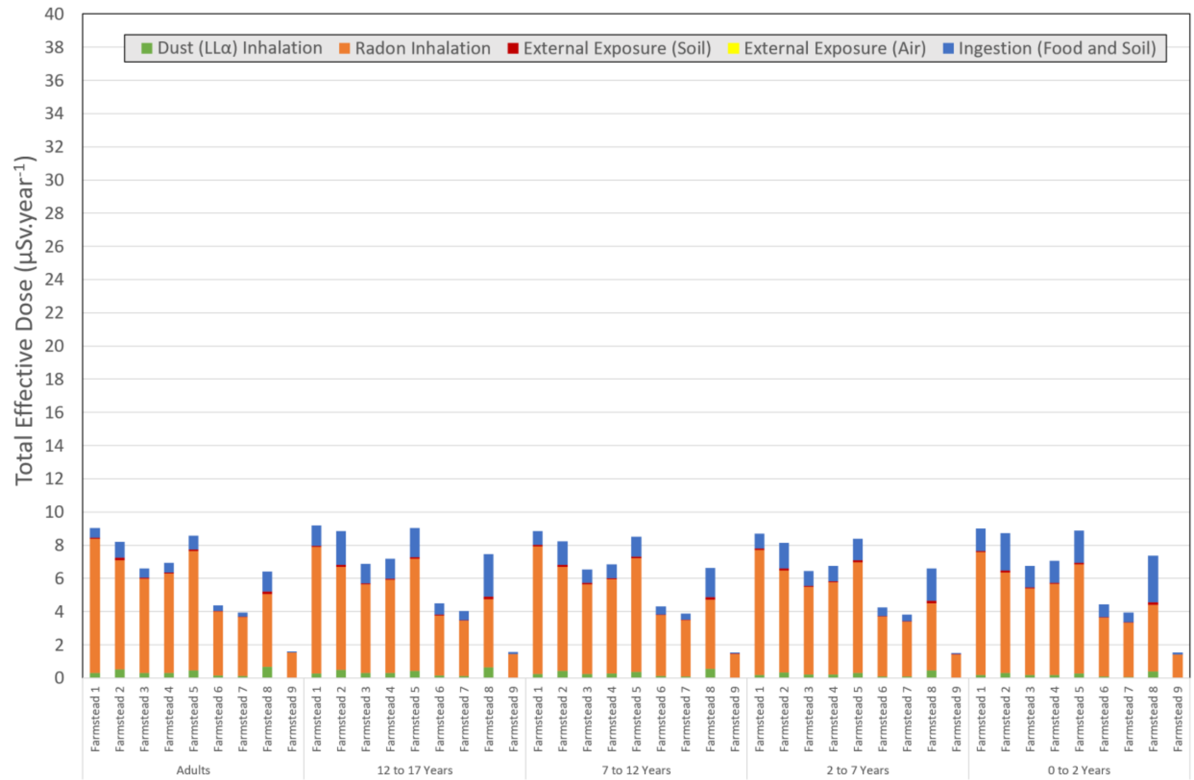

Figure 5.22 Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the Valley TSF in addition to the baseline conditions (see Figure 5.17 to Figure 5.20 for locations).

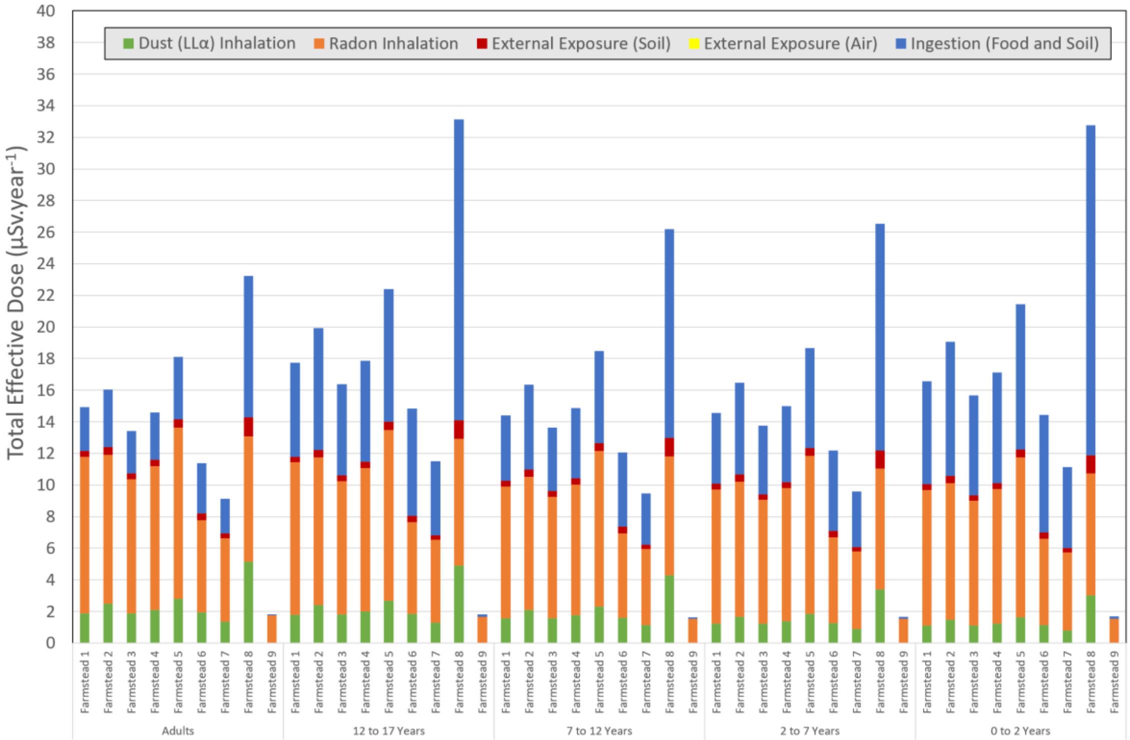

Figure 5.23 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the Nooitgedacht TSF in addition to the baseline conditions (see Figure 5.17 to Figure 5.20 for locations).**

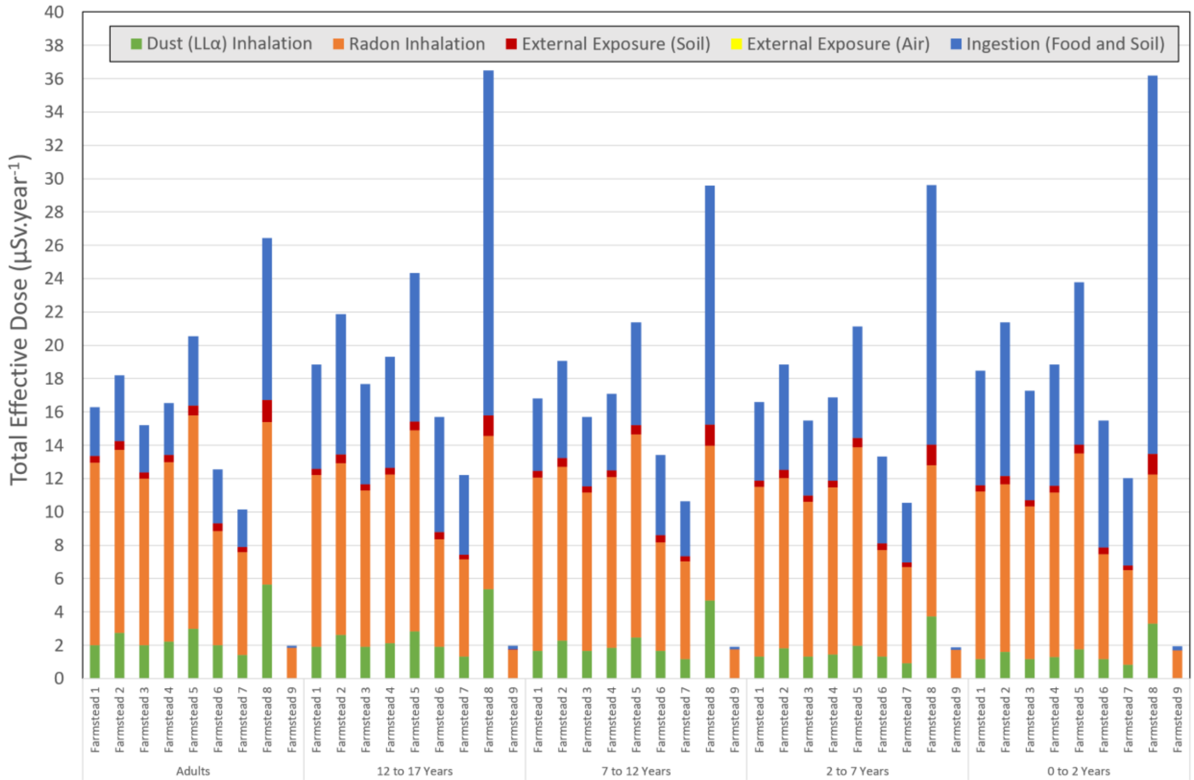

Figure 5.24 **Total effective doses to different age groups at the Commercial Agricultural Exposure Condition receptor locations attributed to the Valley TSF and Nooitgedacht TSF in addition to the baseline conditions (see Figure 5.17 to Figure 5.20 for locations).**

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 Projects. However, the inherent nature of a safety assessment for a mining and mineral processing operation is such that uncertainties exist, both in the conditions assumed and the parameter values used. It was from this perspective that the inexact nature of safety assessments was highlighted in the *Assessment Context* (see Section 2).

