Tronox KZN Sand Port Dunford Mine:

A Prospective Radiological Public Safety and Impact Assessment

AQUISIM CONSULTING (PTY) LTD

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

WSP Groups Africa (Pty) Ltd

Building 1, Maxwell Office Park
Magwa Crescent West, Waterfall City
Midrand, 1685
South Africa

For Attention:

Rob Rowles (Principal Consultant)

Cell: +27 72 548 1841
Email: Rob.Rowles@wsp.com

Compiled by:

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

AquiSim Consulting (Pty) Ltd Offices

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

Authorisation

	Name	Signature	Date
COMPILED	JJ van Blerk		13.01.2025
Radiation Protection Specialist			
CHECKED	R Rowles		
Principal Consultant (WSP)			
CHECKED	B Baxter		
Technical Director: Planning & Advisory (WSP)			
CHECKED			
CHECKED			
APPROVED			

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List of Acronyms

ACR	Authorisation Change Request
ALARA	As Low As Reasonably Achievable
Bq	Becquerel
CoR	Certificate of Registration
CPC	Central Processing Complex
DM	District Municipality
DMRE	Department of Mineral Resources and Energy
DTMUs	dozer trap mining units
EA	Environmental Authorisation
EAP	Environmental Assessment Practitioner
EIA	Environmental Impact Assessment
FELs	front-end loaders
GDP	Gross Domestic Product
GN	Government Notice
GSR	General Safety Requirement
ha	Hectare
HMC	Heavy Mineral Concentrate
IAEA	International Atomic Energy Agency
ICR	Congress of Radiology
ICRP	International Commission on Radiological Protection
ISAM	Improvement of Safety Assessment Methodologies
KZN	KwaZulu-Natal
LLα	Long-Lived Radioactive Dust (Alpha)
LM	Local Municipalities
LoM	Life of Mine
MAP	Mean Annual Precipitation
mbgl	meters below ground level
MMIF	Mesoscale Model Interface Program
MPRDA	Mineral and Petroleum Resources Development Act
MSP	Mineral Separation Plant
mSv	milliSievert
Mt	Million tons
NAAQS	National Ambient Air Quality Standard
NEA	Nuclear Energy Act
NEM:WA	National Environmental Management: Waste Act
NEMA	National Environmental Management Act
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act
NORM	Naturally Occurring Radioactive Materials
NRWMP	National Radioactive Waste Management Policy and Strategy
NUREG	US Nuclear Regulatory Commission
PAEC	Potential Alpha Energy Concentration
PM_{10}	Particulate matter less than 10 microns in size
PWP	Primary Wet Plant
RBCAA	Richards Bay Clean Air Association
RG	Regulatory Guide
RGM	Radon Gas Monitors
RMP	Radiation Management Programme

RoM	Run of Mine
RoR	Rate of Rise
RPO	Radiation Protection Officer
RPP	Radiation Protection Programme
RPS	Radiation Protection Specialist
RPSA	Radiological Public Safety Assessment
RSF	Residual Storage Facilities
S&EIR	Scoping and Environmental Impact Reporting
SAAQIS	South African Air Quality Information Systems
SAWS	South African Weather Service
SPR	Source-Pathway-Receptor
tpa	tons per annum
tph	tons per hour
TSF	Tailings Storage Facilities
TSP	Total Suspended Particles
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WCD	Water Control Dam
WMA	Water Management Area
WML	waste management license
WRD	Waste Rock Dump
WRF	Weather Research and Forecasting

Executive Summary

The purpose of this report is to present the radiological safety and impact of the Port Dunford Mine in alignment with the Scoping and Environmental Impact Reporting (S&EIR) process, the National Nuclear Regulator Act (NNRA) (Act 47 of 1999), the Nuclear Energy Act (NEA) (Act No. 46 of 1999), and the relevant requirements, guidance, and regulations set forth by the National Nuclear Regulator (NNR).

Tronox KZN Sands (Pty) Ltd (herein referred to as Tronox) holds a Certificate of Registration (CoR-43) granted by the NNR in terms of Section 22 of the NNRA for all the Tronox operations. One of the key submissions as part of an initial CoR application is a Radiological Public Safety Assessment (RPSA). Any changes to the scope of the CoR as induced by the Port Dunford Mine require an Authorisation Change Request (ACR) to be prepared and submitted to the NNR. The ACR must include, among other requirements, a quantification of the potential radiological impact that these changes or listed activities may have on members of the public.

A systematic approach is followed that includes the definition of the regulatory framework and technical basis of the assessment, a system description, the systematic definition of public exposure conditions, the consequence analysis of the exposure conditions and the radiological impact assessment.

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

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

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

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

- On average, the total effective dose calculated at receptor locations for the atmospheric pathway varies from 0.01% (Phase 1) to 2.3% (Phase 2) of the public dose constraint of 250 μSv.year^{-1}. The most significant contribution from the atmospheric pathway is from the ingestion of crops and animal products, as well as, radon gas and dust inhalation.
- The contribution from the groundwater pathway was evaluated with the RSF C as the main contributing source. It was illustrated that the potential radiological impact is only visible in thousands of years at maximum total effective doses of less than 250 μSv.year^{-1}, which means that it cannot be considered as a contributing pathway for the Agricultural Area Exposure Condition during the operational phase of the Port Dunford Mine;

- The results for the two public exposure conditions were presented as dose isopleths for the most exposed age group (12 to 17 years), with more detailed exposure route-specific results at the sensitive receptor locations selected to be close to the Port Dunford Mine infrastructure. The results show that notwithstanding the proximity of the receptor locations to the surface infrastructure, the doses are still less than the dose limit for all age groups, with a maximum contribution of less than 50 Sv.year^{-1} from the atmospheric pathway.
- The disposal of the MSP Gypsum in the mine void or the RSF was considered for both the groundwater and atmospheric pathways, with the conclusion that both options are acceptable from a radiation exposure perspective.

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

The total effective dose assessment results were used to derive the radiological impact rating during the different phases of the Port Dunford Mine. The first table below summarises the radiological impact significant rating for the operational phase. All the impacts during the operational phase that were considered achieved a rating of low.

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

The second table below summarises the radiological impact significant rating for the post-closure phase of the Port Dunford Mine. The impacts that were considered during the post-closure period varied from moderate positive to moderate negative.

Impact Description: Implementation of the NNR-approved decommissioning plan of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Positive	5	1	3	5	4	**56**	**P3**
	Significance	**P3 - Moderate**						

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Impact Description: Leaching and migration of radionuclides from the TSF during the post-closure phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

Based on the outcome of the radiological public impact and safety assessment, recommendations were made for the following:

- To extend the baseline site characterisation programme during Phase 1 of the Port Dunford Mine;
- To implement a radiological monitoring programme for the Port Dunford Mine that includes the monitoring of surface water, groundwater, sediment, environmental radon, as well as dust fallout; and
- To evaluate the different phases of the Port Dunford Mine that extend to 2069 on a site-specific basis as part of the regular updates of the RPSAs that are performed every 5 years.

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Credentials: Dr JJ van Blerk

Dr. Japie van Blerk is the Director of AquiSim Consulting (Pty) Ltd (AquiSim), a position he has held for 24 years. Before this, he worked at the South African Nuclear Energy Corporation (Necsa) for 11 years, where he was primarily responsible for the post-closure safety assessment of the Vaalputs National Radioactive Waste Disposal Facility in South Africa. During his tenure at Necsa, Dr. van Blerk earned a PhD in geohydrology from the University of the Free State in South Africa. He is a registered Professional Natural Scientist (Pr.Sci.Nat.) in the fields of Radiation Science and Earth Science (Reg. no 400239/05) through the South African Council for Natural Scientific Professions (SACNASP).

Dr. van Blerk gained extensive expertise in the performance of near-surface radioactive waste disposal systems, particularly in arid conditions, through his responsibility for the post-closure safety assessment of the Vaalputs National Radioactive Waste Disposal Facility. After joining AquiSim Consulting (Pty) Ltd (AquiSim) in 2000, he continued to provide consultancy services to Necsa, focusing on radioactive waste management and post-closure safety assessments. Notably, Dr. van Blerk collaborated with Dr. Matt Kozak from Interra, USA, in 2007 to prepare the current Vaalputs post-closure safety assessment. He is currently contracted by Necsa to update the current assessment, which involves an in-depth review and use of the national inventory of radioactive waste designated for disposal at Vaalputs.

Over the past 24 years, Dr. van Blerk has provided extensive consultancy and technical training services to the International Atomic Energy Agency (IAEA). His work with the IAEA has covered a wide range of fields, including post-closure safety assessment, safety case development, radioactive waste management (including Naturally Occurring Radioactive Material or NORM), the development of disposal concepts for Disused Sealed Radioactive Sources (DSRS), and the cradle-to-grave management of DSRS.

Dr. van Blerk, through his extensive involvement in IAEA-related projects, has developed deep knowledge and experience in the use and application of IAEA safety standards related to radioactive waste disposal and management. His expertise spans all stages of the radioactive waste management cycle, including site selection, site characterization, disposal concept design, disposal, final closure, and the application of post-closure safety assessments to guide decision-making throughout these stages.

In addition to his work in the nuclear sector, Dr. van Blerk has substantial experience in performing and managing radiological public safety assessment projects for mining and mineral processing facilities, particularly those involving Naturally Occurring Radioactive Material (NORM). His work has been conducted both locally and internationally, covering a wide range of operations such as uranium, gold, rare earth elements, copper, mineral sands and phosphate. These assessments have been conducted for regulatory and Environmental and Social Impact Assessment (ESIA) purposes under both operational and post-operational conditions.

Over the past 24 years, Dr. van Blerk has managed and performed more than 80 radiological public safety assessment projects for the NORM and nuclear industries. While many of these projects were based in South Africa, his work has also extended to countries such as Namibia, Mozambique, Madagascar, Ukraine, Kazakhstan, Saudi Arabia, Sierra Leone, Mali, and Malawi.

Complementing his nuclear industry expertise, Dr. van Blerk possesses a strong working knowledge of various environmental processes and disciplines, including geology, geohydrology, geochemistry, hydrology, and meteorology. His understanding of these disciplines, combined with his knowledge of groundwater modelling principles for both saturated and unsaturated conditions, makes him well-suited for reviewing waste disposal programs and assessing their impact on human health and the environment during the post-closure period.

Certification

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

Jacobus Josia van Blerk (PhD)

Director: AquiSim Consulting (Pty) Ltd

1 Introduction

1.1 Background

Tronox KZN Sands (Pty) Ltd (herein referred to as Tronox) holds a prospecting right under the Department of Mineral Resources and Energy ("DMRE") Reference: KZN 30/5/1/1/2/296 PR in respect of ilmenite, rutile and zircon on the farms [Sub 1 and Remainder of Lot 102 uMlalazi No. 13860, Sub 1,2 and Remainder of Lot 131 uMlalazi No. 14098, Sub 1 and Remainder of Lot 103 uMlalazi No. 13880, Sub 2,3 and Remainder of Lot 104 uMlalazi No. 13853 and Sub 1 and Remainder of Lot Hibbert No. 15714] measuring 843.72 hectares in extent in the uMlalazi Local Municipality, KwaZulu-Natal Province (the "Waterloo PR"), which prospecting right was renewed by the DMRE under Section 18 of the Mineral and Petroleum Resources Development Act, 2002 ("MPRDA").

Historically, Tronox held the following two prospecting rights in terms of Section 17 of the MPRDA:

- DMRE Ref: KZN 30/5/1/1/2/10708 PR (formerly 771 PR) in respect of ilmenite, rutile, zircon and heavy minerals on the farms measuring 3 945.95 hectares in extent in the uMhlathuze Municipality, KwaZulu-Natal Province (the "**Port Durnford PR**"); and
- DMRE Ref: KZN 30/5/1/1/2/279 PR in respect of ilmenite, rutile, zircon and heavy minerals on the farms measuring 258.27 hectares in extent in the uMlalazi Municipality, KwaZulu-Natal Province (the "**Penarrow PR**")

Tronox is now applying to convert these Prospecting Rights into a consolidated Mining Right and seeks environmental authorisation to mine for Heavy Minerals (general), Garnet (Abrasive), Kyanite, Leucoxene (heavy mineral), Monazite (heavy mineral), Rutile (heavy mineral), Silica Sand and Zirconium ore.

The Prospecting Rights area is situated in the uMlalazi and uMhlathuze Local Municipalities, under the King Cetshwayo District Municipality. It is located approximately 15km south-west of Richards Bay and is adjacent to the following settlements/towns at different points along the boundaries; **Mtunzini, Port Dunford, Esikhawini, Gobandlovu; and KwaDlangezwa** (see Figure 1.1 and Figure 1.2).

Tronox is now planning on applying for a consolidated Mining Right (MR) for all of these areas and seeking environmental authorisation (EA) to support this. A full Scoping and Environmental Impact Reporting (S&EIR) Process is required to support the MR application in terms of the above-mentioned legislation and the application for EA for the project.

WSP Group Africa (Pty) Ltd (WSP) has been appointed as the independent Environmental Assessment Practitioner (EAP) to undertake the S&EIR Process required in terms of the following legislation:

- Mineral and Petroleum Resources Development Act (Act No. 28 of 2002) (MPRDA),
- National Environmental Management Act (No. 107 of 1998) (NEMA) for submission of application for environmental authorisation (EA) in respect of activities identified in terms of GNR 983, 984 and 985 (7 April 2017, as amended), and
- National Environmental Management: Waste Act (Act No. 59 of 2008) (NEM:WA) and the list of waste management activities (GN 921:2013, as amended), requiring submission of a waste management license (WML) application.

