Radiological Public Impact Assessment for the Blyvoor Gold Mining Project

Report No. ASC-1035F-1

October 2018

Technical Report

Title: Radiological Public Impact Assessment for the Blyvoor Gold Mining Project

Document Reference Number	ASC-1035F-1
Document Version Number:	Reversion 1.0
Date:	October 2018

Prepared by AquiSim Consulting (Pty) Ltd for:

Digby Wells Environmental

Digby Wells House Turnberry Office Park 48 Grosvenor Road Bryanston 2191	Private Bag X 10046 Randburg 2125

For Attention:

Xanthe Taylor (Environmental Consultant)

Tel: +27 (11) 789 9495
Cell: +27 (82) 871 3049
Email: xanthe.taylor@digbywells.com

Compiled by:

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

Offices

109 Bosduif Crescent Wierda Park x1 P.O. Box 51777 Wierda Park CENTURION 0149, South Africa Tel: +27 (0)82 806 6159 Fax: +27 (0)86 689 6006 e-mail: japie@aquisim.co.za	5 Binga Place Faerie Glen, Pretoria P.O. Box 1490 Faerie Glen PRETORIA 0043, South Africa Tel. No.: +27 82 784-2023 Fax. No.: +27 866843449 e-mail: hugo@aquisim.co.za

Directors: J.J. van Blerk (Ph.D.), H. Janse van Rensburg (Ph.D., MBA)

AUTHORISATION

	NAME	SIGNATURE	DATE
COMPILED	JJ van Blerk		October 2018
Radiation Protection Specialist			
CHECKED	Xanthe Taylor		October
Environmental Assessment Practitioner			

DISTRIBUTION

NO	NAME
1	Blyvoor Gold Capital (Pty) Ltd
2	Digby Wells Environmental
3	AquiSim Consulting (Pty) Ltd.
4	
5	
6	
7	
8	
9	
10	

* = Distributed via e-mail

EXECUTIVE SUMMARY

Exploration started at the Blyvooruitzicht Gold Mine in the 1930s, a fully operational mine located approximately 6 km south of Carletonville and situated in the Magisterial District of Oberholzer in the Gauteng Province. In August 2013, Blyvooruitzicht Gold Mining Company Ltd (BGMC) as the owners of the Blyvooruitzicht Gold Mine was placed under provisional liquidation. In 2016, BGMC (in provisional liquidation) lodged an application for the transfer and cession of the Mining Right to Blyvoor Gold Capital (Pty) Ltd (hereafter referred to as Blyvoor Gold) in terms of Section 11 of the Mineral and Petroleum Resources Development Act, 2002 (Act 28 of 2002) (MPRDA) (as amended). Blyvoor Gold intends to return the Blyvooruitzicht Gold Mine to a fully operational mine (hereafter referred to as the Project).

A process was initiated to apply for the environmental approval for the Project in terms of a Section 93 Directive. The purpose of this Directive is to align the existing documentation pertaining to the operations to the National Environmental Management Act, 1998 (Act No. 107 of 1998) (NEMA) and the Environmental Impact Assessment (EIA) Regulations, dated 2014 (as amended in 2017). Two metallurgical processing plants are required to be obtain Air Emission Licences as part of this application. In addition, the environmental authorisation will deal with the underground mine situated at No. 5 Shaft, as well as the retreatment of the Tailings Storage Facilities (TSFs). The tailings retreatment process will not take place immediately as underground mining is the initial priority. Gold ore from underground will be recovered through the No. 5 Shaft metallurgical treatment plant (No. 5 Shaft Plant). Gold-bearing slurry from the TSF retreatment (when commissioned) will be processed at the tailings retreatment plant.

Digby Wells Environmental was commissioned by Blyvoor Gold as the Independent Environmental Practitioner to align the Project with the NEMA and associated EIA Regulations. Due to the presence of naturally occurring radionuclides, the potential radiological impact to nearby members of the public was identified as one of the key issues of concern during the scoping phase. Digby Wells Environmental, therefore, commissioned AquiSim Consulting (Pty) Ltd (AquiSim) as the Radiation Protection Specialist (RPS) to evaluate the radiological impact to members of the public as part of, and as input into, the EIA process. The purpose of this report is to present the radiological impact assessment of the Project to members of the public as part of the EIA process.

To evaluate the potential radiological impact to members of the public, public exposure conditions were defined to evaluate the contribution through the surface water, groundwater and atmospheric pathways. To evaluate the potential contribution of the groundwater pathway, hypothetical conditions supplemented with site-specific conditions were considered to illustrate the radiological impact.

- It was illustrated that the dissolution of radionuclides, the leaching and subsequent migration of radionuclides through an aquifer is a very slow process and it would take hundreds to thousands of years to migrate a few hundred meters from the TSF to an abstraction borehole.
- It was illustrated that for the assumed conditions, the potential contribution from the groundwater pathway at a point 300 m from the Doornfontein TSF No. 1 is only visible in hundreds of thousands of years, and potentially at doses that are below 100 µSv.year^{-1}.

The contribution from radon inhalation to the radiological impact to members of the public were evaluated separately.

- It was illustrated that except for the areas near the TSFs and the ventilation shaft, the radon inhalation dose is less than 25 µSv.year^{-1}. The contribution of the ventilation shaft is the most significant, with doses as high as 250 µSv.year^{-1} in the immediate vicinity of the shaft.
- Due to the nature of the ventilation shaft (point source opposes to areal source), the airborne radon concentration decreases very quickly with distance. This means that the dose contribution from radon inhalation in the area is generally less than 50 µSv.year^{-1}.

The Residential Area Exposure Condition was defined to evaluate the potential radiological impact to members of the public located in the nearby residential areas. The main contributions are expected from the atmospheric and associated secondary pathways.

- It was illustrated that the total effective dose for the different age groups are very similar, with the TSFs as the main contributor. The doses are highest close to the TSFs but decrease very quickly to levels below 100 µSv.year^{-1} with distance away from the Project.
- It was illustrated that the total effective dose for the closest residential areas such as Doornfontein, Northdene, Southdene and Eastdene is less than 100 µSv.year^{-1}.

The Commercial Agricultural Exposure Condition was defined to evaluate the potential radiological impact to members of the public practicing agricultural activities near the Project. The main contributions are expected from the atmospheric, groundwater and associated secondary pathways.

- It was illustrated that it is highly unlikely that the groundwater or surface water pathways will make a significant contribution to a radiological impact, especially during the timescales of concern.
- It was illustrated that the total effective dose for the different age groups are very similar, with the TSFs as the main contributor. The doses are highest close to the TSFs but decrease very quickly to levels below 100 µSv.year^{-1} with distance away from the Project.
- It was illustrated that in areas where agricultural activities can be expected (to the north of the Doornfontein TSF complex, as well as south and west of the Project) the maximum total effective dose that can be expected is less than 100 µSv.year^{-1}.

The radiological impact assessment rating considered the various activities associated with the construction, operational and post-closure phases. Activities that will be performed during the construction phase do not involve the handling, processing or releasing 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.

The tables below present the significant rating for the activities associated with the operational and post-closure phases of the Project. Distinction was made between the impact of the activities without mitigation or management options included and the impact after mitigation of management activities were implemented.

Dimension	Rating	Motivation	Significance
Impact Description: Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	
Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	
Impact Description: Release of contaminated water that contains radionuclides into nearby watercourses during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 56
Duration	Beyond project life (6)	The impact will remain for some time after the life of the project and is potentially irreversible if not managed	

Dimension	Rating	Motivation	Significance
Extent	Municipal area (4)	Exposure potentially extends beyond the mining rights area into the nearby watercourses and their downstream users	
Intensity	On-going serious (4)	Impact expected in the nearby watercourses and associated sediments, with potential exposure to downstream users that are above regulatory compliance	
Probability	Probable (4)	It is probable that the impact will occur in the nearby watercourses	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 14
Duration	Medium term (3)	The impact has not occurred yet and is likely to occur only in the absence of a water management plan, maintenance plan and monitoring plan	
Extent	Limited (2)	The impact will be limited to the site itself and its immediate surroundings	
Intensity	Minor (2)	The intensity of the impact will reduce significantly with the proper implementation of the water management plan, maintenance plan and monitoring plan	
Probability	Improbable (2)	With the implementation of the water management plan, maintenance plan and monitoring plan the probability of the impact to occur is low	
Impact Description: Retreatment of the existing TSFs during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective retreatment and rehabilitation of the footprint area will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Likely (5)	The retreatment of the TSFs is one of the objectives of the project, while the rehabilitation of the footprint areas is a strong recommendation, which means that the probability that the impact will occur is likely	

Dimension	Rating	Motivation	Significance
Impact Description: Implementation of the NNR approved decommissioning plan for the Project			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Almost certain (5)	Within the NNR nuclear authorisation structures, the probability that the impact will occur is likely	
Impact Description: Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	
Impact Description: Leaching and migration of radionuclides from the TSFs the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices are below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practices	

Dimension	Rating	Motivation	Significance
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practices	

The management objective is first to ensure that the 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. From a mitigation and management of the impact perspective, the following was noted:

- The total effective dose as a contribution from radon gas released from the TSFs and ventilation shaft is well below the regulatory compliance criteria, which means that from a compliance perspective no additional management or mitigation measures are required.
- 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 subject to reclamation, 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 total effective dose as a contribution from the windblown dust released from the TSFs and ore crushing is well below the regulatory compliance criteria, which means that from a compliance perspective no additional management or mitigation measures are required.

A cumulative radiological impact to members of the public is possible in the areas, with possible contributions from the Sibanye West Driefontein Operations, Harmony Kusasalethu Operations and the AngloGold Ashanti West Wits Operations. However, the scope of the assessment was limited to the Project and did not make provision for a regional assessment to evaluate cumulative effects. In addition, the application of the dose constraint as regulatory compliance criteria opposed to the dose limit of 1,000 μSv.year^{-1} is to allow for the cumulative impact from more than one operation in an area. In other words, by constraining the Project to 250 μSv.year^{-1}, provision is made for a cumulative impact, while still in compliance with the public dose limit of 1,000 μSv.year^{-1}.

The radiological monitoring plan defined for the Project made a distinction between baseline characterisation and the routine monitoring programme to implement. The objective of the baseline characterisation is to establish the radiological condition of the site and associated infrastructure to develop an appropriate radiation management plan, and to establish the radiological characteristics of radioactive material associated with the TSFs. The following activities were proposed:

- Gamma radiation, dose rate and surface contamination surveys (of the site and associated surface infrastructure) to establish the level of surface contamination associated with the Project and to identify radioactive material that requires management. Depending on the outcome of these surveys, some areas might require rehabilitation and clean-up before operations commence.
- Develop a sampling programme for each TSF to produce statistically representative samples of each TSF for full spectrum analysis. It is proposed that at each location, a sample from 0 to 1 m be collected, and another from deeper than 1 m. The reason being that the sample in the top layer represents the contribution to the atmospheric pathway, whereas the deeper zone represents the contribution to the groundwater pathway through leaching. It is also proposed that the representative sample from the top layer be divided into fractions below 10 micron and above 10 micron. The reason being that the activity concentration is the smaller (inhalable) fraction tends to be higher.

- Determine the radon exhalation rate for each TSF. This involves the sampling of tailings material from different sections of the TSF, which is then used to determine the radon exhalation rate from the samples as a function of the Ra-226 content. This is a laboratory procedure.
- Perform a land use, human behaviour and interaction with the environmental study that can be used for a more comprehensive definition of the public exposure conditions.

The table below summarises the proposed monitoring programme for the Project aimed at public radiation protection. Most of the monitoring points proposed to be part of the monitoring programme coincide with the monitoring programme for the environmental pathways.

Monitoring Element	Comment	Frequency
Surface water	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Biannually
	Total Uranium and Thorium, and Ra-226	Quarterly
Sediments	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Annually
	Total Uranium and Thorium, and Ra-226	Biannually
Groundwater	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Once every two years
	Total Uranium and Thorium, and Ra-226	Biannually
Radon gas	Environmental radon using Radon Gas Monitors (RGMs)	Quarterly for a period of 2 to 3 month
	Radon exhalation from the ventilation shaft using RGMs	Continuously for a period of 2 to 3 month
Dust fallout	Total Uranium and Thorium, and Ra-226	Quarterly

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 General

Exploration started at the Blyvooruitzicht Gold Mine in the 1930s, a fully operational mine located approximately 6 km south of Carletonville and situated in the Magisterial District of Oberholzer in the Gauteng Province. In August 2013, Blyvooruitzicht Gold Mining Company Ltd (BGMC) as the owners of the Blyvooruitzicht Gold Mine was placed under provisional liquidation. In 2016, BGMC (in provisional liquidation) lodged an application for the transfer and cession of the Mining Right to Blyvoor Gold Capital (Pty) Ltd (hereafter referred to as Blyvoor Gold) in terms of Section 11 of the Mineral and Petroleum Resources Development Act, 2002 (Act 28 of 2002) (MPRDA) (as amended). Blyvoor Gold intends to return the Blyvooruitzicht Gold Mine to a fully operational mine (hereafter referred to as the Project).

A process was initiated to apply for the environmental approval for the Project in terms of a Section 93 Directive. The purpose of this Directive is to align the existing documentation pertaining to the operations to the National Environmental Management Act, 1998 (Act No. 107 of 1998) (NEMA) and the Environmental Impact Assessment (EIA) Regulations, dated 2014 (as amended in 2017). Two metallurgical processing plants are required to be obtain Air Emission Licences as part of this application. In addition, the environmental authorisation will deal with the underground mine situated at No. 5 Shaft, as well as the retreatment of the Tailings Storage Facilities (TSFs). The tailings retreatment process will not take place immediately as underground mining is the initial priority. Gold ore from underground will be recovered through the No. 5 Shaft metallurgical treatment plant (hereafter referred to as the No. 5 Shaft Plant) to be constructed at the existing footprint at No. 5 Shaft. Gold-bearing slurry from the TSF retreatment (when commissioned) will be processed at the tailings retreatment plant situated near the golf course.

Naturally occurring radionuclides associated with the uranium, thorium and actinium decay series are associated with the gold-bearing reefs of the Witwatersrand Basin, including the Carbon Leader and the Middelvlei Reefs that will be exploited as part of the Project. These naturally occurring radionuclides will, therefore, be present in the ore that will be brought to the surface for processing and consequently will be carried through to the mineral processing residues (tailings).

Activities that exploit these gold-bearing reefs of the Witwatersrand have the potential to enhance the concentrations of naturally occurring radionuclides in the environment by concentrating and moving radioactive material from inaccessible locations to locations where humans can be exposed. Materials that contain naturally occurring radionuclides are generally referred to as *Naturally Occurring Radioactive Material* or NORM (IAEA, 2007a).

Due to the presence of naturally occurring radionuclides, NORM has the potential to impact negatively on the health of humans that are exposed to this material (Marsh *et al.*, 2010). In addition to the natural background radiation, practices that exploit the earth's resources may enhance the potential for human exposure to naturally occurring radionuclides by way of their products, by-products, residues and wastes.

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 consequently (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*".

In 2003, Blyvooruitzicht Gold Mining Company Ltd was granted a Certificate of Registration (CoR), CoR-41, by the NNR in terms of Section 22 of the NNRA for the Blyvooruitzicht Gold Mine. Since the CoR are non-transferrable, Blyvoor Gold is in the process of applying for new CoRs.

One of the key submissions as part of an initial CoR application is a Radiological Public Safety Assessment (RPSA), the purpose of which is to evaluate and document the radiological impact (in terms of safety) of the associated facilities and activities to members of the public. The latest radiological public safety assessment for the Blyvooruitzicht Gold Mine was performed and submitted to the NNR in 2008.

1.2 Naturally Occurring Radionuclides and Background Radiation

Many radioactive isotopes (or radionuclides) occur naturally throughout the Earth's crust and are present in 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 parent) to the series products. Naturally occurring radionuclides that are of particular interest to radiation protection that is not members of the four decay series include isotopes of potassium (K-40) and rubidium (Rb-87) (Martin, 2006b).

In undisturbed environmental conditions, these naturally occurring radionuclides form part of the natural background radiation, to which all humans are exposed on a daily basis 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 average total dose, over the population of the world, is about 2.8 mSv. As indicated in Figure 1.1, over 85% of this total is from natural sources (2.4 mSv), with about half (1.2 mSv) coming from radon decay products in the home. 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 the body (IAEA, 2004a).

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.

In addition to the natural background radiation, practices that exploit the earth's resources may enhance the potential for human exposure to naturally occurring radionuclides by way of 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 by and potentially increase radiation exposure:

- Moving naturally occurring radionuclides from inaccessible locations to locations where humans can be exposed;
- The concentration of 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 wind).

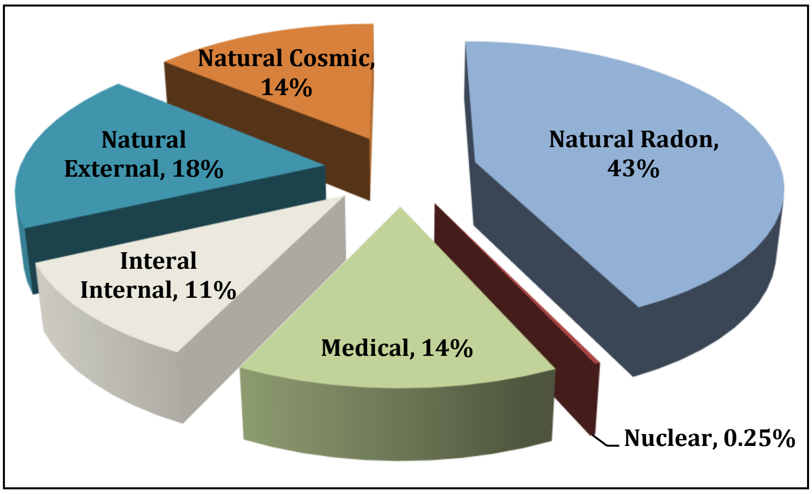

Figure 1.1 Distribution of the background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

1.3 Purpose of This Report

Digby Wells Environmental was commissioned by Blyvoor Gold as the Independent Environmental Practitioner to align the Project with the NEMA and associated EIA Regulations (see Section 1.1).

Due to the presence of naturally occurring radionuclides and thus NORM, the potential radiological impact to nearby members of the public was identified as one of the key issues of concern during the scoping phase of the EIA process (Digby Wells Environmental, 2018a). Digby Wells Environmental, therefore, commissioned AquiSim Consulting (Pty) Ltd (AquiSim) as the Radiation Protection Specialist (RPS) to evaluate the radiological impact to members of the public as part of, and as input into, the EIA process.

The purpose of this report is consequently to present the radiological impact assessment of the Project to members of the public as part of the EIA process in a comprehensive, systematic and transparent manner that is consistent with the NNRA and NEA, as well as with NNR requirements and regulations in general.

1.4 Scope and Structure of the Report

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, an example of which is a document entitled '*Radiation, People and the Environment*' published by the International Atomic Energy Agency (IAEA, 2004a) or the IAEA online Safety Glossary (IAEA, 2018).

While the aim was to perform the radiological impact assessment in a manner that is consistent with the NNRA and NEA, as well as with NNR requirements and regulations in general, the scope of this report is limited to a radiological impact assessment as input into the EIA process and as such is not necessarily suitable to address all the requirements for a comprehensive radiological public safety assessment as input into the NNR process.

The scope of the report is limited to documenting the potential radiological impact to members of the public that reside near the Project as it pertains to exposure to naturally occurring radionuclides potentially released and dispersed into the environment from the Project. As such the occupational exposure of workers to ionising radiation or exposure to non-radiological elements are excluded from the scope of the report, as well as general matters related to mine health and safety.

Different approaches can be followed to perform a RPSA, none of which is considered as the singular or correct approach. What is important is that the approach selected is fit for purpose and ensures confidence in the assessment results with due consideration of the graded approach to safety assessment (IAEA, 2009a). The conceptual framework used to perform the radiological impact assessment for the Project is schematically illustrated in Figure 1.2. 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.

It follows from Figure 1.2 that the assessment framework consists of several interrelated elements. Each of the elements is addressed as a different section in the report, with an overall structure 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 at the Project and includes the regional and local setting and the associated operational components. An overview of the physical environment and the human receptors potentially affected is also presented as appropriate.
- Section 4 presents a discussion of the conditions of public exposure considered for the assessment. The section starts with a source-pathway-receptor analysis as derived from the project and environmental system descriptions, followed by a definition of discrete sets of public exposure conditions.

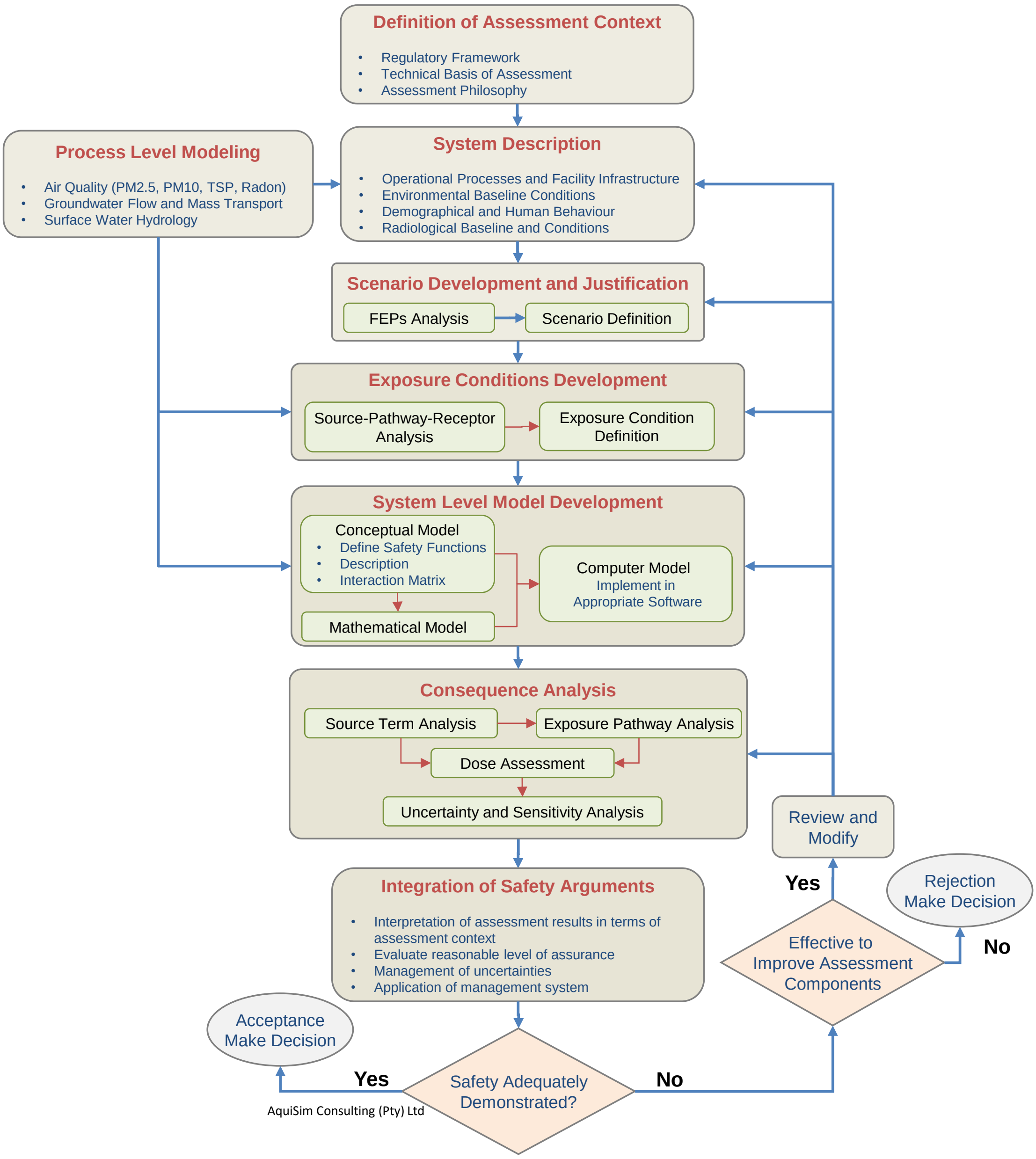

Figure 1.2 Conceptual framework used for the radiological public safety and impact assessment of the Project.

- 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 is devoted to the impact assessment rating for the construction, operational and post-closure phases of the Project.
- Section 7 defines the radiological monitoring plan for the Project that include the monitoring programme and the proposed monitoring locations.
- Section 8 presents some overall conclusions and recommendations for the improvement of public radiation safety, with the Project impact assessment as a basis.

2 Assessment Context

2.1 General

The purpose of the assessment context is to define in simple terms the *basis* or *context,* within which the Project radiological impact assessment was conducted. Generally, it consists of a set of high-level assumptions and constraints that defines the boundary conditions within which the assessment is performed. This includes the regulatory framework that applies to the assessment as presented in Section2.2 and the technical basis of the assessment as presented in Section 2.3.

2.2 Nuclear Regulatory Framework

2.2.1 General

The regulatory framework is defined by a combination of national legislation (see Section 1.1), 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*". 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. According to IAEA (2004a), 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).

The Basic Safety Standards (BSS) published in 1996 was a cornerstone of the IAEA safety standards for many years (IAEA, 1996). GSR Part 3 in the General Safety Requirement series "*Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*" (IAEA, 2014) is now available and supersedes the BSS. The overall objective of the publication is to establish requirements (i.e. *shall* statements) for the protection of people and the environment from harmful effects of ionizing radiation and for the safety of radiation sources.

2.2.2 The ICRP System of Radiological Protection

The ICRP recommended a System of Radiological Protection having the primary aim of providing an appropriate standard of protection for human beings without unduly limiting beneficial practices derived from radiological materials (ICRP, 1991).

To achieve this, the 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 key principles. The first two principles are source-related and apply in all exposure situations, while the third principle is related to 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 (ICRP, 2007), three types of exposure situations are recognised. The exposure situations are intended to cover the entire range of possible exposures, and are described as follows:

- *Planned Exposure Situations*: Planned exposure situations involve the deliberate introduction and operation of sources. It 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, or 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 decision on control must be taken, including prolonged exposure situations after emergencies or those caused by natural background radiation.

2.2.3 Safety Standards for Protection of the Public

To avoid severely inequitable outcomes of the optimisation procedure, there should be restrictions on the doses or risks to individuals from a source of radiation exposure. The regulatory tools that can be used to achieve this 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 situations, 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 reasonable achievable (ALARA), 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.year^{-1}.
- In special circumstances, an effective dose 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.
- In addition, 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 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 the purposes of optimization. *Note that* the *dose constraint is not a dose limit* (IAEA, 2014); *exceeding a dose constraint does not represent non-compliance with regulatory requirements*, but could result in follow-up actions (IAEA, 2014).

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.

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.

2.2.4 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, additional 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. One of the issues addressed in the NRWMP is options for managing radioactive waste generated through the nuclear industry, as well as waste containing un-concentrated natural occurring radioactive materials from the mining and minerals processing industries.

In guiding the national strategy for radioactive waste management, several strategic points of references in dealing with radioactive waste are defined. Two of the guiding principles that are of importance in terms of managing NORM is 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 (1994a) (unless deviations therefrom can be justified). 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 and presented in IAEA (1994a). The IAEA classification scheme has subsequently been revised and is presented in IAEA (2009b).

The NRWMP further 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 2.1 summarises the management options available to each of these classes of NORM waste.

Table 2.1 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 $Bq.g^{-1}$)
Reuse 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	

2.3 Technical Basis of the Assessment

2.3.1 General

Radiological public safety 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 members of the public above the 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 exposure groups, notably workers and members of the public.

As used here, stakeholders are groups or individuals with an interest in the radiological safety of an existing or proposed operation, facility or activity. In some cases, these groups may have specific interests that may affect the purpose, scope and focus of the assessment. This may result in additional assessment endpoints to 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 report 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 in accordance with relevant regulatory guidance and requirements;
- Digby Wells Environmental as the Independent Environmental Practitioner responsible for the alignment of the Project with the NEMA and associated EIA Regulations;
- Management of Blyvoor Gold as the owners and operators of the Project;
- Workers at the Project;
- Members of the public living near the Project,
- Mining and industry, in particular, the interested mining and mineral processing operations in close proximity to the Project; and
- Technical, scientific and environmental groups that might have an interest in the approach followed for the assessment and the subsequent results.

2.3.3 Purpose of the Assessment

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

A key element in this process is the radiological public safety assessment, which can be defined as an analysis to evaluate the performance of the overall system (e.g. mining and mineral processing operation, facility or activity) and its impact, where the performance measure is radiological safety to members of the public and workers (IAEA, 2007b). This definition is consistent with Regulation No. 388.

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

Viewed from this radiological perspective and complemented with the EIA requirements in terms of the NEMA, the purpose of the radiological impact assessment as input into the EIA process is twofold:

- To demonstrate that members of the public living near the Project 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 Project as input into the EIA process. The basis for the impact assessment is the outcome of the radiological 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 the Project, *above natural background radiation*. This means the background radiation is not included in the comparison of the total effective dose with the regulatory compliance criteria.