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

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 Projects. In Section 6.4, the variation in parameter values is discussed.

6.2 Cumulative Radiological Impact

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

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

All facilities and activities considered in this assessment are from CoR-5 of Harmony. It is outside the scope of this report to address the contribution from *all* other contributing facilities or operations areas. For a regional assessment that considers every contributing source from all applicable CoRs, the *dose limit* will be applicable, whereas for facility-specific assessments the *dose constraint* is more applicable, especially to address the issue of multiple contributions. However, the question may still be asked: "*Is there a possibility for a cumulative effect from multiple operations, and is there a reason for concern?*"

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

6.3 Variations in Public Exposure Conditions

6.3.1 General

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

6.3.2 Variation in the Defined Exposure Conditions

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

For example, members of the public who work at industries in the area may be subject to different exposure routes from those defined for the Projects. However, their exposure will be lower than that of the residents in the area because it is most likely limited to inhalation and external exposure and also for shorter periods. In addition, the Commercial Agricultural Exposure Condition is very conservative and assumes that the exposure group is dependent on the land for all its food. It is thus unlikely that any variation in exposure condition 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 condition defined and evaluated in the Projects was considered comprehensive and representative of a wide range of site-specific conditions. It was also argued that variations can be expected but that these variations will lead to a lower radiological impact than those considered in the assessment.

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

6.3.3.2 Tailings Spillage

Several factors determine the potential level of radiation exposure to members of the public, which makes it difficult or almost impossible to provide a general assessment, especially given the widespread and diverse nature of the Projects. 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 is;
- Where the spillage took place (i.e., open field or at or nearby surface water body or nearby residential area), how long the spillage lasted and the lateral extent (area) that was contaminated; and
- How long the potential contamination is left unintended before remedial action for the area is instituted and there is a possibility that members of the public have access to the contaminated area?

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

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

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

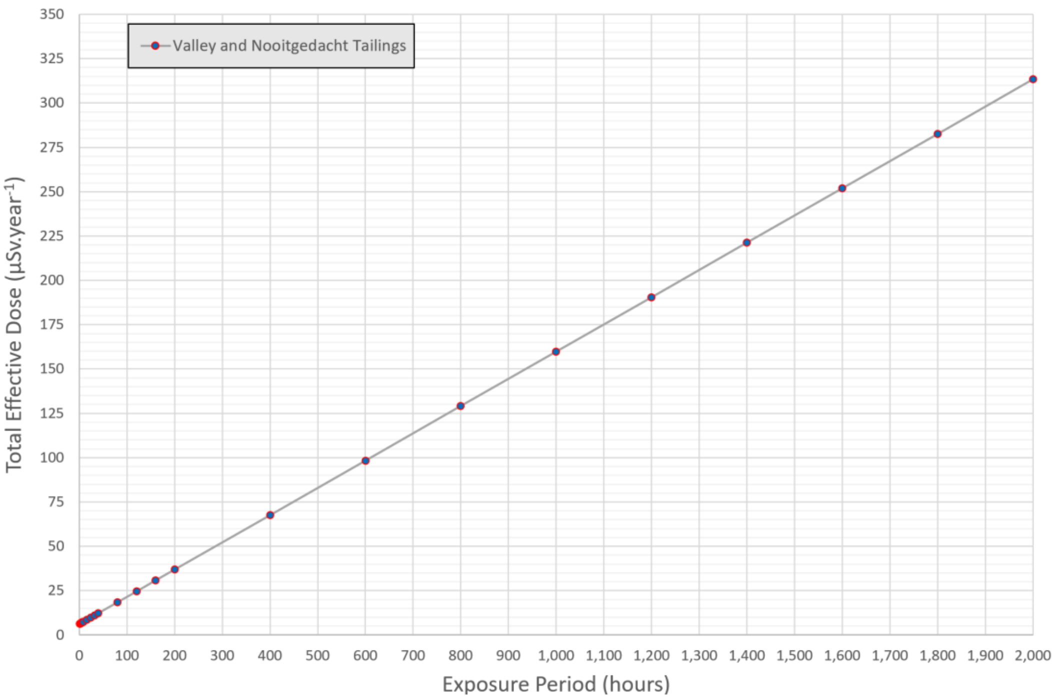

Figure 6.1 Total effective dose for the Projects tailings material as a function of the exposure period.

From Figure 6.1 it is clear that for the assumed Valley TSF and Nooitgedacht TSF tailings material, an exposure period of 2,000 hours will still result in a total effective dose of less than 150 µSv.year^{-1}.

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

6.3.3.3 Water Spillage

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

6.4 Variation in Parameter Values

6.4.1 Human Consumption Values

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

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

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

6.4.2 Dust Deposition Period

The dose calculations for the different exposure conditions were performed assuming a 75-year deposition period, which was assumed to be realistic given the history of the Projects. The dose assessment models assumed a build-up of activity on the soil surface over this period, which by implication influenced the total effective dose. One can thus assume that the surface soil concentration will continue to increase steadily with time.

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

7 Impact Assessment for the Proposed Valley TSF

7.1 General

The purpose of this section is to present the radiological impact assessment rating for the proposed valley TSF. Section 2.3.7.3 presented 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 Projects, as presented in Section 5.

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

The section is structured as follows. Section 7.2 presents the radiological impact expected during the construction phase. The most significant radiological impact is expected during the operational phase, as presented in Section 7.3, followed by the post-closure phase presented in Section 7.4. Section 7.5 discusses any cumulative impact that might be of concern.

7.2 Construction Phase

The proposed Valley TSF is a new facility and infrastructure (e.g., TSF, RWD, and topsoil stockpiles). To establish this infrastructure, some construction work will be necessary, including site clearance and footprint preparation for the TSF extension areas and the construction or upgrade of access roads.

Activities performed in these areas during the construction phase will not induce a potential radiological impact on members of the public since the activities do not involve the handling, processing, or releasing of radioactive material to the environment *per se*. This means that the potential radiological impact on members of the public through the relevant pathway during the construction phase is negligible.

7.3 Operational Phase

7.3.1 General

The radiological impact assessment for the operational phase considers the potential contribution through all three environmental pathways (i.e., surface water, groundwater and atmospheric). However, due to the slow-moving nature of any radionuclide contaminant plume that originates from the facilities through the groundwater system, the potential radiological impact through the groundwater pathway will only occur during the post-closure (see Section 7.4).

7.3.2 Activities

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

- Emission and dispersion of particulate matter containing radionuclides from the existing and proposed TSFs; and

- Exhalation and dispersion of radon gas from the existing and proposed Valley TSF.

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

Table 7.1 Summary of the activities and the impact of the activities during the operational phase of the proposed Valley 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. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion, and external radiation exposure routes

7.3.3 Exhalation and Dispersion of Radon Gases

7.3.3.1 Impact Description

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

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

7.3.3.2 Management/Mitigation Measures

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

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

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

7.3.3.3 Impact Rating

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

Table 7.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the proposed Valley TSF.

<table>
<tr><th>Dimensions</th><th>Score</th><th>Motivation</th><th>Environmental Risk</th><th>Priority Factor</th><th>Final score</th></tr>
<tr><td>Impact</td><td colspan="5">Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the proposed Valley TSF</td></tr>
<tr><td colspan="5">Pre-Mitigation</td><td rowspan="20">-2.75</td></tr>
<tr><td>Nature</td><td>-1</td><td>Likely to result in a negative impact</td><td rowspan="6">-5.5</td><td rowspan="6"></td></tr>
<tr><td>Extent</td><td>2</td><td>The extent of potential impact for the Valley TSF is limited to the site (i.e., within the development property boundary)</td></tr>
<tr><td>Duration</td><td>5</td><td>The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface</td></tr>
<tr><td>Magnitude</td><td>1</td><td>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}</td></tr>
<tr><td>Reversibility</td><td>3</td><td>The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF</td></tr>
<tr><td>Probability</td><td>2</td><td>There is a low probability that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}</td></tr>
<tr><td colspan="5">Post Mitigation</td></tr>
<tr><td>Nature</td><td>-1</td><td>Likely to result in a negative impact</td><td rowspan="6">-2.75</td><td rowspan="6"></td></tr>
<tr><td>Extent</td><td>2</td><td>The extent of potential impact for the Valley TSF is limited to the site (i.e., within the development property boundary)</td></tr>
<tr><td>Duration</td><td>5</td><td>The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface</td></tr>
<tr><td>Magnitude</td><td>1</td><td>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}</td></tr>
<tr><td>Reversibility</td><td>3</td><td>The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF</td></tr>
<tr><td>Probability</td><td>1</td><td>It is improbable that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}</td></tr>
<tr><td colspan="5">Priority Factor Criteria</td></tr>
<tr><td>Confidence</td><td>High</td><td>There is a high level of confidence in the impact prediction</td><td rowspan="3"></td><td rowspan="3">1</td></tr>
<tr><td>Cumulative Impact</td><td>1</td><td>It is unlikely that the impact will result in spatial and temporal cumulative change</td></tr>
<tr><td>Irreplaceable loss</td><td>1</td><td>It is unlikely that the impact will result in an irreplaceable loss of resources</td></tr>
</table>

7.3.4 Emission and Dispersion of Particulate Matter

7.3.4.1 Impact Description

During the operational phase, the TSF areas will wind erosion will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere for the duration of the operational period. These particulate matter containing radionuclides are dispersed into the environment through the atmospheric pathways.