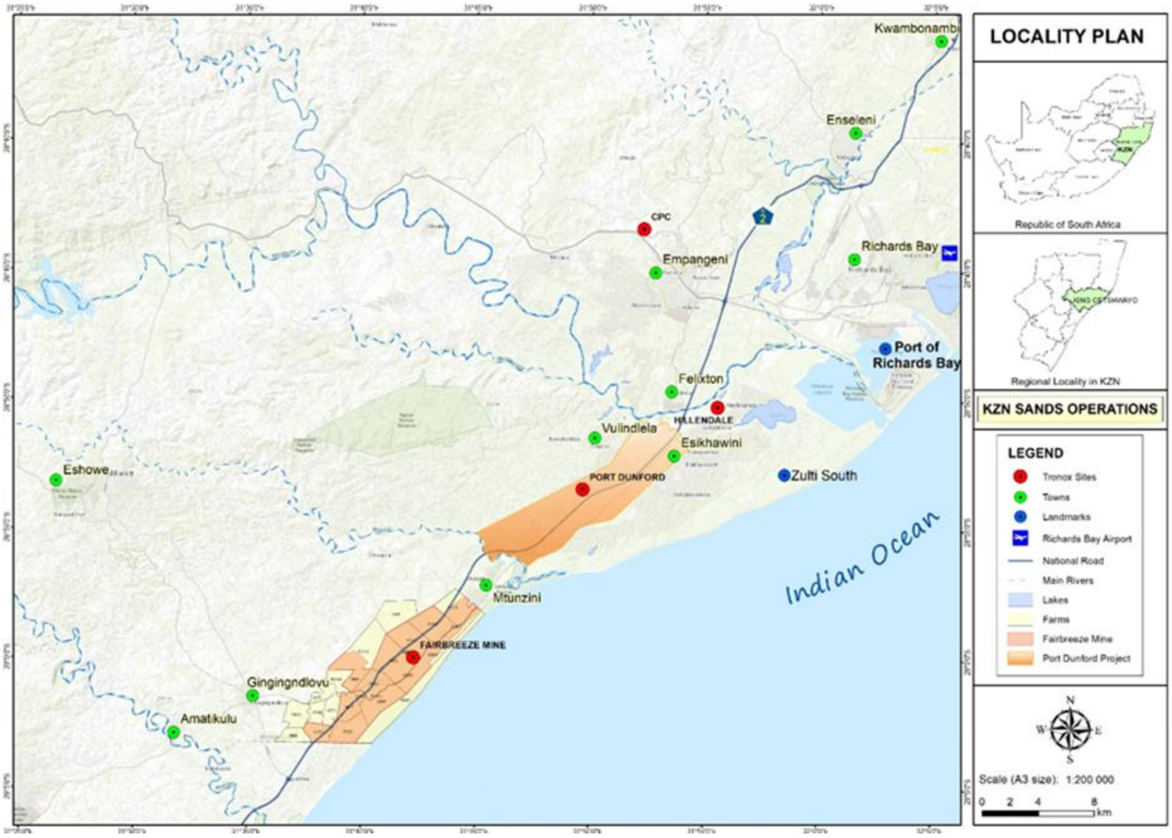

Figure 1.1 **Locality map showing the Tronox operations and proposed Project area at Port Dunford in KwaZulu Natal (WSP, 2024c).**

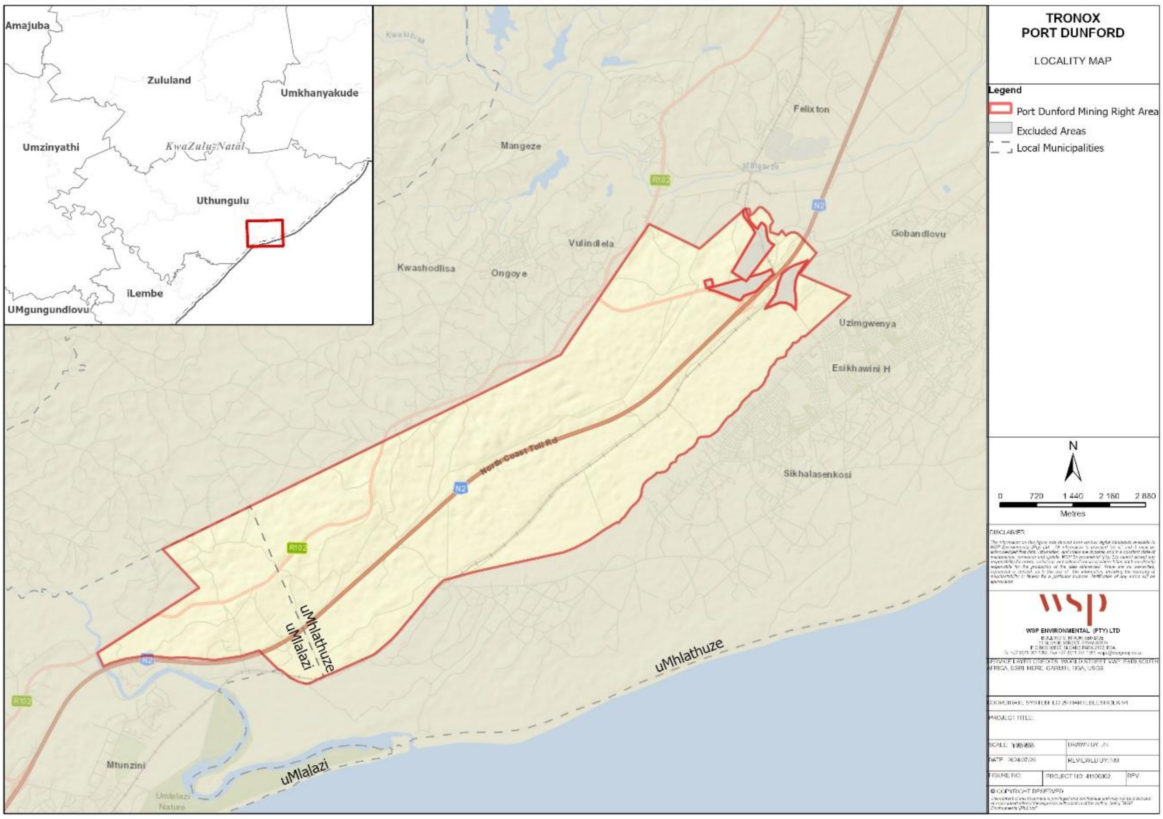

Figure 1.2 **Locality map of the Port Dunford Project area in KwaZulu Natal (see Figure 1.1).**

The DMRE serves as the Competent Authority for the EA application, as it pertains to a mining project, which will be referred to in this report as the Port Dunford Mine or the Project.

The Port Dunford Mine lease area is part of a regional, coast-parallel corridor of terraces and dunes collectively known as the Berea Red Sand that formed along the south-eastern coast of Africa from Durban to Mombasa, in response to static sea levels of the Pliocene-Pleistocene. As with all heavy mineral sand deposits, iron-titanium oxides, rutile, zircon and other minerals in the Heavy Mineral Concentrate (HMC) assemblage at Port Durnford are inherited from their source rock provenance and modified by selective sorting during deposition.

Tronox currently operates the Fairbreeze Mine (see Figure 1.1) where heavy mineral sands are mined southwest of Mtunzini in the Greater Richards Bay area. This is supported by a Tronox Mineral Separation Plant (MSP) and Smelter (collectively known as the Central Processing Complex (CPC)) in the Empangeni area. The Hillendale mining operation located to the north of Port Durnford is currently in the mine closure phase.

In the KwaZulu Natal sand dunes, heavy minerals are associated with naturally occurring radionuclides from the U-238 and Th-232 decay series. These radionuclides were originally present in the parent rocks from which the heavy minerals were derived and were subsequently deposited in the coastal sand dunes, either as separate mineral grains or as inclusions within the structure of the target heavy minerals. As a result, it is expected that naturally occurring radionuclides will be present in the mined mineral sand (ore), any residues generated during the separation of heavy minerals, and the final heavy mineral concentrates and products.

The International Atomic Energy Agency (IAEA) Safety Glossary (IAEA, 2018) classifies materials handled, processed, and produced from mining and mineral processing that contain naturally occurring radionuclides as Naturally Occurring Radioactive Material (NORM). Due to the presence of these radionuclides, NORM can potentially pose health risks to humans exposed to these materials, as highlighted by Marsh *et al.* (2010).

1.2 Naturally Occurring Radionuclides and Background Radiation

Many radioactive isotopes (or radionuclides) occur naturally throughout the Earth's crust and are present in most rocks, soils, river water, as well as in seawater. Most of these naturally occurring radionuclides are members of four radioactive series identified as the uranium (U-238), actinium (U-235), thorium (Th-232), and neptunium (Np-237)[1] series, named according to the radionuclides that serve as progenitor (or parent) to the series products. Naturally occurring radionuclides that are of particular interest to radiation protection, which are not members of any of the four-decay series, include isotopes of potassium (K-40) and rubidium (Rb-87). These isotopes are of interest because of their presence in environmental media and their contribution to human exposure (Martin, 2006b). In undisturbed environmental conditions, these naturally occurring radionuclides form part of the natural background radiation to which all humans are exposed daily through the air they breathe, the water they drink, the soil they live and work on, as well as the food they eat (Kathren, 1998).

The annual dose averaged over the population of the world, is about 2.8 mSv in total. As indicated in Figure 1.3, over 85% of this total is from natural sources, with about half coming from radon decay products in the home (2.4 mSv). Medical exposure of patients accounts for 14% of the total (0.4 mSv), whereas all other artificial sources — fallout, consumer products, occupational exposure, and discharges from the nuclear

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.

industry — account for less than 1% of the total value. Other natural background radiation sources include cosmic radiation, gamma radiation, and internal radiation in our bodies (IAEA, 2004a).

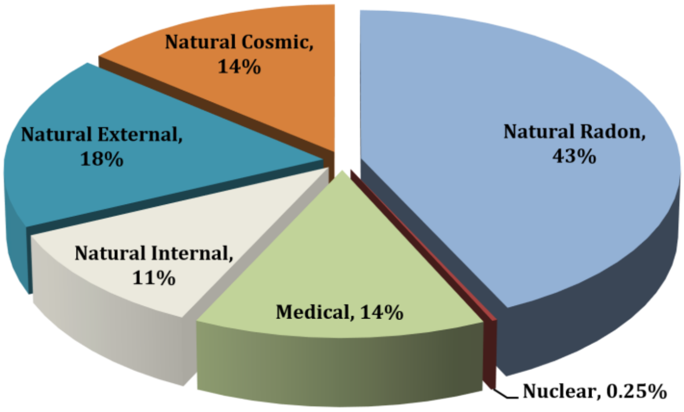

Figure 1.3 Distribution of the background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

Heavy mineral sands are sand deposits enriched with heavy minerals, which form through the natural processes of erosion of the Earth's surface. Wind and wave action play a crucial role in depositing and concentrating these materials into beach and dune deposits. These sands contain commercially valuable minerals, including rutile, ilmenite, zircon, and monazite. The relative proportions of these minerals vary globally from one deposit to another.

Within heavy mineral sands, radionuclides from the U-238, U-235, and Th-232 decay series are naturally occurring, though they are typically present in low concentrations. These radionuclides are primarily associated with specific minerals within the deposits, especially monazite, and to a lesser extent, zircon. The potential radiation hazard posed by these sands increases with the concentration of these specific minerals in the mineral streams.

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

- Moving naturally occurring radionuclides from inaccessible locations to places where humans can be exposed; and
- Concentrating radionuclides in environments accessible to humans; and
- Changing the chemical or physical environment in ways that make previously immobile radionuclides more mobile, such as increasing their solubility in water or their transportability by wind.

Nationally and internationally, the contribution of natural background radiation is generally not subject to regulatory control. Therefore, the focus of assessments like the one for the Port Dunford Mine is on the contribution of the mine to public ionizing radiation exposure conditions beyond natural background levels, known as complementary exposure.

The main approach used to assess public exposure to ionizing radiation from the Port Dunford Mine involves measuring, calculating, or estimating the release rate of radioactivity from sources associated with the mine, determining how this radioactivity disperses into the environment, and analyzing the subsequent interaction of the public with the affected environmental media. This approach is particularly suitable for new or proposed operations that do not have a history of environmental releases.

In cases where it is necessary and justified, this approach is complemented by actual environmental measurements, such as sampling soil, water, sediment, crops, and other relevant media. These measurements help quantify the contribution to the annual effective dose received by members of the public. However, it's important to note that these environmental measurements likely include contributions from natural background radiation, making it essential to distinguish between background and mine-related radiation exposure.

1.3 Regulatory Context

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

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

Tronox holds a Certificate of Registration (CoR-43) granted by the NNR in terms of Section 22 of the NNRA for all the Tronox operations (comprising the Hillendale Mine, the CPC and the Fairbreeze Mine at present). One of the key submissions as part of an initial CoR application is a Radiological Public Safety Assessment (RPSA). Internationally it is accepted as good radiation protection and management practice to revise and update these assessments regularly, say every 3 to 5 years. The most recent RPSA for the Tronox operations were performed and submitted to the NNR in 2019 (AquiSim, 2019a; b; c).

Additionally, any changes to the scope of the CoR as induced by the Port Dunford Mine will require an Authorisation Change Request (ACR) to be prepared and submitted to the NNR. The ACR must include, among other requirements, a quantification of the potential radiological impact that these changes or listed activities may have on members of the public.

WSP, as the appointed EAP for the Project, engaged AquiSim Consulting (Pty) Ltd (AquiSim) as a Radiation Protection Specialist (RPS). The role of AquiSim is to assess the potential radiological safety and impact on members of the public arising from the Port Dunford Mine, as part of the S&EIR process. This assessment is being conducted in alignment with the provisions, requirements, and guidelines provided by the NNR for an ACR.

1.4 Purpose of the Report

Due to the presence of naturally occurring radionuclides in the mineral sands deposit, Tronox is legally obligated to assess the potential radiological impact and safety of the Port Dunford Mine as part of the broader S&EIR process being conducted by WSP. The purpose of the RPSA within this process, and as part of the overall Radiation Management Programme (RMP), is to demonstrate to the NNR and other stakeholders that the potential radiological impact from the Port Dunford Mine meets the compliance criteria for protecting members of the public against exposure to ionizing radiation. Therefore, the findings of the RPSA are designed to effectively communicate the potential radiological impact on the public as part of the S&EIR process.

From this perspective, the purpose of this report is to present the radiological safety and impact of the Port Dunford Mine in alignment with the S&EIR process, the NNRA, the NEA, and the relevant requirements, guidance, and regulations set forth by the NNR.

1.5 Scope and Structure of the Report

The primary focus of this report is on assessing the radiological impact of the Port Dunford Mine as part of an ACR submission to the NNR. However, the report also provides sufficient detail and includes the necessary impact ratings, making it suitable for inclusion in the EIA process prepared by WSP in alignment with the NEMA.

The report assumes that readers have a basic understanding of ionizing radiation and its effects on human health and the environment. For those seeking additional information on these subjects, reference can be made to readily available literature, such as *Radiation, People and the Environment* published by the IAEA (IAEA, 2004a) or "*Radiation Effects and Sources*" published by the United Nations Environmental Programme (UNEP, 2016).

Various approaches can be used to conduct an RPSA, and no single method is considered the definitive or correct approach. What matters is that the chosen approach is fit for purpose, instils confidence in the assessment results, and takes into account the principles of a graded approach to safety assessment (IAEA, 2009a).