The main approach that is followed for this purpose is to determine a source term (release rate) of radioactivity to the environment, estimate dispersion of released radioactivity into the environment, and evaluate the subsequent interaction of members of the public with the affected environmental media.

Where necessary and justified, this assessment approach is complemented by actual environmental measurements and observation to quantify the dose contribution to members of the public.

2.3.4.2 Site-Specific Assessment

The assessment is based on site-specific data as far as practically possible and justified. Where appropriate and justified, the site-specific data and information were supplemented with values from the literature. However, all the assumptions and conditions used in the assessment were documented accordingly.

2.3.4.1 Assessment of Exposure to Radiation

NORM may pose hazards to humans or the environment not only from the presence of naturally occurring radionuclides, but also from toxic elements and compounds present in their products, by-products, residues, and wastes. The focus of the assessment was radiation exposure induced by naturally occurring radionuclides and excludes any health risk considerations that may arise due to non-radioactive substances or any other health and safety aspect.

2.3.4.2 Contaminants of Concern

The contaminants of concern were those naturally occurring radionuclides associated with the uranium and thorium decay series. These series and their radiological properties are listed in Table A 1 to Table A 3 and are illustrated schematically in Figure A 1 (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, therefore, occurs naturally 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 property of emitting ionizing radiation and on 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. These radionuclides are:

- Alpha (α) emitters: U-234, U-235, U-238, Th-230, Ra-226, Po-210, Pa-231, Th-232 and Th-228.
- Beta (β) emitters: Ac-227, Pb-210 and Ra-228.

Where applicable, radioactive decay and in-growth were taken into consideration in the assessment, not only to avoid overly conservative results in the case of the slower transport processes but also to account for the impact of the relevant decay products.

Secular equilibrium[2] was assumed between parent and daughter products in cases where analyses results of the daughters 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.

2.3.4.3 Cumulative Effect

The ICRP principles and consistent national 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 Project.

The focus of the assessment is on the contribution of the Project to the annual effective dose to members of the public. Other potential sources of radionuclides in the area include operational and historic gold mining activities located to the west, north, and east of the Project. These operations, especially the Sibanye West Driefontein Operations, AngloGold Ashanti West Wits Operations and the Kusasalethu Operations of Harmony located directly adjacent, have the potential to influence the ambient concentration of radionuclides in the environment and thus the radiological impact to members of the public.

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.

2.3.4.4 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, 2009), but no specific guidance about dose limits or an assessment framework for practical application has been developed. However, neither the NNR (NNR, 2013) nor Regulation No. 388 requires at present that the impact to non-human biota be addressed.

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 has a different natural environment than in South Africa. Radiological impact on

[2] Secular equilibrium is a steady state condition of equal activities between a long-lived parent radionuclide and its short-lived daughter. The criterion upon which secular equilibrium depends is given in L'Annunziata (1998).

non-human biota is thus excluded from the scope of the safety assessment, since it is assumed that if individual humans are shown to be adequately protected, then non-human biota are also being protected, at least at the species level (ICRP, 1991).

2.3.5 Spatial Domain of Concern

The spatial domain considered in the assessment is largely dictated by an understanding of the processes governing the movement of radionuclides and potential 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 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 mean that the spatial scale is likely to be limited by the selected exposure conditions.

2.3.6 Assessment Timescales

The life cycle of operations, facilities and activities 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. A period of active or passive institutional control may apply to the post- closure period. The national regulations concerned with nuclear authorization does not provide specific guidance on the period or conditions to assume for institutional control.

The NNR Regulatory Guide RG-002 (NNR, 2013) requires an assessment of the operational period. However, it also states that consideration should be given to the effect of long-lived radionuclides. Consequently, the assessment primarily addressed the radiological impact associated with the operational period, but an attempt was made to address the radiological impact that may occur in the distant future to the extent possible and justified.

Note that an 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 after the start of the-operational period. Conditions during the post-closure period are even more uncertain.

2.3.7 Assessment Endpoint

2.3.7.1 General

Assessment (or calculation) endpoints for a safety assessment is determined by the regulatory framework, as well as 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 assessment was the radiological impact to members of the public near the Project (see Section 2.3.2). More specifically, the objective was 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 2.2.2, the primary assessment endpoint was the annual total effective dose rate (unless otherwise stated, the term dose refers to the annual individual effective radiation dose, calculated using the method described in ICRP (1991) to workers and members of the public). 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 EIA Criteria

Digby Wells Environmental prescribed a methodology whereby the significance of each impact was evaluated. The impact was assessed based on the magnitude of the impact as well as the sensitivity of the receiver, culminating in an impact significance that identifies the most important impacts that require management. Based on international guidelines and South African legislation, the following criteria were considered when examining potentially significant impacts:

- Nature of impacts (direct/indirect, positive/negative);
- Duration (short/medium/long-term, permanent(irreversible)/temporary (reversible), frequent/seldom);
- Extent (geographical area, size of affected population/habitat/species);
- Intensity (minimal, severe, replaceable/irreplaceable);
- Probability (high/medium/low probability); and
- Possibility to mitigate, avoid or offset significant adverse impacts.

Details of the impact assessment methodology used to determine the significance of physical, biophysical and socio-economic impacts are provided below. The significance rating process follows the established impact/risk assessment formula:

Significance = Consequence x Probability x Nature

where

Consequence = Intensity + Extent + Duration

and

Probability = Likelihood of an impact occurring

and

Nature = Positive (+1) or negative (-1) impact

Note: In the formula for calculating consequence, the type of impact is multiplied by +1 for positive impacts and -1 for negative impacts

Table 2.2 Significance Rating Description (Note: It is generally sufficient to only monitor impacts that are rated as negligible or minor).

Score	Description	Rating
109 to 147	A very beneficial impact that may be sufficient by itself to justify implementation of the project. The impact may result in a permanent positive change	Substantial (positive)
73 to 108	A beneficial impact which may help to justify the implementation of the project. These impacts would be considered by society as constituting a major and usually a long-term positive change to the (natural and/or social) environment	Major (positive)
36 to 72	A positive impact. These impacts will usually result in a positive medium to the long-term effect on the natural and/or social environment	Minor (positive)
3 to 35	A small positive impact. The impact will result in medium to short-term effects on the natural and/or social environment	Negligible (positive)
-3 to -35	An acceptable negative impact for which mitigation is desirable. The impact by itself is insufficient even in combination with other low impacts to prevent the development from being approved. These impacts will result in a negative medium to short-term effects on the natural and/or social environment	Negligible (negative)
-36 to -72	A minor negative impact requires mitigation. The impact is insufficient by itself to prevent the implementation of the project but which in conjunction with other impacts may prevent its implementation. These impacts will usually result in a negative medium to the long-term effect on the natural and/or social environment	Minor (negative)
-73 to -108	A moderate negative impact may prevent the implementation of the project. These impacts would be considered as constituting a major and usually a long-term change to the (natural and/or social) environment and result in severe changes.	Major (negative)
-109 to -147	A major negative impact may be sufficient by itself to prevent implementation of the project. The impact may result in permanent change. Very often these impacts are immitigable and usually result in very severe effects. The impacts are likely to be irreversible and/or irreplaceable.	Substantial (negative)

Table 2.3 Probability/Consequence Matrix.

Probability	Significance																																					
7	-147	-140	-133	-126	-119	-112	-105	-98	-91	-84	-77	-70	-63	-56	-49	-42	-35	-28	-21	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126	133	140	147
6	-126	-120	-114	-108	-102	-96	-90	-84	-78	-72	-66	-60	-54	-48	-42	-36	-30	-24	-18	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102	108	114	120	126
5	-105	-100	-95	-90	-85	-80	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105
4	-84	-80	-76	-72	-68	-64	-60	-56	-52	-48	-44	-40	-36	-32	-28	-24	-20	-16	-12	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84
3	-63	-60	-57	-54	-51	-48	-45	-42	-39	-36	-33	-30	-27	-24	-21	-18	-15	-12	-9	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63
2	-42	-40	-38	-36	-34	-32	-30	-28	-26	-24	-22	-20	-18	-16	-14	-12	-10	-8	-6	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42
1	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	-21	-20	-19	-18	-17	-16	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6	-5	-4	-3	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	Consequence																																					

Table 2.4 Impact Assessment Parameter Ratings.

RATING	INTENSITY/REPLACEABILITY		EXTENT	DURATION/REVERSIBILITY	PROBABILITY
	Negative impacts	Positive impacts			
7	Irreplaceable damage to highly valued items of great natural or social significance or complete breakdown of natural and/or social order.	Noticeable, on-going natural and/or social benefits which have improved the overall conditions of the baseline.	International The effect will occur across international borders.	Permanent: The impact is irreversible, even with management, and will remain after the life of the project.	Definite: There are sound scientific reasons to expect that the impact will definitely occur. >80% probability.
6	Irreplaceable damage to highly valued items of natural or social significance or breakdown of natural and/or social order.	Great improvement to the overall conditions of a large percentage of the baseline.	National Will affect the entire country.	Beyond project life: The impact will remain for some time after the life of the project and is potentially irreversible even with management.	Almost certain / Highly probable: It is most likely that the impact will occur. <80% probability.
5	Very serious widespread natural and/or social baseline changes. Irreparable damage to highly valued items.	On-going and widespread benefits to local communities and natural features of the landscape.	Province/ Region Will affect the entire province or region.	Project Life (>15 years): The impact will cease after the operational lifespan of the project and can be reversed with sufficient management.	Likely: The impact may occur. <65% probability.
4	On-going serious natural and/or social issues. Significant changes to structures/items of natural or social significance.	Average to intense natural and/or social benefits to some elements of the baseline.	Municipal Area Will affect the whole municipal area.	Long term: 6-15 years and impact can be reversed with management.	Probable: Has occurred here or elsewhere and could therefore occur. <50% probability.
3	On-going natural and/or social issues. Discernible changes to natural or social baseline.	Average, on-going positive benefits, not widespread but felt by some elements of the baseline.	Local Local extending only as far as the development site area.	Medium term: 1-5 years and impact can be reversed with minimal management.	Unlikely: Has not happened yet but could happen once in the lifetime of the project, therefore there is a possibility that the impact will occur. <25% probability.
2	Minor natural and/or social impacts which are mostly replaceable. Very little change to the baseline.	Low positive impacts experienced by a small percentage of the baseline.	Limited Limited to the site and its immediate surroundings.	Short term: Less than 1 year and is reversible.	Rare/improbable: Conceivable, but only in extreme circumstances. The possibility of the impact materialising is very low as a result of design, historical experience or implementation of adequate mitigation measures. <10% probability.
1	Minimal natural and/or social impacts, low-level replaceable damage with no change to the baseline.	Some low-level natural and/or social benefits felt by a very small percentage of the baseline.	Very limited Limited to specific isolated parts of the site.	Immediate: Less than 1 month and is completely reversible without management.	Highly unlikely / None: Expected never to happen. <1% probability.

The matrix calculates the rating out of 147, whereby Intensity, Extent, Duration and Probability are each rated out of seven as indicated in Table 2.2. The weight assigned to the various parameters is then multiplied by +1 for positive and -1 for negative impacts.

Impacts are rated prior to mitigation and again after consideration of the mitigation measure proposed in this EIA/EMP Report. The significance of an impact is then determined and categorised into one of eight categories, as indicated in Table 2.3, which is extracted from Table 2.4. The description of the significance ratings is discussed in Table 2.2.

It is important to note that the pre-mitigation rating takes into consideration the activity as proposed, i.e. there may already be certain types of mitigation measures included in the design (for example due to legal requirements). If the potential impact is still considered too high, additional mitigation measures are proposed.

3 System Description

3.1 Introduction

The purpose of the system description is to provide a summary overview of the Project, with specific reference to the facilities, activities, and associated infrastructure that constitute the Project. This information is normally complemented with a description of the prevailing site characteristics and potentially affected human populations located near the Project.

The section is structured as follows. Section 3.2 presents the regional and local setting of the Project, followed by a description of the local land cover and use in Section 3.3. Section 3.4 provides a description of the Project, processes and associated infrastructure as well as the waste or by-products generated as part of these processes, highlighting the areas and activities that may contribute to the release and dispersion of naturally occurring radionuclides into the environment. With the various specialist studies prepared as part of the EIA for the Project as the primary source, Section 3.5 is limited to a summary of these studies and reports that describes the baseline environmental conditions and the population characteristics observed near the Project. Section 3.6 summarises the radiological data available for the Project at present.

3.2 Site Location

The assets that constitute the Project are located on the following farms:

- Blyvooruitzicht 116 IQ (Portions 1, 2, 5 and 10),
- Twyfelvlakte 105 IQ (Remaining Extent [RE]); and
- Doornfontein 118 IQ (RE of Portion 24).

The Project falls within the Magisterial District of Oberholzer that forms part of the Merafong City Local Municipality. The Merafong City Local Municipality falls within the West Rand District Municipality in the Gauteng Province of South Africa. Figure 3.1 is a locality map showing the local setting of the Project. The mine is located approximately 6 km south of Carletonville, 14 km north of Fochville, and approximately 40 km southwest of Randfontein. The Project is the most westerly mine on the West Wits line.

3.3 Land Cover and Land Use

The predominant land use conditions near the Project are agricultural and mining. Agricultural practices include both animal production and cropping. However, mining and mineral processing activities in the district are more extensive. They are also a major source of employment and have propelled urban development in the area. Other mining and mineral processing operations on the West Wits line near the Project include the Sibanye West Driefontein Operations, Harmony Gold Kusasalethu Operations and the AngloGold Ashanti West Wits Operations. The land comprising the steep slopes of Gatsrand ridge are classified as grazing areas. Steep slopes, shallow stony soils and rocky outcrops tend to preclude arable agriculture. The flatter deeper soiled areas in the north, south and west have an arable potential and are cropped predominantly by maize.

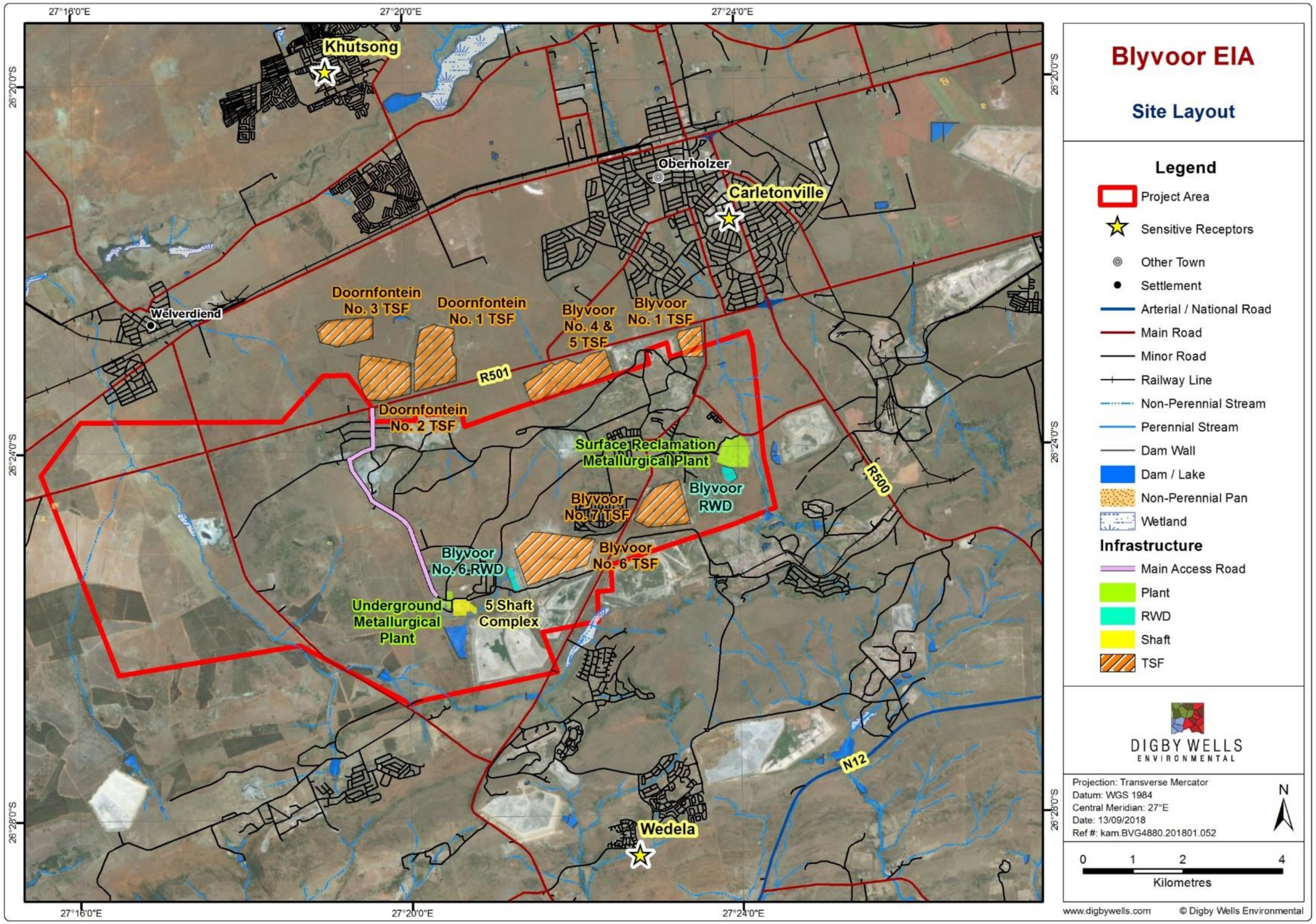

Figure 3.1 Local locality map showing the Project relative to nearby towns and residential areas (Digby Wells Environmental, 2018d).

3.4 Process Description

3.4.1 General

This section summarises the Project processes and associated infrastructure as presented in the final scoping report (Digby Wells Environmental, 2018a). The information served as a basis for the source characterisation process (and associated source term analysis) for the development of public exposure conditions in Section 4. Figure 3.2 is a locality map that shows the site layout and infrastructure that constitute the Project.

3.4.2 Underground Mining, Crushing and Milling of Ore

Blyvoor Gold Mine has an estimated remaining underground resource of approximately 169 million tonnes (Mt) containing 26.4 million ounces (Moz) of gold, at an average grade of 4.85 grams per tonne ($g.t^{-1}$). The underground project requires \$62 to \$65 million to re-commission the hoists, shaft facilities, ventilation fans, compressors, offices and to reinstate services at the No.5 Shaft. Initial production is targeted at 30,000 tonnes per month (tpm), with a growth plan to 40,000 tpm. The recovered grade from underground ore is expected to be over 6 $g.t^{-1}$. This shaft has an installed capacity of some 100,000 tpm and consistently achieved recovered grades exceeding 5.2 $g.t^{-1}$ during its 30-year history.

The mine has an existing layout of underground developed tunnels and stopes, which will be accessed *via* the No. 5 Shaft Complex. The non-utilisation of the installed infrastructure during the period since the liquidation of Blyvooruitzicht has resulted in some degrading of the shaft infrastructure together with some vandalism of the assets situated on the surface. Once access to underground has been secured, including all safety and licensing approvals, a comprehensive clean-up and vamping operation will be implemented to recover easily accessible gold, together with re-establishing the readily accessible existing production stopes in high-grade areas close to the No. 5 Shaft Complex infrastructure. Ore will be excavated in the stope areas underground and will be separated into waste rock and gold ore (unprocessed). The waste rock will be transported to surface separately and deposited on the existing waste rock dump at No. 5 Shaft while the ore will be transported to the surface for crushing and screening followed by metallurgical treatment in the No. 5 Shaft Plant.

Underground mining will commence in the shallow reaches of the deposit above 29-Level and will allow approximately nine years of mining before dewatering is required. From approximately year 10, the deeper deposit below the water level will be mined for the remainder of the life of mine, along with the balance of the resource above the water.

The No. 5 Shaft and the No.5 Sub-vertical Shaft provide access to the mineral resources on the Carbon Leader Reef and on the Middelvlei Reef. The production levels that have been developed above 30-Level (the current water level) are accessible and provide access to some 18 Moz of resources. The remaining 9 Moz is below the water level and a dewatering program is planned to be initiated in year 9 of the underground project. Dewatering will allow the refurbishment of the infrastructure below 29-Level to provide access to the remaining five levels of the No.5 Sub-vertical Shaft.

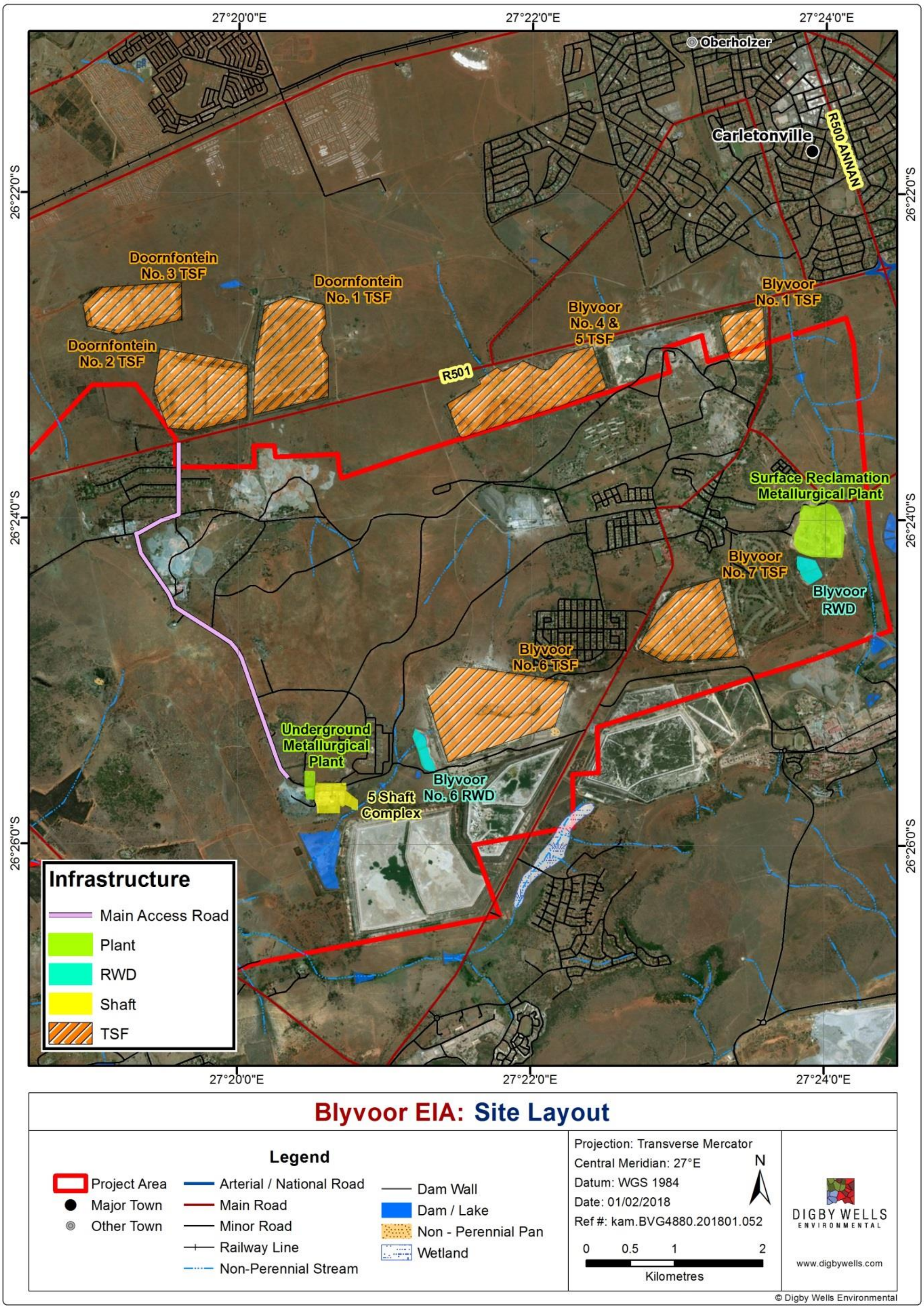

Figure 3.2 locality map showing the site layout and infrastructure that constitute the Project (Digby Wells Environmental, 2018a).

The ore will be hoisted up the existing No.5 Shaft system, discharged into an existing ore bin in the shaft headgear, loaded onto the existing conveyor belt (Conveyor 1). This conveyor will deposit the ore into the coarse ore silo. Ore is drawn out of the silo through an apron feeder and will be fed into a jaw crusher via a static grizzley. The fines and crushed ore report to a conveyor that delivers it to a screen. Screen oversize reports to a recirculation conveyor that deliver the ore to the cone crusher for secondary crushing. The secondary crushed ore also reports to the screen fed conveyor allowing secondary closed circuit crushing.

Screen undersize reports to the crushed ore silo feed conveyor and is delivered to the shuttle conveyor above the crushed ore silos. The shuttle conveyor is used to deposit ore into one of two silos. Ore is drawn out each crushed ore silo by a light duty Apron feeder and discharged onto the mill feed conveyor that delivers it to the mill. Each mill is therefore fed by its own independent silo, feeder and conveyor system.

The milling circuit includes a 100% mill discharge feed to a Falcon gravity concentrator. Concentrate from the concentrator passes over a magnetic separator to remove magnetics before it is leached in a concentrate leach reactor. The tails from the leach reactor reports back to the milling circuit.

Cyclone overflow from the milling circuit flows over a trash screen before it is thickened and delivered to a leach and Carbon in Pulp (CIP) pump cell circuit. The loaded carbon from the pump cells is acid washed, eluted using a Zadra process and electrowinning, and regenerated before being returned for CIP adsorption. The gold plated onto the electrowinning cathodes is washed off, caked in a filter press, then dried and calcined in a calcine oven before smelting into bullion bars for delivery to a refinery.

The plant tailings will pass through an INCO process detox circuit prior to pumping to the tailings dam. Water recovered from the tailings penstock will be gravity and pump fed to the plant process water dam for reuse in the circuit.

Reagents utilised for the process will be stored and mixed on site. Cyanide will be stored and utilised within strict cyanide control requirements including a separate fenced and locked mixing and storage area within the plant boundary fence. Lime will be bulk delivered to a free standing silo from where it is delivered at a controlled rate for mixing and slaking with water prior to circulation around the plant for pH control. Caustic and Hydrochloric acid will be delivered in concentrated liquid form and stored in separate fenced areas within the plant prior to being diluted with water in storage tanks from which it is pumped for plant use.

3.4.3 No. 5 Shaft Treatment Metallurgical Plant

Details pertaining to the reconstruction of the No. 5 Shaft Plant to recover gold from underground material at No.5 Shaft are tabulated in Table 3.1. The tailings from the treatment of the underground ore will initially be deposited onto the nearby Blyvoor TSF No. 6, which has enough capacity to store over 15 years of production tailings as per the Project Plan. Once the No. 5 Shaft Plant has been commissioned, the tailings from the underground ore treatment will be fed directly into this treatment circuit to avoid double handling costs.

Table 3.1 Details pertaining to the reconstruction of the No. 5 Shaft Plant.

Infrastructure	Reconstruction
Gravity Circuit	From the mills, all milled ore will discharge into a gravity separator located immediately at the base of the mill discharges. The gravity separator is a new addition to the treatment circuit, but it has a small footprint and operates as an in-line addition to the standard treatment circuit. The gravity separator will remove all the fine gravity gold from the milled product, which is anticipated to be around 40% of the contained gold. From here, the gravity gold product will be routed directly to a gravity gold elution plant, whilst the balance of the material from the gravity separator will be routed to the CIP tanks.
CIP Tanks	The CIP tanks will receive the milled ore discharged from the CIP feed thickener. The first CIP tank will allow for peroxidation using a high shear reactor. The oxidised ore then cascades to the first and then second leach tanks to which cyanide and extra lime are added for the leach process. Leaching will take place in a further 4 leach tanks before the leached slurry gravitates to the CIP pump cell plant. The civil foundations for these tanks exist and will be re-used. No new civil works are anticipated for the tank foundations, although some minor modifications to accommodate the new tanks may be required and the operation thereof is anticipated to be standard in its design, construction and operation.
Elution Circuit	There will be two elution circuits, quite separate; one for the gravity concentrate and one to treat the CIP concentrate and to recover the carbon. The gravity High-Intensity leach will be housed in the new Gold room building and receive feed directly from the centrifugal concentrator. The elution circuits are of standard design and will use the existing civil foundations with some minor modifications.
Induction Smelter	The smelting will be done using an induction smelter. The electrical requirements to power the induction smelter are relatively low, of the order of 250 KVA.
Cranage	Cyanide storage will be on site. Cyanide consumption will be an absolute maximum of 45 tons per month and a maximum of 2 truckloads (2x30 tons) in dry cyanide stock at any time or alternatively 2 x 30 tons tanks of liquid cyanide. The cyanide storage and liquid delivery area will be per the "Guideline for the Compilation of a mandatory code of practice on cyanide management for gold mining". The cyanide storage yard will be next to the cyanide make-up area and will be bunded and any rain or wash water flow will be directed to the cyanide bund spillage pump, which directs spillage to the leach tank or the detox tank in absolute emergencies. The cyanide make-up bund has a capacity of 125% of the total makeup and storage tank capacity. In addition, the cyanide bund will be directly "uphill" from the leach tank bund.