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

7.3.4.2 Management/Mitigation Measures

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

The contribution of dust inhalation is less than 10% (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 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 external gamma radiation. The contribution of animal and crop ingestion is less than 15% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for the ingestion pathways.

In addition, the total effective dose at the same locations is less than 5% (on average) of the dose constraint of 250 $\mu Sv.year^{-1}$ for public exposure.

From a dose optimisation perspective, the following mitigation measures can be applied. These measures, which are in line with the measures proposed in the air quality impact assessment (Airshed, 2023), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Develop an air quality management plan for the proposed Valley 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.

7.3.4.3 Impact Rating

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

7.4 Post-Closure Phase

7.4.1 General

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

7.4.2 Activities

Considering that a decommissioning plan of the proposed Valley TSF is not available at present but will be defined and implemented as mentioned in Section 7.4.1, the following activities were identified that may result in a radiological impact on the receptors during the post-closure phase:

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

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

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

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

7.4.3 Implementation of the Decommissioning Plan

7.4.3.1 Impact Description

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

A gamma radiation survey supplemented with full-spectrum radioanalysis of soil samples will be performed at the infrastructure sites, followed by appropriate rehabilitation and clean-up operations for conditional or unconditional clearance from the regulatory authority. In addition, any area that may have become contaminated during or because of operational activities will also be rehabilitation and clean-up for conditional or unconditional clearance.

Table 7.4 Summary of the activities and the impact of the activities during the post-closure phase of the proposed Valley TSF.

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

7.4.3.2 Impact Rating

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

7.4.4 Exhalation of Radon Gas and Particulate Matter

7.4.4.1 Impact Description

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

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

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

Table 7.5 Impact significant rating for the implementation of the decommissioning plan of the proposed Valley TSF.

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

7.4.4.2 Management/Mitigation Measures

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

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

From a dose optimisation perspective, the following mitigation measures that are in line with the measures proposed by the air quality impact assessment (Airshed, 2023) 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.

7.4.4.3 Impact Rating

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

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

<table>
<tr><th>Dimensions</th><th>Score</th><th>Motivation</th><th>Environmental Risk</th><th>Priority Factor</th><th>Final score</th></tr>
<tr><td>Impact</td><td colspan="5">Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Valley TSF</td></tr>
<tr><td colspan="5">Pre-Mitigation</td><td rowspan="15">-2.5</td></tr>
<tr><td>Nature</td><td>-1</td><td>Likely to result in a negative impact</td><td rowspan="6">-5</td><td rowspan="6"></td></tr>
<tr><td>Extent</td><td>2</td><td>The extent of potential impact for the Valley TSF is limited to the site (i.e., within the development property boundary)</td></tr>
<tr><td>Duration</td><td>5</td><td>The impact will occur for as long as the TSF is at the surface</td></tr>
<tr><td>Magnitude</td><td>1</td><td>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 $\mu Sv.year^{-1}$</td></tr>
<tr><td>Reversibility</td><td>2</td><td>The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF</td></tr>
<tr><td>Probability</td><td>2</td><td>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 $\mu Sv.year^{-1}$</td></tr>
<tr><td colspan="5">Post Mitigation</td></tr>
<tr><td>Nature</td><td>-1</td><td>Likely to result in a negative impact</td><td rowspan="6">-2.5</td><td rowspan="6"></td></tr>
<tr><td>Extent</td><td>2</td><td>The extent of potential impact for the Valley TSF is limited to the site (i.e., within the development property boundary)</td></tr>
<tr><td>Duration</td><td>5</td><td>The impact will occur for the duration of the operational phase and thereafter for as long as the TSF is at the surface</td></tr>
<tr><td>Magnitude</td><td>1</td><td>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 $\mu Sv.year^{-1}$</td></tr>
<tr><td>Reversibility</td><td>2</td><td>The impact is reversible without incurring significant time and cost to reduce the wind erosion from the TSF</td></tr>
<tr><td>Probability</td><td>1</td><td>It is improbable that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the</td></tr>
</table>

		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			

7.4.5 Leaching and Migration of Contaminants from the Proposed Valley TSF

7.4.5.1 Impact Description

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

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

7.4.5.2 Management/Mitigation Measures

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

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

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

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

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

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

7.5 Cumulative Impact

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

Firstly, the radiological safety assessment process considers the cumulative contribution from all relevant exposure pathways including the surface water, groundwater, and atmospheric pathways, as appropriate.

This means that the radiological impact assessment includes the cumulative impact of the exposure pathways, as appropriate and justified.

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

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

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

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

Finally, on a more regional scale, the assessment context makes provision for a cumulative impact from all contributing operations (or practices) in the area that may contribute to the total effective dose to members of the public. This is important since the public dose limit of 1,000 $\mu Sv.year^{-1}$ is from all contributing sources and operations. However, as stated in Section 2.3.4.5, the scope of the assessment was limited to the Projects and did not make provision for a regional assessment to evaluate cumulative effects from all contributing operations.

8 Impact Assessment for the Proposed Nooitgedacht TSF

8.1 General

The purpose of this section is to present the radiological impact assessment rating for the proposed Nooitgedacht TSF. Section 2.3.7.3 presented 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 Projects, as presented in Section 5.

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

The section is structured as follows. Section 7.2 presents the radiological impact expected during the construction phase. The most significant radiological impact is expected during the operational phase, as presented in Section 7.3, followed by the post-closure phase presented in Section 7.4. Section 7.5 discusses any cumulative impact that might be of concern.

8.2 Construction Phase

The proposed Nooitgedacht TSF is a new facility and infrastructure (e.g., TSF, RWD, and topsoil stockpiles). To establish this infrastructure, some construction work will be necessary, including site clearance and footprint preparation for the TSF extension areas and the construction or upgrade of access roads.

Activities performed in these areas during the construction phase will not induce a potential radiological impact on members of the public since the activities do not involve the handling, processing, or releasing of radioactive material to the environment *per se*. This means that the potential radiological impact on members of the public through the relevant pathway during the construction phase is negligible.

8.3 Operational Phase

8.3.1 General

The radiological impact assessment for the operational phase considers the potential contribution through all three environmental pathways (i.e., surface water, groundwater and atmospheric). However, due to the slow-moving nature of any radionuclide contaminant plume that originates from the facilities through the groundwater system, the potential radiological impact through the groundwater pathway will only occur during the post-closure (see Section 7.4).

8.3.2 Activities

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

- Emission and dispersion of particulate matter containing radionuclides from the existing and proposed TSFs; and

- Exhalation and dispersion of radon gas from the existing and proposed Nooitgedacht TSF.

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

Table 8.1 Summary of the activities and the impact of the activities during the operational phase of the proposed Nooitgedacht 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. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion, and external radiation exposure routes

8.3.3 Exhalation and Dispersion of Radon Gases

8.3.3.1 Impact Description

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

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

8.3.3.2 Management/Mitigation Measures

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

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

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

8.3.3.3 Impact Rating

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

Table 8.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the proposed Nooitgedacht TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the proposed Nooitgedacht TSF				
Pre-Mitigation					-3.25
Nature	-1	Likely to result in a negative impact	-6.5		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF			
Probability	2	There is a low probability that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-3.25		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. The contribution of radon inhalation to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	3	The impact is reversible by incurring significant time and cost to reduce the radon exhalation rate from the TSF			
Probability	1	It is improbable that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources			

8.3.4 Emission and Dispersion of Particulate Matter

8.3.4.1 Impact Description

During the operational phase, the TSF areas will wind erosion will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere for the duration of the operational period. These particulate matter containing radionuclides are dispersed into the environment through the atmospheric pathways.

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

8.3.4.2 Management/Mitigation Measures

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

The contribution of dust inhalation is less than 10% (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 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 external gamma radiation. The contribution of animal and crop ingestion is less than 15% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for the ingestion pathways.

In addition, the total effective dose at the same locations is less than 5% (on average) of the dose constraint of 250 $\mu Sv.year^{-1}$ for public exposure.

From a dose optimisation perspective, the following mitigation measures can be applied. These measures, which are in line with the measures proposed in the air quality impact assessment (Airshed, 2023), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Develop an air quality management plan for the proposed Nooitgedacht 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.

8.3.4.3 Impact Rating

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

8.4 Post-Closure Phase

8.4.1 General

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

8.4.2 Activities

Considering that a decommissioning plan of the proposed Nooitgedacht TSF is not available at present but will be defined and implemented as mentioned in Section 7.4.1, the following activities were identified that may result in a radiological impact on the receptors during the post-closure phase:

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

- Leaching and migration of radionuclides from the remaining facilities (e.g., TSF).

Table 8.3 Impact significant rating for the particulate matter emission and dispersion that contains radionuclides during the operational phase of the proposed Nooitgedacht TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the proposed Nooitgedacht TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. 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}	-6		
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	2	There is a low probability that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			-3
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	2	Low. 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}	-3		
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	1	It is improbable that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction			
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			

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

8.4.3 Implementation of the Decommissioning Plan

8.4.3.1 Impact Description

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

A gamma radiation survey supplemented with full-spectrum radioanalysis of soil samples will be performed at the infrastructure sites, followed by appropriate rehabilitation and clean-up operations for conditional or unconditional clearance from the regulatory authority. In addition, any area that may have become contaminated during or because of operational activities will also be rehabilitation and clean-up for conditional or unconditional clearance.