Figure 1.4 illustrates schematically the conceptual framework used to perform the RPSA of the Port Dunford Mine. It resembles the IAEA ISAM (Improvement of Safety Assessment Methodologies) methodology developed for the safety assessment of near-surface radioactive waste disposal facilities (IAEA, 2004b). It is inherently systematic and structured and allows for the continual improvement of the assessment or components of the assessment through successive iterations.

The assessment framework consists of several interrelated elements that will be followed and presented in a different section of this report. The report has been structured as follows:

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

- Section 8 defines the radiation monitoring plan for the Port Dunford Mine that includes the monitoring programme and the proposed monitoring locations.
- Section 9 presents some overall conclusions and recommendations for the improvement of public radiation safety, with the Port Dunford Mine safety and impact assessment as a basis for the conclusions and recommendations.

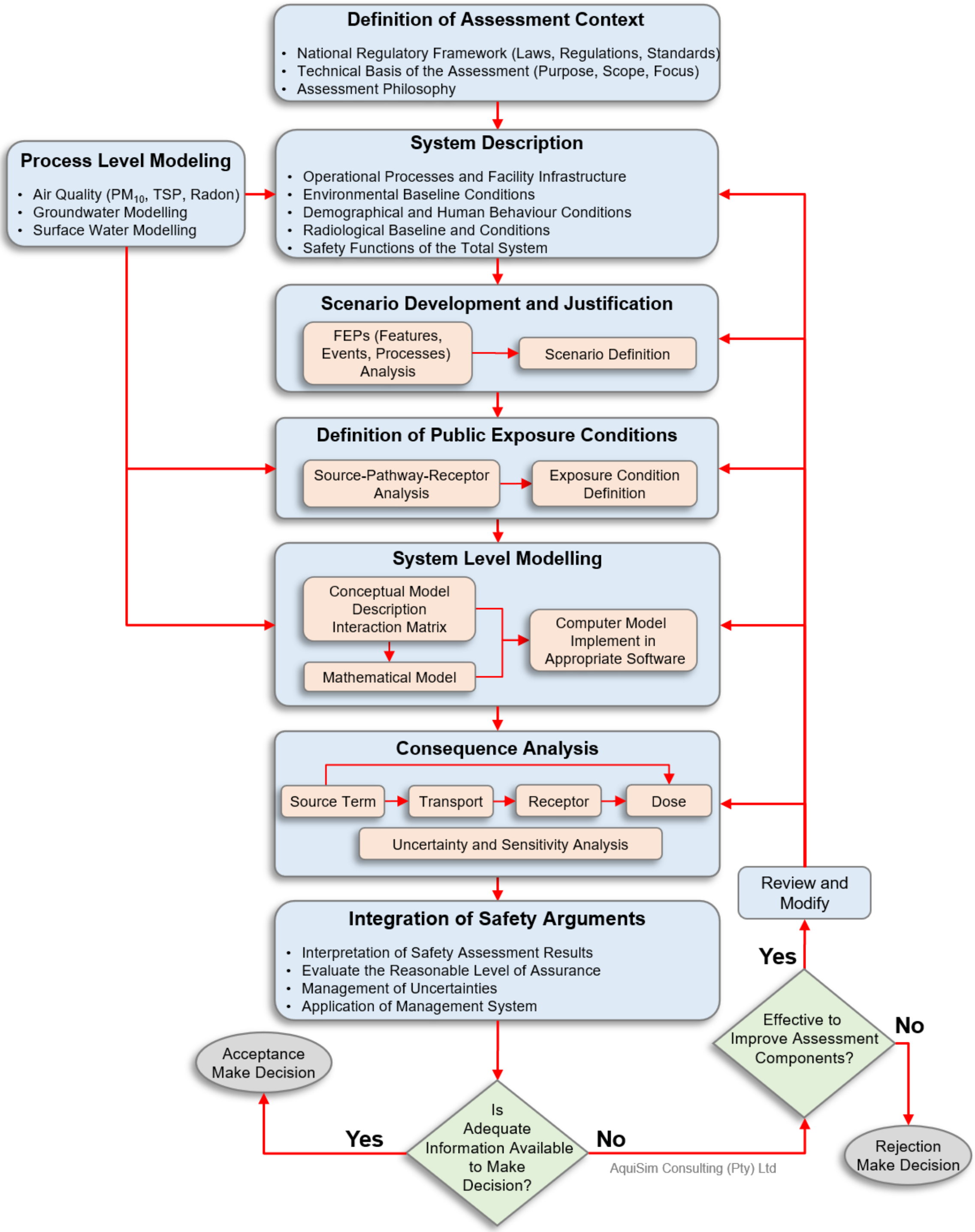

Figure 1.4 Schematic illustration of the conceptual assessment framework used to perform the radiological public safety and impact assessment of the Port Dunford Mine.

2 Assessment Context

2.1 General

Within the conceptual framework presented in Figure 1.4 and consistent with the IAEA safety assessment methodology, the purpose of the assessment context is to define in simple terms the *basis* or *context,* within which the Port Dunford Mine radiological public safety and impact assessment is conducted. Generally, it consists of a set of high-level assumptions and constraints that define the boundary conditions within which an assessment is performed, i.e., what is included and excluded and a justification for the choices made.

The section is structured as follows. Section 2.2 defines the nuclear regulatory framework that applies to the assessment from a national and international regulatory perspective, while Section 2.3 presents the technical basis of the assessment that includes the purpose, scope and focus as applicable to the assessment.

2.2 Nuclear Regulatory Framework

2.2.1 General

The regulatory framework is defined by a combination of national legislation (see Section 1.3), and regulations, requirements, and guidance 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 mineral processing facilities.

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

The international framework for radiation protection in the nuclear, medical, and mining industries is well-established and recognised. 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 IAEA.

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

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

2.2.2 The ICRP System of Radiological Protection

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

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

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

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

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

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

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

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

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

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

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

2.2.4 Safety Standards for the Protection of the Public

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

In planned exposure situations, the ICRP recommends that public exposure is controlled by the procedures of optimisation below the source-related constraint and using dose limits. In an emergency or existing exposure situation, the ICRP uses the term 'reference level' for the restriction on dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented.

The ICRP recommends that any exposure caused by human activity above natural background radiation should be kept as low as reasonably achievable (ALARA) with economic and social factors being taken into account, but below the following individual dose limits (ICRP, 1991):

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

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

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

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

Note that a *dose constraint is not a dose limit*; *exceeding a dose constraint does not represent non-compliance with regulatory requirements*, but could result in follow-up actions as required by the regulatory body (IAEA, 2014).

This means that the criteria of 1 mSv in a year adopted for the protection of the public in South Africa in Regulation No. 388 are consistent with the ICRP and IAEA recommendations for public exposure. The Regulation No. 388 dose constraint of 0.25 mSv in a year for public exposure per CoR holder is also within the range of 0.1 to 0.3 mSv per year proposed by the ICRP and IAEA.

2.2.5 National Radioactive Waste Management Policy and Strategy

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

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

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

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

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

In implementing the NRWMP, South Africa followed the IAEA guidelines regarding the definition and classification of radioactive waste as presented in IAEA (1994a) (unless deviations therefrom can be justified)

Table 2.1 summarises the waste classification scheme adopted for this purpose. Note that when the NRWMP was drafted in 2005, the waste classification scheme was in line with the IAEA waste classification scheme applicable at the time (IAEA, 1994a). The IAEA classification scheme has subsequently been revised and is presented in IAEA (2009b).

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

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

Waste Class	Waste Description	Waste type / Origin	Waste Criteria	Generic waste treatment / conditioning requirements (1)	Disposal / Management Options
1 HLW	Heat generating radioactive waste with high long and short-lived radionuclide concentrations.	1 Used fuel declared as waste or used fuel recycling products 2 Sealed sources	1 Thermal power > 2 kW/m^3. **OR** 2 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels > levels specified for LILW-LL 3 **OR** Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) above 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 100 years). The waste form shall be solid with additional characteristics as prescribed for a specific repository.	1 (a) Regulated deep disposal (100's of metres). (b) Reprocessing, Conditioning and Recycling (c) Long Term Above Ground Storage
2 LILW-LL	Radioactive waste with low or intermediate short-lived radionuclide and intermediate long-lived radionuclide concentrations.	1 Irradiated uranium (isotope production). 2 Un-irradiated uranium (nuclear fuel production). 3 Fission and activation products (nuclear power generation and isotope production) 4 Sealed sources.	1 Thermal power (mainly due to short-lived radio nuclides (T ½ < 31 y) < 2 kW/m^3) **AND** 2 Long-lived radio nuclides (T ½ > 31 y) concentrations. ❖ Alpha: < 4000 Bq/g ❖ Beta and gamma: < 40000 Bq/g (Maximum per waste package up to 10x the concentration levels specified above). **OR** 3 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) between 10 and 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 50 years). The waste form shall be solid with additional characteristics as for a specific repository.	1 Regulated medium depth disposal (10's of metres). 2 Managed as NORM-E waste (un-irradiated uranium)

Waste Class	Waste Description	Waste type / Origin	Waste Criteria	Generic waste treatment / conditioning requirements [(1)]	Disposal / Management Options
3 LILW-SL	Radioactive waste with low or intermediate short-lived radionuclide and / or low long-lived radionuclide concentrations.	1 Un-irradiated uranium (nuclear fuel production). 2 Fission and activation products (nuclear power generation and isotope production. 3 Sealed sources.	1 Thermal power (mainly due to short-lived radio nuclides (T ½ < 31 y) < 2 kW/m^3. **AND** 2 Long-lived radio nuclide (T ½ > 31 y) concentrations. ❖ Alpha: < 400 Bq/g ❖ Beta and gamma: < 4000 Bq/g (Maximum per waste package up to 10x the concentration levels specified above). 3 **OR** Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) below 10 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 10 years). The waste form shall be solid with additional characteristics as for a specific repository.	1 Regulated near surface disposal (< 10 metres). 2 Managed as NORM-E waste (un-irradiated uranium)
4 VLLW	Radioactive waste containing very low concentration of radioactivity.	1 Contaminated or slightly radioactive material originating from operation and decommissioning activities.	1 Clearance or authorised discharge or reuse criteria and levels approved by the relevant regulator.	Waste stream specific requirements and conditions.	1 Clearance. 2 Authorized disposal, discharge or reuse
5 NORM-L (low activity)	Potential Radioactive waste containing low concentrations of NORM.	1 Mining and minerals processing. 2 Fossil fuel electricity generation. 3 Bulk waste - un-irradiated uranium (Nuclear fuel production).	1 Long-lived radio nuclide concentration: < 100 Bq/g.	Unpackaged waste in a miscible waste form.	1 Re-use as underground backfill material in an underground area. 2 Extraction of any economically recoverable minerals, followed by disposal in any mine tailings dam or other sufficiently confined surface impoundment 3 Authorised disposal 4 Clearance
6 NORM-E (enhanced activity)	Radioactive waste containing enhanced concentrations of NORM.	1 Scales 2 Soils contaminated with scales	1 Long-lived radio nuclide concentration: > 100 Bq/g.	Packaged or unpackaged waste in a miscible or solid form with additional characteristics for a specific repository.	1 Dilute and re-use as underground backfill material in an identified underground area. 2 Extraction of any economically recoverable minerals, followed by dilution and disposal in an identified mine tailings dam or other sufficiently confined surface impoundment 3 Regulated deep or medium depth disposal.

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

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

2.2.6 Waste Categorisation for Mining and Mineral Processing Facilities

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

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

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

Note that the proposed management strategy of Category III waste (more than 1,000 $Bq.g^{-1}$) is still storage on a licensed site in an approved storage facility. This is because a long-term (permanent) solution for the management of this waste (i.e., high-level waste) is not available in South Africa at present.

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

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

2.3 Technical Basis of the Assessment

2.3.1 General

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

The purpose of this section is to define the technical basis of the assessment, which is largely defined by the purpose, scope and focus of the assessment, but *inter alia* the spatial and temporal boundary conditions and associated assessment endpoints.

2.3.2 Interested Parties to the Assessment

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

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

- Regulatory authorities that include the NNR as a statutory body responsible for regulating NORM and that is responsible for monitoring the process to ensure that the operational activities are performed by following relevant regulatory guidance and requirements;
- Tronox management and the shareholders and investors in the Port Dunford Mines;
- WSP as the Independent Environmental Assessment Practitioner responsible for the alignment of the Port Dunford Mine with the NEMA and associated EIA Regulations;
- Tronox workers that are involved in the implementation of the Port Dunford Mine;
- Members of the public that live near the Port Dunford Mine that may potentially be affected by the proposed facilities and activities (e.g., ward councillors, labour unions, agriculture, and landowners);
- Mining and industry, in particular the interested and affected mines and industries in the area, as well as other international mineral sands mining operations; and
- Local, provincial and national government departments that will be responsible for evaluating the applications for environmental authorisation and that must ensure that the environmental investigations are performed according to relevant regulatory guidance and requirements; and
- Technical, scientific and environmental groups that might have an interest in the approach followed for the assessment and the subsequent results.

2.3.3 Purpose of the Assessment

Any company endeavouring to develop a mining or mineral processing operation must undergo a rigorous permitting effort to convince regulators and public interested parties 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 and impact assessment, which can be defined as an analysis to evaluate the performance of the overall system (e.g. mining and mineral processing operation, facility or activity) and its impact, where the performance measure is the radiological safety in terms of a total effective dose criterion to workers and members of the public (IAEA, 2007).

The nuclear regulatory framework (see Section 2.2) is clear on the overall safety objective (IAEA, 2006) and the associated need to protect human health and the environment over the timescales of concern for all facilities and activities, including mining and mineral processing operations (IAEA, 2009a; ICRP, 2000). These assessments are required for all facilities and activities, including new or existing mining and mineral processing operations. Viewed from this radiological perspective and complemented with the S&EIR Process requirements, the purpose of the radiological impact assessment as input into the S&EIR Process is twofold:

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

2.3.4 Scope and Focus of the Assessment

2.3.4.1 Prospective Assessment

The facilities and activities associated with the proposed Port Dunford Mine have not been implemented as yet and, therefore, are still in the planning and design phase. Consequently, the assessment to determine their potential radiological safety and impact on members of the public is *prospective* (see Section 2.3.1).

2.3.4.2 Natural Background Radiation

The contribution of naturally occurring radionuclides to background radiation was introduced in Section 0. 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 Port Dunford Mine, *above natural background radiation*. This means the background radiation is not included in the comparison of the total effective dose with the regulatory compliance criteria.