3.4.4 Tailings Retreatment

3.4.4.1 General

Eight Tailings Storage Facilities (TSFs) were included in the cession of the Mining Right to Blyvoor Gold, which includes Blyvoor TSFs No. 1, No. 4, No. 5, No. 6 and No. 7 and Doornfontein TSFs No. 1, No. 2 and No. 3. The retreated tailings will initially be deposited on Doornfontein TSFs No. 1 and No. 2, followed by the reuse of the Blyvoor TSF No. 7 after its retreatment. Blyvoor TSF No.7 is intended to be retreated first and the remainder of the TSFs will remain in care and maintenance until retreatment. The planned method of retreatment is hydraulic mining and processing at the Tailings Retreatment Plant.

The retreated tailings will be pumped to a reception tank *via* a trash screen on top of the reception tank. The clean slurry is pumped to a cyclone which diverts coarse ore to the milling circuit and size ore to the thickener feed trash screen. The thickened slurry is pumped to a preoxidation tank in which the ore is oxidised by oxygen injection into a leach reactor. The oxidised ore reports to a Carbon in Leach (CIL) circuit that leaches and adsorbs the gold in a preg robbing environment. The gold will then be recovered through the existing plant elution and smelting circuit. The residue from the CIL will be pumped and disposed of, onto Blyvoor TSF 6.

3.4.4.2 Tailings Retreatment Plant

The Tailings Retreatment Plant is located to the east of the former Blyvooruitzicht Golf Club. This plant will require major reconstruction to be operational again. The water pipeline servitude which runs from the plant to both Blyvoor TSF No. 7 and Blyvoor TSF. No. 6 is also approved but will need to be reconstructed due to being vandalised. The previously existing gold plant will be returned to operation and will be used to process the retreated tailings. The retreated tailings do not require a milling process. The plant process for the retreatment of tailings consists of thickening and leaching of slurry, gold absorption by a pump cell, carbon treatment, gold recovery (elution/smelting) and finally, residue disposal. The tailings after retreatment at the plant will be disposed on Blyvoor TSF No. 6 initially and thereafter onto the area vacated by the retreatment of Blyvoor TSF No. 7.

Additional deposition, if required could be accommodated on existing TSF sites without further impact on the environment or alternatively on a new site such as the golf course which is currently being evaluated. The water recovered from the tailings deposition will be returned to the treatment plant in an HDPE lined open channel for re-use.

The return water will pass through a sediment trap with the clear water discharged to Blyvoor TSF No. 7 Return Water Dam (RWD). Water will be fed under gravity from the RWD to the plant. In total, Blyvoor have now purchased eight TSFs that can be retreated. These are described in more detail below.

3.4.4.3 Blyvoor TSFs

Table 3.2 provides details of the five TSFs associated with the Project, namely Blyvoor TSFs No.1, No. 4, No. 5, No.6 and No.7. The deposition will continue onto Blyvoor TSF No. 6, while Blyvoor TSF No. 7 will be retreated and then used as a deposition site. Blyvoor TSFs No. 4 and No. 5 will be the first TSFs to be retreated. The remainder of the TSFs associated with the Mining Right will be under care and maintenance until these resources are retreated.

3.4.4.4 The Doornfontein TSFs

Table 3.3 provides details of the three Doornfontein TSFs that formed part of the sale to the Project and that occur within the Mining Right area, namely Doornfontein TSFs No. 1, No. 2, and No. 3. Due to the historic nature of the TSFs, these TSFS are not lined. While the waste rock dumps (WRDs) are not owned by Blyvoor Gold, it is also noted that they do not have underdrainage systems.

Table 3.2 Detail characteristics of the Blyvoor TSFs.

TSF	Description	Footprint	Height	Volume	Tonnes
Blyvoor TSF No. 1	Blyvoor TSF No. 1 was operated as an emergency dam and because of its relatively small top surface area. The deposition could only take place for a few hours per day. The TSF is a paddock dam.	29 ha	20 m	4,633,829	6,797,827
Blyvoor TSFs No. 4 and No. 5	Mostly retreated, but unlined.	69 ha	N/A	N/A	435,500
Blyvoor TSF No.6	Blyvoor TSF No. 6 was used for tailings placement during the retreatment of Blyvoor TSFs No.4 and 5 and underground operations. This ended in August 2013. Tailings were placed in a cyclone upstream deposition method. Prior to the retretment of TSFs No. 4 and No. 5. TSF No. 6 was divided into two daywall operated compartments. The RWD associated with the total capacity of the existing RWD is 143,000 m^3, this excludes the volume which has been allowed for the regulatory freeboard of 800 mm.	132 ha	26 m	2,9019,056	44,399,155
Blyvoor TSF No. 7	TSF No. 7 dam is a paddock dam. The dam is the highest TSF and, as indicated in the EMP, dated 2012, the TSF started showing signs of depression on the western flank of the upper compartment.	75 ha	48 m	26,741,680	40,460,161

Table 3.3 Detail characteristics of the Doornfontein TSFs.

TSF	Description	Footprint	Height	Volume	Tonnes
Doornfontein TSF No. 1	This TSF was mothballed when it attained its maximum designed height. The dam is characterised by steep side slopes with no step-ins. The dam was rehabilitated by the construction of cross walls and perimeter walls on the top surface. Catchment paddocks have been constructed around the toe of the dam to prevent the migration of eroded material. The dam is situated on the gently sloping ground and is not near to any watercourses. The area is fenced. The dam is situated on dolomite; as indicated in the EMP, dated 2012, no sign of instability had been noted.	54 ha	36 m	15,546,000	22,479,516
Doornfontein TSF No. 2	The TSF is characterised by fairly steep side slopes (1:2) with no step-ins. The dam is situated on the gently sloping ground. Catchment paddocks have been constructed around the toe of the dam to contain eroded material. Rehabilitation of the dam was implemented by the construction of cross walls and perimeter walls on the top surface. The area is fenced. The dam is situated on dolomite; as indicated in the EMP, dated 2012, no sign of instability had been noted.	37 ha	12 m	6,641,000	9,496,630
Doornfontein TSF No. 3	This TSF is situated on the gently sloping ground and consists of a tow paddock construction. Tailings were delivered *via* an in-wall piping system into a day wall operation. Surface water was decanted off the top surfaces of the paddocks *via* a penstock decant system. The penstock decant pipes conveyed the water by gravity to two return water dams approximately 500 m from the tailings dam. Catchment paddocks have been constructed around the toe of the tailings dam to contain eroded material. The area is fenced and there are no structures or services nearby.	73 ha	32 m	11,487,000	17,127,117

3.4.5 Support Infrastructure

3.4.5.1 General

The support infrastructure includes power supply, roads, water resources and management, as well as waste management on site.

3.4.5.2 Power Supply and Roads

Electricity supply to the surface and underground infrastructure will be a 132 kV Eskom supply ex the existing Doornfontein main substation, which will be refurbished. Electricity for the TSF plant will be obtained from an existing 22kV supply excluding the Eskom pump substation.

All road infrastructure required for operation is in place and approved.

3.4.5.3 Water Use and Resources

Blyvoor Gold has a Water Use Licence No 08/C23E/AEFGJ/1000 and water for hydraulic retreatment will be sourced from underground. Portable water will be supplied by Merafong Municipality.

3.4.5.4 Stormwater Management

The polluted runoff from the metallurgical plant areas used to be collected in trenches and directed to a sump and pumped back into the plant. Perimeter berms preventing clean stormwater runoff from entering the site were also in place. Optimisation of the clean and dirty water separation system at the plant areas will take place during the refurbishing of the plant.

The stormwater management measures that will be required for the re-mining of Blyvoor TSFs No. 7 and No. 6 are a berm and channel system around the perimeter of the TSFs to prevent clean water from entering the re-mining area and polluted runoff from leaving the re-mining area. The stormwater runoff from the re-mining area (for Blyvoor TSF No. 7) will be captured in a pollution control dam and re-used in the re-mining process or managed in the control dam if not possible to us in re-mining. The stormwater management system will be sized to comply with Regulation 704 of the National Water Act, 1998 (Act 36 of 1998) (NWA).

The clean stormwater runoff diversion system constructed around the perimeter of the TSFs will be sized to convey the flood peak generated from a 50-year 24-hour storm on the clean catchments. The RWD at Blyvoor TSF No. 6 has the capacity to store the runoff from a 50-year 24-hour storm event. The RWD capacity has been confirmed by external consultants. Similarly, the perimeter berm is sized to prevent the flood peak from a 50-year 24-hour storm falling on the re-mining area from entering the clean water system. The polluted runoff is directed to the pollution control dam. The pollution control dam is sized to spill on average once in 50 years as per Regulation 704. Consideration must also be given to integrating the clean water runoff system with the current diversion channel system preventing runoff from reporting to the Wonderfontein Spruit to reduce the risk of sinkhole formation.

3.4.5.5 Waste Management

General domestic waste (such as paper, plastic, organic matter, building rubble, wood, etc.) will be collected in bins and skips on site and transported to the Merafong Municipal landfill site. Hazardous waste, such as used oil and grease, and oil sludges from oil separators, etc., will be temporarily stored in a central collection point (in a bunded area), such as at the on-site salvage yard, for removal by a reputable company for recycling (such as Oilkol) or disposal.

Domestic wastewater (sewage) will be managed using chemical toilets and existing sewage plants (a plant designed to handle 1 per Ml per day and using the activated sludge process is located at No.5 Shaft – treated effluent will be discharged to the Wonderfontein Spruit or used for irrigation of vegetated areas on the TSFs). The No.5 Shaft sewage treatment plant (STP) will be refurbished to treat No.5 Shaft flows and flows from the underground ore metallurgical treatment plant sewage.

3.4.6 Employment

The Social and Labour Plan (SLP) dated 31 July 2017 and approved with the transfer of the mining operation form the liquidators to Blyvoor Gold, proposes targets of employment from surrounding areas and further afield. The SLP proposed a target of 70% of the workforce on the mine be from Merafong Local Municipality, and the remaining 30% be employed from within the Gauteng Province. The projected employment requirements for the first five years of operation are estimated between 729 and 732 employees as defined in the SLP for this period. After the first five years, the 2017 EMP projects employment of approximately 842 workers.

3.4.7 Proposed Mining Schedule

The estimated Life of Mine (LoM) for the Blyvoor underground operation exceeds 30 years, of which Blyvoor Gold has an operational strategic plan for the first 15. Tailings retreatment will be staggered within the 30-year LoM. Underground mining will take precedence and TSF retreatment will commence at a later stage of operations.

3.5 Baseline Conditions

The baseline conditions observed near the Project are comprehensively described in a series of specialist studies that serve as input into the EIA process. Instead of repeating the information, the reports listed below will be used and referenced as appropriate for information on the topography and drainage, geology and hydrogeology, meteorological conditions, as well as the population characteristics and social conditions:

- A description of the topography and associated surface water drainage characteristics of the area is provided in Digby Wells Environmental (2018e);
- A description of the local geology and associated hydrogeology is provided in Digby Wells Environmental (2018b);
- A description of the local meteorological conditions observed near the Project is provided in Digby Wells Environmental (2018d); and

- A description of the population characteristics and social conditions observed near the Project is provided in Digby Wells Environmental (2018c).

Where necessary and appropriate, the reports and associated descriptions are supplemented with information from the 2017 Environmental Management Programme (EMP) report for the retreatment and underground mining prepared by Golder Associates Africa (Golder Associates Africa, 2017) and the final scoping report (Digby Wells Environmental, 2018a).

Within the conceptual framework in Figure 1.2, this information provides input into understanding the potential release, subsequent distribution and accumulation of radioactivity from the Project into the environment and associated environmental media. It is thus used as a basis for the Source-Pathway-Receptor analysis presented in Section 4.

3.6 Radiological Conditions

3.6.1 General

The purpose of this section is to provide a summary overview of the radiological conditions associated with the Project. Section 3.6.2 discusses the radionuclide concentrations in the raw materials, products and by-products. Section 3.6.4 discusses the radioactivity released to the environment and observed through the monitoring and sampling of environmental media.

Note that very little radiological data and information of the site-specific conditions associated with the Project are available at present. The best information available is from a Public Hazard Assessment Report prepared for the Blyvooruitzicht Gold Mine in 2008. The author(s) of the report is unknown at present but since the report is useful as a reference, it was used and included as the Project report, referenced as Blyvoor Gold (2008).

3.6.2 Raw Materials and Residue Materials

3.6.2.1 General

Given the historical perspective of the Project, the expectation is that an extensive radiological data record exists of the raw material (e.g., orebody) and residue materials (e.g., tailings material) generator through the historical mining operation. However, all indications are that if such a record did exist, then it got lost following the liquidation of the mine in 2013.

The documentation that was recovered and that is available at present contains no information that can be used to describe the radiological characteristics in terms of radionuclide content (i.e., full spectrum analysis results) of the raw and residue material generated by the mine in the past.

3.6.2.2 Activity Concentration of Tailings Material

Table 3.4 presents *estimated* radionuclide specific activity concentrations (with standard deviations) of the tailings materials associated with the Project. These values were derived based on values deemed representative of the tailings material generated from the orebodies in the area.

Table 3.4 Estimate of the radionuclide specific activity concentrations of the tailings material associated with the Project.

Radionuclide	Activity Concentration	Standard Deviation
	Bq.kg^{-1}	
U-238	413	58
U-234	419	58
Th-230	419	58
Ra-226	461	20
Pb-210	561	30
Po-210	561	30
U-235	19	3
Pa-231	19	3
Ac-227	19	3
Ra-223	19	3
Th-232	31	7
Ra-228	40	12
Th-228	39	11

3.6.2.3 Radon Exhalation Rate

Due to the presence of Ra-226 in the tailings material, radon gas will continuously be emitted to the atmosphere for as long as the facility, or a part thereof, remains on the surface. To calculate the radon exhalation rate for the TSFs associated with the Project, the actual radon exhalation rate was scaled from the Ra-226 concentration in Table 3.4, using the following relationship derived from numerous studies conducted throughout the mining industry on TSFs. The relationship is given by (Ellis, 2006):

$$\text{Radon Exhalation Rate (Bq.m}^{-2}\text{.s}^{-1}\text{)} = (0.000554 \pm 0.000014) \text{ x (Ra-226)},$$

where Ra-226 is measured in Bq.kg^{-1}. This means that the estimated radon exhalation rate for the TSFs is in the order of 0.249 to 0.262 Bq.m^{-2}.s^{-1}.

3.6.3 Ventilation Shaft

Upcast ventilation shafts (or vent shafts) release air circulated through the underground workings to the atmosphere. Associated with this air from the underground working environment are particulates and radon gas that have the potential to expose members of the public living downwind of the release points to radioactivity. Radon concentrations measured in return air from underground workings is used to estimate the radon released from ventilation shafts.

It follows from the process description (see Section 3.4) that a brattice ventilation shaft for fresh and exit air will be implemented as part of the underground mining operation at No. 5 Shaft. Further details are not known at present. Assuming an average radon concentration of 2,000 Bq.m^{-3} in the exit flow, and an average flow rate of 700 m^{3}.s^{-1}, then the radon exhalation rate from the ventilation shaft will be in the order of 1.40E+06 Bq.s^{-1}.

3.6.4 Environmental Monitoring

3.6.4.1 General

Environmental monitoring data that are generally useful in the safety assessment process include radioanalytical results for samples collected from surface water, groundwater, soil, crops, animal products and fish. Again, no official records such as laboratory results are available at present. The 2008 report contains some data that was used in the dose assessment (Blyvoor Gold, 2008). However, no laboratory records were included in the report.

3.6.4.2 Water

The 2008 report include radioanalytical results from a watercourse near the Eastdene residential area that originates upstream from the AngloGold Ashanti Operation. However, the sampling location or when the sample was collected is unknown. The results are presented in Table 3.5.

Table 3.5 Summary of historical full spectrum analysis results available for the Project taken from Blyvoor Gold (2008).

Radionuclide	Water	Fish	Root vegetables	Leafy Vegetables	Fruit
	mBq.L-1	Bq.kg-1			
U-238	2080	1.13	1.9	3.06	0
U-234	2048	0	1.92	3.09	0
Th-230	71.6	0	0	0	0
Ra-226	204.2	0	3.8	4.76	2.94
Pb-210	1.8	0	0	0	0
Po-210	3.242	0.624	0.498	1.96	0.136
U-235	103.1	0.0521	0.087	0.141	0
Th-227	34.47	0	0	0	0
Ra-223	38.05	0	0	0	0
Th-232	8.62	0	0.217	0.25	0.13
Th-228	13.57	0	3.68	0	0
Ra-224	74.11	0	0	0	0

3.6.4.3 Fish, Crops and Fruit

The 2008 report include radioanalytical results from a fish sample, as well as a few crops samples that include root and leafy vegetables, and fruit. However, it is unknown where or when the samples were collected. The results are presented in Table 3.5.

3.6.4.4 Environmental Radon

Radon Gas Monitor (RGM) cups are used to measure the ambient radon concentration at specific locations. The RGMs are normally employed for periods of 2 to 3 months, after which the airborne radon concentration (in $Bq.m^{-3}$) can be calculated. Table 3.6 summarises the environmental monitoring data that are reported in Blyvoor Gold (2008) for locations near the Project.

Table 3.6 Summary of the environmental radon monitoring data reported in Blyvoor Gold (2008).

Location	RGM No			90th Percentile (Bq.h.m^{-3})	Exposure Period (h)	Radon Concentration. (Bq.m^{-3})
1 Power Street	88871	11806	33095	2.7E+04	1.4E+03	1.9E+01
1 Power Street	88872	11849	32907	2.6E+04	1.4E+03	1.8E+01
21 Southdene Crescent - Southdene	88873	11892	32699	3.7E+04	1.4E+03	2.6E+01
10 Kloof Street SouthDene	88875		32989	1.7E+04	1.4E+03	1.2E+01
26 Kloof Street SouthDene	88881	11310	32906	3.5E+04	1.4E+03	2.4E+01
CMTC	88886	11304	33094	3.4E+04	1.4E+03	2.4E+01
GM House Blyvoor Village	88890	11856	32767	2.2E+04	1.4E+03	1.5E+01
4 Ridge road Blyvoor Village	88896	11778	33116	2.1E+04	1.4E+03	1.4E+01
1st Avenue Blyvoor Village	88905	11785	32805	2.8E+04	1.4E+03	2.0E+01
Eastdene	88921	11818	32655	1.9E+04	1.4E+03	1.3E+01
DFN General Offices	88919	11301	33092	2.1E+04	1.4E+03	1.5E+01
6# SPH Offices	88924		32757	3.5E+04	1.4E+03	2.4E+01
5# Hostel Gate 1	88935	11303	33018	2.2E+04	1.4E+03	1.5E+01
DFN Pitstop	88948	11835	33012	1.8E+04	1.4E+03	1.2E+01
DFN 2nd Street	88952	11860		2.1E+04	1.4E+03	1.4E+01
DFN 2nd Street	88963	11302	32642	3.2E+04	1.4E+03	2.2E+01
DFN 1st Street	88961	11772	32852	3.4E+04	1.4E+03	2.3E+01
DFN 1st Street	88950	11826		8.9E+03	1.4E+03	6.2E+00

4 Source-Pathway-Receptor Analysis

4.1 Introduction

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

The radiological 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 for illustrating normal or probable situations of radiation exposure to receptors, which may include emergency exposure situations and existing exposure situations.*

The purpose of this section is to use the current understanding of the Project and its surroundings (see Section 3), bounded by the conditions and assumptions defined in the assessment context (see Section 2), to develop relevant public exposure conditions for the Project. Different approaches can be used to derive a discrete set of public exposure conditions. Consistent with the assessment framework presented in Figure 1.2, a Source-Pathway-Receptor (SPR) analysis approach was judged appropriate for the assessment. The SPR analysis approach is inherently systematic, traceable, and transparent, and provides the opportunity to identify and evaluate all possible exposure situations that may exist both now and in the future.

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

4.2 Key Concepts used in the SPR Analysis Approach

The SPR analysis approach consists of three interrelated steps. The first step is to identify all current, future and historical *sources* of radiation exposure associated with the Project. As used here, *sources* refer to any entity that contains radioactivity *and* have the potential to release the radioactivity into the environment to pose a potential radiological risk to humans and the environment. The sources are characterised in terms of its unique composition (i.e. specific radioactive substances present or emitted) and its 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 must be evaluated. In this context, *pathways* refer to how radionuclides may be dispersed or transferred within or between compartments of the environmental system, to a point where humans interact with the compartment. An *exposure route* refers to the route of entry into the human body to pose a radiation risk, such as ingestion, inhalation, or external exposure. Finally, *receptors* are defined and characterised. Receptors refer to humans that potentially may 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

In terms of the SPR approach, all relevant sources of radiation exposure associated with the Project must be identified. Sources of radiation exposure associated with mining and mineral processing facilities are induced by activities that enhance concentrations of naturally occurring radionuclides in the accessible environment. To pose a radiological risk to members of the public and the environment, these radionuclides first must be released from the sources of radiation exposure into the environment. Release mechanisms can be generalised into the following natural and human-induced conditions:

- Solid-, water-, and gas mediated release of radionuclides (natural);
- Direct gamma radiation (natural); and
- Controlled or uncontrolled releases of radionuclides into the environment (human-induced).

The sources are characterised in terms of their unique composition (i.e. specific radioactive substances present or emitted) and their characteristics, which will determine how contaminants may be distributed in the environment. Based on the description of the Project (see Section 3.4), two main types of sources can be identified: those that release airborne contaminants, and those that release waterborne contaminants.

In addition, note that 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 where naturally occurring radionuclides are released or stored as NORM with the potential to be released to the environment. *Secondary sources* are a consequence of primary sources and refers to the build-up of radioactivity in the environment.

4.3.2 Sources of Airborne Contaminants

4.3.2.1 General

The air quality impact assessment (Digby Wells Environmental, 2018d) focussed on all sources that may contribute to an airborne PM_{10} concentration and deposition of Total Suspended Particles (TSP). However, some of these sources may not contain naturally occurring radionuclides and, therefore, will not contribute to the radiological impact induced by the Project.

The radon exhalation and subsequent dispersion of radon gas through the atmosphere as input into the radiological impact assessment was evaluated by ParcScientific (Parc Scientific, 2018) and included all potential sources of radon exhalation.

4.3.2.2 Stack Emissions at the Metallurgical Plants

Two metallurgical plants are included in the Project process description. The No. 5 Shaft Plant will be used for the processing ore extracted from underground, while the Tailings Retreatment Plant will be used for the reprocessing of tailings material.

At this stage, it is uncertain whether these plants will be equipped with stacks. However, normally the releases of particulate matter from the processing plant stacks are insignificant at very low levels of naturally occurring radionuclides. This means that the contribution from the processing plants stacks to a radiological impact is expected to be insignificant as well.

4.3.2.3 Crushing, Milling and Screening Sections

Operational activities such as loading, crushing, milling and screening of RoM at the No. 5 Shaft Plant may generate dust and thus contribute to an airborne dust load. This group, if not associated with a wet process, may be a significant dust source, but the radiological properties of the RoM may be less significant relative to the more concentrated tailings material, for example. This means that the contribution from the crusher to a radiological impact is expected to be insignificant as well.

4.3.2.4 Tailings Storage Facility

Eight TSF complexes are associated with the Project. The way these TSFs will emit radioactivity to the atmosphere will differ since some of the TSFs are dormant, some will be retreated or used as deposition sites, while others have already been retreated.

Generally, the TSFs serves as the most significant source of airborne dust load. Windblown dust that may be emitted from the TSFs contains long-lived alpha radiating isotopes, which are dispersed into the atmosphere (solid-mediated release of contaminants, resulting in an *airborne activity concentration*). This radioactive dust is generally referred to as long-lived radioactive dust (LLα). In addition, the Ra-226 content of the tailings material may result in the emission of radon gas in the air (gas-mediated release of contaminants, resulting in an increase in *airborne activity concentrations*).

4.3.2.5 Ventilation Shaft

Up-cast ventilation shafts are the point on the surface at each mine where the air from underground is vented to the atmosphere. The contribution of the ventilation shafts as a point source of airborne radioactivity include:

- The release of dust particulates that contain LLα that are dispersed into the atmosphere, resulting in a quantifiable concentration of airborne radioactivity; and
- The emission of radon gas in the air resulting in a quantifiable concentration of airborne radon.

The refurbished No. 5 Shaft will also be utilised as the fresh and exit ventilation shaft for the underground workings. Figure 4.1 is a photo of the abandoned ventilation units at No. 5 Shaft.

Figure 4.1 Photo of the ventilation units at No. 5 Shaft. Fans being refurbished currently and diesel back up fan operational.

4.3.3 Sources of Waterborne Contamination

4.3.3.1 General

Several facilities or areas associated with the Project may contribute and serve as a potential source of waterborne contaminants. However, some of these facilities or areas are of importance from an inorganic contaminant perspective and may not necessarily contribute to the contamination of waterborne sources containing naturally occurring radionuclides.

4.3.3.2 Tailings Storage Facility

The main source of waterborne contaminants expected at the Project is the TSFs. Infiltration and subsequent percolation of water through the TSFs may induce leaching of radionuclides to the underlying aquifer (water-mediated release of contaminants, resulting in a *groundwater activity concentration*).

4.3.3.3 Plant Areas

The plant areas are included as a potential source of inorganic waterborne contaminants, because of the material that is handled and the possibility of spillages in the area. However, all run-offs from the plant area are contained and captured in the stormwater management system. It is, therefore, unlikely that the plant area with serve as a significant source of radiation exposure through the waterborne pathways.

4.3.3.4 Water Management Facilities

Several water management facilities are associated with the Project. These include return water dams and channels for the transfer of water between facilities. The nature of these water management facilities is such that their contribution as a source of radiation exposure is largely limited to water infiltration and subsequent leaching of radionuclides to the underlying aquifer (water-mediated release of contaminants, resulting in a *groundwater concentration*). However, the rate of infiltration is expected to be low compared to that of the larger area sources such as the TSFs.

4.3.3.5 Authorised Discharge of Water

The Project is licenced to discharge treated sewage effluent as well as surplus dewatered groundwater from the underground working into the Wonderfontein Spruit. The treated sewage effluent is not expected to contain naturally occurring radionuclides. However, the surplus underground water is expected to contain naturally occurring radionuclides. *Note that at the time of writing the report, more detailed information about the discharge of water was not available.*

4.3.4 Radiological Characteristics of the Sources

Section 3.6 summarised the available radiological data and information for the Project. As discussed in Section 3.6.2, no data are available for the raw or residue material generated at the mine at present, or that are re-released to the environment as part of the Project. Assumptions for the radiological characteristic of sources will be made as part of the consequence analysis (see Section 3.6).

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 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 another 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.

4.4.2 Atmospheric Pathway

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

- The release and distribution of radon gas into the atmosphere and the subsequent inhalation of 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 on 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 atmospheric dispersion modelling for the Project uses information on dust emission from the sources identified in Section 4.3.2, together with meteorological data of the area to estimate dust concentrations and dust deposition rates at various distances from the sources. Figure 4.2 is a graphical representation of airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$), dispersed from all the atmospheric pathway sources at the Project, as derived from data presented in Digby Wells Environmental (2018d).

The modelled concentrations are shown as shaded zones with similar concentrations presented by a single colour (concentration isopleths) overlaid on a map of the Project and surrounding areas. The graphical edges of these concentration zones should not be interpreted as concentration boundaries, but rather as a continuum with some overlap between the indicated concentration values. In addition, the outside boundary of the concentration isopleths is not a cut-off beyond where there are no more airborne contaminants. It is a representation of the extent of the airborne pollutants at the lowest concentration value on the scale. Airborne pollutant concentrations continue beyond this boundary but are all lower than the lowest concentration value on the scale.

A similar representation of the annual average daily dust deposition rate (in units of $mg.m^{-2}.day^{-1}$) for the same sources is presented in Figure 4.3, while Figure 4.4 presents the airborne radon gas dispersion concentrations as derived from all radon sources. From Figure 4.2 and Figure 4.3 it is clear that the airborne dispersion of particulates and the subsequent deposition of TSP are not dominant in a specific direction but centred around the atmospheric pathway sources, with the TSFs the dominant contributors. What is also clear from Figure 4.2 to Figure 4.4 is that the area of impact diminishes very quickly, with the result that receptor locations such as Carletonville, Wadala, Khutsong and Welverdiend seems unaffected.