Table 8.4 Summary of the activities and the impact of the activities during the post-closure phase of the proposed Nooitgedacht TSF.

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

8.4.3.2 Impact Rating

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

8.4.4 Exhalation of Radon Gas and Particulate Matter

8.4.4.1 Impact Description

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

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

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

Table 8.5 Impact significant rating for the implementation of the decommissioning plan of the proposed Nooitgedacht TSF.

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

8.4.4.2 Management/Mitigation Measures

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

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

From a dose optimisation perspective, the following mitigation measures that are in line with the measures proposed by the air quality impact assessment (Airshed, 2023) 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.

8.4.4.3 Impact Rating

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

Table 8.6 Impact significant rating for the exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Nooitgedacht TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the proposed Nooitgedacht TSF				
Pre-Mitigation					-2.5
Nature	-1	Likely to result in a negative impact	-6		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	2	Low. The contribution of dust and radon gas inhalation, as well as the dust deposition (and the subsequent secondary pathway) to the total effective dose, is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	2	There is a low probability that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-2.5		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. The contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) to the total effective dose is significantly lower than the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Reversibility	2	The impact is reversible without incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	1	It is improbable that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction		1	
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources			

8.4.5 Leaching and Migration of Contaminants from the Proposed Nooitgedacht TSF

8.4.5.1 Impact Description

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

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

8.4.5.2 Management/Mitigation Measures

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

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

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

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

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

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

8.5 Cumulative Impact

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

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

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

Table 8.7 Impact significant rating for the leaching and migration of radionuclides from the TSF during the post-closure phase of the proposed Nooitgedacht TSF.

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

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

Finally, on a more regional scale, the assessment context makes provision for a cumulative impact from all contributing operations (or practices) in the area that may contribute to the total effective dose to members of the public. This is important since the public dose limit of 1,000 µSv.year^{-1} is from all contributing sources and operations. However, as stated in Section 2.3.4.5, the scope of the assessment was limited to the Projects and did not make provision for a regional assessment to evaluate cumulative effects from all contributing operations.

9 Radiation Monitoring Programme

9.1 General

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

The purpose of this section is to define a radiation monitoring programme for the Projects. 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 9.2 discusses the characterisation of the baseline conditions associated with the Projects. Section 9.3 presents the proposed monitoring programme, while Section 9.4 presents the proposed monitoring locations.

9.2 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 Projects. No baseline characterisation has been done in the Projects area yet. It should include, to the extent possible, soil, surface water and groundwater samples, as well as an airborne environmental radon survey in the area using RGMs.

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

9.3 Monitoring Programme

The Projects TSFs fall within the scope of CoR-5 with an approved public Radiation Protection Programme (RPP), which makes provision for environmental monitoring and analysis to ensure that members of the public are sufficiently protection from releases into the environment. The responsibility for the implementation and execution of the monitoring programme lies with the Radiation Protection Function (RP Function) which may include legally appointed persons consisting of a Radiation Protection Monitor(s) (RPM), a Radiation Protection Officer (RPO), and a Radiation Protection Specialist (RPS).

Table 9.1 summarises the proposed monitoring programme for the Projects aimed at public radiation protection.

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

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

Table 9.1 Summary of the environmental monitoring programme proposed for the Projects aimed at public radiation protection.

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

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

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

9.4 Proposed Monitoring Points

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

- The surface water monitoring locations should coincide with the existing surface water monitoring points currently included in the public RPP. The principle to be applied is that the monitoring locations should be upstream and downstream of the Projects area in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the existing groundwater monitoring points. The principle to be applied is that the monitoring locations should be upstream and downstream of the Projects 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 (2023).
- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

10 Conclusions and Recommendations

10.1 General

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

The section is structured as follows. Section 10.2 presents some general conclusions as derived from the radiological impact assessment results, while Section 10.3 presents recommendations for the improvement of the radiological public safety and impact assessment.

10.2 Conclusions

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

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

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

- The most significant contribution from the atmospheric pathway is from the inhalation of airborne radon gas. This is due to the presence of Ra-226 in the source material.
- The contribution from the groundwater pathway was evaluated with the Projects TSFs as the main contributing source. It was illustrated that the potential radiological impact is only visible in thousands of years at maximum total effective doses of less than 200 µSv.year-1, which means that it cannot be considered as a contributing pathway for the Commercial Agricultural Exposure Condition during the operational phase of the Projects;
- 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 Projects. The results show that notwithstanding the proximity of the receptor locations to the surface infrastructure, the doses are still less than the dose constraint for all age groups, with a maximum contribution of less than 40 µSv.year^{-1} from the atmospheric pathway.

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

These total effective dose assessment results were used to derive the radiological impact rating during the different phases of the Projects. Table 10.1 summarises the radiological impact significant rating for the operational phase of the Valley TSF, while Table 10.2 summarises the radiological impact significant rating for the post-closure phase of the proposed Valley TSF. Table 10.3 summarises the radiological impact significant rating for the operational phase of the Nooitgedacht TSF, while Table 10.4 summarises the radiological impact significant rating for the post-closure phase of the proposed Nooitgedacht TSF.

10.3 Recommendations

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

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

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

- The surface water monitoring locations should coincide with the existing surface water monitoring points currently included in the public RPP. The principle to be applied is that the monitoring locations should be upstream and downstream of the Projects area in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the existing groundwater monitoring points. The principle to be applied is that the monitoring locations should be upstream and downstream of the Projects 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 (2023).

- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

Table 10.1 Summary of the radiological impact significant rating for the operational phase of the proposed Valley TSF.

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

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

Table 10.2 Summary of the radiological impact significant rating for the post-closure phase of the proposed Valley TSF.

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

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

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
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 the migration of radionuclides from the TSF into the environment			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
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 10.3 Summary of the radiological impact significant rating for the operational phase of the proposed Nooitgedacht TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the proposed Nooitgedacht TSF				
Pre-Mitigation					-3.25
Nature	-1	Likely to result in a negative impact	-6.5		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. The contribution of radon inhalation to 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 by incurring significant time and cost to reduce the radon exhalation rate from the TSF			
Probability	2	There is a low probability that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
Post Mitigation					
Nature	-1	Likely to result in a negative impact	-3.25		
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. The contribution of radon inhalation to 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 by incurring significant time and cost to reduce the radon exhalation rate from the TSF			
Probability	1	It is improbable that the radon inhalation dose will be above the regulatory compliance criteria (dose constraint) of 250 $\mu Sv.year^{-1}$			
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			
Dimensions	Score	Motivation			
Impact	Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the proposed Nooitgedacht TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. 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}	-6		
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	2	There is a low probability that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			-3
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	2	Low. 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}	-3		
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	1	It is improbable that the contribution of dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction			
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			

Table 10.4 Summary of the radiological impact significant rating for the post-closure phase of the proposed Nooitgedacht TSF.

Dimensions	Score	Motivation	Environmental Risk	Priority Factor	Final score
Impact	Implementation of the NNR-approved decommissioning plan of the proposed Nooitgedacht TSF				
Pre-Mitigation					
Nature	1	Likely to result in a positive impact			
Extent	2	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within the development property boundary)	16		16
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after closure			

Magnitude	4	The impact on members of the public will be high and widespread			
Reversibility	5	The implementation of a good decommissioning plan is irreversible			
Probability	4	There is a low probability that the secondary pathway induced by wind erosion will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	1	Likely to result in a positive impact			
Extent	2	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within the development property boundary)			
Duration	5	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after closure	-2.5		
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			
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 proposed Nooitgedacht TSF				
Pre-Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
Duration	5	The impact will occur for as long as the TSF is at the surface			
Magnitude	2	Low. 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}	-6		
Reversibility	2	The impact is reversible by incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	2	There is a low probability that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact			-2.5
Extent	3	The extent of potential impact for the Nooitgedacht TSF is limited to the site (i.e., within 5 km of the site)			
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	2	Low. 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 without incurring significant time and cost to reduce the wind erosion from the TSF			
Probability	1	It is improbable that the contribution of radon inhalation, dust inhalation and dust deposition (and the subsequent secondary pathway) will be above the regulatory compliance criteria (dose constraint) of 250 μSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact		1	

		prediction			
Cumulative Impact	1	It is unlikely that the impact will result in spatial and temporal cumulative change			
Irreplaceable loss	1	It is unlikely that the impact will result in an irreplaceable loss of resources			
Impact	Leaching and migration of radionuclides from the TSF during the post-closure phase of the proposed Nooitgedacht 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			
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	3	The impact is reversible only by incurring significant time and cost to reduce the migration of radionuclides from the TSF into the environment			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Post Mitigation					
Nature	-1	Likely to result in a negative impact			
Extent	3	Exposure extent beyond the mining rights area into the immediate surroundings with agricultural land use conditions in the direction of flow			-6
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 the migration of radionuclides from the TSF into the environment			
Probability	2	There is a low probability that the contribution of radionuclides released from the TSF into the environment will be above the regulatory compliance criteria (dose constraint) of 250 µSv.year^{-1}			
Priority Factor Criteria					
Confidence	High	There is a high level of confidence in the impact prediction			
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			