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

2.3.4.3 Site-Specific Assessment

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

2.3.4.4 Ionising Radiation Exposure Assessment

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

2.3.4.5 Contaminants of Concern

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

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

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

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

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

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

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

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

2.3.4.6 Cumulative Effect

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

The focus of the assessment is on the contribution of the Port Dunford Mine to the annual effective dose to members of the public. Other operations that may contribute to radiation exposure in the area include the now-closed Hillendale Mine and Fairbreeze Mine. 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.

2.3.4.7 Worker Safety Assessment

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

2.3.4.8 Assessment of Non-Human Biota

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

2.3.4.9 Human Behavioural Conditions and Age Groups

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

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

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

2.3.5 Spatial Domain of Concern

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

2.3.6 Assessment Timescales

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

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

2.3.7 Assessment Endpoint

2.3.7.1 General

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

2.3.7.2 Radiological Public Safety Assessment Endpoints

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

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

A radiological public safety assessment should not rely on an evaluation of a single assessment endpoint, such as an individual effective dose rate (IAEA, 1997; 2004c). Multiple lines of reasoning may be useful and sometimes of significant importance, since regulatory bodies and other stakeholders may use and require a wide range of arguments and endpoints to help determine the adequacy of a public safety assessment.

Viewed from this perspective, activity concentrations in environmental media may serve as a complementary assessment endpoint. While it may not be necessary from a regulatory compliance perspective, reporting these endpoints contributes to the overall transparency of the assessment. Therefore, radionuclide concentrations in environmental media can be used as complementary safety indicators to the dose criterion. These may be compared with natural background concentrations in environmental media as observed near the site.

Activity concentrations in the following environmental media may thus be reported in addition to the annual individual effective dose:

- Airborne dust activity concentration in units of $Bq.m^{-3}$ for PM_{10} (or less than 10 microns);
- Dust fallout or deposition rate in units of $Bq.m^{-2}.year^{-1}$ for Total Suspended Particulates (TSP);
- Airborne radon concentration in units of $Bq.m^{-3}$;
- Activity concentration in surface water or groundwater in units of $Bq.m^{-3}$ or $Bq.L^{-1}$; and
- Activity concentration in surface soils in units of $Bq.kg^{-1}$.

When evaluating the performance of a facility or an individual component of the total system, the release rate of radioactivity from the facility into the wider environment also serves as a useful criterion, especially if containment of radioactivity is of importance. These results could be used as feedback into the design process, to reduce the release rate if required.

2.3.7.3 S&EIR Process Criteria

The following WSP methodology and rationale were used to assess the significance of the potential impacts of the Port Dunford Mine on the surrounding biophysical and socio-economic environment.

The assessment of impacts and mitigation evaluates the likely extent and significance of the potential impacts on identified receptors and resources against defined assessment criteria, to develop and describe measures that will be taken to avoid, minimise or compensate for any adverse environmental impacts, to enhance positive impacts, and to report the significance of residual impacts that occur following mitigation.

The key objectives of the risk assessment methodology are to identify any additional potential environmental issues and associated impacts likely to arise from the proposed Port Dunford Mine and to propose a significance ranking. Issues/aspects are reviewed and ranked against a series of significance criteria to identify and record interactions between activities, aspects, resources and receptors to provide a detailed discussion of impacts.

As required by the EIA Regulations (2014) as amended, the determination and assessment of impacts are based on the following criteria:

- The nature of the impact;
- The significance of the impact;
- The consequence of the impact;
- The extent of the impact;
- The duration of the impact;
- The probability of the impact;
- The degree to which the impact

- Can be reversed;
- May cause irreplaceable loss of resources; and
- Can be avoided, managed or mitigated.

Following international best practices, additional criteria have been included to determine the significant effects. These include the consideration of the following:

- Magnitude: to what extent environmental resources are going to be affected
- Sensitivity of the resource or receptor (rated as high, medium and low) by considering the importance of the receiving environment (international, national, regional, district and local), the rarity of the receiving environment, benefits or services provided by the environmental resources and perception of the resource or receptor) and
- The severity of the impact, measured by the importance of the consequences of change (high, medium, low, negligible) by considering inter alia magnitude, duration, intensity, likelihood, frequency and reversibility of the change.

The significance, which is determined through a synthesis of the characteristics described above (refer to the formula below) and can be assessed as low, medium or high:

- The status, which is described as either positive, negative or neutral;
- The degree to which the impact can be reversed;
- The degree to which the impact may cause irreplaceable loss of resources; and
- The degree to which the impact can be mitigated.

The following risk assessment model has been used to determine the significance of impacts, with a description of the different parameters used in the assessment listed in Table 2.6:

Significance (S) = (Extent (E) + Duration (D) + Reversibility (R) + Magnitude (M)) x Probability (P)

Environmental impacts can therefore be rated as high, medium or low significance on the following basis:

where the impact must have an influence on the decision process to develop in the area	High	> 60 points
where the impact could influence the decision to develop in the area unless it is effectively mitigated	Medium	31 – 60 points
where this impact would not have a direct influence on the decision to develop in the area	Low	< 30 points
Indicates a positive impact rating		

The impact significance without mitigation measures will be assessed with the design controls in place. Impacts without mitigation measures in place are not representative of the proposed development's actual extent of impact and are included to facilitate an understanding of how and why mitigation measures were identified. The residual impact remains following the application of mitigation and management measures and is thus the final level of impact associated with the development. Residual impacts also serve as the focus of management and monitoring activities during Project implementation to verify that actual impacts are the same as those predicted in this EIA Report. Given that there are two phases of mining development, it is intended that the assessment will be undertaken for the following stages of the Project:

- Phase 1 – Operation: Site establishment/Construction for Phase 2 (to be undertaken in parallel with Phase 1 Operation);
- Phase 2 – Operation (please assess this according to the mine plan. This may be broken down further at your discretion); and
- Decommissioning and Closure.

Table 2.6 Description of the parameters used for assessing risks.

Nature of the Impact	
Beneficial / Positive	An impact that is considered to represent an improvement on the baseline or introduces a positive change.
Adverse / Negative	An impact that is considered to represent an adverse change from the baseline, or introduces a new undesirable factor.
Direct	Impacts that arise directly from activities that form an integral part of the Project (e.g. new infrastructure).
Indirect	Impacts that arise indirectly from activities not explicitly forming part of the Project (e.g. noise changes due to changes in road or rail traffic resulting from the operation of the Project).
Secondary	Secondary or induced impacts caused by a change in the Project environment (e.g. employment opportunities created by the supply chain requirements).
Cumulative	Impacts are those impacts arising from the combination of multiple impacts from existing projects, the Project and/or future projects.
The physical extent (E)	
1	the impact will be limited to the site;
2	the impact will be limited to the local area (local study area);
3	the impact will be limited to the region;
4	the impact will be national; or
5	the impact will be international;
The duration (D), wherein it is indicated whether the lifetime of the impact will be:	
1	of very short duration (0 to 1 year)
2	of short duration (2 to 5 years)
3	medium term (5–15 years)
4	long term (> 15 years)
5	permanent (this is considered permanent if the impact will be experienced post-mine closure)
Reversibility (R): An impact is either reversible or irreversible. How long before impacts on receptors cease to be evident.	
1	The impact is immediately reversible.
2	The impact is reversible within 2 years after the cause or stress is removed; or
3	The activity will lead to an impact that is in all practical terms permanent.
The magnitude (M) of impact on ecological processes is quantified on a scale from 0-5, where a score is assigned.	
0	small and will not affect the environment
1	minor and will not result in an impact on processes (to be defined by individual specialist fields).
2	low and will cause a slight impact on processes
3	moderate and will result in processes continuing but in a modified way
4	high (processes are altered to the extent that they temporarily cease).
5	very high and results in the complete destruction of patterns and permanent cessation of processes.
The probability of occurrence (P), which describes the likelihood of the impact actually occurring. Probability is estimated on a scale where	
1	very improbable (probably will not happen).
2	improbable (some possibility, but low likelihood).
3	probable (a distinct possibility).
4	highly probable (most likely).
5	definite (impact will occur regardless of any prevention measures).

The objective of the Impact Assessment is to rate the significance of the potential impacts of the Port Dunford Mine before and after the implementation of mitigation measures. The methodology encompasses an assessment of the nature, consequence (magnitude, extent, duration) and probability (likelihood) of the identified potential environmental and social impacts of the Port Dunford Mine. The reversibility of the impact, as well as the cumulative impact, are also considered. The impact is assessed before and after the implementation of potential mitigation measures.

3 System Description

3.1 Introduction

Within the conceptual framework presented in Figure 1.4, the purpose of the system description is first to provide a summary overview of the Project with specific reference to the facilities, activities, and associated infrastructure. This information is normally complemented with a description of the prevailing site characteristics and potentially affected human populations located near the Port Dunford Mine area, as well as the associated radiological conditions.

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

The section is structured as follows. Section 3.2 presents the regional and local setting of the Port Dunford Mine. Section 3.3 describes the Port Dunford Mine, 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 S&EIR process for the Port Dunford Mine as the primary references, Section 3.4 summarises the baseline environmental conditions and the population characteristics observed near the Port Dunford Mine area. Section 3.5 summarises the available radiological data and information available for the Port Dunford Mine at present.

3.2 Project Location

The Project area is located in the uMlalazi and uMhlathuze Local Municipalities in the King Cetshwayo District Municipality of the KwaZulu-Natal Province of South Africa. It is located approximately 15 km south-west of Richards Bay and is adjacent to the following settlements/towns at different points along the boundary (see Figure 1.1):

- Mtunzini – 200 m southwest;
- Port Durnford – 60 m south-southeast;
- Esikhawini – 200 m southeast; and
- Gobandlovu – 200 m northeast.

The N2 highway as well as the R102 traverse the length of the proposed mining area, the R102 being located to the northwest and the N2 running through the centre. There is also a railway line just south of the N2 that also traverses the mining right area. The proposed mining right area is approximately 4,734 ha. However, only 1,152 ha are earmarked for development and mining.

The Project area includes the southern areas of Waterloo (KZN30/5/1/1/2/296 PR), as well as the Penarrow area (KZN30/5/1/1/2/279 PR) that has a lapsed prospecting right. Mondi plc is currently leasing the majority of properties under the prospecting rights for commercial forestry purposes.

The predominant land use in the Project area is agriculture, with commercial timber plantations and forestry. The largest portion of the Project area is currently used for commercial Eucalyptus plantations. Endemic vegetation in the form of swamp forests, wetlands and small portions of coastal dune forests, occurs in the drainage channels and streams between the plantations. Other land uses in the area include mining, commercial sugarcane farming, aquaponics exotic fish farming, organic flower farming, tea-tree cultivation, fruit farming, university, rural and urban settlements, Umlalazi Nature Reserve, industry, roads and railways. General infrastructure in the Project area includes electric power lines, which cross the area in an east-to-west direction, as well as a railway line that transects the eastern portion of the area (WSP, 2024b).

3.3 Project Description

3.3.1 General

The Port Dunford Mine was briefly introduced in Section 1.1. The intent is to mine for Heavy Minerals (general), Garnet (Abrasive), Kyanite, Leucoxene (heavy mineral), Monazite (heavy mineral), Rutile (heavy mineral), Silica Sand and Zirconium ore to produce (WSP, 2024a):

- Titanium dioxide (T_iO_2) pigment, which is used in paints, plastics, paper laminates, ink and the food market;
- Titanium metal;
- Welding consumables;
- Titanium feedstocks, which are used in the manufacture of brake pads, roof tiles and the glass industry; and
- Zircon, which is used for the manufacturing of ceramics, foundry, refractory, zirconia and other zircon chemicals.

It is proposed that the mining activity will be undertaken in two phases (WSP, 2024a):

- Phase 1 is a low-rate mining operation at approximately 70,400 tpa (tons per annum) for approximately 10 years from 2025 to 2035. It is anticipated that the mining operations will increase in throughput after 2035; and
- Phase 2 (Full Scale) is an operation with a mining rate of 3,000 tph (tons per hour), which will operate until the close of the mine in 2069.

Presented here is a more detailed description of the Port Dunford Mine and the associated activities and infrastructure using information from the Scoping Report prepared for the Port Dunford Mine (WSP, 2024a). Figure 3.1 is a locality map showing the planned infrastructure associated with the Port Dunford Mine.

3.3.2 Need for the Port Dunford Mine

The Fairbreeze Mine will be reaching the end of its life span within the next fifteen years, while the previous mining operation at Hillendale is currently in the mine closure stage of its life. It is intended that the Heavy Mineral Concentrate (HMC) produced at the Port Dunford Mine will be used to replace Fairbreeze Mine commitments to the Mineral Separation Plant (MSP) and the Empangeni Smelter.

The mineral suite in the Port Durnford ore body closely matches that of the Fairbreeze ore bodies, with all previous test work showing that Port Durnford mineral products would effectively be a ‘like for like’ replacement for Fairbreeze mineral products. The Project will thus secure continued feed to the CPC in Empangeni, allow for the continued supply of customers and realise sustained economic benefits.

Figure 3.1 **Locality map showing the planned infrastructure associated with the Port Dunford Mine (WSP, 2024a).**

3.3.3 Physical Extent of the Port Dunford Mine

Figure 3.1 shows the physical extent of the Port Dunford Mine. The Port Dunford Mine boundary covers an area of about 4,454 ha, with about 16 km in a northeast-southwest direction and about 3.5 km in a northwest-southeast direction. Within this area, provision is made for the road corridors, Phase 1 and Phase 2 mining areas, the Primary Wet Plant (PWP), the establishment of Residual Storage Facilities (RSF), Sandtails areas, the storage of topsoil, and water control dams. The closest residential areas are Port Durnford (60 m), Mtunzini (200 m), Gobandlovu (200 m), and Esikhawini (200 m).

3.3.4 Construction and Operation: Phase 1

The Phase 1 mining operations will be situated on the Remainder of Richards 16802 and will have a mining footprint of 41 ha over a ten (10) year period between 2025 and 2035. This land is currently under commercial forestry, leased by Mondi, and owned by the Phalani Community Trust. The proposed location for the Phase 1 operation and infrastructure is indicated in Figure 3.2. The mining will operate at a rate of 100 tph or 70,400 tpa. Active mining will take place five (5) days a week per month, for 12 hours a day.

The run-of-mine (RoM) material will be mined mechanically with front-end loaders (FELs) and hauled via trucks to the Fairbreeze Mine on public roads (the R102 and N2) for stockpile and further processing. This means that no processing facilities, tailings or fines disposal facilities will be developed on the Port Durnford lease area during Phase 1. It is expected that 4 x 30 ton Trucks will be used to transport the mined material from the Port Dunford Mine to the Fairbreeze Mine. It is anticipated that 9 truck cycles will be used per day for the 5 days each month that the site is being actively mined.