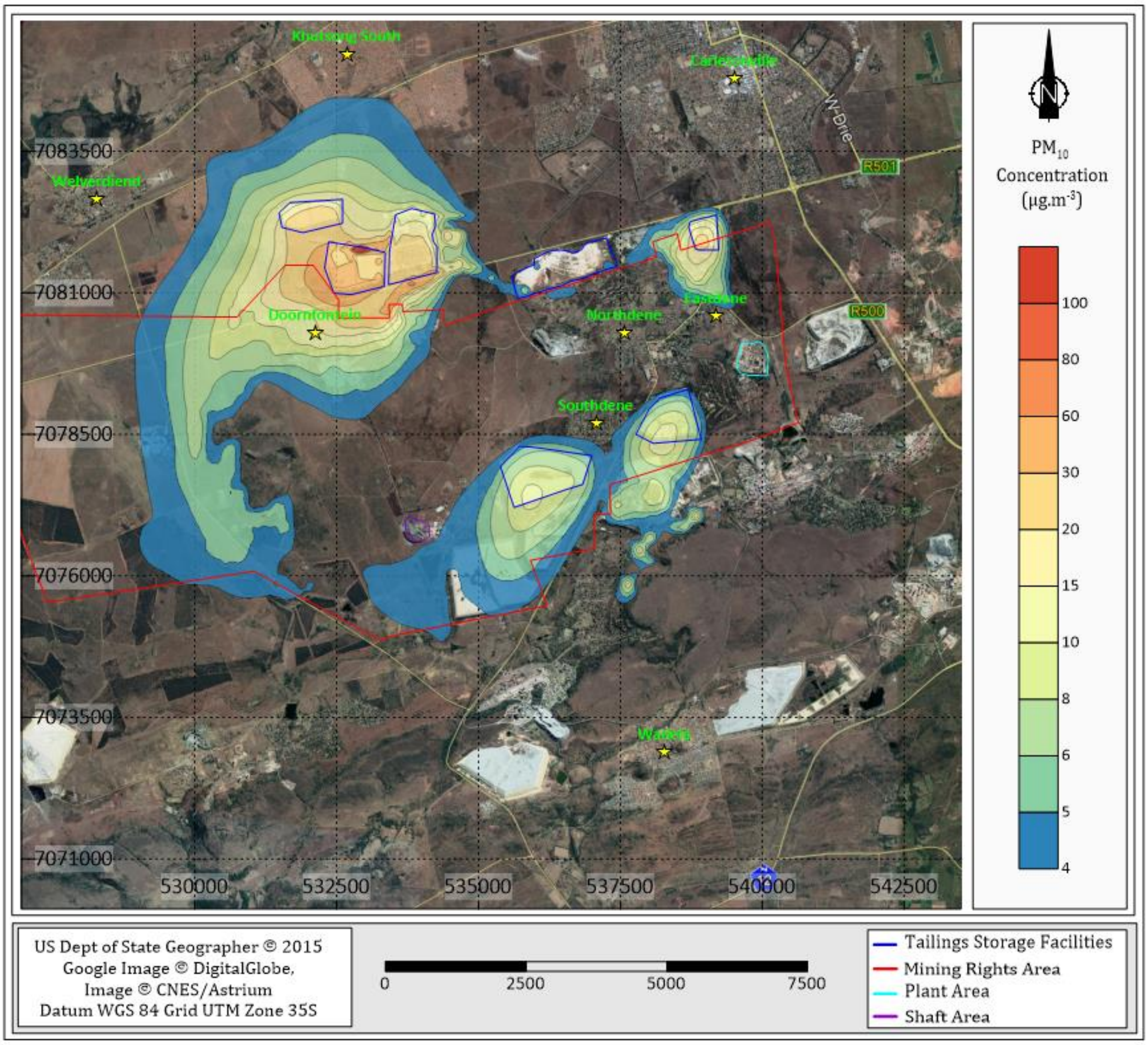

Figure 4.2 Annual average airborne PM_{10} concentrations at the Project using data from Digby Wells Environmental (2018d).

The flow diagram in Figure 4.5 can be used to evaluate the contribution of the atmospheric pathway to a quantitative total effective dose. As shown in Figure 4.5, airborne contaminants may be deposited onto surface soil, resulting in an increase in the concentration of radionuclides in the soil. 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 contaminated soil also contributes to an external gamma radiation dose (ground shine). In a similar manner, airborne contaminants may be deposited onto the surface water bodies, contributing to the contamination of surface water pathway (see Section 4.4.4). 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;

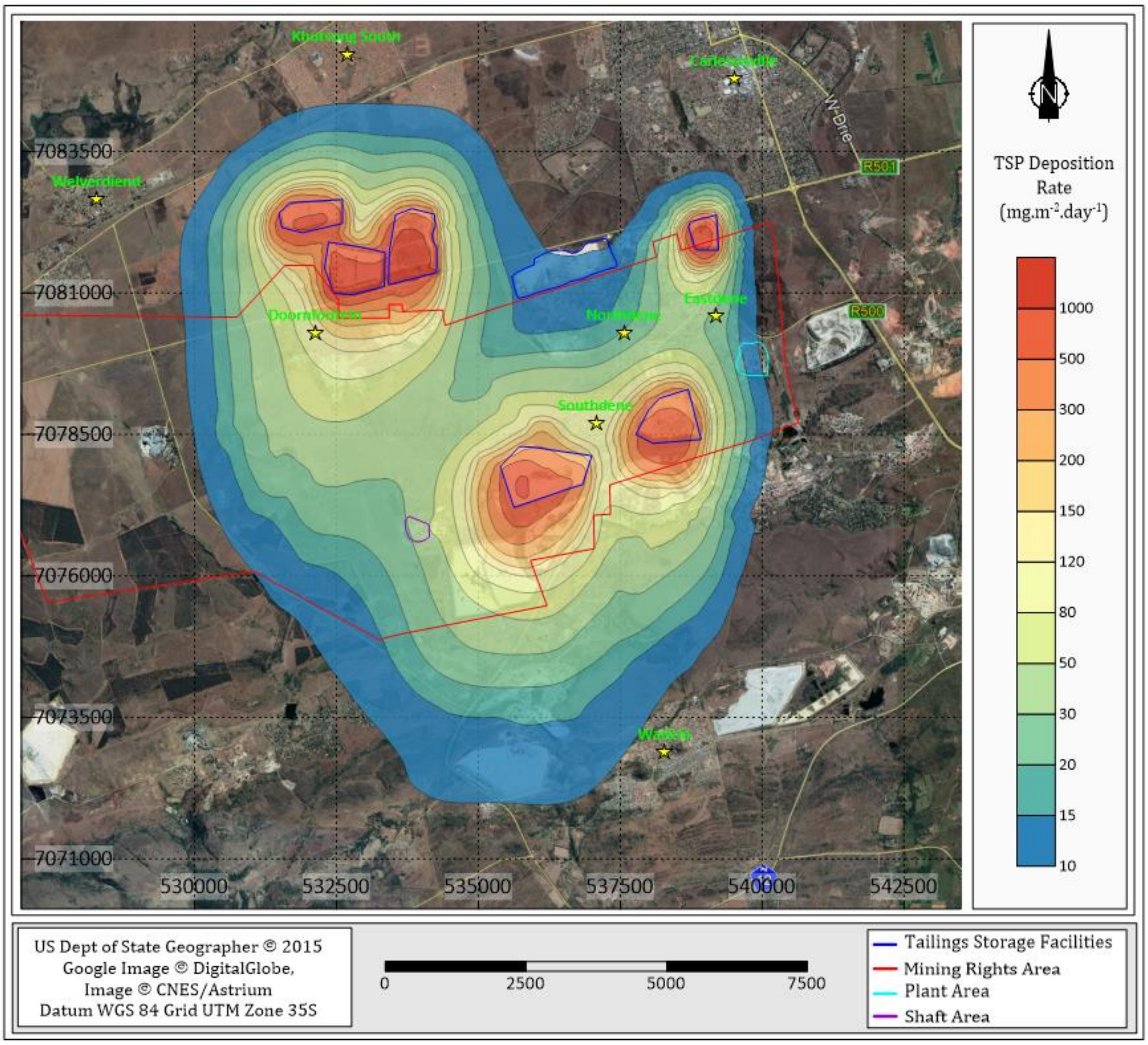

Figure 4.3 Annual average dust deposition rate of TSP at the Project using data from Digby Wells Environmental (2018d).

- Deposition of airborne contaminants onto the soil surface, followed by root uptake of contaminants from the soil; 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 plants (contributing to the radionuclide concentration of the soil). 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 may 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 of radiation received through the atmospheric pathway is the sum of the individual doses received through the ingestion, inhalation, and external gamma exposure routes.

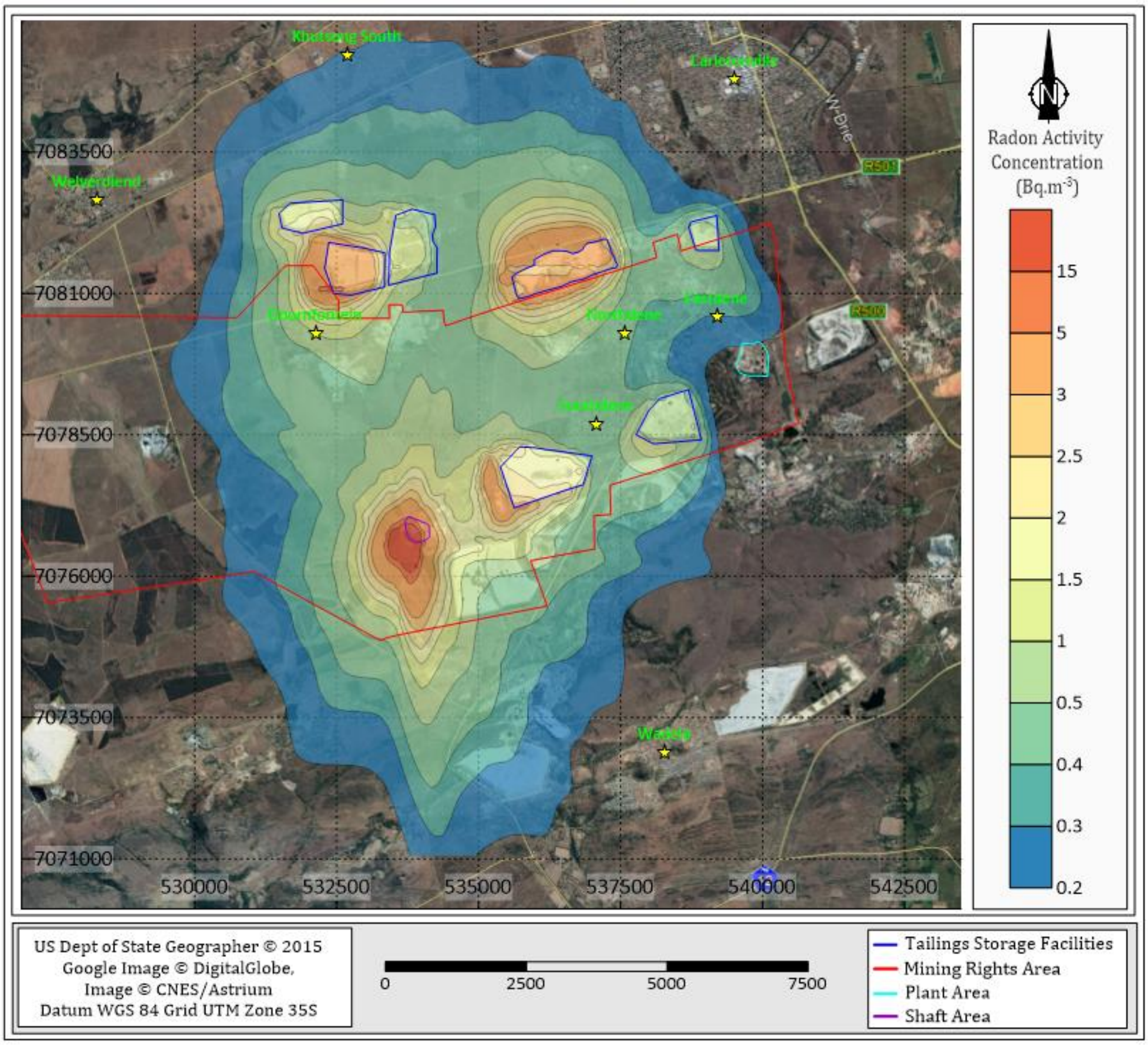

Figure 4.4 Annual average radon concentration for the Project, using the radon exhalation rates listed in Section 3.6.2.3 and Section 3.6.3 for the TSFs and ventilation shaft, respectively.

4.4.3 Groundwater Pathway

The significance of the groundwater pathway is due to naturally occurring radionuclides associated with some of the waterborne sources at the Project (see Section 4.3.3). During and after the operational period of the Project, these radionuclides may be released to the underlying aquifer.

The groundwater flow regime at the Project are documented in the currently available groundwater specialist studies (Digby Wells Environmental, 2018b). A numerical groundwater flow model is not available at present, but indications are that regionally the water levels follow the topography, which means that generally, the flow would be towards the low-lying areas. However, one can assume that on a local scale the regional flow regime is disturbed by large-scale abstraction and dewatering of the underlying compartments. Any groundwater flow would, therefore, be in the limited near-surface weathered aquifer.

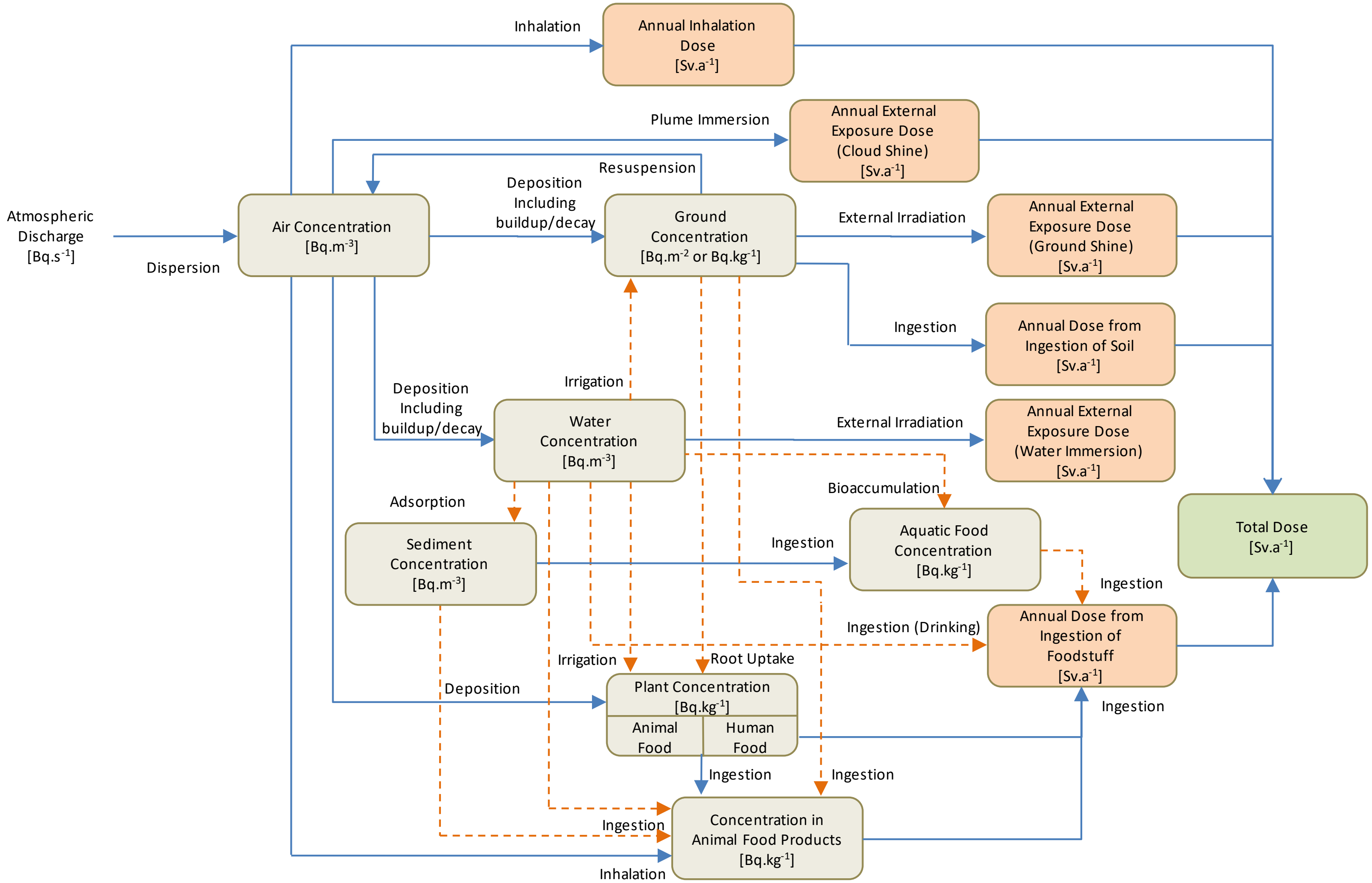

Figure 4.5 Features, processes and associated exposure modes that should be considered to calculate the contribution of the atmospheric pathway to a total dose.

The contribution of the groundwater pathway to the total effective dose is expected to occur through the release of naturally occurring radionuclides to the underlying aquifer, the subsequent migration of these radionuclides along the groundwater flow pathway to a point where members of the public abstract the groundwater. The total effective dose depends on how the abstracted groundwater is used, i.e., for personal (household) purposes, to irrigate a household garden, or to irrigate and sustain a farm system.

The flow diagram in Figure 4.6 can be used to calculate the contribution of the groundwater pathway to a quantitative total effective dose. Varying flow and the geochemical process will cause contaminants to leach from the various groundwater pathway sources to the underlying aquifer, resulting in a groundwater concentration. Through groundwater flow and radionuclide transport processes (e.g. advection, dispersion and diffusion), migration to various discharge points (e.g. surface water streams, rivers, dams, springs or boreholes) will occur. This will result in an increase in the groundwater concentration at these points. Groundwater movements may be very slow and geochemical reactions may retard the movement of radionuclides relative to the groundwater flow even further. Consequently, the radionuclides may take tens to thousands of years to migrate to groundwater discharge points such as boreholes (e.g. monitoring, drinking or irrigation borehole), fountains, and surface water bodies.

Depending on the radionuclide concentration of the groundwater as well as the human habit and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.6. These pathways are very 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.

4.4.4 Surface Water Pathway

Under normal operational 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 4.7 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).

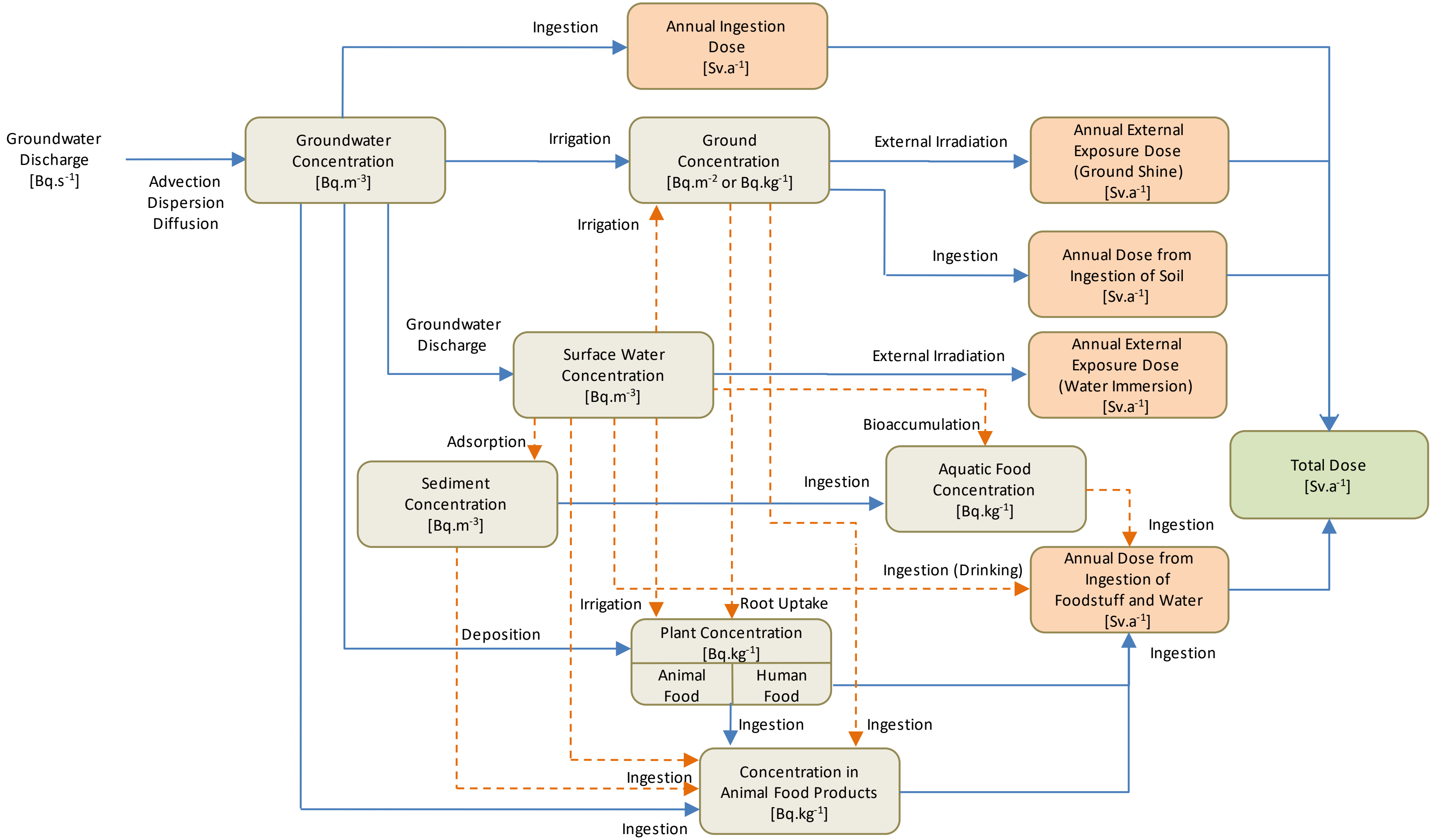

Figure 4.6 Features, processes and associated exposure modes that should be considered to calculate the contribution of the groundwater pathway to a total dose.

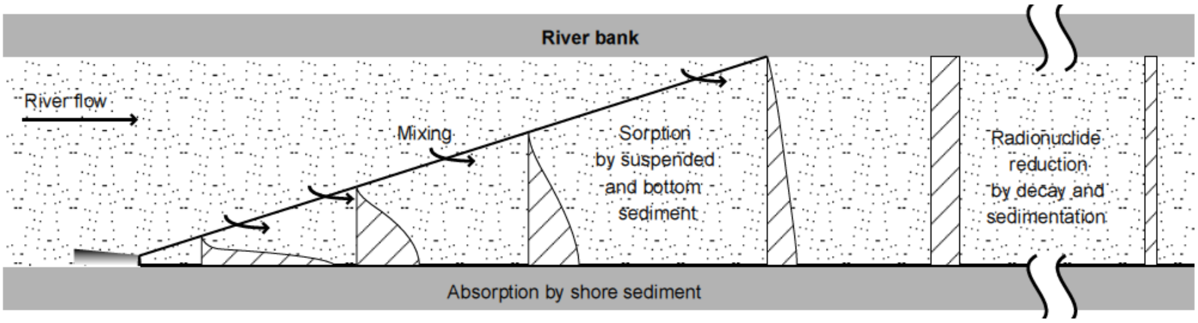

Figure 4.7 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001).

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.

The area is drained locally by small tributaries that drain north into the Mooiriverloop. The Mooiriverloop drains in a southwesterly direction where it flows into the Mooi River that flows southwards towards the Vaal River. Apart from these natural drainage courses, several water management facilities such as Return Water Dams are associated with the operations.

The flow diagram in Figure 4.8 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 habit and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.8. These pathways are very similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation with contaminated water contributes to radionuclide concentrations in crops or soil.

Direct exposure to the 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.

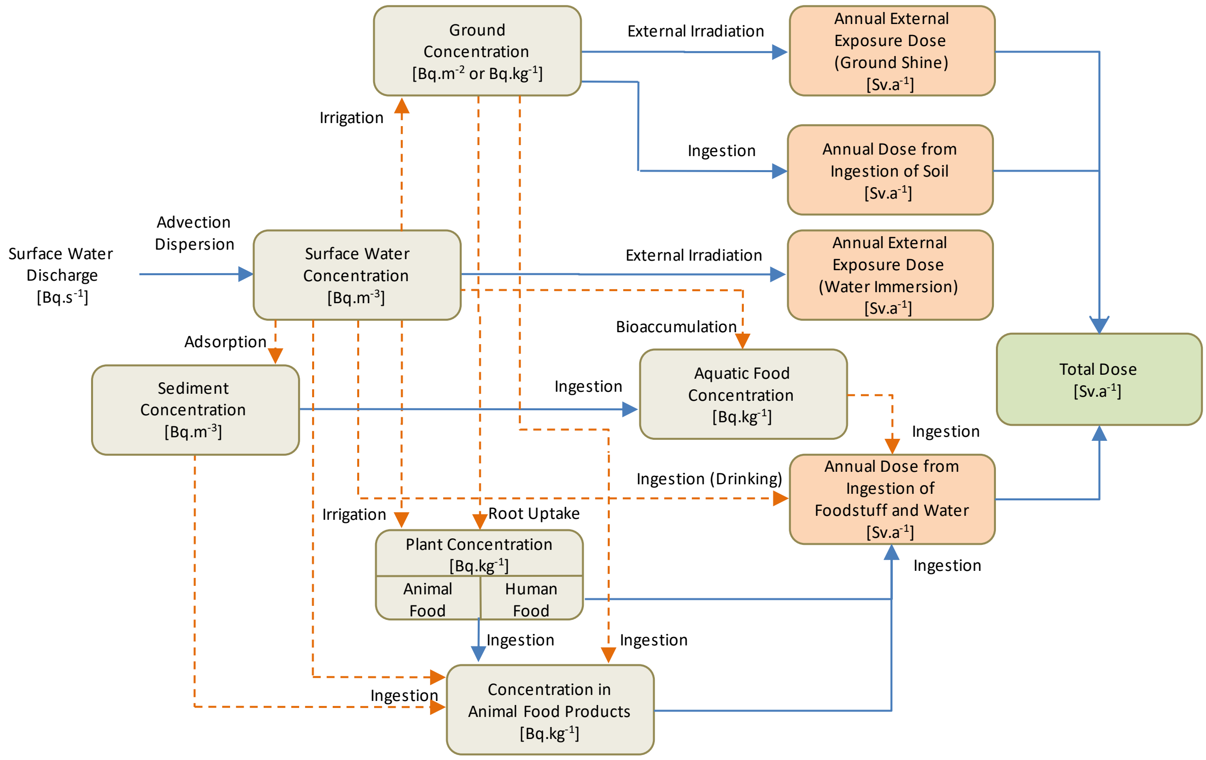

Figure 4.8 Features, processes and associated exposure modes that should be considered to calculate the contribution of the surface water pathway to a total dose.

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 (*external gamma radiation*). The main sources that are associated with external gamma radiation are the TSF. Gamma radiation from releases of contamination to the environment (secondary sources) is expected to be limited. Noted that 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).

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.

Regionally the land use conditions are characterised by commercial agricultural, formal and informal housing, and mining. Large population centres on a regional scale include Carletonville, and Oberholzer, Khotsong, and Wedela. On a local scale, the land use conditions are similar, with the Blyvooruitzicht mine's residential village areas (Northdene, Southdene, Eastdene, The Village, The Hillside and Doornfontein) as the closest areas of human settlement to the mine.

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 in a diverse manner. 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 generally 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 as 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 1.2 and Figure 4.9.

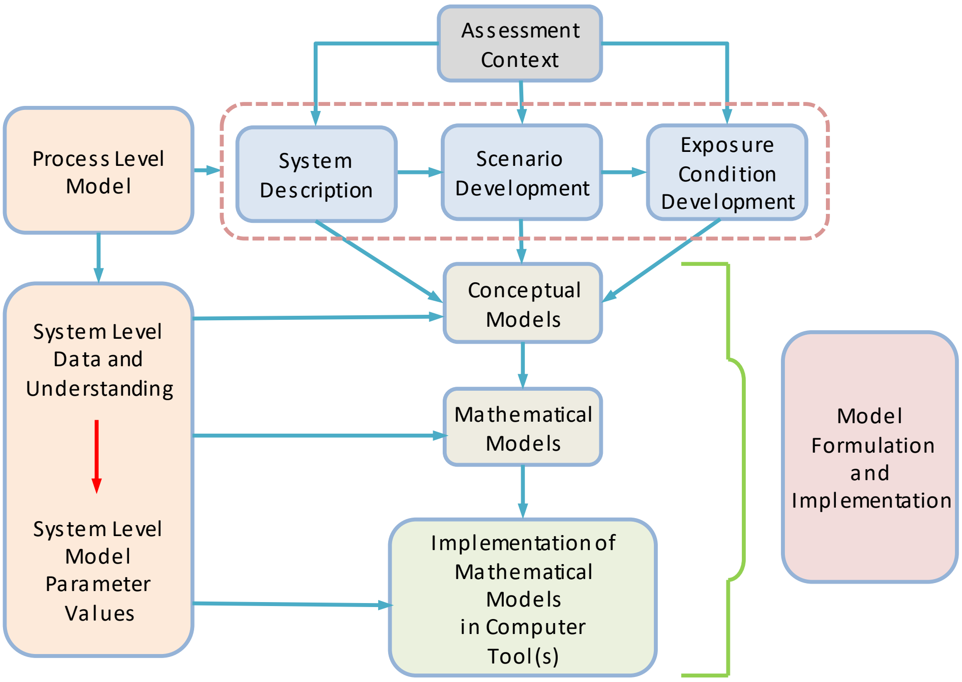

Figure 4.9 The model development process in relation to other elements of the assessment framework presented in Figure 1.2.