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APPENDIX A: RADIONUCLIDE AND ELEMENT-DEPENDENT DATA

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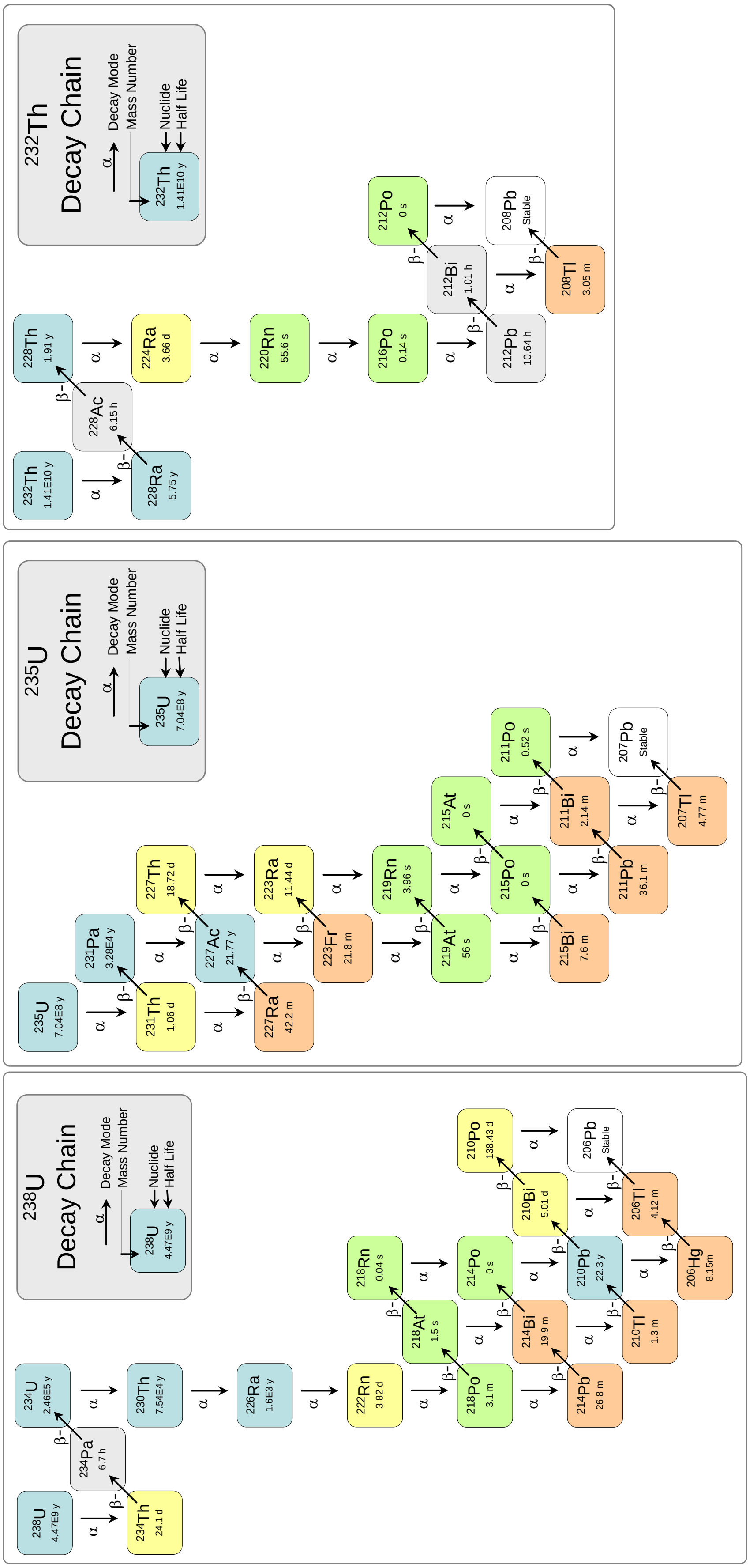

Figure A 1 **Schematic illustrations of the U-238, U-235, and Th-232 decay chains.**

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

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

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

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

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

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

APPENDIX B: METHODOLOGICAL APPROACH TO DOSE CALCULATION

Dose Conversion Factors

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

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

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

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

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, 2013b).

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

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

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

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

Inhalation Exposure (LLα, Radon and Thoron)

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

Equation 1

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

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

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

Equation 2

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

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

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

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

Parameter	Indoors	Outdoors	At Work	Unit
Dose Coefficient (UNSCEAR)[4]	9.00E-06			(mSv.hour^{-1}) per (Bq.m^{-3})
1 Conversion Coefficient = Ratio of PAEC (Potential Alpha Energy Concentration) and EEC (Equilibrium Equivalent Concentration) of Radon 2 Annual exposure per unit radon concentration = 5.56E-06 x 0.4 x 7,000 3 Annual dose conversion factor = 1.56E-02 x 1.1 4 EEC of Radon				

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

Equation 3

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

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

Equation 4

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

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

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

Equation 5

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

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

Ingestion Exposure

Ingestion Rates

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

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

Water Ingestion

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

Equation 6

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

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

Inadvertent Ingestion of Contaminated Soil

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

Equation 7

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

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

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

Ingestion of Contaminated Crops

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

Equation 8

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

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

Equation 9

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

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

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

Ingestion of Contaminated Animal Products

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

Equation 10

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

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

Equation 11

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

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

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

Equation 12

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

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

Equation 13

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

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

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

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

Equation 14

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

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 $\mathbf{Ing}_{past}$ is the consumption rate of pasture by the animals (kg.day^{-1} fresh weight of pasture).

External Gamma Irradiation: Air

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

Equation 15

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

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

External Gamma Irradiation: Soil

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

Equation 16

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

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

External Gamma Irradiation: Water

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

Equation 17

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

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

Time-Dependent Soil Concentration

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

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

Equation 18

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

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

Equation 19

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

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

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

Equation 20

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

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

Equation 21

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

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

Equation 22

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

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

Equation 23

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

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

Equation 24

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

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

Equation 25

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

$\lambda_{Leach,RZ}$ (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 is calculated using the differential equation:

Equation 31

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

Calculation of the Airborne Radon Concentration

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

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

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

Equation 32

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

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

Equation 33

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

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

Equation 34

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

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

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

Equation 35

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

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

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

Equation 36

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

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

Calculation of the Radon and Thoron Exhalation Rates for Sembehun

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

Equation 37

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

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

ε = emanation rate

ρ = bulk density [kg.m^{-3}]

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

λ = radon decay constant [s^{-1}]

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

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

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

Equation 38

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

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

Equation 39

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

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

Equation 40

$$Z_R / Z_T = 77.5$$

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

Equation 41

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

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

Equation 42

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

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

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APPENDIX C:
CALCULATION PARAMETER VALUES

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

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, 2013a).

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, 2013a).

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, 2013a).

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, 2013a), compared to ranges of literature values.

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

Table C 6 Ingestion rates for different age groups as defined by the adult ingestion rates.

Ingestion Pathway	Unit	Ingestion Rates for Different Age Groups				
		0 - 2 Years	2 - 7 Years	7 - 12 Years	12 – 17 Years	Adult
% of Adult Rate	-	40	50	60	85	100
Water	L.year^{-1}	2.40E+02	3.00E+02	3.60E+02	5.10E+02	6.00E+02
Milk		4.80E+01	6.00E+01	7.20E+01	1.02E+02	1.20E+02
Soil	kg.year^{-1}	1.48E-02	1.85E-02	2.22E-02	3.15E-02	3.70E-02
Grain		1.00E+01	1.25E+01	1.50E+01	2.130E+01	2.50E+01
Fruit		2.11E+01	2.64E+01	3.17E+01	4.49E+01	5.28E+01
Leafy Vegetables		8.56E+00	1.07E+01	1.28E+01	1.82E+01	2.14E+01
Root Vegetables		1.78E+01	2.23E+01	2.68E+01	3.79E+01	4.46E+01
Meat (beef)		1.20E+01	1.50E+01	1.80E+01	2.55E+01	3.00E+01
Meat (mutton)		1.00E+01	1.25E+01	1.50E+01	2.13E+01	2.50E+01
Meat (pork)		8.00E+00	1.00E+01	1.20E+01	1.70E+01	2.00E+01
Poultry		2.00E+01	2.50E+01	3.00E+01	4.25E+01	5.00E+01
Eggs		6.00E+00	7.50E+00	9.00E+00	1.28E+01	1.50E+01

Table C 7 Parameters used in describing radionuclide uptake in plants and crops.

Parameter	Unit	Root	Leafy	Fruit	Cereal	Forage	Grain	Hay
Crop Yield	kg.m^{-2}	2.4E+00	2.9E+00	2.4E+00	3.9E-01	1.9E+00	6.6E-01	1.9E+00
Growing Period	Days	9.0E+01	4.5E+01	9.0E+01	9.0E+01	3.E+01	9.0E+01	4.5E+01
Translocation Factor	-	1.0E-01	1.0E+00	1.0E-01	1.0E-01	1.0E+00	1.0E-01	1.0E+00
Food processing	-	9.0E-01	9.0E-01	9.0E-01	9.0E-01	0.0E+00	0.0E+00	0.0E+00
Weathering rates	year^{-1}	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01	1.8E+01
Crop Interception Factor	-	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01	3.0E-01
Soil contamination of crop	-	2.0E-03	1.2E-03	4.0E-03	3.4E-03	1.0E-03	1.0E-03	1.0E-03
Mass Interception Factor	m^{-2}.kg^{-1}	3.0E-01	3.0E-01	3.0E-01	3.0+00	3.0+00	3.0+00	3.0+00

Table C 8 Annual water, soil, and fodder consumption rates by animals (beef, sheep, goats, pigs, and poultry) compiled from various sources.