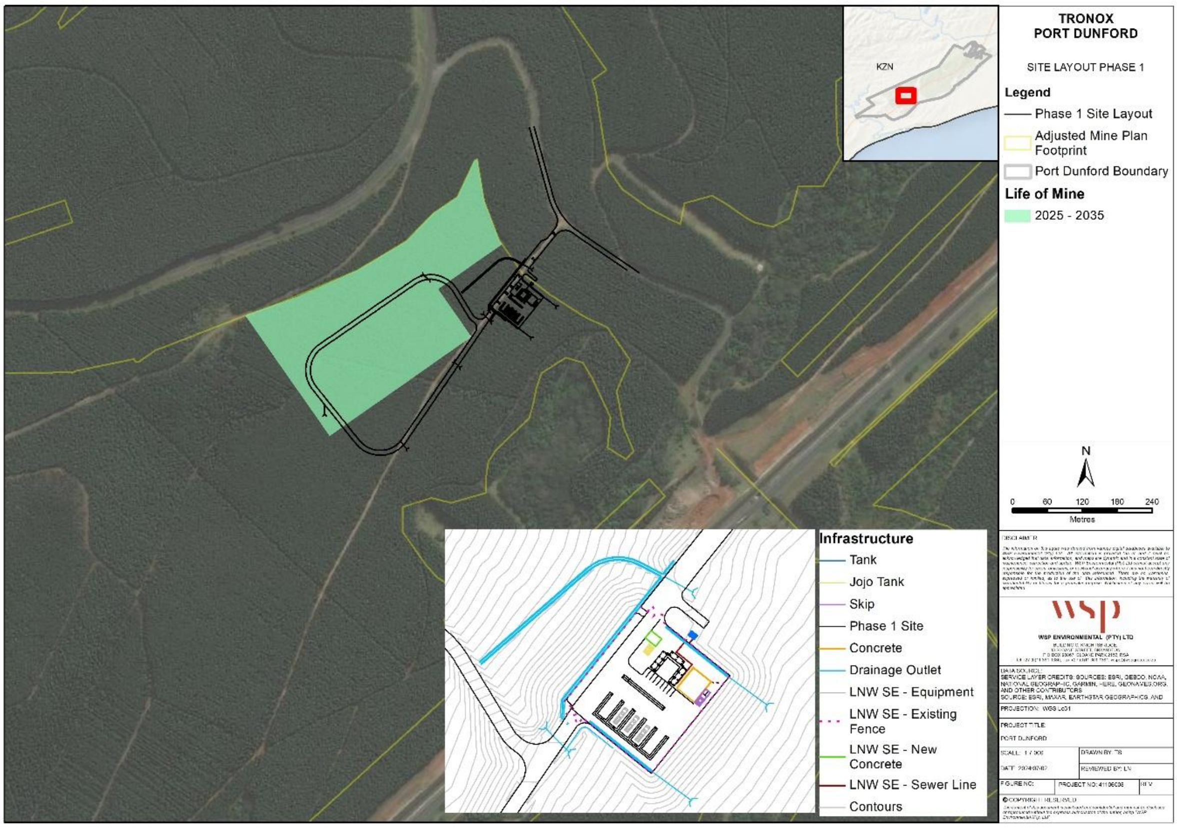

Figure 3.2 The proposed Phase 1 layout and associated infrastructure for the Port Dunford Mine (WSP, 2024a).

The mined-out ore bodies at the Fairbreeze Mine will be used for pit infill from Phase 1 for the first 11 years of mining. The hydraulic mining process at the Fairbreeze Mine will continue as per current practice, to process the stockpiled material. Hydraulically reclaimed ROM slurry will be pumped to the existing Fairbreeze PWP for processing. The processed material will then be trucked to the existing MSP located at the CPC in Empangeni as part of the Fairbreeze product.

Figure 3.3 illustrates the process flow during Phase 1 operations. Since the mined material will loaded and transported directly to the Faibreeze Mine, only limited infrastructure is required to be implemented during Phase 1 (see Figure 3.2). From a radiological impact assessment perspective, it is only the mined-out area and possibly the haulage roads to Fairbreeze Mine that are of importance.

The primary water use on site will be dust suppression. It is anticipated that 4,800 m_3 per annum will be required for Phase 1, with municipal water supply trucked and stored in JoJo tanks as the preferred source of water.

Figure 3.4 shows that three possible transport routes were considered for the Phase 1 operation for transporting mined material between the mining area and Fairbreeze Mine, with the route in red as the preferred option and two alternative routes in blue and yellow. This transport route will be used for the first 10 years of mining during Phase 1. Once Phase 2 commences, all RoM will be processed at the Port Dunford Mine PWP, which will have been constructed by that time.

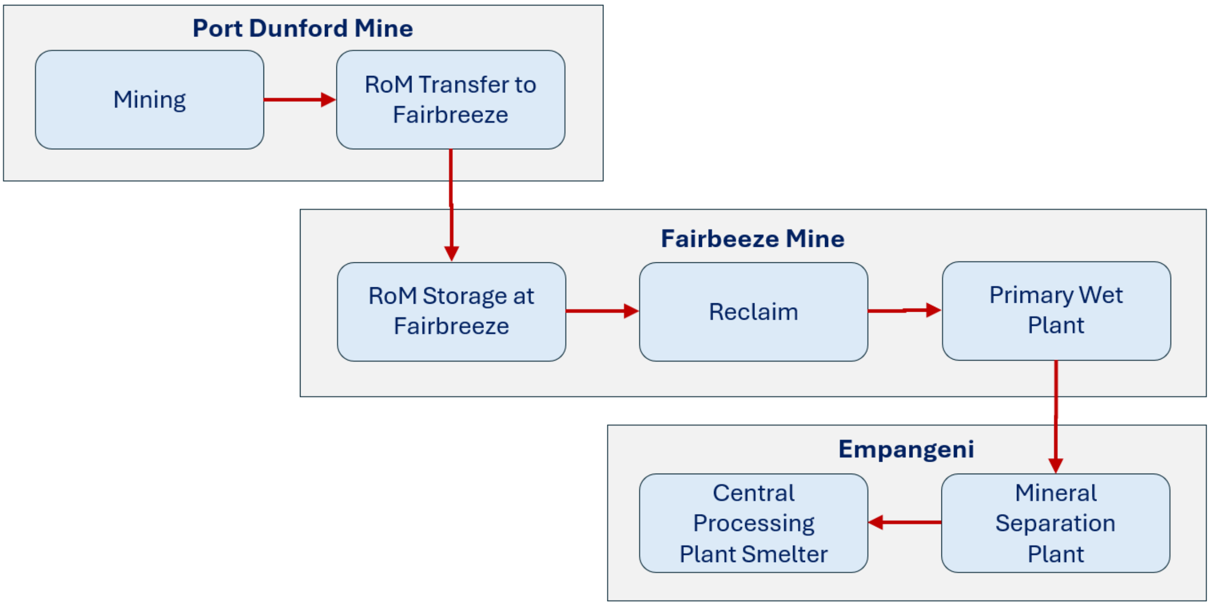

Figure 3.3 **Block diagram of the process flow during Phase 1 of the Port Dunford Mine (WSP, 2024a).**

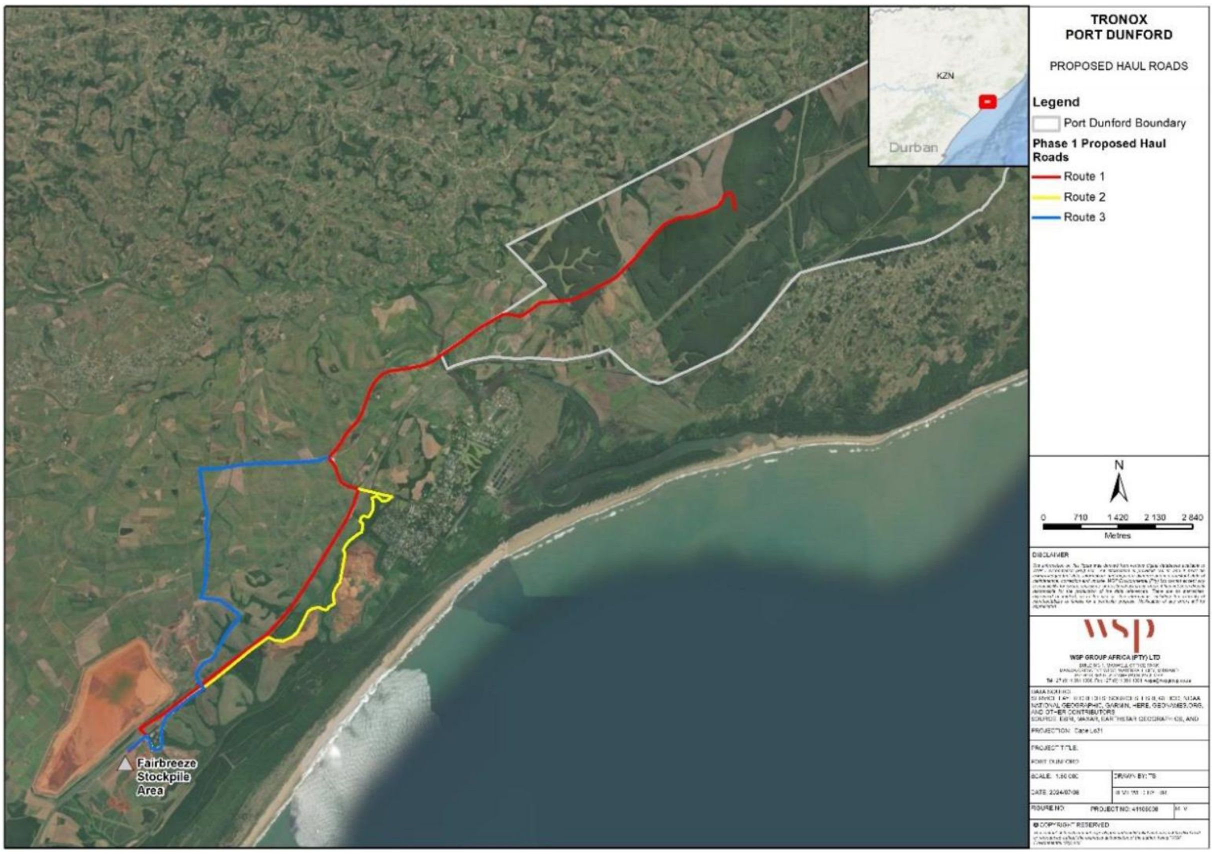

Figure 3.4 **The proposed haulage routes from the Port Dunford Mine to the Fairbreeze Mine for Phase 1 of the Port Dunford Mine (WSP, 2024a).**

3.3.5 Construction and Operation: Phase 2

3.3.5.1 Mine Plan

The infrastructure for Phase 2 will be constructed during the Phase 1 mining period (2025 to 2036). However, mining and processing for Phase 2 will only commence in 2036.

The proposed Phase 2 operation comprises opencast mining, on-site processing of RoM material in an on-site PWP, the on-site backfill and disposal of both coarse and fine sand tailings from the PWP and the transport of HMC to the MSP located in Empangeni within the CPC. At the MSP the concentrate is further beneficiated to yield the target minerals. Coarse sand tailings that are not separated at the PWP and are thus transported to the MSP as part of the concentrate, but which do not yield product, are returned to the mine and are reintroduced into the coarse sand tailings backfill stream.

The Phase 2 Port Dunford Mine footprint is 1,152 ha, which will be mined over 33 years, between 2036 and 2069. The planned rate of mining will be 3,000 tph, 24 hours a day, 365 days a year. Figure 3.5 indicates the proposed location for the Phase 2 operation and infrastructure.

Figure 3.5 **The proposed Phase 2 layout and associated infrastructure for the Port Dunford Mine (WSP, 2024a).**

The planned mining schedule (mine block plan including time sequencing) is presented in Figure 3.6. The mining schedule is also presented in Figure 3.7, with mining blocks grouped into 5-year units for ease of interpretation of mine progress through time. On these plans, the position of the fine Residue Storage Facilities (RSFs in orange outline) and the sand dumps (in beige outline) are also indicated together with the position of the PWP (orange rectangle).

Figure 3.6 **The proposed Phase 2 LoM plan for the Port Dunford Mine (WSP, 2024a).**

Figure 3.7 **The proposed Phase 2 LoM plan for the Port Dunford Mine, showing 5-year mining windows (WSP, 2024a).**

Mining commences in Phase 2 in 2035 at the site of the Phase 1 pit to complete mining that block. Thereafter, the active mining window moves to a position immediately east of the PWP and sequentially progresses in an easterly direction until the eastern extent of the mine is reached in 2061. In 2051, mining is also initiated in the western extent of the proposed mining footprint and progresses in an easterly direction back towards the PWP, with the final block which lies immediately north of the PWP, being mined in 2069.

RSF 9 in the west of the site will be developed on the unmined ground, while RSF C in the east of the site, will be developed sequentially on the pit floor as each corresponding five-year mining block has been completed space becomes available. During these periods, the washed sand tailings cannot be backfilled into the pit and consequently must at times be deposited on the surface. All pit areas will be backfilled with either coarse sand tailings or fine residue (within the RSF). The sand dump positions (beige outline) reflect where a sand dump will be developed above the current ground surface and will remain as a permanent aboveground feature on the post-mining landscape. Similarly, RSF Site C will also end at a height above the current ground surface.

3.3.5.2 Sequence of Mining Activity

The basic sequence of mining activities for Phase 2 is as follows (WSP, 2024a):

- Before mining starts a minimum of 0.3 m of topsoil will be stripped. This material will preferably be placed directly in an area available for rehabilitation. If that is not possible, it will be placed in a stockpile for later use (see Section 3.3.8 on topsoil management);
- Then, the *in situ* sands are mined. In the Port Dunford Mine, the sands are mineralised from the surface to the base of the economic mining limit within the pit. Consequently, there is mineralisation even in the topsoil that is set aside (see Section 3.3.5.3, which describes the mining method);
- After a pit has reached the economic limit for mining it becomes available to be backfilled. Backfill material comprises the washed course tailings;
- Once the pit is backfilled to the design height, it becomes available for rehabilitation and the topsoil is replaced; and
- The top soiled areas are revegetated following the approach described in Section 3.3.8.