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. Specialist studies to quantify the behaviour of some of these environmental pathways have been done as part of the EIA process (Digby Wells Environmental, 2018b; d; e). Conceptual models developed as part of these studies will not be repeated here.

4.6.3 Representation of Conceptual Models for Exposure Conditions

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

Two methods are used to represent the exposure conditions conceptually: a process flow diagram and a RES Matrix or Interaction Matrix (Kozak and Zhou, 1998). In an Interaction matrix, the main variables or parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. A simple example of a 2x2 matrix is illustrated in Figure 4.10, 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.

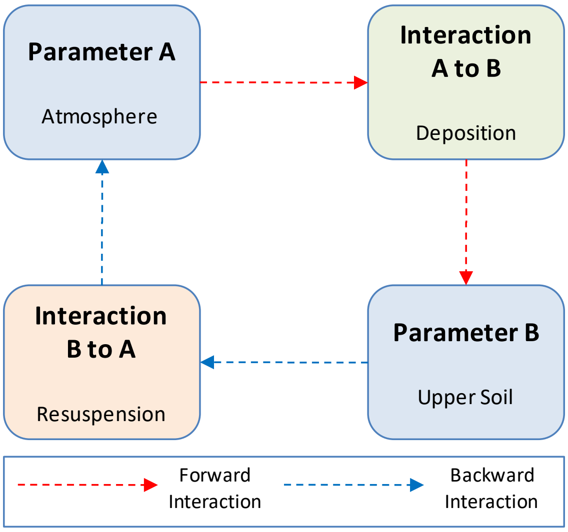

Figure 4.10 A simple 2x2 Interaction Matrix, showing the interaction between features, events and processes in a safety assessment.

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 influences the backward moment. This is illustrated in Figure 4.11, 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.

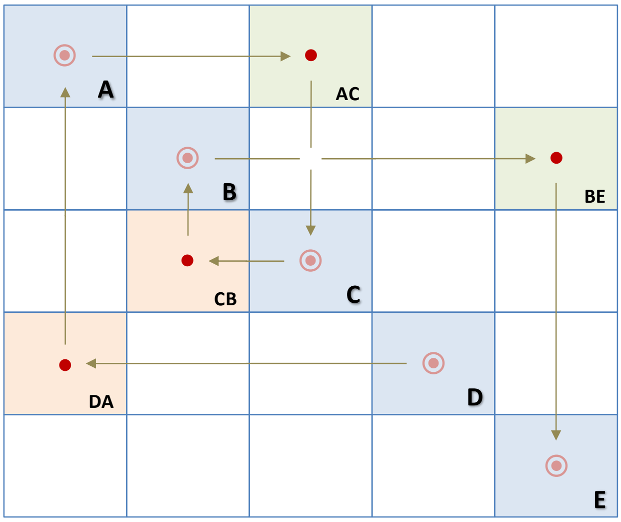

Figure 4.11 Principle of a radionuclide migration path through the Interaction Matrix.

Figure 4.12 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.

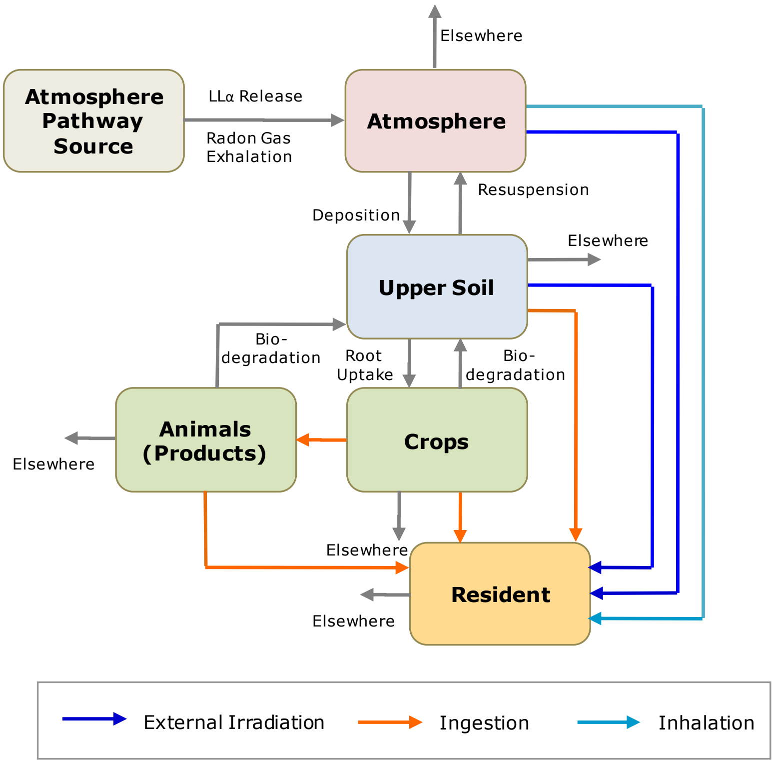

Figure 4.12 A flow diagram as an example of a conceptual model for a specific exposure condition, showing the exposure pathways and the relationship between the different compartments of the system.

4.7 Public Exposure Conditions for the Project

4.7.1 General

It follows from Section 4.1 that the radiological impact to members of the public can be evaluated through the development of a discrete set of site-specific public exposure conditions. Consistent with the provisions of RG-002 (NNR, 2013), the definition of an exposure condition can be further explained with the aid of a graphical representation that indicates all possible elements and parameters in the model, as well as the interactions between these elements (see Section 4.6).

4.7.2 Identification of Exposure Groups and Exposure Conditions

The SPR analysis presented in Section 4.3 to Section 4.5 identified various population groups, whose habits, location and other characteristics could cause them to receive a higher potential total effective dose than the rest of the exposed population. The three groups identified based on the available social and land use data as the most likely to be exposed to radionuclides released from the Project are:

- Residents (members of the public) residing in formal and informal residential areas;
- The small-scale and commercial farming community residing near the Project;
- Workers at nearby mines and other industries; and
- Downstream users of surface water from authorised discharge point.

Understandably, defining all exposure conditions for every potential receptor of radiation exposure at a mining and mineral processing operation is an impossible task, especially with the purpose of evaluating the potential radiological consequences. For this reason, the approach is to revert to a discrete number of exposure conditions that capture the diversity and complexity associated with the environment. With due consideration of the sources, pathways and receptors described above, the following three public exposure conditions can be defined to evaluate the potential radiological impact of the Project to members of the public under normal operating conditions:

- Residential Area Exposure Condition;
- Commercial Agricultural Exposure Condition; and
- Downstream Water User Exposure Condition.

More exposure conditions can be defined that would be relevant to the area and the Project. The key point of judgement whether the discrete set of exposure conditions are representative for 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.

4.7.3 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 formal structures (houses) and informal structures (less formal houses) in the affected residential areas near the Project. This includes areas such as Carletonville and Oberholzer, Khutsong, Wedela and the Blyvooruitzicht mine's residential village areas (Northdene, Southdene, Eastdene, The Village, The Hillside and Doornfontein).

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

The main contributor to a total effective dose for the Residential Area Exposure Condition is from the atmospheric and associated secondary pathways (i.e., the ambient air conditions). This may include contributions from external gamma radiation, internal exposure following ingestion of contaminated soil and crops, and internal exposure from the inhalation of airborne radon and LLα dust.

- Members of the public living in these residential areas are not dependent on surface water or groundwater as their only source of water since water is supplied through municipal structures.
- The contribution of the aquatic pathways will be evaluated as more realistic as part of the Commercial Agriculture Exposure Condition. Given the nature of this exposure condition, this would also represent a more conservative approach (i.e. cautious realistic).

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 consistent of fruits, vegetables (leafy and root) and cereal (mealies), which fulfil in 40% 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 40 % of their daily rate of protein consumption.
- Some food preparation methods (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, 2013), Table 4.1 lists the age group specific indoor and outdoor occupancy factors assumed for the purpose of the assessment.
- As a conservative assumption, the rate of incidental soil ingestion is maintained at 100% the value published in RG-002 (NNR, 2013).

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

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

The conceptual model for the Informal Residential Area Exposure Condition is presented in Figure 4.13 and Figure 4.14 using a flow diagram and Interaction Matrix, respectively.

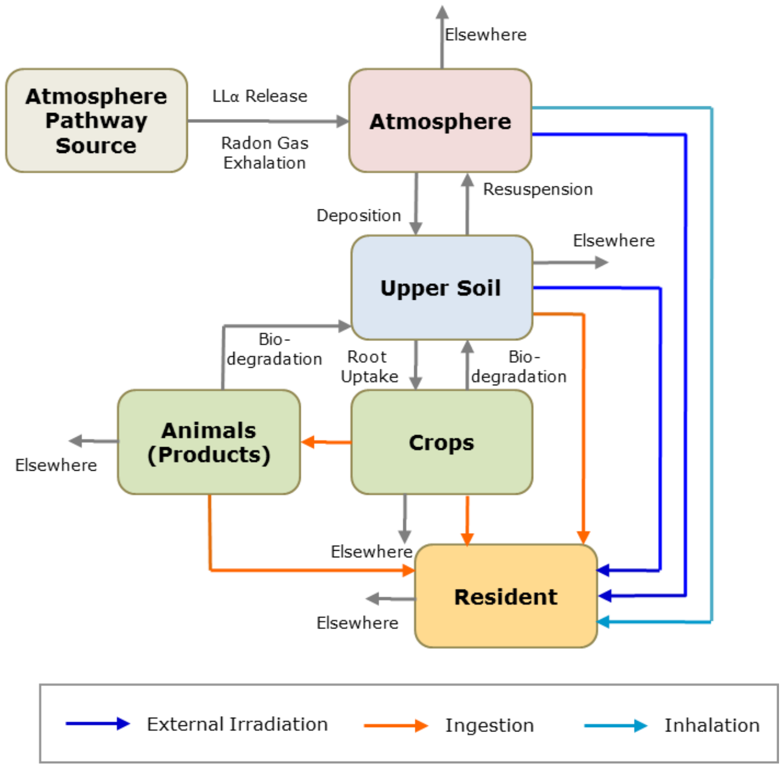

Figure 4.13 Conceptual flow diagram of the exposure pathways associated with the Residential Area Exposure Condition.

Radon gas and LLα released from the atmospheric pathway sources are dispersed into the environment, contributing to the increase in concentrations 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 4.13 and Figure 4.14, 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 4.13 and Figure 4.14, 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	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 4.14 Conceptual Interaction Matrix of the exposure pathways associated with Residential Area Exposure Condition.

4.7.4 Commercial Agricultural Exposure Condition

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

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

- The exposure groups (farmer 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 their 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 to 100% to their annual consumption rate.
- Some food preparation methods are used (e.g. boiling) that may contribute to a reduction in radioactivity concentrations. However, for this assessment, it is assumed that not food preparation takes place.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.1 lists the age group specific indoor and outdoor occupancy factors assumed for the purpose of the assessment.
- The conceptual model for the Commercial Agricultural Exposure Condition is presented in Figure 4.15 and Figure 4.16 using a flow diagram and Interaction Matrix, respectively.

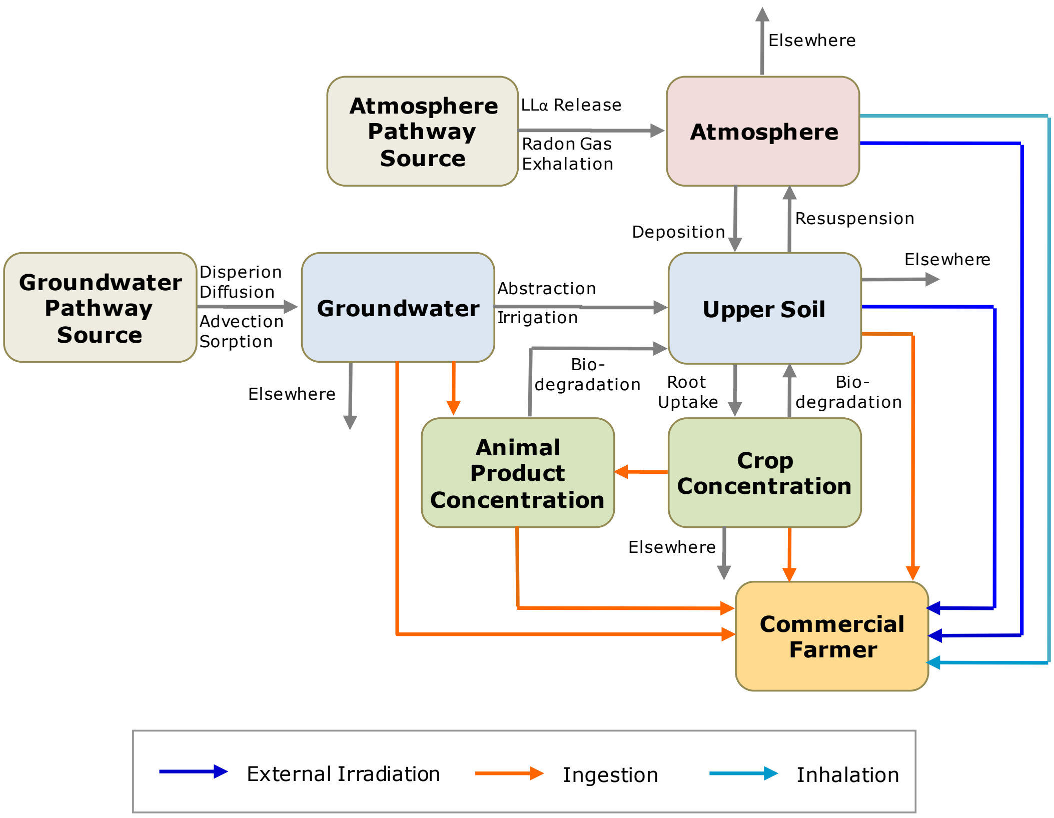

Figure 4.15 Conceptual flow diagram of the exposure pathways associated with the Commercial Agricultural Exposure Condition.

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.

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

Radionuclides leached from the groundwater pathway sources enter the underlying aquifer, from where it dispersed into the groundwater and surface water environments. Members of the public practising agriculture use groundwater abstracted from a borehole for their own 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 an 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.

Note that, as illustrated in Figure 4.15 and Figure 4.16, 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 4.15 and Figure 4.16, 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

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).

4.7.5 Downstream Water User Exposure Condition

The purpose of the Downstream Water User Exposure Condition is to evaluate the potential radiological impact to members of the public that might use surface water downstream from the authorised discharge point in the Wonderfontein Spruit. The main source of the discharged water is treated effluent that is not expected to contain naturally occurring radionuclides, and surplus underground water, which is expected to contain naturally occurring radionuclides.

5 Consequence Analysis

5.1 Introduction

Consistent with the safety assessment methodology (see Figure 1.2) and technical approaches therein, the purpose of this section is to assess and analyse the potential radiological consequences of the public exposure conditions in terms of the total annual effective dose as compliance criteria. The assessment results are then interpreted in terms of the regulatory compliance criteria (boundary conditions) as defined in the *Assessment Context* report (see Section 2.3.7). 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 Commercial Agricultural Exposure Condition. Section 5.3 presents an assessment and representations of the estimated total effective dose for the exposure conditions defined in Section 4.7.

5.2 Contribution from Groundwater Pathway

The Commercial Agricultural Exposure Condition assumes that groundwater abstracted from a borehole can be used to sustain the farm system. In principle, it is possible that the groundwater abstracted from the borehole is contaminated following leaching from the nearby TSFs. However, the leaching and subsequent lateral migration of radionuclides are a very 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 material and 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 numerical groundwater model using a compartmental modelling approach to represent the migration and fate of contaminants in the environment. The conceptual representation of the model System Level compartmental model implemented in Ecolego (Version 6) is presented in Appendix D.

To evaluate the potential radionuclides concentration in groundwater and the subsequent ingestion dose, hypothetical conditions complemented with site-specific conditions is used to illustrate the relative insignificance of the groundwater pathway over a short period of time (e.g. operational period). The activity concentrations listed in Table 3.4 are used as the initial activity concentrations, while Table 5.1 summarises a few additional parameter values assumed for the purpose of the leaching analysis.

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 a very conservative, assuming very 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 clearly represents a very conservative approach*.

Table 5.1 Summary of facility-specific parameter values necessary to calculate the leaching of radionuclides from the Doornfontein TSF No. 1.

Parameter	Units	Doornfontein TSF No. 1
Mean Annual Precipitation (MAP)	[mm]	781
Recharge Rate through TSF	[%]	6%
Annual Infiltration Rate 6% of MAP	[$m.y^{-1}$]	4.69E-02
Volumetric Moisture Content	[$m^3.m^{-3}$]	3.0E-01
Density of Tailings Material	[$kg.m^{-3}$]	2.625E+03
Average Height	[m]	36
Average Area	[m^2]	5.40E+05
Assumed Length and Width (√Area)	[m]	7.35E+02
Volume	[m^3]	2.65E+04

For this analysis, the areal extent (area) of the TSF listed in Table 3.3 was used. In addition, the unsaturated zone underneath the TSFs is conservatively assumed to be only 1 m thick, with a dry bulk density of 1,800 $kg.m^{-3}$, 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.

To estimate the potential migration of radionuclides in the underlying aquifer with time and distance, the following is further assumed for the underlying aquifer in each area:

- A conservative constant effective porosity of 0.02 (2%);
- A Longitudinal Dispersivity (α_L) of 50 m;
- A dry bulk density of 1 800 $kg.m^{-3}$;
- An aquifer thickness of 15 m; and
- A distance of 300 m to the nearest borehole.

The Doornfontein TSF No. 1 drains northwards towards the Mooiriverloop, which is about 4 km to the north of the TSF. Assuming a groundwater flow velocity in the underlying aquifer in the order of 1.2 $m.day^{-1}$ near the TSF towards the Mooiriverloop means the estimated Darcy velocity is in the order of 9 $m.year^{-1}$.

Figure 5.1 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 4,500 years (the Th-232 decay chain only become visible after 40,000 years). If one assumes the RG-002 (NNR, 2013) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.1 translate to water ingestion doses shown in Figure 5.2. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a point 300 m from the Doornfontein TSF No. 1 is only visible in hundreds of thousands of years, and potentially at doses that are below 100 $\mu Sv.year^{-1}$.

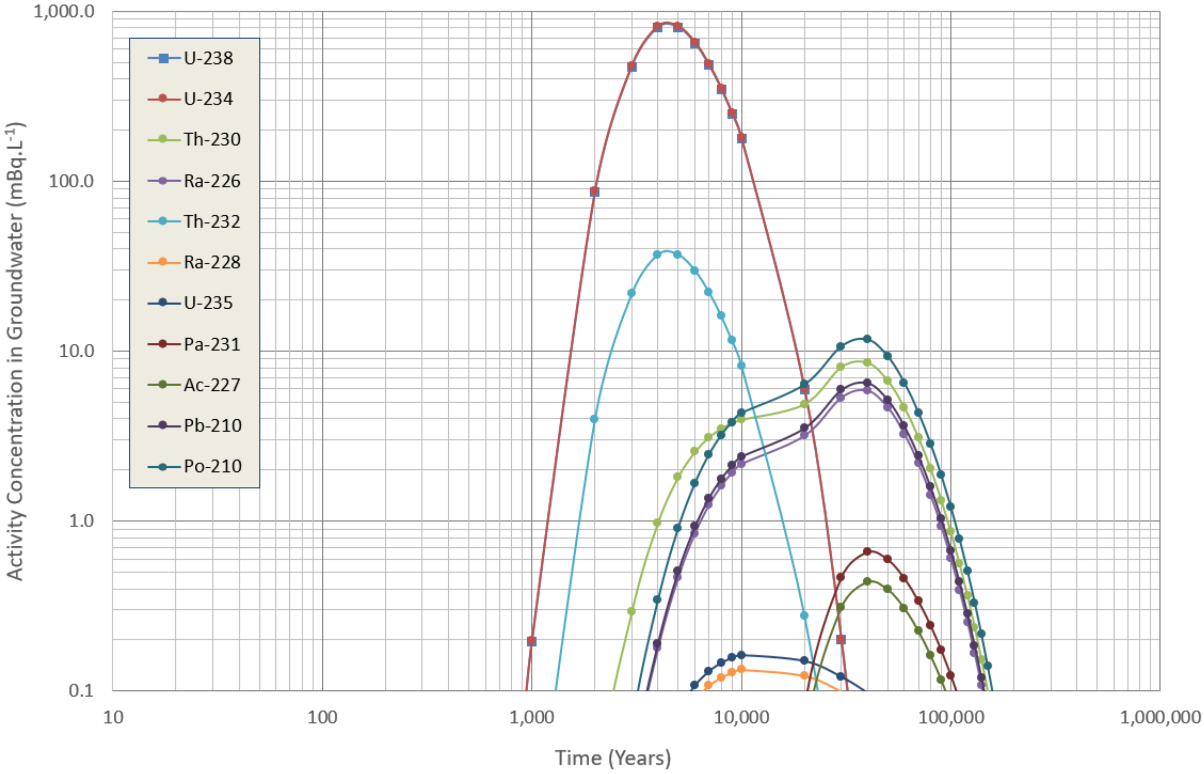

Figure 5.1 The simulated activity concentration in groundwater abstracted from a borehole 500 m from the Doornfontein TSF No. 1.

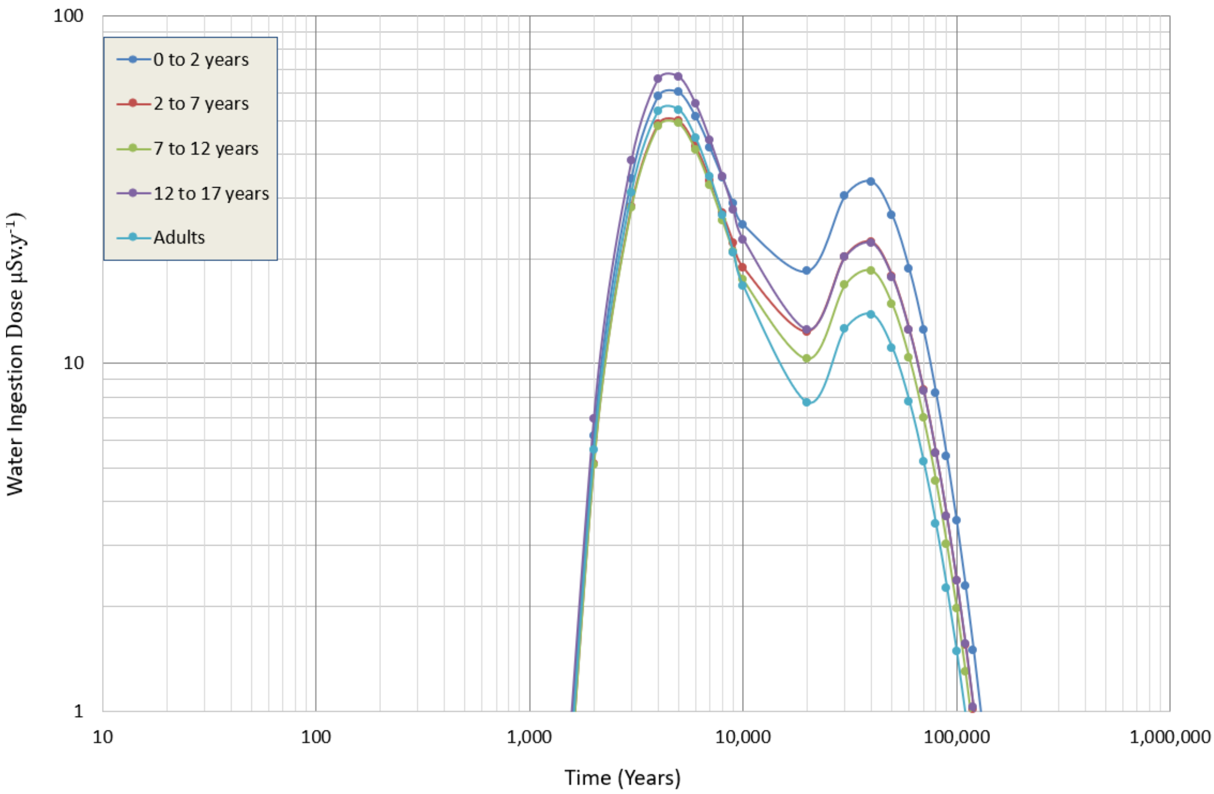

Figure 5.2 The simulated water ingestion dose to the different age groups 500 m from the Doornfontein TSF No. 1, using the activity concentrations in Figure 5.1.

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 each public exposure condition defined in Section 4.7 for the Project. 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.

5.3.2 Radon Inhalation Dose

The radon inhalation dose was calculated separately based on data provides in Parc Scientific (2018) and the resulting airborne radon concentration presented in Figure 4.4. Figure 5.3 presents the resulting radon inhalation dose using the dose conversion factor listed in Table B 2.

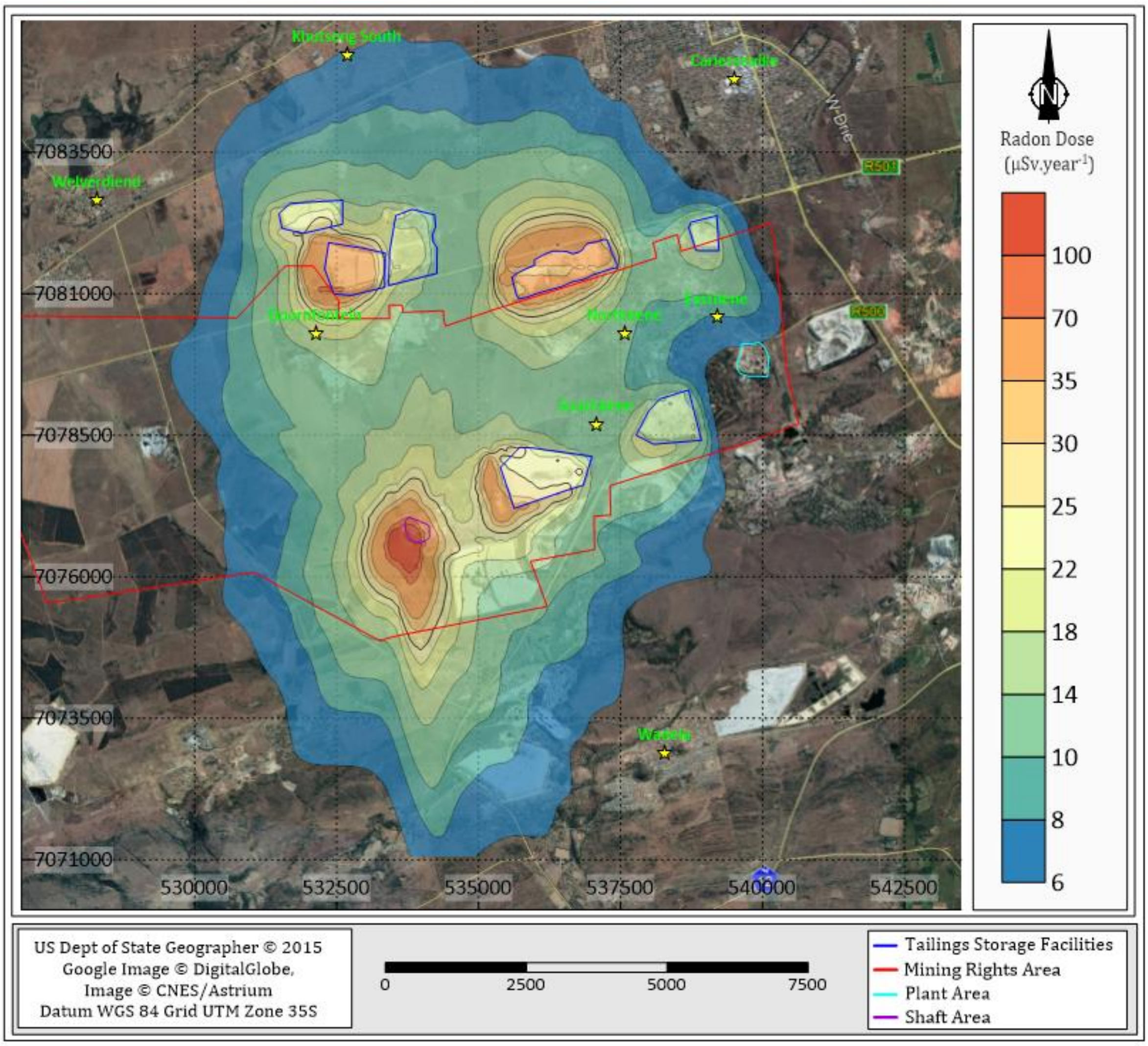

Figure 5.3 The distribution of the radon inhalation dose induced by the facilities associated with the Project, using the airborne radon concentration distribution in Figure 4.4.