Water	Fodder	Soil	Reference
Beef Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			
75	16	1.25	RG-002
60	55 (wet)	0.6-	(IAEA, 2003)
80	10	0.6	(Kozak and Stenhouse, 2002)
20 to 200	9 to 300	0.1 to 2.2	(Kozak and Stenhouse, 2002)
35.6	33	1.5	(Penfold *et al.*, 1999)
20 to 100	10 to 25	-	(IAEA, 1994a)
50 to 60	25	0.5	(IAEA, 2003)
Sheep/Pig Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			Reference
15	1.5	0.8	RG-002
3 to 10	0.5 to 3.5	-	(IAEA, 1994a)
Poultry Water (L.d^{-1}), Soil and Fodder (kg.d^{-1}) Consumption Rates			Reference
0.3	0.15	-	RG-002
0.1 to 0.3	0.05 to 0.15	-	(IAEA, 1994a)
0.3	0.15	0.01	

Table C 9 Soil to secondary crop concentration factors (Bq.kg^{-1} crop per Bq.kg^{-1} dry soil) compiled from various sources.

U	Th	Ra	Pb	Po	Pa	Ac	Reference
Leafy Vegetables							
2.0E-02	1.2E-03	9.1E-02	8.0E-02	7.4E-03	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
8.3E-04	1.8E-04	4.9E-03	1.0E-03	1.1E-05	1.1E-04	1.1E-04	(De Beer, *et al.*, 2002)
3.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	2.1E-02	3.2E-04	(Penfold *et al.*, 1999)
1.7E-03	3.6E-04	9.8E-03	2.0E-03	2.4E-04	9.4E-05	9.4E-05	(Staven *et al.*, 2003)
Root Vegetables							Reference
8.4E-03	8.0E-04	7.0E-02	1.5E-02	5.8E-03	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
2.2E-03	4.8E-05	7.8E-03	1.6E-03	1.8E-05	1.8E-04	1.8E-04	(De Beer, *et al.*, 2002)
3.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-03	5.0E-04	3.0E-01	6.0E-02	2.0E-04	2.0E-02	6.0E-04	(Penfold *et al.*, 1999)
3.0E-03	8.5E-05	5.0E-04	1.5E-03	1.8E-03	8.8E-05	8.5E-05	(Staven *et al.*, 2003)
Fruit							Reference
1.5E-02	7.8E-04	1.7E-02	1.5E-02	1.9E-04	-	-	RG-002[2]
2.2E-03	4.8E-05	7.8E-03	1.6E-03	1.8E-05	1.8E-04	1.8E-04	(De Beer, *et al.*, 2002)
7.2E-04	4.5E-05	1.1E-03	1.8E-03	2.2E-04	4.5E-05	4.5E-05	(Staven *et al.*, 2003)
Cereal							Reference
1.5E-02	6.4E-05	2.4E-03	1.2E-03	2.4E-04	-	-	RG-002[1,3]
1.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
1.1E-03	2.9E-05	1.0E-03	4.0E-03	4.4E-04	4.4E-04	4.4E-04	(De Beer, *et al.*, 2002)
1.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
1.0E-04	1.0E-03	4.0E-02	1.0E-02	2.0E-04	1.3E-02	1.9E-04	(Penfold *et al.*, 1999)
1.2E-03	3.1E-05	1.1E-03	4.3E-03	2.1E-03	2.0E-05	2.0E-05	(Staven *et al.*, 2003)
Grain (Animal Feed)							Reference
7.8E-03	1.8E-03	1.8E-02	2.8E-03	2.4E-04	-	-	RG-002[1,4]
1.2E-03	3.1E-05	1.1E-03	4.3E-03	2.1E-03	2.0E-05	2.0E-05	(Staven *et al.*, 2003)
Forage, Hay (Animal Feed)							Reference
4.6E-02	9.9E-02	7.1E-02	9.2E-02	1.2E-01	-	-	RG-002[1]
1.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(IAEA, 2003)
2.3E-02	1.1E-02	8.0E-02	1.1E-03	2.0E-02	2.0E-02	2.0E-02	(De Beer, *et al.*, 2002)
8.0E-03	5.0E-04	4.0E-02	1.0E-02	2.0E-04	4.0E-02	1.0E-03	(Kozak and Stenhouse, 2002)
5.0E-04	5.0E-04	4.0E-02	1.0E-02	2.0E-04	3.2E-02	4.8E-04	(Penfold *et al.*, 1999)
8.3E-03	1.8E-03	4.9E-02	1.0E-02	1.2E-03	4.7E-04	4.7E-04	(Staven *et al.*, 2003)
Average Crop Concentration Factors							Reference
2.7E-03	3.9E-04	1.0E-02	4.0E-03	1.3E-03	1.2E-04	1.2E-04	(Staven *et al.*, 2003)

(1) Concentration factors from RG-002 are given based on dry weight concentration in the plant to the dry weight concentration in the soil, (2) RG-002 values for fruit are given as wet weight concentration in fruit per dry weight concentration in soil. (3) Values for grain from RG-002 are specifically for maize. (4) Animal feed from grain is for maize stalks and roots, which are commonly used as animal feed.

Table C 10 Transfer coefficients from the animal feed to animal products in $d.kg^{-1}$ and $d.L^{-1}$ compiled from various sources.

U	Th	Ra	Pb	Po	Pa	Ac	Reference
Transfer Coefficients for Meat ($d.kg^{-1}$)							
3.9E-04	2.3E-04	1.7E-03	7.0E-04	5.0E-03	-	-	RG-002 (Beef)
3.0E-02	5.0E-03	5.0E-03	7.1E-03	5.0E-03	-	-	RG-002 (Mutton)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	5.0E-05	1.6E-04	(IAEA, 2003)
3.4E-04	9.0E-04	9.4E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
6.0E-04	2.7E-03	1.3E-03	1.0E-02	4.0E-03	5.0E-05	1.6E-04	(Kozak and Stenhouse, 2002)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	2.6E-05	1.6E-04	(Penfold *et al.*, 1999)
3.0E-04	4.0E-05	9.0E-04	4.0E-04	5.0E-03	4.0E-05	4.0E-04	(Staven *et al.*, 2003)
Transfer Coefficients for Milk ($d.L^{-1}$)							Reference
1.8E-03	5.0E-06	3.8E-04	1.9E-04	2.1E-04	-	-	RG-002
4.0E-04	5.0E-06	1.3E-03	3.0E-04	3.4E-04	5.0E-06	4.0E-07	(IAEA, 2003)
4.0E-04	1.7E-06	1.3E-03	2.0E-04	1.0E-03	1.0E-03	1.0E-03	(De Beer, *et al.*, 2002)
3.7E-04	5.0E-06	1.3E-03	3.0E-04	3.0E-04	5.0E-06	4.0E-07	(Kozak and Stenhouse, 2002)
4.0E-04	5.0E-06	1.3E-03	2.7E-04	3.4E-04	5.0E-06	4.0E-07	(Penfold *et al.*, 1999)
4.0E-04	5.0E-06	1.3E-03	2.6E-04	3.4E-04	5.0E-06	2.0E-05	(Staven *et al.*, 2003)
Transfer Coefficients for Poultry ($d.kg^{-1}$)							Reference
7.5E-01	4.0E-03	9.9E-04	2.0E-03	2.4E+00	-	-	RG-002
3.0E-04	9.0E-04	9.0E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
1.0E+00	6.0E-03	3.0E-02	8.0E-01	2.3E+00	6.0E-03	6.0E-03	(Staven *et al.*, 2003)
Transfer Coefficients for Eggs ($d.kg^{-1}$)							Reference
1.1E+00	2.0E-03	2.0E-05	2.0E-03	3.1E+00	-	-	RG-002
1.0E+00	2.0E-03	2.0E-05	2.0E-03	1.8E-02	1.8E-02	1.8E-02	(De Beer, Ramlakan and Schneeweiss, 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, 2013a).

Activity	0 – 2 Years	2 – 7 Years	7 – 12 Years	12 – 17 Years	Adult
Time spent indoors	7 914	7 775	7 568	7 665	7 050
Time spent outdoors	846	985	1 192	1 092	1 710
Working on contaminated sediments and land	0	0	0	0	2 000
Playing on contaminated sediments and land	200	383	383	300	0
Swimming	19.2	27.4	30.2	27.8	9
Boating	0	78	76	110	170
Fishing	0	78	76	110	170

APPENDIX D:
CONCEPTUAL REPRESENTATION OF THE GROUNDWATER MODEL IN ECOLEGO

Figure D 1 to Figure D 3 present simplified representations of the groundwater pathway for different site-specific conditions. Viewed simplistically, the main components of the groundwater system are a source, an unsaturated zone of limited thickness, a saturated zone, a mixing zone between clean and contaminated water in the aquifer, and a receptor of groundwater contamination that could be in the form of an abstraction borehole or a surface water body such as a river or a lake. The source as used here could be a contaminated soil layer with a relatively limited thickness and lateral extent, a surface stockpile facility (e.g., Tailings Storage Facility or Waste Rock Dump) with a relatively large lateral extent and thickness, or a below-grade layer of contaminated waste material.