3.3.5.3 Mining Method

The Port Dunford Mine is an opencast sand mine, not dissimilar to the current Fairbreeze Mine. However, the mining method will differ. At the Port Dunford Mine, mobile skid-mounted dozer trap mining units (DTMUs) will be used within the active mining areas. The mining process entails dozing the sand material down to the DTMU where it is combined with water and pumped to the PWP. Each DTMU is anticipated to be fed by two D11 dozers and a CAT390 excavator. A DTMU is equipped with a vibrating screen to separate oversized material and is accompanied by a primary pump. Each DTMU is connected to a raw water feed pipeline, a RoM slurry delivery pipeline, and a power connection. Figure 3.8 shows a typical DTMU for visual reference.

3.3.5.4 Mineral Processing

The RoM material is processed at the PWP to remove fine material from the plant feed and separate the non-mineralised sand fraction to produce a heavy mineral concentrate. The RoM feed is typically comprised of 76% coarse sand tails, and 20% sand tail fines with the remaining 4% being the HMC, which is then transported off-site to the MSP in Empangeni. The primary processing entails:

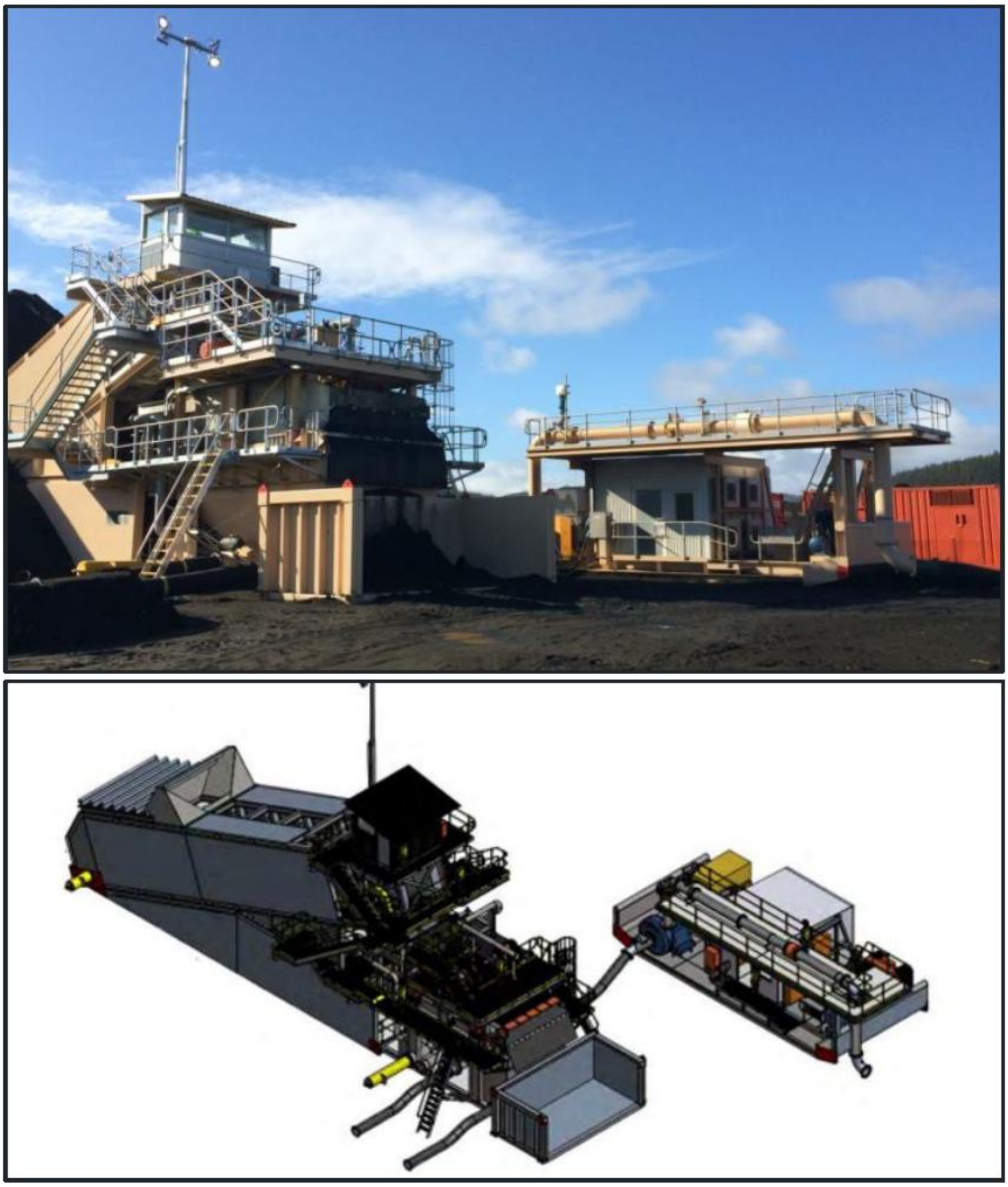

Figure 3.8 A typical dozer trap mining unit (DTMU) showing the trap on the LHS, into which material is dozed and an associated pump unit on the RHS.

- Mined material is deslimed and placed through a spiral circuit to separate the coarse sand tailings (+45 μm),
- The coarse sand tailings will be used for backfilling and the establishment of the walls of the RSFs;
- The spiral concentrate is put through a magnetic separation circuit to remove the reject magnetite, which is fed back into the coarse tailings circuit;
- The non-magnetic material forms the HMC; and
- The fine tailings (-45 μm) are collected from the desliming process, a thickener is added and process water is retrieved before disposal at the RSFs.

The PWP will be designed to process 22,866,000 tpa RoM at a nominal rate of 3,000 tph. Figure 3.9 is a block diagram of the proposed process flow during Phase 2 of the Port Dunford Mine operations. Raw water will be supplied to the Port Dunford Mine from the existing uMhlatuze bulk water supply station directly to the PWP raw water dam via a take-off from the main pipeline currently supplying water to the Fairbreeze Mine.

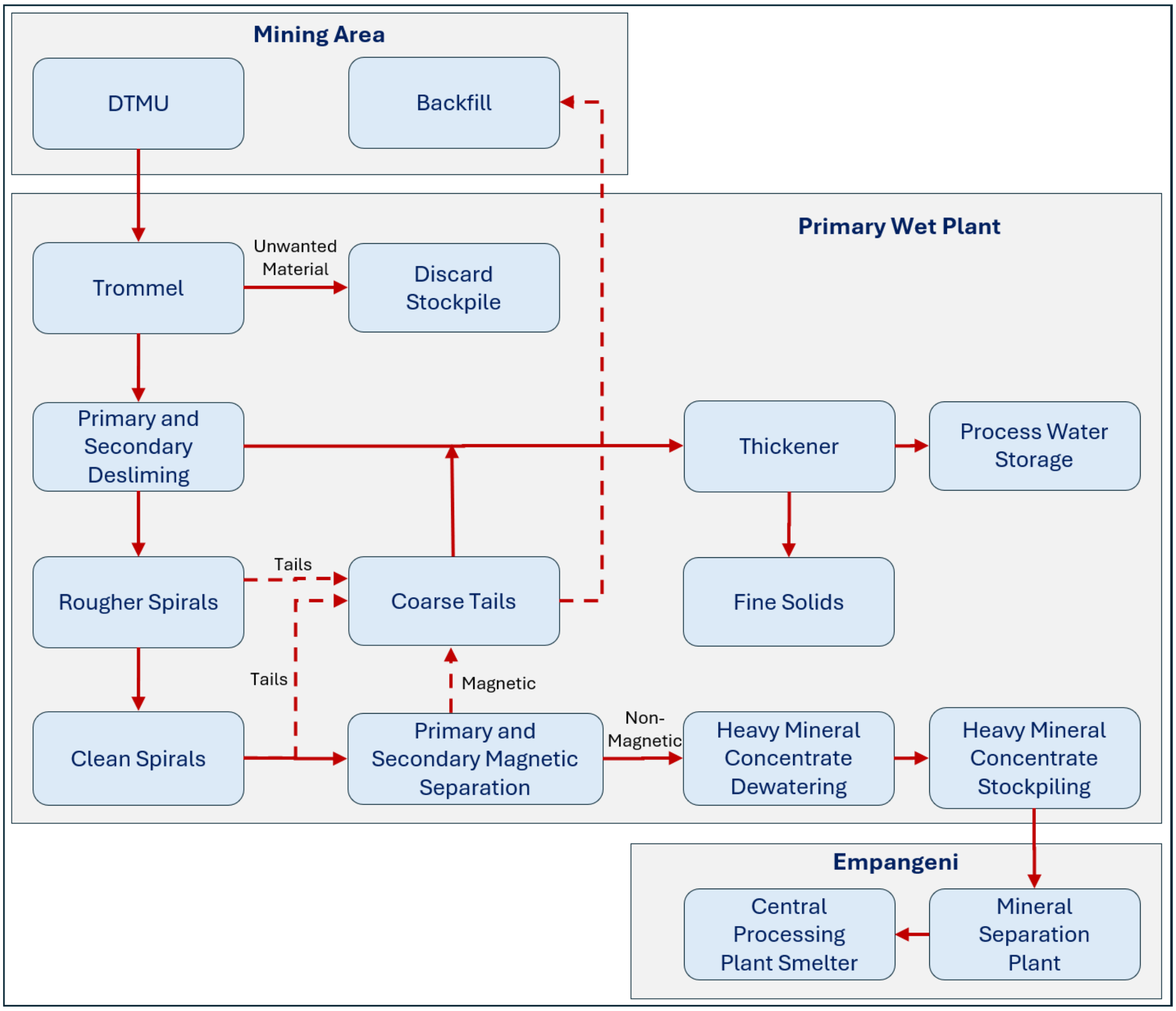

Figure 3.9 Block diagram of the proposed process flow during Phase 2 of the Port Dunford Mine (WSP, 2024a).

3.3.6 Waste Streams

Three "waste streams" are produced from the proposed mining operation, namely coarse sand tails, fine residue and gypsum filter cake. The following tails products are received from the CPC (Empangeni) for disposal with the various tails products at the PWP at the Port Dunford Mine:

- MSP coarse tails are received by tip truck from the MSP. These are tipped directly into a slurry hopper where it is slurried before pumping directly into the rougher sand tails tank for disposal with the sand tails at the PWP. It is expected that the total MSP tails received for disposal will be between 260 and 330 kt per annum (or 15.6 to 18.5 million tonnes per annum). Approximately 678 Mt of sand tails will be deposited during the planned LoM. Large sand tail stockpiles will be utilised for sand tail disposal from 2036 within the Port Dunford Mine mining boundary.
- Gypsum filter cake from the MSP is received via truck from the CPC. The gypsum cake is fed into a material handling facility for re-slurrying before being fed to the thickener underflow tank for disposal together with the fines to the RSF. It is estimated that between 4,800 and 9,600 tons per annum of gypsum will be disposed of into the RSF feed stream each year.

3.3.7 Coase Sand Tails Disposal

It is anticipated that the Port Dunford Mine will have a sand tails material balance of approximately 678 Mt over the full LoM; thus between 15.6 to 18.5 Mt of sand per annum requiring handling and management. All 678 Mt of coarse sand tails over a planned 34-year mining period have been accounted for in the current mine plan. Approximately 63 Mt of coarse sand tailings will be used for RSF dam wall construction and the remaining 615.2 Mt will be used for pit backfill, for RSF capping or will be permanently deposited onto sand dumps. Tronox assessed different sand tails disposal alternatives and proposed the following:

- For the first 7 years of mining in Phase 2 (2036 to 2047), while opening and mining the pit area for the first compartment of RSF Site C, coarse sand tails (57 Mt) will be used in containment wall construction at RSF 9 or deposited outside of the mining pit footprint (sand dump sites A1, A2, and A3 south of the N2) or later used in RSF C compartment 1 wall construction;
- For 5 years (2048 to 2053) Backfill Area 8 will be used for the deposition of 89 Mt of sand tails;
- In the years 2049 to 2051, approximately 21 Mt of sand tails will be used in further wall construction for RSF Site C Phase 3;
- In the years 2053 to 2059, 117 Mt of sand tails will be deposited in backfill Area 4; and
- In the year 2064, 2.7 Mt of sand tails will be stockpiled in backfill Area 3.

Table 3.1 presents the proposed sand tails deposition schedule over the LoM. In this schedule, the identified sand deposition areas have been called sand "backfill" areas. These are not necessarily pit backfill areas but rather sites for permanent sand placement which will remain in the post-mining landscape.

Table 3.1 The proposed sand tails deposition schedule for the Port Dunford Mine (WSP, 2024a).

Sand tails	Capacity (Mt)	2036-2038	2039-2047	2045-2046	2047-2055	2054-2064	Post 2064
Backfill A1,A2,A3	150			-	-	-	
RSF Site 9	18			-	-	-	
RSF Site C (Phase 1)	18						
RSF Site C (Phase 2)	21						
Backfill 8	89						
RSF Site C (Phase 3)	21						
Backfill 4	117						
RF Site C (Phase 4)	4						
Backfill 5	96						
Backfill 3 (post 2064)	133	-		-	-	-	

The sand tails material will be transported to the sand tails stockpiles through feed pipelines, which will run alongside roads on site. Cyclones will help deposit the sand tails on the top of each stockpile area, and a return water pipeline will recycle the water back to the primary wet plant. The existing road infrastructure will be utilized for the pipeline routing as far as possible. A topsoil berm will surround each sand tail dump to contain the sand tails and stormwater runoff.

The following information will apply to the sand tails deposition strategy:

- The sand tails stockpiles have been designed with a 1:3 vertical height. Each stockpile will have a 100 m buffer from the stockpile to the nearest public infrastructure (roads, railways and residential areas) and a 30 m buffer to the nearest environmentally sensitive area;

- Sand tailings stockpiles will vary in height from approximately 65 m (stockpile A1) to over 100 m (stockpile 8) above average natural ground surface;
- Capping the RSF facilities with coarse sand will be subject to RSF stability and surface bearing capacity, which will be determined during detailed design and subsequent operational monitoring;
- The mined-out pit volumes are included in the available airspace calculation for backfill areas 3,4, and 5. In these areas, sand deposition will also occur above the original ground surface within the identified areas indicated below; and
- Utilising co-disposal of fines and coarse sand mix will be explored with this operation. There are reports of positive results with in-pit mixing with the aid of re-flocculation in deposition piping. This could result in better consolidation and water recovery resulting in higher densities of the deposited residue and overall space saving.

A total of 926.3 have been identified for coarse sand tails disposal within the Port Durnford Boundary, of which 451 ha is LoM/sandtails and 475.3 ha are sandtails (see Figure 3.5).