Figure 5.3 shows that except for the areas near the TSFs and the ventilation shaft, the radon inhalation dose is less than 25 μSv.year^{-1}. The contribution of the ventilation shaft is the most significant, with doses as high as 250 μSv.year^{-1} in the immediate vicinity of the shaft. Note that these results are directly dependent on the radiological conditions assumed in Section 3.6.2 and Section 3.6.3 for the radon exhalation rate from the TSFs and the ventilation shaft.

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 living in residential areas near the Project. This includes larger residential areas such as Carletonville, Wedela and Khutsong, but also smaller areas such as Welverdiend, Doornfontein, Northdene, Southdene, and Eastdene.

The main contributor to a total effective dose for the Residential Area Exposure Condition is from the atmospheric and associated secondary pathways (i.e., the ambient air conditions). Consistent with the definition of the Residential Area Exposure Condition in Section 4.7.3, the total annual effective dose was calculated for a member of the public exposed through the following routes:

- Internal exposure following the inhalation of airborne radon and long-lived radioactive dust (LLα);
- External exposure from airborne long-lived radioactive dust (cloud shine), as well as from deposited dust on the soil surface (ground shine);
- Internal exposure following the ingestion of contaminated crops (fruit, leafy and root vegetables), cereal (mealies), and animal products (meat, milk, poultry and eggs); and
- Inadvertent ingestion of contaminated soil induced by the deposition of dust.

A dust deposition period of 40 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative. The calculations further assume that soil and crops are ingested at 40% of the published annual ingestion rate (see Section 4.7.3).

5.3.3.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Project and surrounding area. Figure 5.4 shows the dose isopleths for each of the five age group categories listed in Table B 1. Based in the doses estimated at the locations of the closest formal residential receptors, the '12 to 17 years' age group was shown to receive the highest annual total effective dose. Figure 5.5 presents the dose isopleths for the 12 to 17-year age group.

5.3.3.3 Interpretation of Results

From Figure 5.4 and Figure 5.5 it is clear that the dose isopleths for the different age groups are very similar, with the TSFs as the main contributor to the total effective dose, as expected. The doses are, therefore, highest close to the TSFs but decrease very quickly to levels below 100 μSv.year^{-1} with distance away from the Project.

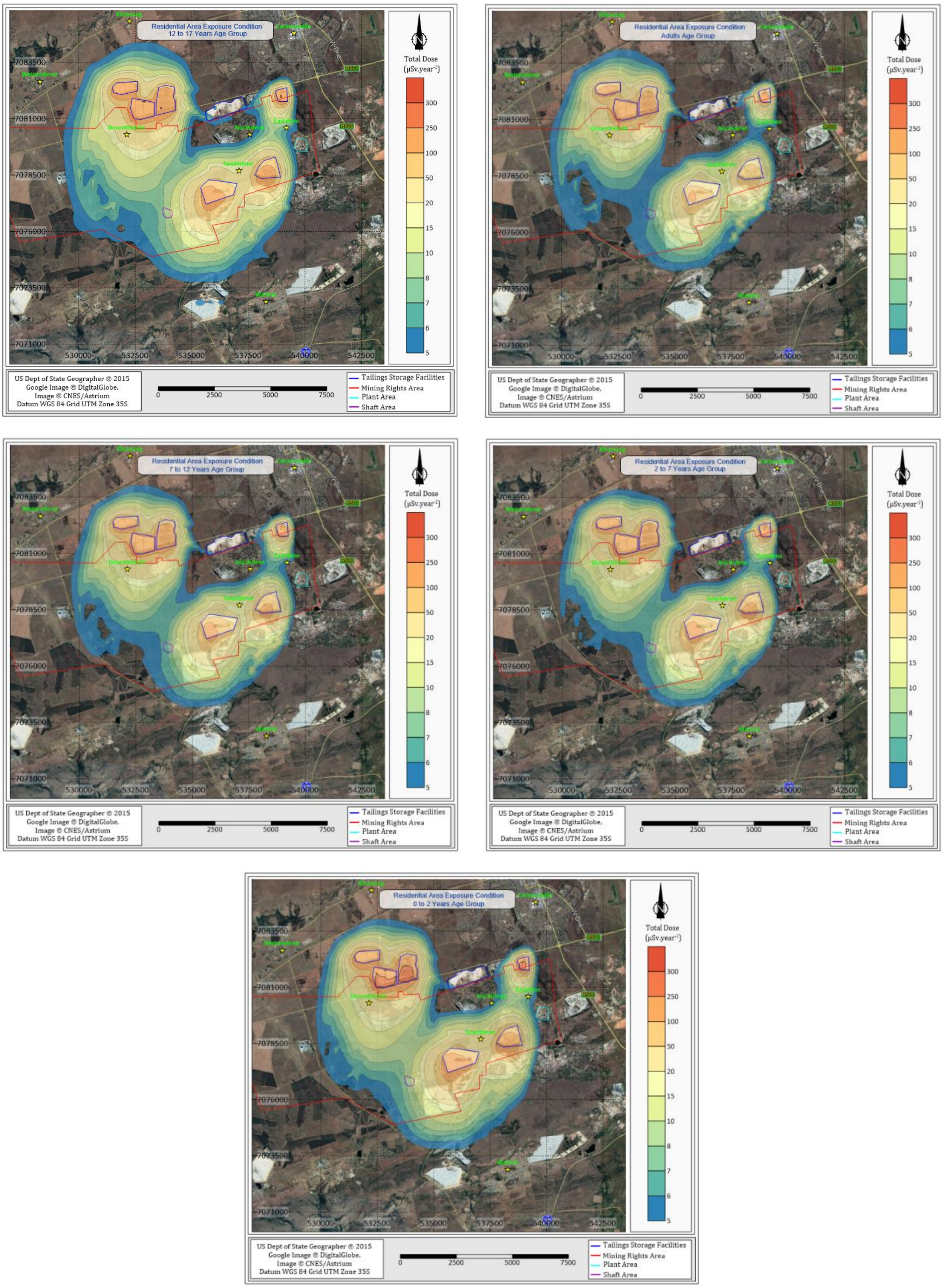

Figure 5.4 Age group specific dose isopleths representing the total effective dose associated with the Residential Area Exposure Condition for the Project.

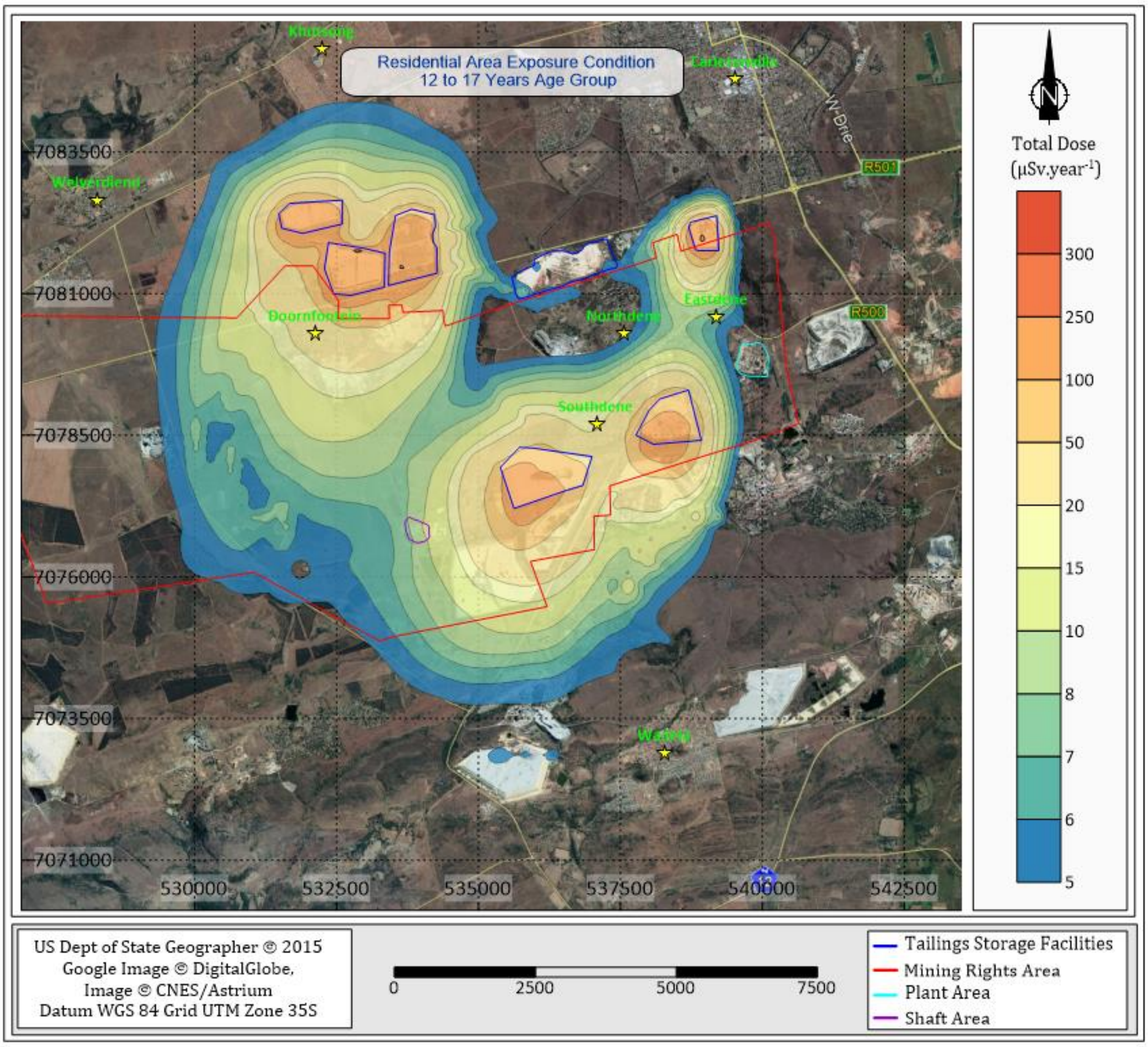

Figure 5.5 Dose isopleths representing the total effective dose associated with the 12 to 17 year age group for the Residential Area Exposure Condition for the Project.

In fact, the maximum total effective dose observed for this exposure condition is less than 200 μSv.year^{-1} outside the TSF boundaries of the Project, which means that even with the radon inhalation dose presented in Section 5.3.2 (see Figure 5.3) added, the dose will still be below 250 μSv.year^{-1}.

In addition, note that the dose isopleths presented in Figure 5.4 and Figure 5.5 represent a Residential Area Exposure Condition in any of the areas covered by the isopleths. However, not all these areas are necessarily residential areas. The total effective dose for the closest residential areas such as Doornfontein, Northdene, Southdene and Eastdene is less than 100 μSv.year^{-1}.

Note that the air quality study did not include the Blyvoor TSFs No. 4 and No. 5 in the estimate of the PM_{10} and TSP concentrations and deposition rates. This will result in an additional contribution similar to that of the radon inhalation dose shown in Figure 5.3. However, it is not expected to increase the total effective dose in the residential areas to level above those reported here. The conclusions will, therefore, remain the same.

5.3.4 Commercial Agricultural Exposure Condition

5.3.4.1 Dose Assessment

The purpose of the Commercial Agricultural Exposure Condition is to evaluate the radiological consequences to members of the public practising commercial farming near the Project. However, the exposure condition is equally relevant to agricultural activities practices anywhere near the Project. This means that this exposure condition relates to any farming activity for the conditions and assumptions presented in Section 4.7.4.

It follows from Section 4.7.4 that the main concern for the Commercial Agricultural Exposure Condition is the atmospheric, groundwater and associated secondary pathways. However, as illustrated in Section 5.2, it is highly unlikely that the groundwater or surface water pathways will make a significant contribution to a radiological impact, especially during the timescales of concern. The only remaining pathway is thus the atmospheric and associated secondary pathways (i.e., the ambient air conditions). Consistent with the definition of the Commercial Agricultural Exposure Condition in Section 4.7.4, the total annual effective dose was calculated for a member of the public exposed through the following routes:

- Internal exposure following the inhalation of airborne radon, thoron and long-lived radioactive dust (LLα);
- External exposure from airborne long-lived radioactive dust (cloud shine), as well as from deposited dust on the soil surface (ground shine);
- Internal exposure following the ingestion of contaminated crops (cereal, fruit, leafy and root vegetables) and animal products (mutton, beef, milk, poultry and eggs); and
- Inadvertent ingestion of contaminated soil induced by the deposition of dust.

A dust deposition period of 40 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative. The calculations further assume that soil, crops and animal products are ingested at 100% of the published annual ingestion rate (see Section 4.7.4).

5.3.4.2 Results

The results are presented in graphical form as dose isopleths overlain on a map of the Project and surrounding area. Figure 5.6 shows the dose isopleths for each of the five age group categories listed in Table B 1. Based in the doses estimated at the locations of the closest actual farmhouse, the ’12 to 17 years’ age group was shown to receive the highest annual total effective dose. Figure 5.7 presents the dose isopleths for the ’12 to 17 year age group.

5.3.4.3 Interpretation of Results

From Figure 5.6 and Figure 5.7 it is clear that the dose isopleths for the different age groups are very similar, with the TSFs as the main contributor to the total effective dose, as expected. The doses are therefore highest close to the TSFs but decrease very quickly to levels below 200 $\mu Sv.year^{-1}$ with distance away from the Project. However, as expected the calculated doses are higher than for the Residential Area Exposure Condition since it was assumed that the farmer and his family is 100% dependent on the land (oppose to the 40%).

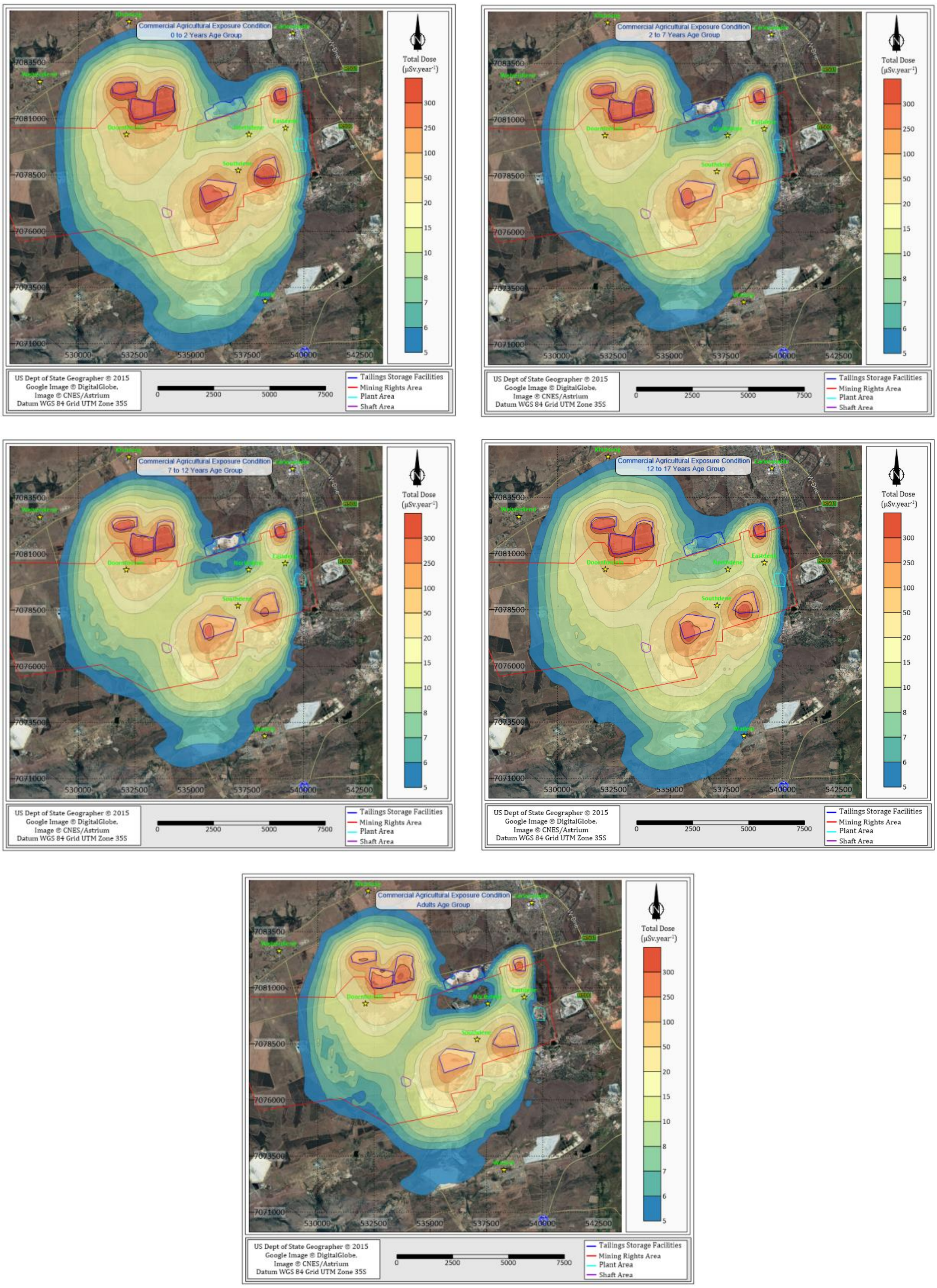

Figure 5.6 Age group specific dose isopleths representing the air pathway portion of the total effective dose associated with the Commercial Agriculture Exposure Condition.

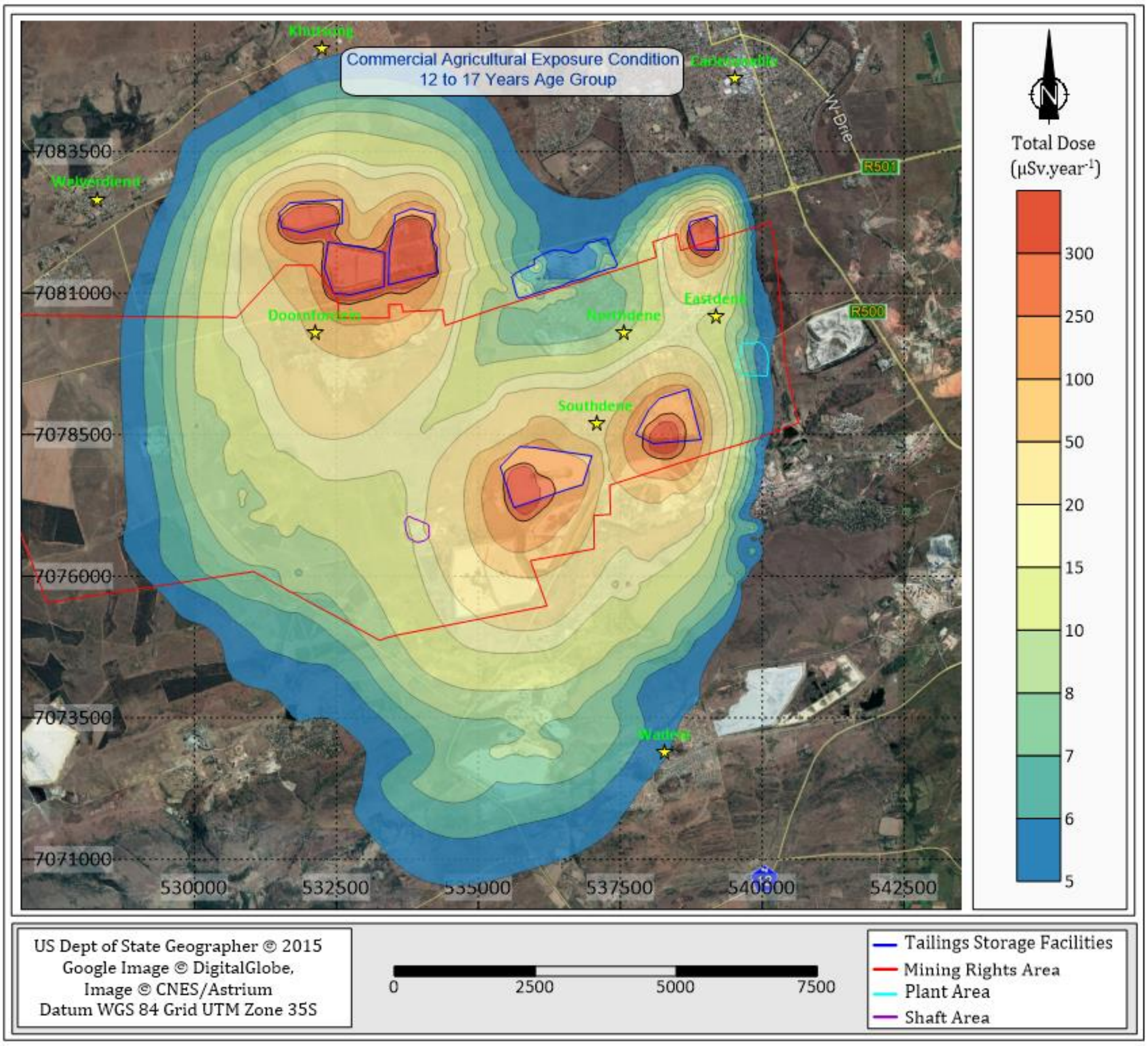

Figure 5.7 Dose isopleths representing the total effective dose associated with the 12 to 17 year age group for the Commercial Agriculture Exposure Condition for the Project.

The dose isopleths presented in Figure 5.6 and Figure 5.7 represents a Commercial Agricultural Exposure Condition in any of the areas covered by the isopleths. However, not all these areas are necessarily agricultural areas. In areas where agricultural activities can be expected (to the north of the Doornfontein TSF complex, as well as south and west of the Project) the maximum total effective dose that can be expected is less than 50 µSv.year^{-1}, which means that even with the radon inhalation dose presented in Section 5.3.2 (see Figure 5.3) added, the dose will still be below 100 µSv.year^{-1}.

Note that the air quality study did not include the Blyvoor TSFs No. 4 and No. 5 in the estimate of the PM_{10} and TSP concentrations and deposition rates. This will result in an additional contribution similar to that of the radon inhalation dose shown in Figure 5.3. However, it is not expected to increase the total effective dose in the agricultural areas to level above those reported here. The conclusions will, therefore, remain the same.

5.3.5 Downstream Water User Exposure Condition

Very little information is available for the conditions associated with this exposure condition, such as the activity concentration of the discharged water and the surface water stream at the point of discharge, the volume of water that is released, or the actual point of release. The same applies for the downstream users of the water.

While this exposure condition can, therefore, not be evaluated quantitatively it is still important to note that this might lead to a public radiation exposure condition. However, since it is assumed that it is an NNR authorised activity, it is also assumed that the potential public exposure is below the regulatory compliance criteria of 250 µSv.year^{-1}.

5.3.6 Conclusions

5.3.6.1 General

The conclusions presented here is based on the conditions and assumptions that were considered in the definition of the public exposure conditions for the Project and the associated parameters values that were used to derive the assessment results. This is important to note since very little site-specific information was available. In addition, the results are directly related to results and information available from specialist studies for the environmental pathways, notably the surface water, groundwater and atmospheric pathways.

5.3.6.2 Contribution from the Groundwater Pathway

Hypothetical conditions and parameter values supplemented with available site-specific information were used to evaluate the potential contribution of the groundwater pathway to a total effective dose.

The simulation results presented in Section 5.2 showed that radionuclides will be released (leached) from the different TSFs to the underlying aquifer for as long as the facility remains at the surface. However, the dissolution of radionuclides, the leaching and subsequent migration of radionuclides through the aquifer is a very slow process and it would take hundreds to thousands of years to migrate a few hundred meters from the TSF to an abstraction borehole. Even then the effective dose from the ingestion of the water is relatively low compared to the dose constraint (assuming the TSF remain at the surface for 1,000 years). If the facility is removed earlier, then the dose will be even lower.

5.3.6.3 Contribution from Radon Inhalation

A site-specific radon dispersion study was performed for the Project, with the various TSFs and the ventilation shaft as the main contributing sources. However, the radon exhalation rate from these sources was based on realistic but hypothetical parameter values.

The simulation results presented in Section 5.3 showed that the radon inhalation dose is highest close to the sources, with a general north-south dispersion pattern. The most significant contribution is from the ventilation shaft, followed by the Doornfontein TSF No. 1 and the Blyvoor TSFs No. 4 and No. 5. Note that the latter is just a footprint but remain a radon exhalation source.

Due to the nature of the ventilation shaft (point source opposes to areal source), the airborne radon concentration decreases very quickly with distance. This means that the dose contribution from radon inhalation in the area is generally less than 50 μSv.year^{-1}.

5.3.6.4 Residential Area Exposure Condition

The definition of the Residential Area Exposure Condition presented in Section 4.7.3 is conservative and assume that members of the public are dependent on household garden plots for 40% of their annual food requirements that include maize, vegetables, fruits, and animal products (eggs, milk and meat). The reason for this approach is to make provision for informal residential areas with different socio-economic requirements.

The main contribution for this exposure conditions is from the atmospheric pathway, with the results from the air quality study presented in Digby Wells Environmental (2018d) in terms of PM_{10} and TSP the basis of the assessment. The results are, therefore, directly related to the results of the air quality study.

The dose assessment simulation results presented in Section 5.3.3 showed that in the nearby residential areas such as Doornfontein, Northdene, Southdene and Eastdene, the total effective dose that includes the contribution of radon inhalation is less than 100 μSv.year^{-1}.

5.3.6.5 Commercial Agricultural Exposure Condition

The definition of the Commercial Agricultural Exposure Condition presented in Section 4.7.4 is conservative and assume that members of the public are dependent on the farm system for 100% of their annual food requirements that include maize, vegetables, fruits, and animal products (eggs, milk and meat). The reason for this approach is to make provision for subsistence farming conditions that might occur in the area.

With the groundwater pathway excluded (see Section 5.3.6.2), the main contribution for this exposure conditions is from the atmospheric pathway, with the results from the air quality impact assessment presented in Digby Wells Environmental (2018d) in terms of PM_{10} and TSP the basis of the assessment. The results are, therefore, directly related to the results of the air quality study.

The dose assessment simulation results presented in Section 5.3.4 showed that in the areas where agricultural activities can be expected (to the north of the Doornfontein TSF complex, as well as south and west of the Project) the maximum total effective dose that can be expected is less than 100 μSv.year^{-1}.

6 Impact Assessment

6.1 General

The purpose of this section is to present the radiological impact assessment rating for the Project. 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 Project, as presented in Section 5.

The impact assessment rating makes a distinction between the different phases of the project (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 because the timescales over which the pathways contribute to a potential radiological impact to members of the public differs. Where required, mitigation measures are proposed for activities during the different phases, followed by an impact rating for the revised (mitigated) conditions.

The section is structured as follows. Section 6.2 presents the radiological impact expected during the construction phase. The most significant radiological impact is expected during the operational phase, as presented in Section 6.3, followed by the post-closure phase presented in Section 6.4. Section 6.5 discusses any cumulative impact that might be of concern.

6.2 Construction Phase

All the Project TSFs and associated infrastructure are historical, and there is no intention to construct new TSFs. In addition, existing mining and processing infrastructure is used as far as possible, which means that construction activities will be limited to the refurbishment of the existing No. 5 Shaft and the upgrade of the existing infrastructure at the Processing Plant (within the existing footprints). The duration of these activities is expected to be short.

Activities that will be performed during the construction phase do not involve the handling, processing or releasing 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.

6.3 Operational Phase

6.3.1 General

The radiological impact assessment for the operational phase considers the potential contribution through all three the environmental pathways. However, due to the slow-moving nature of any radionuclide contaminant plume that originates from the Project facilities through the groundwater system, the potential radiological impact through the groundwater pathway will only occur during the post-closure (see Section 6.4).

6.3.2 Activities

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

- Exhalation and dispersion of radon gas from the dormant and operational TSFs, as well as the ventilation shaft;
- Emission and dispersion of particulates matter containing radionuclides from the dormant and operational TSFs, as well as during the crushing of ore from underground at the processing plant; and
- Controlled and uncontrolled releases of water containing radionuclides to surface water bodies;

Table 6.1 summarises the activities associated with the operational phase that may have a potential radiological impact on the receptors identified for the Project.

Table 6.1 Summary of the activities and the impact of the activities during the operational phase.