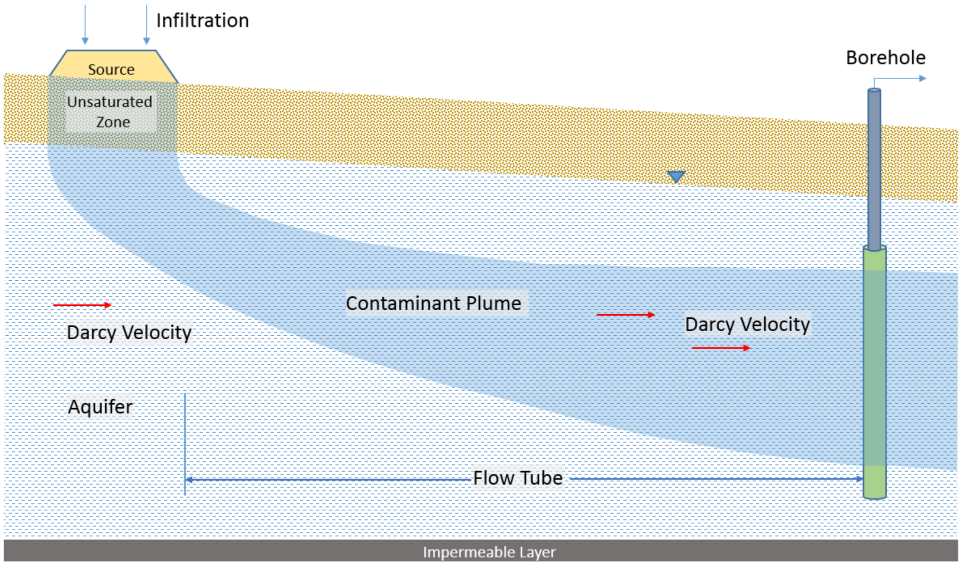

Figure D 1 Schematic representation of the groundwater system to calculate the migration of radionuclides through a deep (thick) aquifer system and a relatively small lateral extent source term, with an abstraction borehole as a receptor.

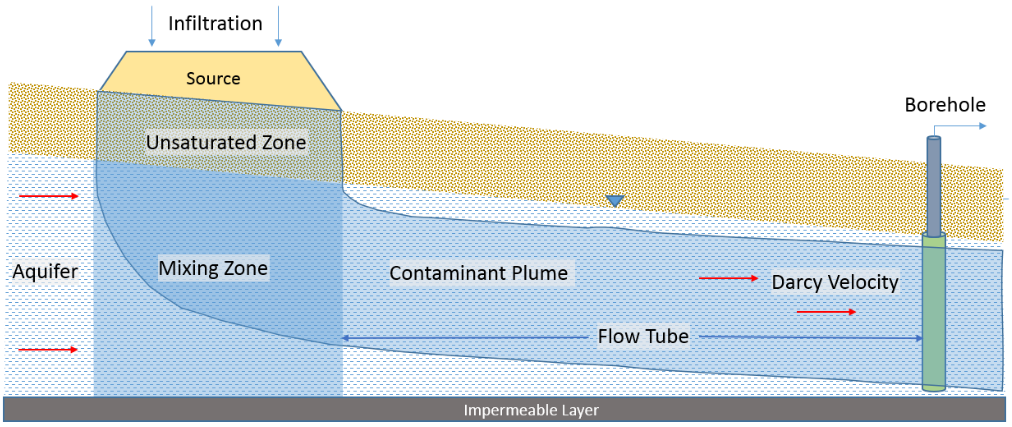

Figure D 2 Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with an abstraction borehole as a receptor.

It is assumed that radionuclides contained in the source are released following the infiltration and dissolution of precipitation into and through the source. The radionuclides that leach from the source migrate vertically through the unsaturated zone towards the groundwater table (i.e., an interface between the unsaturated and saturated zone). Upon entering the aquifer (saturated zone), mixing between contaminated and uncontaminated water will occur, after which the radionuclides migrate along with the groundwater flow path towards the downstream borehole or surface water body.

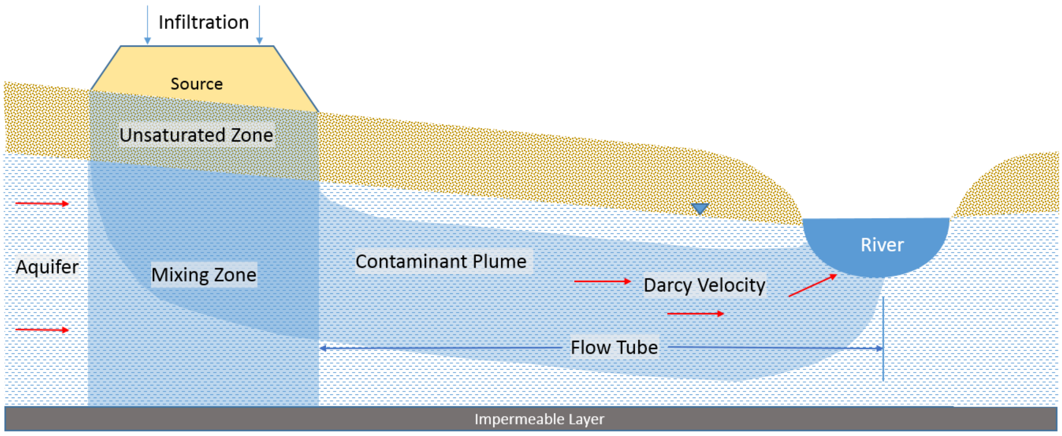

Figure D 3 Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with a river as a receptor.

Steady-state flow conditions are assumed for radionuclide migration. The processes consider advection, hydrodynamic dispersion, radioactive decay, and radionuclide sorption by the soil matrix. For the latter, instantaneous and reversible sorption described by a linear isotherm (also known as a K_d-model or sorption distribution coefficient) is assumed. Figure D 1 is a conceptual representation of a source term with limited thickness and lateral extent, with a thick aquifer system that underlies the source, whereas Figure D 2 and Figure D 3 represent a shallow (thin) aquifer system and a relatively large lateral extent source term.

The *System Level* model that was used to evaluate the contribution of the groundwater pathway was implemented in Ecolego® Version 6 (http://ecolego.facilia.se/ecolego/show/HomePage). A conceptual representation of the different compartments of the *System Level* Model is presented in Figure D 4 to Figure D 8.

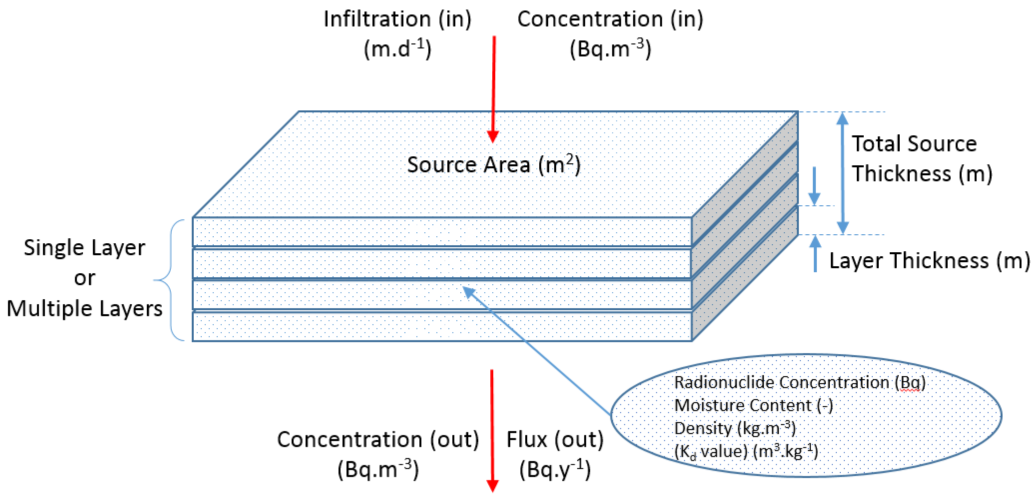

Figure D 4 Conceptual representation and associated parameter values for the source term model.

Figure D 4 shows that the source term model is a function of the radionuclide specific activity concentration (Bq), the volumetric moisture content ($m^3.m^{-3}$), the dry bulk density of the source material ($kg.m^{-3}$), and the radio element-specific distribution coefficient or K_d-value ($m^3.kg^{-1}$). The advective transfer coefficient that represents the loss of radionuclides from the total source, or from one layer to the next, is given by the model described in IAEA (2004b) and :

Equation 43

$$\lambda_w = \frac{I_w}{\theta_w H_w R_w}$$

where I_w is the infiltration rate to the source layer (m.year^{-1}), θ_w is the soil moisture content in the source (unitless) and H_w is the thickness of source (m) R_w is the retardation coefficient in the source (unitless):

Equation 44

$$R_w = 1 + \frac{\rho_w \, K_{dw}}{\theta_w}$$

where, ρ_w is the soil bulk density in the source (kg.m^{-3}) and $K_{d,w}$ is the sorption distribution coefficient in the source (m^3.kg^{-1}). For multiple layers with different properties, the transfer coefficient is defined for each layer with its associated parameter values. Figure D 4 shows that the output from the source term model is the radionuclide concentration (Bq.m^{-3}) or flux (Bq.year^{-1}) leaving the compartment.

The transfer coefficient accounting for the effect of dispersion in transport from compartment *i* to compartment *j* ($\lambda_{D,ij}$, year^{-1}) is calculated using the following equation (IAEA, 2004b):

Equation 45

$$\lambda_{D,ij} = \frac{\alpha_L}{H_i} \cdot \lambda_{w,ij}$$

where α_L *i*s the longitudinal dispersivity (m) and H_i is the compartment thickness. Note that the transfer coefficient in Equation 45 represents the dispersion of radionuclides between the compartments in both directions.