3.3.8 Topsoil Management

For all areas that will be used for mining and mine infrastructure at the Port Dunford Mine, 0.3 m of topsoil within the “project footprint” will be removed and kept aside for rehabilitation. This standard practice applies to the RSF Site 9, the mining footprint, sand tails dump areas and the PWP plant site. Wherever possible within the mining areas topsoil will be stripped and placed directly in areas available for rehabilitation. When space has been depleted in the designated 44 ha of topsoil stockpile areas topsoil will be stockpiled and used as stormwater runoff berms around the sand tail deposition areas.

Before mining or stockpiling, the top 300 mm of soil will be stripped and stockpiled in designated topsoil stockpile sites within the Port Durnford mining right boundary (see Figure 3.6 where topsoil stockpiles are indicated in brown).

The topsoil stockpiles will be afforded a 30 m buffer from the edge of the nearest wetland or delineated sensitive environmental area. Each topsoil stockpile area will be cleared of large trees or tree stumps before placement of soil. The height of stockpiles should not exceed 3 m wherever possible and stockpiles will be protected from stormwater erosion by use of diversion berms. No road development over the surface of the topsoil stockpiles will be permitted to avoid unintended compassion of the valuable topsoil resource. The topsoil stockpiles will be grassed with a mix of indigenous grass seeds.

3.3.9 Fine Residue Deposition

3.3.9.1 General

Fine residue will need to be managed throughout the life of mine. The RSF capacity for the Port Dunford Mine has been designed for a 28-year LoM between 2036 and 2064. It is understood that RSF capping and shaping of the sand tails dump sites with the remaining sand tails will take place between 2064 and 2069.

The RSF facilities will be constructed in a phased approach. The RSF dam walls will be constructed with coarse sand tails from the mining operation and be compacted. The dam walls will be erected to the designed heights to create a “holding shell” for the incoming fine residue. Each RSF facility has a determined lifespan of RSF disposal. Each RSF site will have a maximum height and storage capacity. Once the RSF facility has reached its design capacity (design capacity in terms of storage volume and height) the facilities will be capped with coarse sand tailings and vegetated.

The waste classification has assessed the RSF waste stream to be a Type 4 waste for design. Type 4 waste facilities require only a Class D foundation, which means that no liner system is required for the RSF. RSF Site 9 will have a Water Control Dam (WCD) to receive water from the RSF dams and intercept stormwater falling within the managed RSF area. Excess water will be recovered from the surface of the RSF and under the drainage system and returned for reuse in mining. The RSF dams will use a barge/turret system for excess water removal. The RSF sites will be installed with herringbone, toe, and blanket drainage systems to assist in dewatering the fine tailings to aid stability, manage seepage and control the phreatic surface within RSF.

Stormwater control berms and trenches will be used to manage external water, with toe paddocks to control material, which has been eroded from the RSF outer slopes. The fine residue disposal concept study and supporting concept designs have been updated.

3.3.9.2 RSF Site 9

RSF Site 9 will be built from the sand tailings material from the Phase 2 mining activity. After 11 years of Phase 1 mining, Phase 2 mining will start adjacent to the then-constructed PWP plant in 2037. The sand tails that are produced in the first block of Phase 2 mining will be used to construct the dam walls of RSF Site 9. RSF Site 9 will be situated on the southwestern side of the proposed mining footprint, on Portion 1/13602 and the remaining portion of 13602 of Lot 132. This property is leased by Mondi and owned by the Philani Community Trust. This RSF facility will be used for the first 6 years of mining in Phase 2. RSF Site 9 will be 268 ha in size and have a final height of approximately 55 m above average ground level. The facility will be designed to store up to 26.9 Mt of fines residue and 18.2 Mt of sands residue.

The terminal Rate of Rise (RoR) for Site 9 is 3.3 $m.year^{-1}$, meaning that the RSF facility can safely increase in height by 3.3 $m.year^{-1}$.

The water control dam for RSF Site 9 was redesigned to avoid environmentally sensitive areas. This dam will be approximately 19 ha in extent and have an 870,000 m^3 storage capacity. A barge/turret system will be used to transport water from the RSF to the WCD.

It is anticipated that RSF Site 9 will be operational for 6 years and reach full capacity in 2042. Thereafter, capping of the RSF surface with coarse sand tailings site will commence in 2046 assuming that the surface of the RSF has dried out and stabilised sufficiently by that stage. Once backfilled, the site will be topsoiled in 2048. Outer slopes of the RSF will be topsoiled and vegetated as areas become available to stabilise the side slopes against erosion. The RSF will be returned to the landowner once Tronox is satisfied that the facility, and the chosen vegetation cover, have stabilised. Figure 3.10 is a conceptual design of RSF 9.

3.3.9.3 RSF Site C

RSF Site C will be utilised during the Phase 2 mining activity. It will be located immediately east of the PWP plant. It will be built in sequential phases (Phase 1 to Phase 4). RSF Site C will utilise mined-out pits for RSF dam storage capacity. Mining here is expected to last approximately 27.5 years before Phase 1 to Phase 4 are completed. The four planned RSF cells for RSF Site C will be converted to RSF storage space as each RSF cell reaches capacity. The phased development of RSF Site C is as follows:

- Phase 1 is expected to operate for 2.9 years and store 12.7 Mt of fines and 18 Mt of sand tails. Phase 1 will be approximately 78 ha in size. This facility will be built at a RoR of 9.8 $m.year^{-1}$;

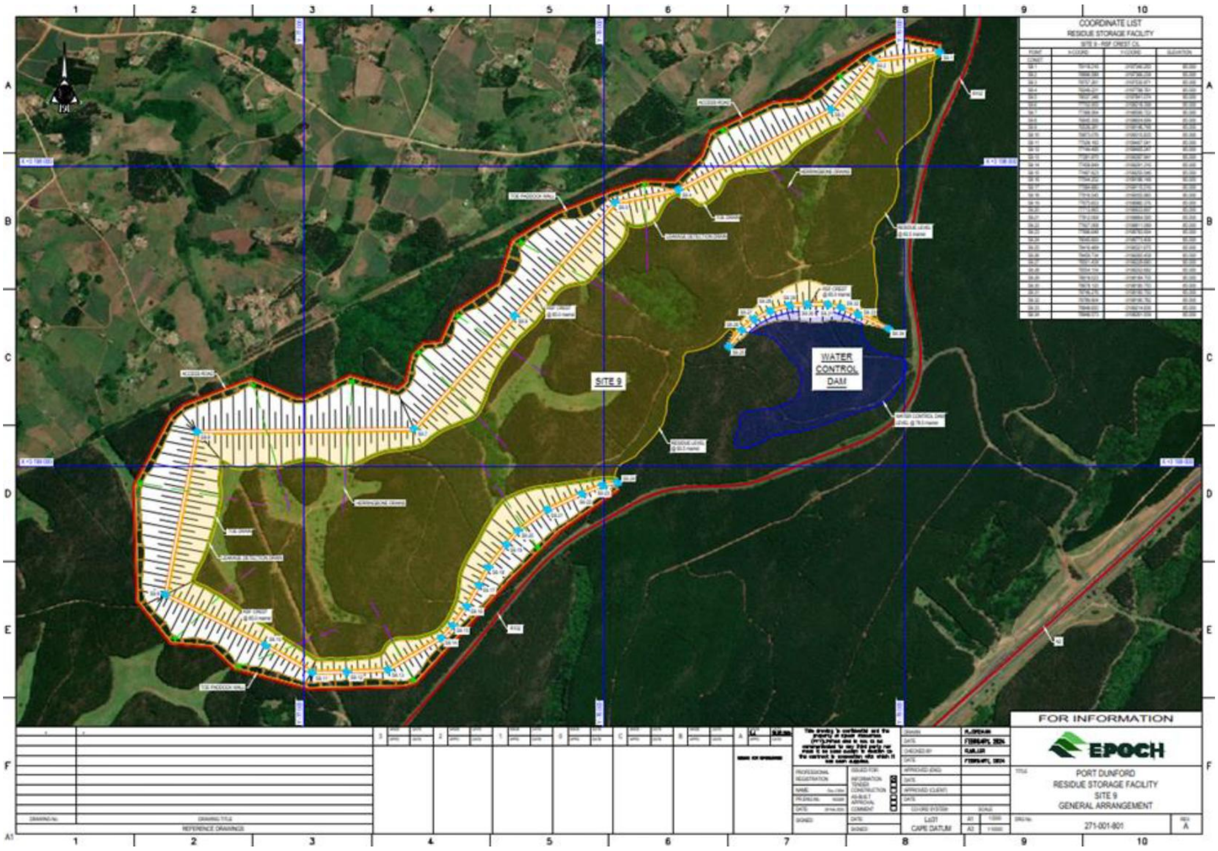

Figure 3.10 RSF Site 9 general arrangement design indicating impoundment walls and inundation area for the Port Dunford Mine (WSP, 2024a).

- Phase 2 is expected to operate for 8.1 years and store 35.2 Mt of fines and 21 Mt of sand tails. Phase 2 will be approximately 121 ha in size. This facility will be built at a RoR of 5.1 m.year^{-1};
- Phase 3 is expected to operate for 8.1 years and store 40.2 Mt of fines and 21 Mt of sand tails. Phase 2 will be approximately 147 ha in size. This facility will be built at a RoR of 5 m.year^{-1}; and
- Phase 4 is expected to operate for 8.3 years and store 39.1 Mt of fines and 4 Mt of sand tails. Phase 2 will be approximately 162 ha in size. This facility will be built at a RoR of 3.5 m.year^{-1}.

RSF Site C will be designed to store up to 127.3 Mt of fines residue and 64.5 Mt of sands residue. The total footprint area of RSF Site C is expected to be 670 ha and will have a final height of approximately 50 m above the current average ground level. A 13.75 ha, 540,000 m^3 Return Water Dam has been planned for RSF Site C. The dam will be located between RSF Site C Phase 1 RSF Dam and the PWP plant. The dam will be 500 m long, 275 m wide and will be 9 m high at its highest point (see Figure 3.11).

It is anticipated that RSF Site C will be operational for 27.5 years and reach full capacity in 2064. Thereafter, the site will be backfilled in 2069, affording the facility 4 years to dry out and stabilise. Once backfilled the site will be rehabilitated with topsoil and returned to the Landowner (lessee) thereafter.

3.3.10 End Land Use

Once mining is complete and the mined-out areas rehabilitated, the land will be returned to the landowner. It is anticipated that some land will be used for forestation, and others for crops and informal grazing land. The topography of the mined-out areas within the broader mining rights area is expected to change substantially. The RSF sites and sand tails deposition areas will leave permanent elevated features on the landscape.

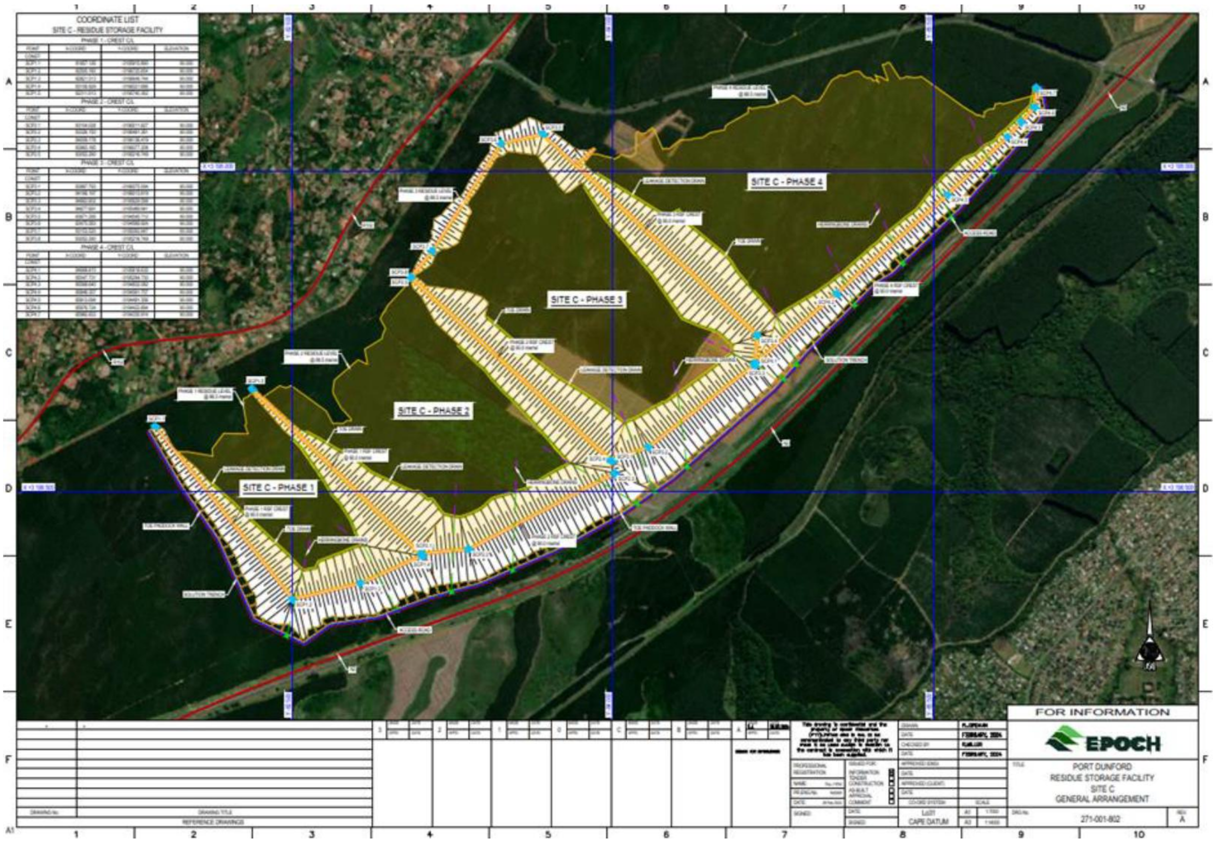

Figure 3.11 RSF Site C general arrangement design indicating impoundment walls and inundation area for the Port Dunford Mine (WSP, 2024a).

3.4 Description of the Baseline Environment

3.4.1 General

The purpose of this section is to describe the environmental baseline conditions associated with the Port Dunford Mine. Within the conceptual assessment framework presented in Figure 1.4, this information would provide input into understanding the potential distribution of radioactivity released from the Port Dunford Mine into the environment (e.g., atmosphere, groundwater and surface water), the accumulation of radioactivity in the associated environmental media and the subsequent interaction of members of the public with the impacted environmental media.

The environmental baseline conditions observed near the Port Dunford Mine are comprehensively described in the scoping report (WSP, 2024a) and a series of specialist studies that serve as a basis and input into the S&EIR process (WSP, 2024b; c; d). These reports are used and referenced for information on the topography and drainage, geology and hydrogeology, soils, meteorological conditions, as well as the human behavioural and social conditions as appropriate and justified.