Interaction	Impact
Exhalation and dispersion of radon gas to the atmosphere	Radon gas will be vented to the surface as part of the underground ventilated system, while the radon gas generated in the tailings material due to the presence of Ra-226 will be exhaled to the atmosphere. Inhalation of the radon gas contributes to the total effective dose.
Emission and dispersion of particulate matter to the atmosphere	Wind erosion at the TSFs and ore crushing will cause particulate matter containing radionuclides to be emitted to 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.
Controlled and uncontrolled releases of water containing radionuclides into nearby watercourses	Controlled releases refer to authorised discharges of contaminated water into nearby watercourses, whereas uncontrolled releases refer to unauthorised discharges as well as runoff from contaminated areas and dirty water discharges into nearby watercourses. Ingestion of the contaminated water contributes to the total effective dose.
Retreatment of existing TSFs	The retreatment of existing TSFs means the removal of a source of radiation exposure to receptors identified for the Project that, in principle, means a potential reduction in the total effective dose through all relevant exposure routes.

6.3.3 Exhalation and Dispersion of Radon Gas

6.3.3.1 Impact Description

During the operational phase and for the duration of the LoM, radon gas generated underground will be exhaled into the atmosphere from the ventilation shaft and dispersed into the atmosphere. During the same period, radon gas generated in the tailings material due to the presence of Ra-226 will be exhaled from the various TSFs. These TSFs will be subject to different activities (see Section6.3.4.1), but these activities will not have a significant influence on the rate at which radon gas is exhaled from these facilities.

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 identified for the Project.

6.3.3.2 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 TSFs and ventilation shaft is well below the regulatory compliance criteria, which means that from a compliance perspective no additional management or mitigation measures are required. From dose optimisation perspective, the following can be noted.

The radon exhalation rate from the ventilation shaft is a function of the radon gas concentration underground and the air flow rate to surface from these areas. The latter is a function of the underground ventilation requirements, both in terms of providing sufficient air and to reduce the radon concentration underground for occupational exposure, which is critical. The only proposed management option for radon gas exhalation from the ventilation shaft is, therefore, to optimise the underground ventilation system in terms of the flow rate and the radon concentration underground.

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 subject to retreatment, 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 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.

6.3.3.3 Impact Rating

Table 6.2 presents the impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the Project.

Table 6.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	

6.3.4 Emission and Dispersion of Particulate Matter

6.3.4.1 Impact Description

During the operational phase and for the duration of the LoM, various TSFs will be subject to different activities that will influence the way in which particulate matter containing radionuclides will be dispersed into the environment through the atmospheric pathways. These activities include:

- Blyvoor TSF No. 6 will be operational as a deposition site for tailings material generated from the underground (mining) and surface (retreatment) operations;
- Blyvoor TSFs No. 4, No. 5, No. 6 and No. 7 will be remined to extract residual gold from the tailings material;

- Maintenance will be performed at the inactive TSFs that include Blyvoor TSF No. 1, Doornfontein TSF No. 1, Doornfontein TSF No. 2, and Doornfontein TSF No. 3; while
- Blyvoor TSFs No. 4 and No. 5 will serve as alternative deposition site that may become operational during the LoM.

Under worst case conditions, these facilities will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere for the duration of the operational period. Retreatment using hydraulic sluicing will reduce wind erosion only in those areas.

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

6.3.4.2 Management/Mitigation Measures

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

The total effective dose as a contribution from the windblown dust released from the TSFs and ore crushing is well below the regulatory compliance criteria, which means that from a compliance perspective no additional management or mitigation measures are required. 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 (Digby Wells Environmental, 2018d), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Develop a dust management plan for the Project;
- Use of electrostatic precipitators and a dust extractor system at the crusher;
- Application of wetting agents, dust suppressant or binders on the exposed area of the TSFs; and
- Vegetation of exposed area of the TSFs.

6.3.4.3 Impact Rating

Table 6.3 presents the impact significant rating for the emission and dispersion of particulate matter that contains radionuclides during the operational phase of the Project.

Table 6.3 Impact significant rating for the emission and dispersion of particulate matter that contains radionuclides during the operational phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	

6.3.5 The Release of Radioactivity to Surface Water Bodies

6.3.5.1 Impact Description

Authorised discharges of water containing radionuclides into watercourses will be within the regulatory compliance criteria and will not cause a significant radiological impact to downstream users of water. However, nearby watercourses may become contaminated due to unauthorised discharge of contaminated water as well as runoff from contaminated surfaces within the mining rights area into these watercourses. The dirty water areas associated with the Project include the TSFs and associated infrastructure, Mine Plant areas and the pollution control dams.

Contamination of watercourses will lead to the deterioration of water quality and associated sediments. Contributions to the total effective dose to receptors identified for the Project (downstream water users) include ingestion of contaminated water, soil, crops and animal products, and external gamma radiation through groundshine.

6.3.5.2 Management/Mitigation Measures

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

The conditions for authorised discharge into watercourses took into consideration the activity concentration of the water that is released, the volume of water released, the effect of dilution at the point of discharge, and the water use conditions downstream from the discharge point. The potential radiation exposure to members of the public will be below the regulatory compliance criteria for as long as the Project comply with the conditions of authorisation.

From a dose optimisation perspective, the following mitigation measures can be applied for the remainder of the activities. These measures, which are in line with the measures proposed in the surface water impact assessment (Digby Wells Environmental, 2018e), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- A surface water management plan should be developed to ensure that all runoff from dirty areas are directed to the existing stormwater management infrastructure (PCDs) and should not be allowed to flow into any of the nearby watercourses;
- Discharge of water that can potentially contain radionuclides to the nearby watercourses should only be allowed if discharge authorisation has been granted by the relevant authorities (including the NNR);
- The PCDs and dirty water channels should be lined either by concrete or High-Density Polyethylene (HDPE) to prevent contamination of groundwater through seepage; and
- Water quality monitoring should continue downstream and upstream of the mine site, and within all surface water circuits at the mine to detect any contamination arising from operational activities.

6.3.5.3 Impact Rating

Table 6.4 presents the impact significant rating for the release of contaminated water that contains radionuclides into nearby watercourses during the operational phase of the Project.

Table 6.4 Impact significant rating for the release of contaminated water that contains radionuclides into nearby watercourses during the operational phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Release of contaminated water that contains radionuclides into nearby watercourses during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 56
Duration	Beyond project life (6)	The impact will remain for some time after the life of the project and is potentially irreversible if not managed	
Extent	Municipal area (4)	Exposure potentially extends beyond the mining rights area into the nearby watercourses and their downstream users	
Intensity	On-going serious (4)	Impact expected in the nearby watercourses and associated sediments, with potential exposure to downstream users that are above regulatory compliance	
Probability	Probable (4)	It is probable that the impact will occur in the nearby watercourses	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 14
Duration	Medium term (3)	The impact has not occurred yet and is likely to occur only in the absence of a water management plan, maintenance plan and monitoring plan	
Extent	Limited (2)	The impact will be limited to the site itself and its immediate surroundings	
Intensity	Minor (2)	The intensity of the impact will reduce significantly with the proper implementation of the water management plan, maintenance plan and monitoring plan	
Probability	Improbable (2)	With the implementation of the water management plan, maintenance plan and monitoring plan the probability of the impact to occur is low	

6.3.6 Retreatment of Existing TSFs

6.3.6.1 Impact Description

One of the main objectives of the project is the retreatment of the existing TSFs, which by implication means that the facility is removed from the surface. Once removed and provided that the footprint area of the TSF is rehabilitated and clean-up, the implication is that the source of radiation exposure to receptors identified for the Project is removed. Under these conditions, this will result in a reduction of the total effective dose induced by wind erosion and radon exhalation.

6.3.6.2 Impact Rating

Table 6.5 presents the impact significant rating for the retreatment of the existing TSFs during the operational phase of the Project.

Table 6.5 Impact significant rating for the retreatment of the existing TSFs during the operational phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Retreatment of the existing TSFs during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective retreatment and rehabilitation of the footprint area will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Likely (5)	The retreatment of the TSFs is one of the objectives of the project, while the rehabilitation of the footprint areas is a strong recommendation, which means that the probability that the impact will occur is likely	

6.4 Post-Closure Phase

6.4.1 General

Before the actual closure of the Project and as part of the NNR licensing (CoR) conditions and requirements, a decommissioning plan will be prepared for submission and approval by the NNR. 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.

6.4.2 Activities

Considering that a decommissioning plan for the Project is not available at present, but will be defined and implemented as mentioned in Section 6.4.1, the following activities were identified that may result in a radiological impact to the receptors identified for the Project during the post-closure phase:

- Implementation of the NNR approved decommissioning plan;
- Exhalation of radon gas and the emission of particulates matter (PM_{10} and TSP) that contain radionuclides from the dormant TSFs (including those with unrehabilitated footprint areas); and
- Leaching and migration of radionuclides from the dormant TSFs (including those with unrehabilitated footprint areas).

Table 6.6 summarises the activities associated with the post-closure phase that may have a potential impact on the receptors identified for the Project.

Table 6.6 Summary of the activities and the impact of the activities during the post-closure phase.

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 are contaminated with radionuclides. These areas and any other area that was contaminated will be rehabilitated and cleaned for clearance by the NNR.
Exhalation of radon gas and particulate matter from the remaining TSFs to the atmosphere	Radon gas generated in the tailings material due to the presence of Ra-226 will be exhalated to the atmosphere. Inhalation of the radon gas contributes to the total effective dose. Wind erosion at the TSFs will cause particulate matter containing radionuclides to be emitted to the atmosphere. The airborne dust (PM_{10}) and deposited dust (TPS) contribute to the total effective dose through inhalation, ingestion and external radiation exposure routes.
Leaching and migration of radionuclides from the TSFs	Radionuclides will leach from the TSFs into the underlying aquifer, after which it 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.

6.4.3 Implementation of the Decommissioning Plan

6.4.3.1 Impact Description

The implementation of the decommissioning plan results in a positive impact in the sense that all surface infrastructure that contained or that are contaminated with radionuclides are demolished, decontaminated (to the extent possible), and removed from the site once compliance with clearance criteria has been demonstrated. A gamma radiation survey is performed at the infrastructure sites, followed by rehabilitation and clean-up for conditional or unconditional clearance from the NNR. In addition, an area that becomes contaminated during or because of operational activities will also be rehabilitation and clean-up for conditional or unconditional clearance.

6.4.3.2 Impact Rating

Table 6.7 presents the impact significant rating for the implementation of the decommissioning plan for the Project.

Table 6.7 Impact significant rating for the implementation of the decommissioning plan for the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Implementation of the NNR approved decommissioning plan for the Project			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Almost certain (5)	Within the NNR nuclear authorisation structures, the probability that the impact will occur is likely	

6.4.4 Exhalation of Radon Gas and Particulate Matter from TSFs

6.4.4.1 Impact Description

During the post-closure phase, some of the TSFs will remain at the surface as deposition sites for tailings generated from the underground operations and surface retreatment. Also, if the decommissioning plan was not implemented to its full extent, then there is a possibility that the unrehabilitated footprint of retreated TSFs is still at the surface.

Under worst case conditions, 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 material due to the presence of Ra-226 will be exhaled from the various TSFs.

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

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 identified for the Project.

6.4.4.2 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 and radon gas released from the TSFs is well below the regulatory compliance criteria, 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 (Digby Wells Environmental, 2018d) can be applied for the post-closure phase:

- Vegetation of exposed area of the TSFs to reduce wind erosion; and
- Covering layer over the exposed area of the TSFs to reduce wind erosion and radon exhalation.

6.4.4.3 Impact Rating

Table 6.8 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 Project.

6.4.5 Leaching and Migration of Contaminants from the TSFs

6.4.5.1 Impact Description

From the commissioning of a TSF, radionuclides contained in the tailings material leach from the TSFs to the underlying strata. The rate of leaching is controlled by complex geochemical and hydrological processes but generally are a very 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 to receptors identified for the Project through direct ingestion of water or the ingestion of crops and animal products as secondary pathways. The radiological impact along the groundwater pathway only manifest itself during the post-closure period after hundreds to thousands of years after closure.

Table 6.8 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 Project.

Dimension	Rating	Motivation	Significance
Impact Description: Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	

6.4.5.2 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 TSFs was hypothetically illustrated to be below the regulatory compliance criteria, which means that from a compliance perspective no additional management or mitigation measures are required. However, from an 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 as active institutional control periods.

Table 6.9 presents the impact significant rating for the leaching and migration of radionuclides from the TSFs the post-closure phase of the Project.

Table 6.9 Impact significant rating for the leaching and migration of radionuclides from the TSFs the post-closure phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Leaching and migration of radionuclides from the TSFs the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices are below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practices	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practices	

6.5 Cumulative Impact

Section 2.3.4.3 noted that a cumulative radiological impact to members of the public is possible in the areas, with possible contributions from the Sibanye West Driefontein Operations, Harmony Kusasalethu Operations and the AngloGold Ashanti West Wits Operations.

The scope of the assessment was limited to the Project and did not make provision for a regional assessment to evaluate cumulative effects (see Section 2.3.4.3). In addition, the application of the dose constraint as regulatory compliance criteria opposed to the dose limit of 1 $mSv.year^{-1}$ (or 1,000 $\mu Sv.year^{-1}$), as defined in Section 2.2.3, is to allow for the cumulative impact from more than one operation in an area. In other words, by constraining the Project in terms Regulation 388 to 250 $\mu Sv.year^{-1}$, provision is made for a cumulative impact while still in compliance with the public dose limit of 1,000 $\mu Sv.year^{-1}$.

7 Radiological Monitoring Plan

7.1 General

The NNR regulatory process requires CoR holders to submit a public Radiation Protection Programme (RPP) for approval by the NNR. The basis for the definition of the public RPP is the outcome of the comprehensive radiological public safety assessment and includes a monitoring programme, a surveillance programme and a control programme.

The purpose of this section is to define a radiological monitoring plan for the Project. The basis for the definition of the monitoring plan presented here is the outcome of the radiological impact assessment presented in this report, taken into consideration the radiological information available at present (see Section 3.6).

The section is structured as follows. Section 7.2 discuss the characterisation of the baseline conditions associated with the Project. Section 7.3 presents the proposed monitoring programme for the Project, while Section 7.4 presents the proposed monitoring locations.

7.2 Baseline Characterisation

Even though the Project is a historical operation, indications are that very little site-specific radiological information and data are available at present. For this assessment, the lack of facility-specific full spectrum analysis results was noted. In addition, it can be assumed that some areas that are included in the scope of the Project became contaminated during past operational activities.

The objective of the baseline characterisation is two-fold. Firstly, to establish the radiological condition of the site and associated infrastructure to develop an appropriate radiation management plan, and secondly to establish the radiological characteristics of radioactive material associated with the TSFs and other stockpile facilities that might be identified. For this purpose, the following activities are proposed:

- Gamma radiation, dose rate and surface contamination surveys (of the site and associated surface infrastructure) to establish the level of surface contamination associated with the Project and to identify radioactive material that requires management. Depending on the outcome of these surveys, some areas might require rehabilitation and clean-up before operations commence.
- Develop a sampling programme for each TSF to produce statistically representative samples of each TSF for full spectrum analysis. It is proposed that at each location, a sample from 0 to 1 m be collected, and another from deeper than 1 m. The reason being that the sample in the top layer represents the contribution to the atmospheric pathway, whereas the deeper zone represents the contribution to the groundwater pathway through leaching. It is also proposed that the representative sample from the top layer be divided into fractions below 10 micron

and above 10 micron. The reason being that the activity concentration is the smaller (inhalable) fraction tends to be higher.

- Determine the radon exhalation rate for each TSF. This involves the sampling of tailings material from different sections of the TSF, which is then used to determine the radon exhalation rate from the samples as a function of the Ra-226 content. This is a laboratory procedure.
- Perform a land use, human behaviour and interaction with the environmental study that can be used for a more comprehensive definition of the public exposure conditions.

The reason why these activities are not included in the monitoring programme defined in Section 7.3 is because for now it can be regarded as once of activities that might be repeated in 3 to 5 years, or as required for operational or authorisation requirements. The full spectrum analysis would be required for the NNR CoR application and associated radiological public safety assessment.

7.3 Monitoring Programme

Table 7.1 summarises the proposed monitoring programme for the Project aimed at public radiation protection. The responsibility for the implementation and execution of the monitoring programme lies with the Radiation Protection Function (RP Function) that include legally appointed persons consisting of a Radiation Protection Monitor(s) (RPM), a Radiation Protection Officer (RPO), and a Radiation Protection Specialist (RPS).

Table 7.1 Summary of the environmental monitoring programme proposed for the Project aimed at public radiation protection.

Monitoring Element	Comment	Frequency
Surface water	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Biannually
	Total Uranium and Thorium, and Ra-226	Quarterly
Sediments	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Annually
	Total Uranium and Thorium, and Ra-226	Biannually
Groundwater	Full spectrum analysis (U-238, U-235, Th-232 and progeny)	Once every two years
	Total Uranium and Thorium, and Ra-226	Biannually
Radon gas	Environmental radon using Radon Gas Monitors (RGMs)	Quarterly for a period of 2 to 3 month
	Radon exhalation from the ventilation shaft using RGMs	Continuously for a period of 2 to 3 month
Dust fallout	Total Uranium and Thorium, and Ra-226	Quarterly

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 analysis, as well as the Ra-226 analysis 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 is not expected in groundwater, oppose to surface water, for example. Therefore, a less frequent sampling schedule is proposed for groundwater. The same principle applies for the sediment samples at the same locations as the surface water sample.

The RGMs to 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 monitoring frequency for the ventilation shaft is continuous, since the exhalation of radon gas from the shaft is continuous.

7.4 Proposed Monitoring Points

Most of the monitoring points proposed to be part of the monitoring programme coincide with the monitoring programme for the environmental pathways. The following can be noted:

- The surface water monitoring locations should coincide with the monitoring points proposed in Digby Wells Environmental (2018e). The principle to be applied is that the monitoring locations should be upstream and downstream of the Project in potentially affected surface water streams, as well as upstream and downstream of specific 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 monitoring points proposed in Digby Wells Environmental (2018b). The principle to be applied is that the monitoring locations should be upstream and downstream of the Project, 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 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 influence by whether a secured location is available to improve the recovery rate of the RGMs.
- The dust fallout monitoring locations should coincide with the monitoring points (dust buckets) proposed in Digby Wells Environmental (2018d).

8 Conclusions and Recommendations

8.1 General

The purpose of the radiological impact assessment was defined as to demonstrate that members of the public living near the Project will not be exposed to levels of ionizing radiation above the regulatory compliance criteria for public protection and to assess the radiological impact on members of the public living near the Project as input into the EIA 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.

Presented here is some general conclusions in Section 8.2 derived from the radiological impact assessment results and recommendations in Section 8.3 for the improvement of the radiological impact assessment.

8.2 Conclusions

Following a systematic approach, three public exposure conditions were derived to be representative for the area, namely a Residential Area Exposure Condition, a Commercial Agricultural Exposure Condition and a Downstream User Exposure Condition. The atmospheric contributes to both the first two exposure conditions, whereas the groundwater pathway was included as a contributing pathway for the Commercial Agricultural Exposure Condition.

The focus of the Downstream User Exposure Condition was the authorised discharge of surplus underground water to the Wonderfontein Spruit. Due to a lack of site-specific data and information, this exposure condition was only evaluated qualitatively, with the conclusion that exposure will be below the regulatory compliance criteria for public protection.

Very little site-specific data and information related to the radiological characteristics of the Project were available. The results and conclusion from this study are, therefore, for the conditions and parameter values assumed for the assessment. These may change if site-specific data and information is used. The following was concluded from the total effective dose assessment results:

- The contribution from the groundwater pathway is only visible in thousands of years at maximum total effective doses less than 100 µSv.year^{-1}, which means that it cannot be considered as a contributing pathway for the Commercial Agricultural Exposure Condition during the operational phase of the Project;
- Conservatively no distinction was made between the formal and informal residential areas in the definition of the Residential Area Exposure Condition. The potential total effective dose in these areas during the operational period is not expected to be higher than 100 µSv.year^{-1} during the operational phase of the Project; and

- Conservatively it was assumed that commercial farmers are 100% dependent on the farm system to supply in their annual need for crops, fruit, vegetables and animal products as part of the Commercial Agricultural Exposure Condition. The potential total effective dose in these areas during the operational period is not expected to be higher than 100 μSv.year^{-1} during the operational phase of the Project.

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

These total effective dose assessment results were used to derive the radiological impact rating during the different phases of the Project. Table 8.1 summarises the radiological impact significant rating for the operational phase of the Project, while Table 8.2 summarises the radiological impact significant rating for the post-closure phase of the Project.

8.3 Recommendations

The radiological impact assessment made extensively use of assumptions for conditions and parameter values required for the dose assessment, which is not ideal. To improve this situation and to facilitate a more detailed assessment of the potential radiological impact that is consistent with the requirements for the NNR, it is recommended that the baseline characterisation, as well as the radiological monitoring programme defined in Section 7.3 be implemented at the locations defined in Section 7.4.

Table 8.1 Summary of the radiological impact significant rating for the operational phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	
Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	

Dimension	Rating	Motivation	Significance
Impact Description: Release of contaminated water that contains radionuclides into nearby watercourses during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 56
Duration	Beyond project life (6)	The impact will remain for some time after the life of the project and is potentially irreversible if not managed	
Extent	Municipal area (4)	Exposure potentially extends beyond the mining rights area into the nearby watercourses and their downstream users	
Intensity	On-going serious (4)	Impact expected in the nearby watercourses and associated sediments, with potential exposure to downstream users that are above regulatory compliance	
Probability	Probable (4)	It is probable that the impact will occur in the nearby watercourses	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 14
Duration	Medium term (3)	The impact has not occurred yet and is likely to occur only in the absence of a water management plan, maintenance plan and monitoring plan	
Extent	Limited (2)	The impact will be limited to the site itself and its immediate surroundings	
Intensity	Minor (2)	The intensity of the impact will reduce significantly with the proper implementation of the water management plan, maintenance plan and monitoring plan	
Probability	Improbable (2)	With the implementation of the water management plan, maintenance plan and monitoring plan the probability of the impact to occur is low	
Impact Description: Retreatment of the existing TSFs during the operational phase of the Project.			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective retreatment and rehabilitation of the footprint area will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Likely (5)	The retreatment of the TSFs is one of the objectives of the project, while the rehabilitation of the footprint areas is a strong recommendation, which means that the probability that the impact will occur is likely	

Table 8.2 Summary of the radiological impact significant rating for the post-closure phase of the Project.

Dimension	Rating	Motivation	Significance
Impact Description: Implementation of the NNR approved decommissioning plan for the Project			
Prior to Mitigation / Management			
Nature	Positive		Minor (positive) – 70
Duration	Permanent (7)	The effective implementation of the decommissioning plan will have an irreversible impact that will remain after the life of the project	
Extent	Limited (2)	The impact will be limited to the site and its immediate surroundings	
Intensity	On-going (5)	The impact on members of the public will be on-going and widespread	
Probability	Almost certain (5)	Within the NNR nuclear authorisation structures, the probability that the impact will occur is likely	
Impact Description: Exhalation, emission and dispersion of radon gas and particulate matter that contains radionuclides during the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practised	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture is practised is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practised	

Dimension	Rating	Motivation	Significance
Impact Description: Leaching and migration of radionuclides from the TSFs the post-closure phase of the Project			
Prior to Mitigation / Management			
Nature	Negative		Minor (negative) – 66
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Local (3)	Exposure extent beyond the mining rights area into the immediate surroundings	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices are below the regulatory dose constraint	
Probability	Almost Certain (6)	It is almost certain that impact will occur in the residential areas and where commercial agriculture is practices	
Post- Mitigation / Management			
Nature	Negative		Minor (negative) – 50
Duration	Project life (5)	The impact will occur for the duration of the operational phase	
Extent	Limited (2)	Exposure beyond the mining rights area into the immediate surroundings is limited	
Intensity	On-going (3)	Impact expected in residential areas and where commercial agriculture practices is below the regulatory dose constraint	
Probability	Likely (5)	It is likely that impact will occur in the residential areas and where commercial agriculture is practices	

9 References

Baes, C. F., and R. D. Sharp (1983), A proposal for estimation of soil leaching and leaching constats in assessment models, *J. Eviron. Qual.*, *12*, 17-28.

Blyvoor Gold (2008), Public Hazard Assessment Report Blyvooruitzicht Gold Mining Company Limited Blyvooruitzicht Gold Mine.

Chambers, D. B., L. M. Lowe, and D. G. Feasby (2012), Radiological Aspects of Naturally Occurring Radioactive Material (NORM) in the Processing and Production of Rare Earth Element Concentrates, paper presented at Rare Earths 2012 51st Annual Conference of Metallurgists of CIM (COM 2012), Niagara, ON, Canada.

De Beer, G. P., A. Ramlakan, and R. Schneeweiss (2002), An Assessment of the Post-Closure Radiological Impact of Rössing Uranium Mine, *NECSA Report No. GEA 1582*, South African Nuclear Energy Corporation Ltd, Pretoria.

Digby Wells Environmental (2018a), Final Scoping Report. Environmental Authorisation for the Blyvoor Gold Mine Processing Plants, Near Carletonville, West Rand, Gauteng, *BVG4880*, Digby Wells and Associated (South Africa) Pty Ltd, Randburg, South Africa.

Digby Wells Environmental (2018b), Environmental Licensing Process at the Blyvoor Gold Mine, West Rand. Groundwater Report, *BVG4880*, Digby Wells and Associated (South Africa) Pty Ltd, Randburg, South Africa.

Digby Wells Environmental (2018c), Environmental Impact Assessment and Environmental Management Plan for the Blyvoor Gold Mining Project near Carletonville, Gauteng. Addendum Social Impact Assessment, *BVG4880*, Digby Wells and Associated (South Africa) Pty Ltd, Randburg, South Africa.

Digby Wells Environmental (2018d), Environmental Impact Assessment for Blyvoor Gold Capital (Pty) Ltd. Air Quality Impact Assessment Report, *BVG4880*, Digby Wells and Associated (South Africa) Pty Ltd, Randburg, South Africa.

Digby Wells Environmental (2018e), Environmental Impact Assessment for the Blyvoor Gold Mining Project, West Rand, Gauteng. Surface Water Impact Assessment, *BVG4880*, Digby Wells and Associated (South Africa) Pty Ltd, Randburg, South Africa.

DME (2005), Radioactive Waste Management Policy and Strategy for the Republic of South Africa, Department of Mineral and Energy, Pretoria.

Eckerman, K. F., and J. C. Ryman (1993), Federal Guidance Report No 12, External Exposure to Radionuclides in Air, Water and Soil, Report EPA-402-R-93-081, Oak Ridge National Laboratories, Oak Ridge, Tennessee.

Eckermann, K. F., A. B. Wolbarst, and A. C. B. Richardson (1988), Federal Guidance Report No 11, Limiting Values of Radionuclide Intake and Air Concentrations and Dose Conversion Factors for Inhalation, Submersion and Ingestion, Oak Ridge National Laboratories, Oak Ridge, Tennessee.

Ellis, J. F. (2006), Vaal River Public safety Assessment, *Report No. VRPUBRADASS*, AngloGold Ashanti Limited Klerksdorp, South Africa.

Golder Associates Africa (2017), EMP Update for Tailings Reclamation & Underground Mining at Blyvooruitzicht Gold Mine *Report No. 1656096-307570-3*, Golder Associates Africa (Pty) Ltd, Midrand South Africa.

IAEA (1992), Measurements and Calculation of Radon Releases from Uranium Mill Tailings, Technical Report Series No. 333, International Atomic Energy Agency, Vienna.

IAEA (1994a), Classification of Radioactive Waste, *Safety Series No. 111-G-1.1*, International Atomic Energy Agency, Vienna, Austria.

IAEA (1994b), Handbook of parameter values for the prediction of radionuclide transfer in temperate environments, Technical Report Series No. 364, International Atomic Energy Agency, Vienna.

IAEA (1996), International Safety Standards for Protection against Radiation and for the Safety of Radiation Sources, *International Atomic Energy Agency Basic Safety Standards Report No. 115*, International Atomic Energy Agency, Vienna.

IAEA (2001), Generic Models for Use in Assessing the Impact of Discharges of Radioactive Substances to the Environment, Safety Report Series No.19, International Atomic Energy Agency, Vienna.

IAEA (2002), Monitoring and Surveillance of Residue from the Mining and Milling of Uranium and Thorium, Safety Report Series No.27, International Atomic Energy Agency, Vienna.

IAEA (2003), Derivation of Activity Limits for the Disposal of Radioactive Waste to Near-Surface Facilities, *IAEA TECDOC-1380*, International Atomic Energy Agency, Vienna.

IAEA (2004a), Radiation, People and the Environment, *IAEA/PI/A.75/ 04-00391*, International Atomic Energy Agency, Vienna.

IAEA (2004b), Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a Co-ordinated Research Project. Volume I: Review and Enhancement of Safety Assessment Approaches and Tools, *IAEA-ISAM*, International Atomic Energy Agency, Vienna.

IAEA (2006), Fundamental Safety Principles *Safety Standard Series No. SF-1*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2007a), Safety Glossary, Terminology Used in Nuclear Safety and radiation Protection, International Atomic Energy Agency, Vienna.