Figure D 5 shows that the unsaturated zone model is a function of the volumetric moisture content (m^3.m^{-3}) and the dry bulk density of the unsaturated zone (kg.m^{-3}), the radioelement specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the unsaturated soils, as well as the dispersivity (m). The advective and dispersive transfer coefficients that represent the transfer and loss of radionuclides from the unsaturated zone to the saturated zone (aquifer) are similar to those presented in Equation 43 to Equation 45, except that it is for the unsaturated zone parameter values.

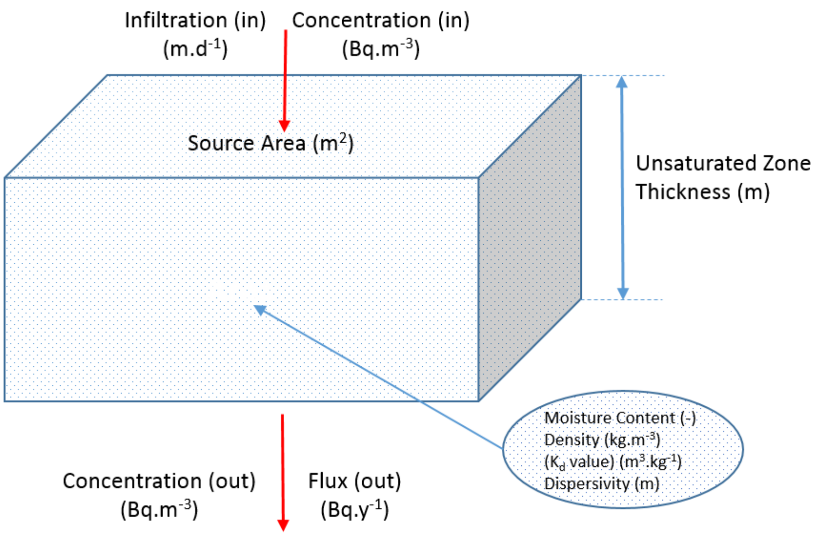

Figure D 5 Conceptual representation and associated parameter values for the unsaturated zone model.

Figure D 6 is a simplified representation of the aquifer mixing zone and the most important parameters. The infiltration rate (m.year^{-1}) is assumed constant (i.e., steady-state conditions) and equal to the infiltration rate to the unsaturated zone. The radionuclide concentration (Bq.m^{-3}) of water (moisture) entering the mixing zone is equal to the concentration flowing from the unsaturated zone. It is assumed that the mixing zone is represented as one compartment of known thickness. The area is the same as that of the source, while the depth is equal to the aquifer thickness.

The water entering the mixing zone may contain a radionuclide concentration, but it is assumed that the radionuclide concentration (Bq.m^{-3}) of the water is zero. The Darcy velocity (m.year^{-1}) defines the flow rate entering the mixing zone and that flow rate through the zone. The output after mixing defines the concentration (Bq.m^{-3}) and flux (Bq.year^{-1}) into the flow tube (aquifer).

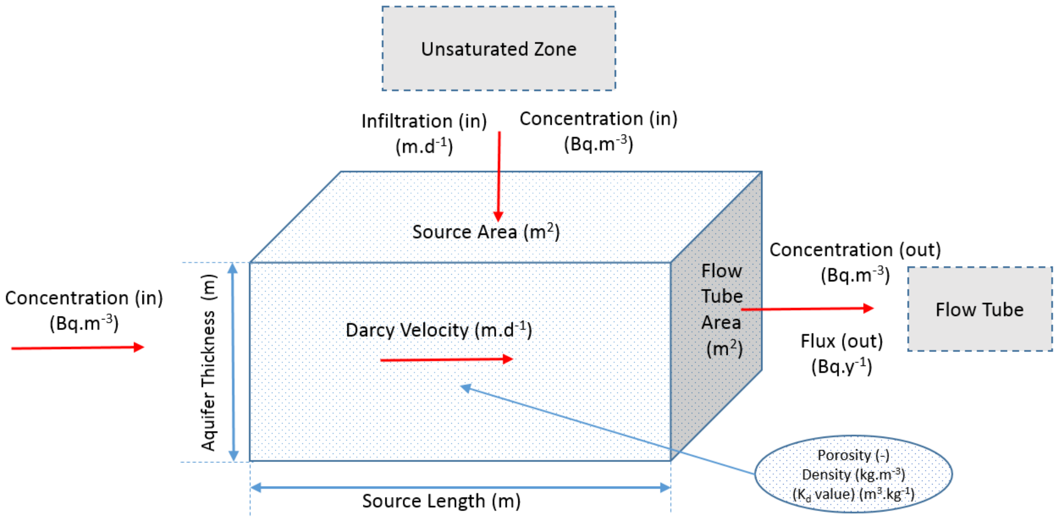

Figure D 6 Conceptual representation and associated parameter values for the aquifer mixing zone model.

Figure D 6 shows that the aquifer mixing zone model is a function of the Darcy velocity (m.year^{-1}), the dry bulk density of the aquifer (kg.m^{-3}), and the radio element-specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the aquifer.

The radionuclide concentration (Bq.m^{-3}) of water entering the aquifer compartment is equal to the outflow concentration from the aquifer mixing zone. The Darcy velocity (m.year^{-1}) in the aquifer is assumed to be constant with time. The output at the receptor point defines the concentration (Bq.m^{-3}) and flux (Bq.year^{-1}) at the borehole.

Figure D 6 shows that the aquifer model is a function of the Darcy velocity (m.year^{-1}), the aquifer porosity, the dry bulk density of the aquifer (kg.m^{-3}), the radioelement specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the aquifer, and the dispersivity (m). The advective and dispersive transfer coefficients that represent the transfer and loss of radionuclides from the aquifer are similar to those presented in Equation 43 to Equation 45, except that it is for the aquifer parameter values.

The concentration of the water abstracted from the borehole is simplistically taken as the sum of the flow tube concentration (Bq.m^{-3}) multiplied by the fraction of the borehole intersecting the plume, and the background concentration (Bq.m^{-3}) multiplied by the fraction intersecting the uncontaminated water. As a conservative assumption, it is assumed that the whole screen intersection the contaminant plume.

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

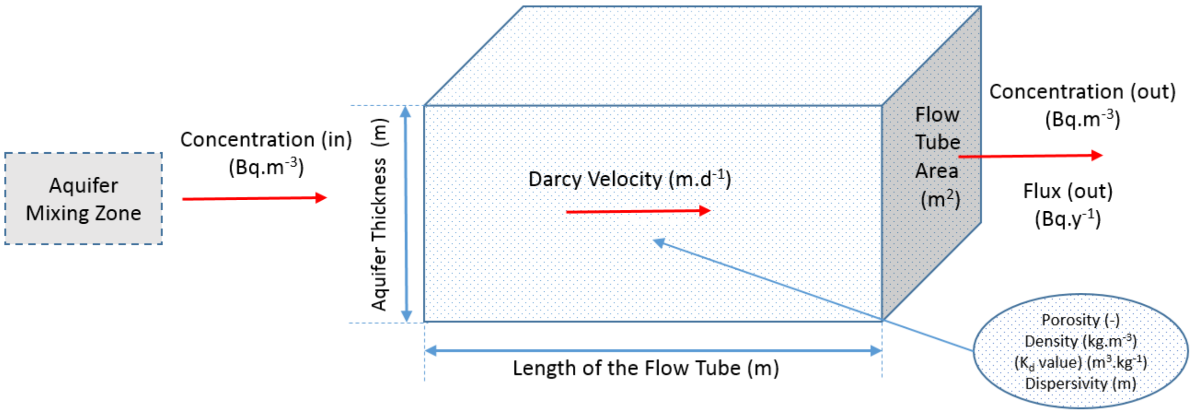

Figure D 7 **Conceptual representation and associated parameter values for the aquifer (saturated zone) model.**

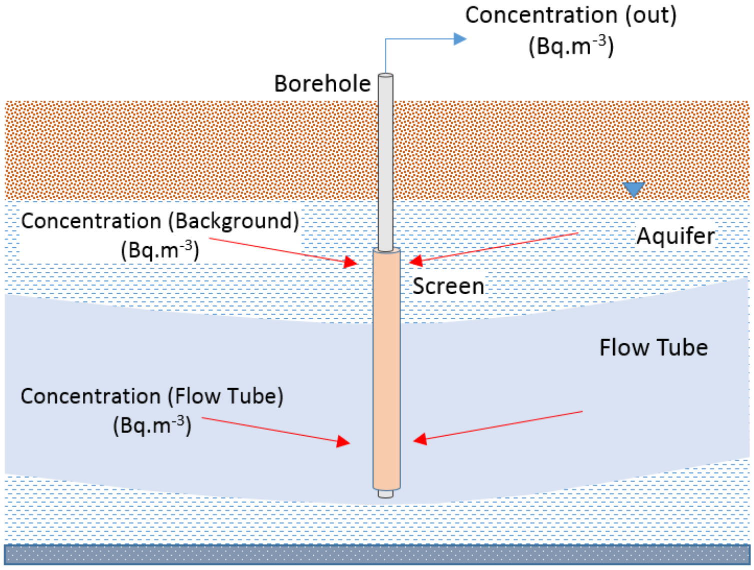

Figure D 8 **Conceptual representation and associated parameter values for the borehole abstraction model.**