IAEA (2007b), IAEA Safety Glossary. Terminology used in Nuclear Safety and Radiation Protection, *2007 Edition*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2009a), Safety Assessments for Facilities and Activities, *Safety Standard Series No. GSR Part 4*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2009b), Classification of Radioactive Waste, *Safety Standard Series No. GSG-1*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2011), Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards: General Safety Requirements, *IAEA Safety Standards Series No. GSR Part 3 (Interim)*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2013), Measurement and Calculation of Radon Releases From NORM Residues, International Atomic Energy Agency, Vienna.

IAEA (2014), Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards: General Safety Requirements, *IAEA Safety Standards Series No. GSR Part 3*, International Atomic Energy Agency, Vienna, Austria.

IAEA (2018), IAEA Safety Glossary https://kos.iaea.org/iaea-safety-glossary.html, edited, International Atomic Energy Agency, Vienna Austria.

ICRP (1991), 1990 Recommendations of the International Commission on Radiological Protection. Annals of the ICRP 21 (1-3), *ICRP Publication 60*, International Commission on Radiological Protection.

ICRP (1996), Age Dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients, *ICRP Publication 72 Volume 26 No. 1*, Pergamon Press, Oxford.

ICRP (2000), *Publication 82. Protection of the Public in Situations of Prolonged Radiation Exposure. The Application of the Commission's System of Radiological Protection to Controllable Radiation Exposure Due to Natural Sources and Long-Lived Radioactive Residues. Annals of the ICRP*, First ed., Elsevier Science Ltd, Oxford.

ICRP (2007), The 2007 Recommendations of the International Commission on Radiological Protection, *ICRP Publication 103. Ann. ICRP*, *Volume 37*(Issue 2-4).

ICRP (2008), Publication 103, Recommendations of the ICRP - Annals of the International Commission on Radiological Protection (ICRP), Published for the ICRP by Elsevvier Inc, Vienna.

ICRP (2009), Publication 108, Environmental Protection: The Concept and Use of reference Animals and Plants, Annals of the International Commission on Radiological Protection (ICRP), Elsevier Science Inc, Vienna.

Kathren, R. L. (1998), NORM Sources and Their Origins, *Applied Radiation and Isotopes*, *49*(3), 149-168.

Klaassen, C. D. (2001), *Casarett and Doull's Toxicology, The Basic Science of Poisons*, 6th ed., McGraw-Hill, New York (NY).

Kozak, M. W., and W. Zhou (1998), The Use of Interaction Matrices to Improve Assessment Transparency, TR-108732, EPRI, Palo Alto.

Kozak, M. W., and M. J. Stenhouse (2002), Background Information for Development of Waste Acceptance Criteria for Vaalputs, South Africa, Report MSCI-2201-1, Revision 1, Monitor Scientific LLC, Denver.

Marsh, J. W., J. D. Harrison, and D. Laurier (2010), Dose Conversion Factors for radon:Recent Developments, *Health Physics*, *99*(4), 511 - 516.

Martin, J. E. (2006a), *Physics for Radiation Protection: A Handbook*, Wiley-VCH, Weinheim.

Martin, J. E. (2006b), *Physics for Radiation Protection: A Handbook. Second Edition, Completely Revised and Enlarge*, Wiley-VCH, Weinheim.

NNR (2013), Regulatory Guide: Safety Assessment of Radiation Hazards to members of the Public from NORM Activities, edited, National Nuclear Regulator, Pretoria.

NRC (2003), *Conceptual Models of Flow and Transport in the Fractured Vadose Zone*, National Academy Press, Washington, D.C.

Parc Scientific (2018), Atmospheric Dispersion of Radon Sources at Blyvooruitzicht Site, Parc Scientific (Pty) Ltd., Boskruin, Johannesburg.

Penfold, J. S. S., N. S. Cooper, R. H. Little, M. J. Kozak, M. J. Stenhouse, and B. M. Watkins (1999), Assessment Calculations for the Drigg LLW Disposal Facility: Financial Year 1998: AMBER Calculations and Results, IE5038B-13v1.0(draft), QuantiSci, Henley-on-Thames.

Rogers, V., and K. Nielson (1991), Correlations for Predicting Air Permeabilities and Rn-222 Diffusion Coefficients of Soil, *Health Physics*, *61*(2), 225-230.

Staven, L. H., K. Rhoads, B. A. Napier, and D. L. Strenge (2003), A Compendium of Transfer Factors for Agricultural and Animal Products, Pacific North West Laboratory.

Yu, C., A. Zielen, J. Cheng, D. LePoire, E. Gnanapragasam, S. Kamboj, J. Arnish, A. Wallo III, W. Williams, and H. Peterson (2001), User's Manual for RESRAD Version 6, *ANL/EAD-4*, Environmental Assessment Division, Argonne National Laboratory.

Appendix A:
Radionuclide and Element Dependent Data

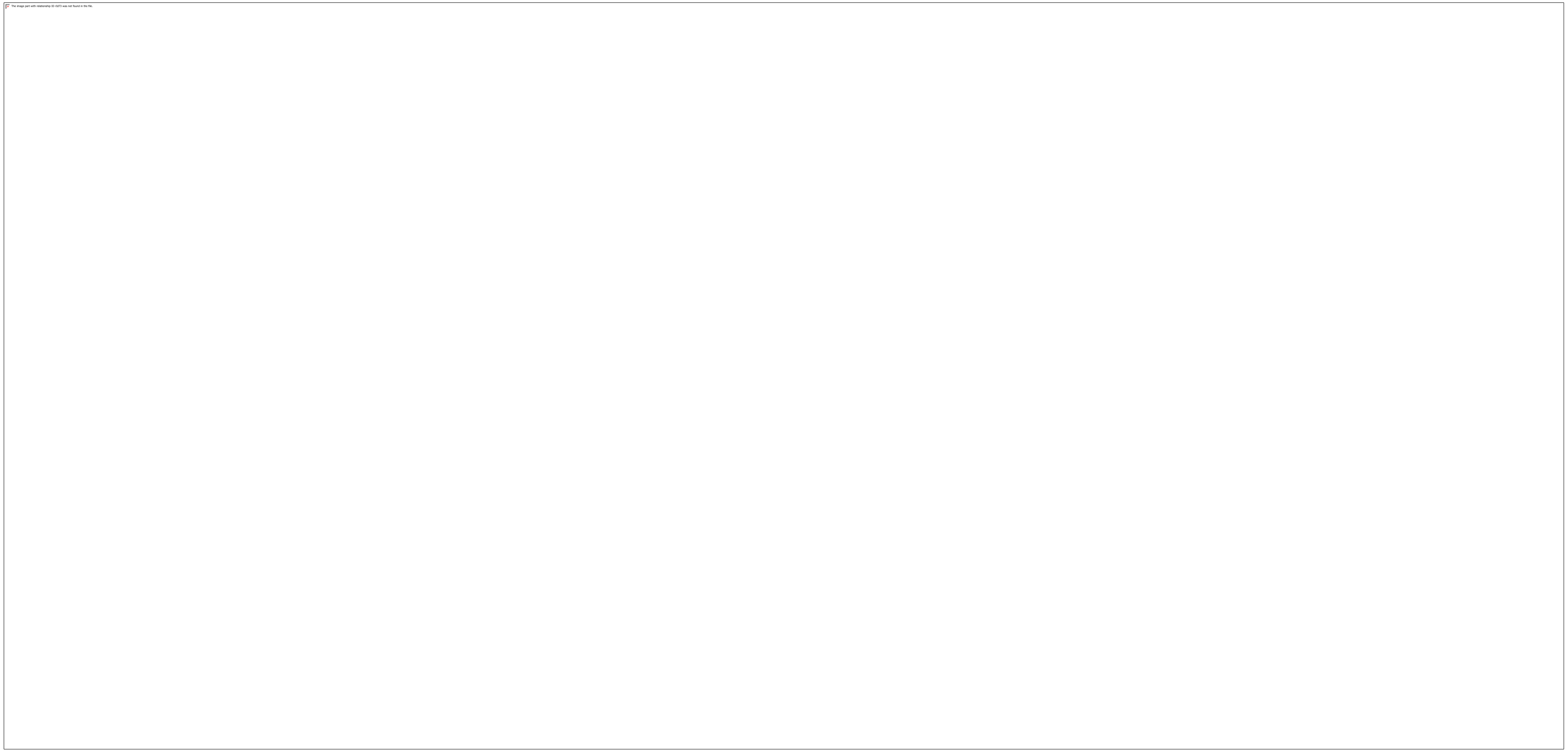

Figure A 1 Schematic illustrations of the U-238, U-235, and Th-232 decay chains.

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 a particular tissues or organs exposed to the radiation (Eckermann *et al.*, 1988). These numerical factors, referred to as 'dose conversion factors', are used to convert radioactivity concentrations members of the public are exposed to, to a total effective dose. The estimation of the **total annual effective radiation dose** that an individual is exposed to is the sum of the internal and external effective doses. Radioactivity that enters the body fluids from inhalation (respiratory tract) and ingestion (gastrointestinal tract) constitute the internal effective doses.

As indicated in Section 2, the most pertinent guidance currently available for conducting prior and operational public safety assessments for NORM facilities is the Regulatory Guide RG-002 (NNR, 2013). This guide summarises dose conversion factors for use in the assessment of inhalation and ingestion exposure to radionuclides, as obtained from the ICRP Publication 72 (ICRP, 1996) and the IAEA Safety Standards Series (IAEA, 2011) documents. The dose conversion factors published in RG-002 make a distinction between different age groups, which represent the ranges of age groups as listed in Table B 1.

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

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

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

In addition to ingestion and inhalation, radioactivity may also enter the body through the skin, which constitutes external radiation exposure. For external exposures, the kinds of radiation of concern are those sufficiently penetrating to traverse the overlying tissues of the body and deposit ionising energy in radiosensitive organs and tissues. Photons and electrons are the most important radiations emitted by radionuclides distributed in the environment that can penetrate the body from 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 nearly uniform irradiation of the body. The estimation of the dose is therefore independent of the age of the person exposed and the conversion factors are therefore age independent.

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

Inhalation Exposure (LLα and Radon)

The effective dose from the inhalation of dust containing LLα radionuclides ($ED_{Inh_{LL\alpha}}$, in μSv.y^{-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.y^{-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.h^{-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.h^{-1}) per (mJ.m^{-3})
Exposure period	7 000	1 760	2 000	[h]
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.h.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.h^{-1}) per (Bq.m^{-3})
Dose Coefficient (UNSCEAR)[4]	9.00E-06			(mSv.h^{-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

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 largely 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.y^{-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 3

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

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.y^{-1}) per age group.

Inadvertent Ingestion of Contaminated Soil

The effective dose rate from the ingestion of contaminated soil ($ED_{ing,soil}$, in µSv.y^{-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 4

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

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.y^{-1}).

The activity concentration in the soil can increase over time through 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.y^{-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 5

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

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.y^{-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 6

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

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 days of year (unitless), Int_{crop} is the interception fraction (irrigation water and deposition) on crop (unitless), I_{rate} is the annual depth of irrigation applied to the crop (m.y^{-1}), Dep_{rate} is the deposition rate of airborne contaminants (Bq.m^{-2}.y^{-1}). Y_c is the crop yield (kg.m^{-2}, fresh weight of crop), λ_w is the removal rate of contaminants on the on the crop (through irrigation or deposition) by weathering processes (y^{-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 6 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 deposition of airborne dust, represented by the term $Int_{crop}\, f_{growth}\, Dep_{rate}$; and
- External contamination of the crop due to irrigation of the crops, represented by the term $Int_{crop}\, f_{growth} C_{water}\, I_{rate}$.

A concentration factor (CF_{crop}) defines the transfer of activity from contaminated soil to crops planted in the soil and consumed by humans or animals. The concentration factor reflects only the uptake of radionuclides from the soil via roots and excludes the effects of deposition of radionuclides onto the plant surfaces by re-suspension, deposition, and fallout. Concentration factors prescribed in RG-002 (NNR, 2013) are presented for different soil groups. The RG-002 values are listed in Table C 7 in Appendix C, where it is listed alongside values from other literature sources. Where data for a specific nuclide are not available from RG-002, the values from Staven *et al.* (2003) will be used. Values for the other parameters given in Equation 6 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.y^{-1}) (e.g. beef, mutton, pork, poultry milk, and eggs) is calculated from measured or modelled (using Equation 6) radionuclide concentrations of the secondary animal product, by multiplication with appropriate ingestion dose coefficients and animal product ingestion rates, and is given by:

Equation 7

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

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.y^{-1} fresh weight of 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.y^{-1}) can be calculated using the following equation:

Equation 8

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

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

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

Equation 9

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

where CF_{Anm} is the concentration factor for the animal product (d.kg^{-1} fresh weight of 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.d^{-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.d^{-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.d^{-1} wet weight of soil). Similarly, of 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.d^{-1} wet weight of sediment). Similarly, the concentration in animal milk from (C_{milk}) can be calculated using the following equation:

Equation 10

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

where CF_{milk} is the concentration factor for the animal milk (d.L^{-1}), and the remain 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, is applicable 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 6, but without the food preparation loss term. The activity concentration in pasture (C_{past}, in Bq.kg^{-1}) can be calculated using the following equation:

Equation 11

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

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.y^{-1}) and Dep_{rate} is the deposition rate of airborne contaminants (Bq.m^{-2}.y^{-1}). Y_{past} is the pasture yield (kg.m^{-2}, fresh weight of pasture), λ_w is the removal rate of contaminants on the on the pasture (through irrigation or deposition) by weathering processes (y^{-1}), and Ing_{past} is the consumption rate of pasture by the animals (kg.d^{-1} fresh weight of pasture).

External Gamma Irradiation: Air

The effective dose from external exposure to contaminated air (ED_{Ext_a}, in µSv.y^{-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 12

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

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.h^{-1} per Bq.m^{-3}), and EP_w is the annual human exposure period to contaminated air (h.y^{-1}). Exposure is age group specific and the values used in this assessment, as obtained from RG-002, is 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.y^{-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 13

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

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.h^{-1} per Bq.kg^{-1}), and EP_s is the annual human exposure period to contaminated air (h.y^{-1}). 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.y^{-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 14

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

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.h^{-1} per Bq.m^{-3}), and EP_w is the annual human exposure period to contaminated water (h.y^{-1}). Duration of exposure for different age groups is presented in Table C 11 in Appendix C.

Time Dependent Soil Concentration

The radionuclide concentration of 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 radionuclide 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 15

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

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 16

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

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

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

Equation 17

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

where $Rate_{dep}$ (Bq.m^{-2}.y^{-1}) is 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 18

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

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

Equation 19

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

where $Rate_{eros}$ (kg. m^{-2}.y^{-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, $\lambda_{Eros,RZ}$ (y^{-1}) is calculated by:

Equation 20

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

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. $\lambda_{BioT,DZ}$ (y^{-1}) is calculated by:

Equation 21

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

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

Equation 22

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

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

Equation 23

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

where I_{nfil} ($m^3.m^{-2}.y^{-1}$) 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 24

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

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

Equation 25

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

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 26

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

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 27

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

where Y_{crop} is the annual crop yield ($kg.m^{-2}$), Num_{crop} is the number of crops harvested annually (y^{-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 28

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

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 stockpiles material $Flux_t$, (Bq.y^{-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 29

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

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 30

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

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 31

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

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 29 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. In order to simplify 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 to 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 32

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

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 33

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

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).

Appendix C:
Calculation Parameter Values

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

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

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

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

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

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

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

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

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

Ingestion Pathway	Unit	RG-002	NUREG-5512 Vol. 4		
			Average	Minimum	Maximum
Water	$L.y^{-1}$	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	$kg.y^{-1}$	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 from 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	$L.y^{-1}$	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	$kg.y^{-1}$	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	y^{-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, 1994b)
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, 1994b)
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, 1994b)
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 on basis of dry weight concentration in the plant to the dry weight concentration in the soil, (2) RG-002 values for fruit given as wet weight concentration in fruit per dry weight concentration in soil. (3) Values for grain from RG-002 are specifically for maize. (4) Animal feed from grain is for maize stalks and roots, which are commonly used as animal feed.

Table C 10 Transfer coefficients from the animal feed to animal products in $d.kg^{-1}$ and $d.L^{-1}$ compiled from various sources.

U	Th	Ra	Pb	Po	Pa	Ac	Reference
Transfer Coefficients for Meat ($d.kg^{-1}$)							
3.9E-04	2.3E-04	1.7E-03	7.0E-04	5.0E-03	-	-	RG-002 (Beef)
3.0E-02	5.0E-03	5.0E-03	7.1E-03	5.0E-03	-	-	RG-002 (Mutton)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	5.0E-05	1.6E-04	(IAEA, 2003)
3.4E-04	9.0E-04	9.4E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
6.0E-04	2.7E-03	1.3E-03	1.0E-02	4.0E-03	5.0E-05	1.6E-04	(Kozak and Stenhouse, 2002)
3.0E-04	2.7E-03	9.0E-04	4.0E-04	5.0E-03	2.6E-05	1.6E-04	(Penfold *et al.*, 1999)
3.0E-04	4.0E-05	9.0E-04	4.0E-04	5.0E-03	4.0E-05	4.0E-04	(Staven *et al.*, 2003)
Transfer Coefficients for Milk ($d.L^{-1}$)							Reference
1.8E-03	5.0E-06	3.8E-04	1.9E-04	2.1E-04	-	-	RG-002
4.0E-04	5.0E-06	1.3E-03	3.0E-04	3.4E-04	5.0E-06	4.0E-07	(IAEA, 2003)
4.0E-04	1.7E-06	1.3E-03	2.0E-04	1.0E-03	1.0E-03	1.0E-03	(De Beer, *et al.*, 2002)
3.7E-04	5.0E-06	1.3E-03	3.0E-04	3.0E-04	5.0E-06	4.0E-07	(Kozak and Stenhouse, 2002)
4.0E-04	5.0E-06	1.3E-03	2.7E-04	3.4E-04	5.0E-06	4.0E-07	(Penfold *et al.*, 1999)
4.0E-04	5.0E-06	1.3E-03	2.6E-04	3.4E-04	5.0E-06	2.0E-05	(Staven *et al.*, 2003)
Transfer Coefficients for Poultry ($d.kg^{-1}$)							Reference
7.5E-01	4.0E-03	9.9E-04	2.0E-03	2.4E+00	-	-	RG-002
3.0E-04	9.0E-04	9.0E-04	4.0E-04	5.0E-03	5.0E-03	5.0E-03	(De Beer, *et al.*, 2002)
1.0E+00	6.0E-03	3.0E-02	8.0E-01	2.3E+00	6.0E-03	6.0E-03	(Staven *et al.*, 2003)
Transfer Coefficients for Eggs ($d.kg^{-1}$)							Reference
1.1E+00	2.0E-03	2.0E-05	2.0E-03	3.1E+00	-	-	RG-002
1.0E+00	2.0E-03	2.0E-05	2.0E-03	1.8E-02	1.8E-02	1.8E-02	(De Beer *et al.*, 2002)
1.0E+00	4.0E-03	3.1E-01	1.0E+00	7.0E+00	4.0E-03	4.0E-03	(Staven *et al.*, 2003)

Table C 11 Occupancy factors taken from RG-002 (NNR, 2013).

Activity	0 – 2 Years	2 – 7 Years	7 – 12 Years	12 – 17 Years	Adult
Time spent indoors	7 914	7 775	7 568	7 665	7 050
Time spent outdoors	846	985	1 192	1 092	1 710
Working on contaminated sediments and land	0	0	0	0	2 000
Playing on contaminated sediments and land	200	383	383	300	0
Swimming	19.2	27.4	30.2	27.8	9
Boating	0	78	76	110	170
Fishing	0	78	76	110	170

Appendix D:
Conceptual Representation of the Groundwater Model in Ecolego

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 1 to Figure D 5.

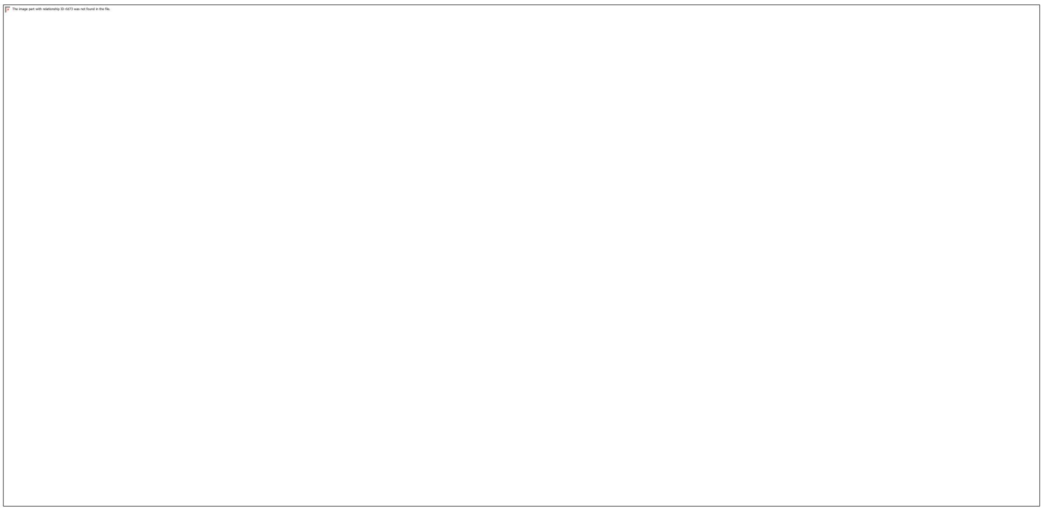

Figure D 1 Conceptual representation and associated parameters values for the source term model.

Figure D 1 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 Baes and Sharp (1983):

Equation 34

$$\lambda_w = \frac{I_w}{\theta_w H_w R_w}$$

where I_w is the infiltration rate to the source layer ($m.y^{-1}$), 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 35

$$R_w = 1 + \frac{\rho_w K_{dw}}{\theta_w}$$

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 parameters values. Figure D 1 shows that the output from the source term model is the radionuclide concentration ($Bq.m^{-3}$) or flux ($Bq.y^{-1}$) leaving the compartment.

The transfer coefficient accounting for the effect of dispersion in transport from compartment *i* to compartment *j* ($\lambda_{D,\,ij}$, y^{-1}) is calculated using the following equation (IAEA, 2004b):

Equation 36

$$\lambda_{D,ij} = \frac{\alpha_L}{H_i} \cdot \lambda_{w,ij}$$

where α_L is the longitudinal dispersivity (m) and H_i is the compartment thickness. Note that the transfer coefficient in Equation 36 represents the dispersion of radionuclides between the compartments in both directions.

Figure D 2 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) is similar to those presented in Equation 34 to Equation 36, except that it is for the unsaturated zone parameter values.

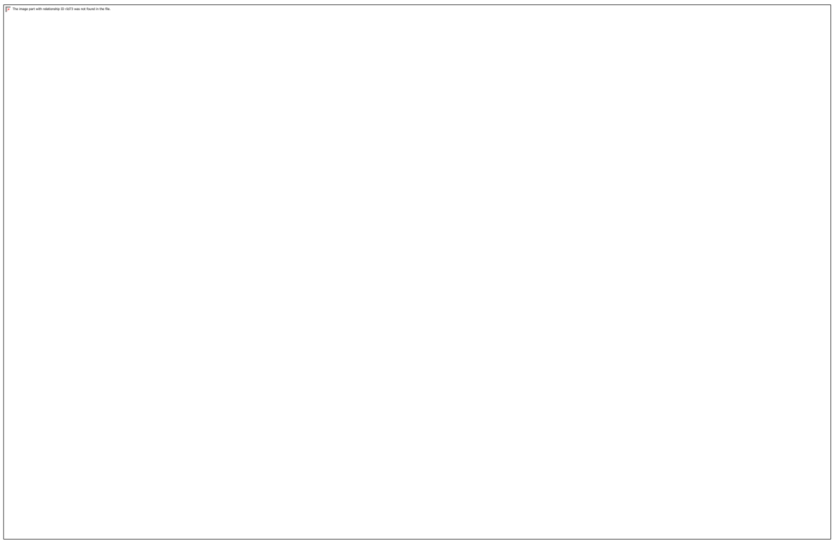

Figure D 2 Conceptual representation and associated parameters values for the unsaturated zone model.

Figure D 3 is a simplified representation of the aquifer mixing zone and the most important parameters. The infiltration rate ($m.y^{-1}$) 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 ($m.y^{-1}$)

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 ($Bq.y^{-1}$) into the flow tube (aquifer).

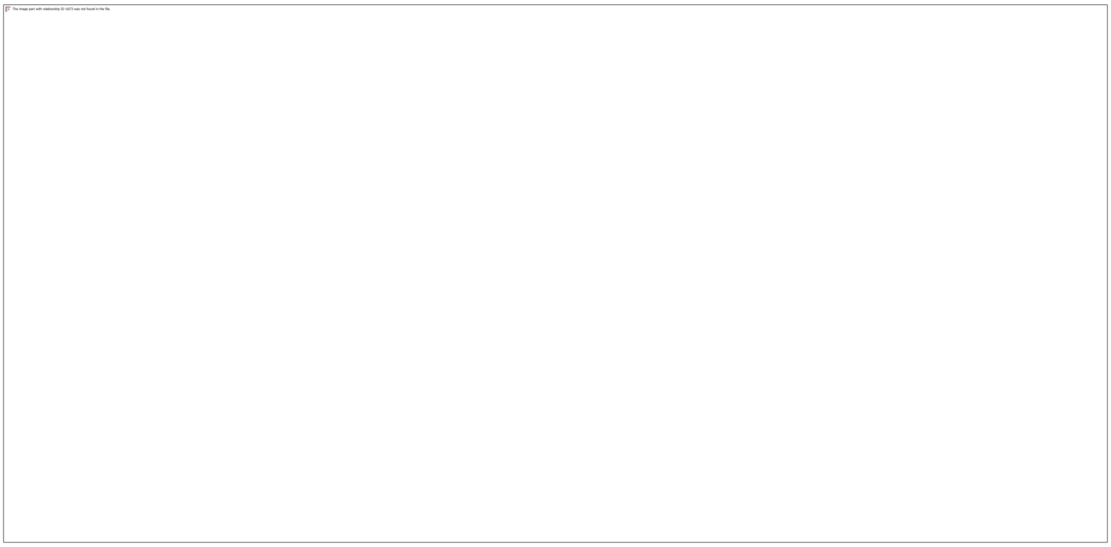

Figure D 3 Conceptual representation and associated parameters values for the aquifer mixing zone model.

Figure D 3 shows that the aquifer mixing zone model is a function of the Darcy velocity ($m.y^{-1}$), 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 ($m.y^{-1}$) in the aquifer is assumed to be constant with time. The output at the receptor point defines the concentration ($Bq.m^{-3}$) and flux ($Bq.y^{-1}$) at the borehole.

Figure D 3 shows that the aquifer model is a function of the Darcy velocity ($m.y^{-1}$), 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 is similar to those presented in Equation 34 to Equation 36, 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 intersect the plume, and the background concentration ($Bq.m^{-3}$) multiplied with the fraction intersect the uncontaminated water. As a conservative assumption, it is assumed that the whole screen intersection the contaminant plume.

Figure D 5 is a simplified representation of the borehole abstraction module and the most important parameters.

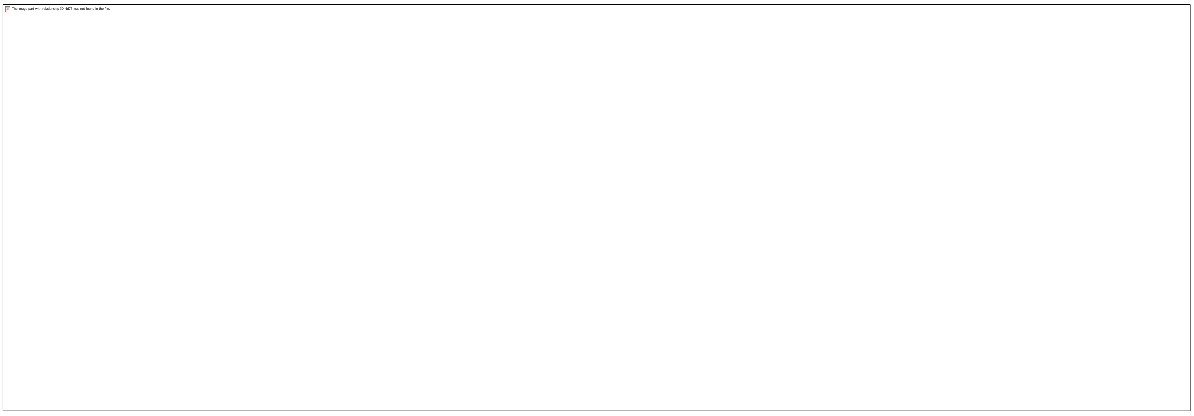

Figure D 4 Conceptual representation and associated parameters values for the aquifer (saturated zone) model.

Figure D 5 Conceptual representation and associated parameters values for the borehole abstraction model.