3.4.2 Topography

The surrounding topography is characterised by a gently undulating coastal plain with low-lying areas approximately 0.5 metres above mean sea level (mamsl) surrounded by a gently sloping topography with elevation changes above 400 mamsl. Low-lying plains are located to the south and southeast and steep slopes are predominantly located to the northeast of the proposed boundary. Terrain influences the dispersion of pollutants, especially during periods of stable conditions (WSP, 2024b) (see Figure 3.12).

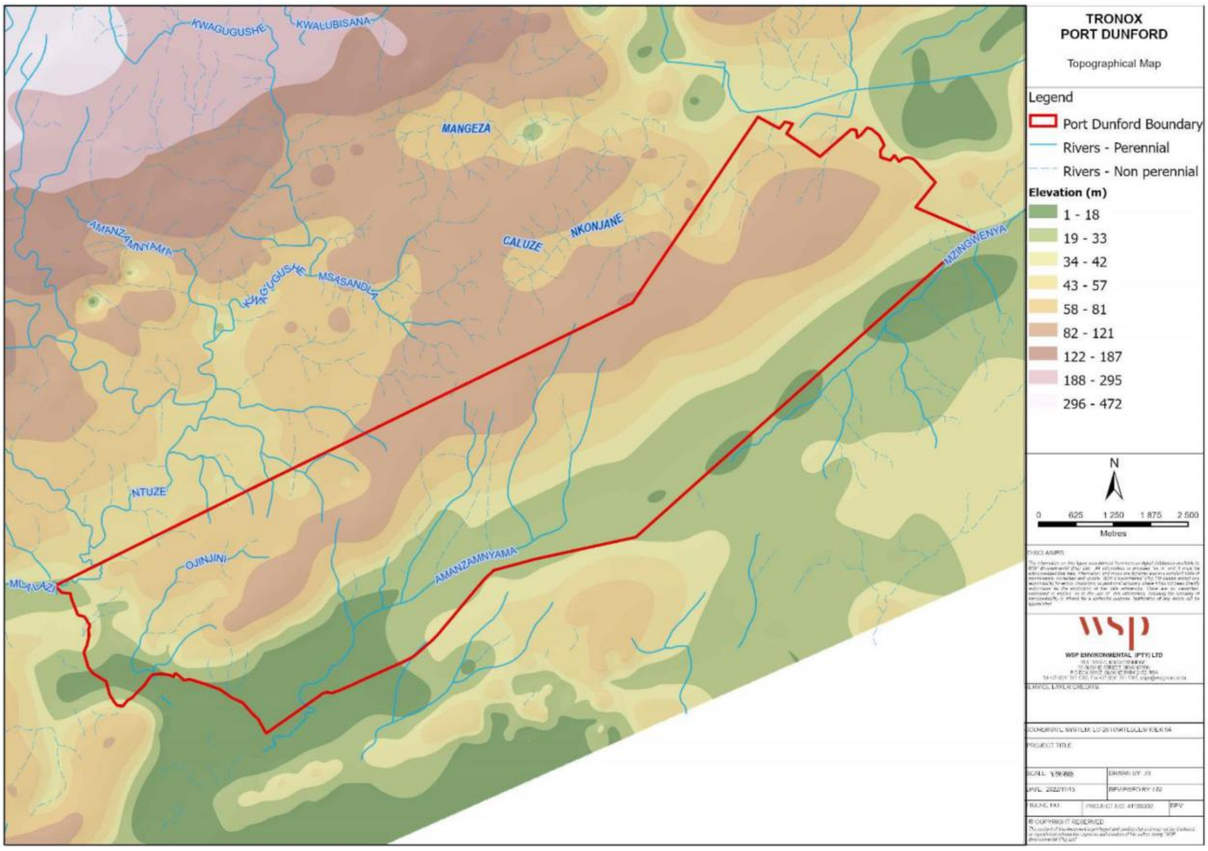

Figure 3.12 **Map showing the topography of the area associated with the Port Dunford Mine (WSP, 2024b).**

3.4.3 Drainage and Catchment

The Port Dunford Mine is situated within the Usuthu to Mhlathuze water management area (WMA) and is bisected by two quaternary catchments: W12F (north-east) and W13B (south-west) indicated in Figure 3.13. Within the W12F quaternary catchment, the perennial Mhlathuze River flows past the northern boundary and its tributaries drain the north-western areas. The perennial Mzingwenya River and its associated tributaries flow along the eastern site boundary from southwest to northeast where it drains into Lake Qhubu.

Within the W13B quaternary catchment, the perennial Amanzamnyama and Ojinjini Rivers and their associated tributaries flow from north-east to south-west within the site boundary and confluences with the Mlalazi River. Another tributary of the Mlalazi River runs further south of this site boundary. The Mlalazi River runs along the southwestern site boundary and eventually drains into the Indian Ocean.

Where the groundwater intersects the land surface in topographical depressions between the coastal dunes, wetlands are likely to occur. Significant interflow is likely to contribute to stream flow from sloped land surfaces.

3.4.4 Geological Setting

3.4.4.1 Regional Geology

A regional geological map of the area is provided in Figure 3.14. According to the 1:250,000 Geological Map Series 2830 Dundee, lithologies of the Natal Metamorphic Province outcrop west and north of the Port Dunford Mine area, and consist mainly of ultramafic rocks and gneiss. This is overlain by sedimentary rocks of the Natal Group which outcrop in the north-west and southwest. This is in turn overlain by shales and sandstones of the Ecca Group, and Karoo Supergroup, which is found southwest of the site. Rocks of the Ecca Group are finally overlain by Quaternary deposits of the Maputaland Group which form the coastal dune deposits in the area (WSP, 2024d).

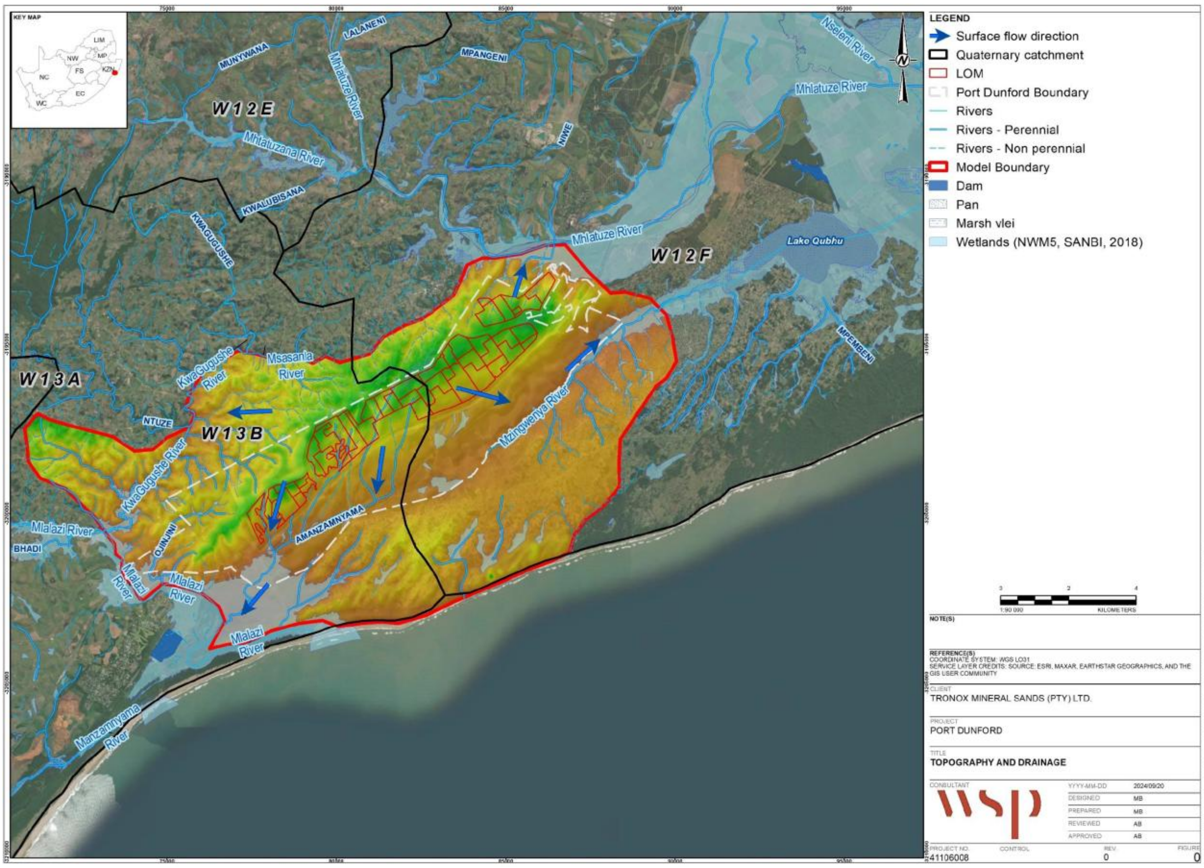

Figure 3.13 **Map showing the topography together with the regional catchment and water management areas associated with the Port Dunford Mine (WSP, 2024d).**

3.4.4.2 Local Geology

Locally, the lithologies of the Matigulu Group and Buhleni Gneiss of the Natal Metamorphic Province mainly consist of ultramafic rocks, amphibolite gneiss, biotite gneiss and quartz-feldspathic gneiss outcrop in the west and north of the Port Dunford Mine and form the base of the succession. A small outcrop of the Natal Group consisting of basal conglomerate, sandstone, siltstone, and shale occurs in the southwest. The Ecca Group outcrops south of this and comprises medium to coarse-grained sandstones, micaceous shale, and coal. Dolerite dykes and sills are found as intrusions in the rocks from the Ecca Group (WSP, 2024d).

The bedrock layers are overlain by deposits of the Maputaland Group. The basal contact with granitoid rocks has a mean elevation of 76 mamsl, whilst the contact in the eastern portion occurs at ~15 mamsl. The thickness of the Maputaland Group may be more than 50 m thick (WSP, 2024d).

The tertiary Uloa and Umkwelane Formations form the base of the Maputaland Group. The Umkwelane Formation is overlain by Berea-type red sands. This is in turn overlain by the quaternary Port Durnford Formation which comprises calcarenite at the base, fossiliferous mudrock as well as beachrock, coral-bearing coquina and lignite. Throughout the thickness of the Port Durnford deposit, heavy minerals are deposited. Mineralization gradually decreases with depth (WSP, 2024d).

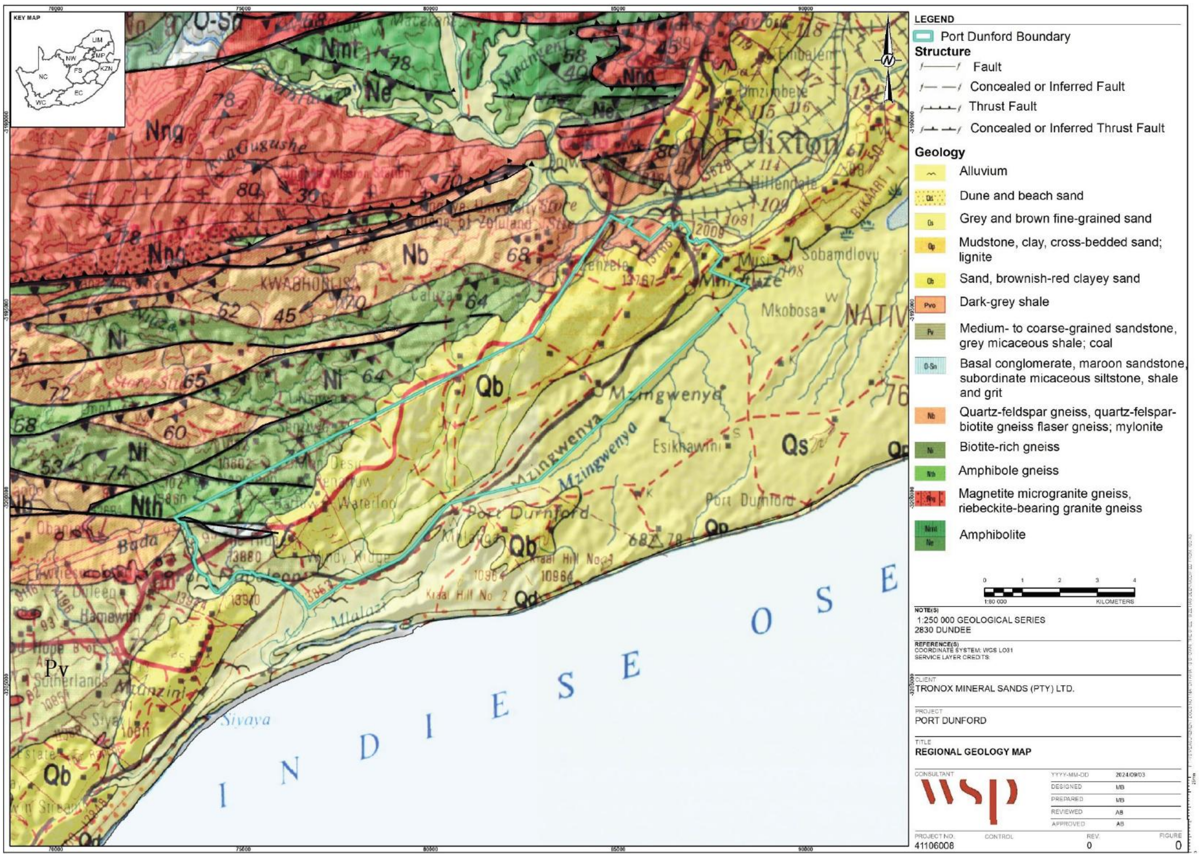

Figure 3.14 The local geology map of the area associated with the Port Dunford Mine (WSP, 2024d).

The Kosi Bay Formation overlies the Port Durnford Formation and is in turn overlain by Berea-type red sands. The Port Durnford deposit is covered by the Berea Type Red Sands. The KwaMbonambi Formation lies east of the Port Durnford prospecting area, which is characterized by a low-lying coastal plain. The dunes in this Formation are approximately 10m thick and are non-calcareous. Further towards the coast, dunes of the Sibayi Formation occur with an average thickness of ~10m (WSP, 2024d).

3.4.4.3 Geological Structures

Thrust faults trending predominantly west to east are observed to the west of the MRA (Figure 5-1) the most notable include (WSP, 2024d):

- The Mhlatuze Fault trends in a West-East direction to the northwest, whilst the Mlalazi Fault extends in a westerly direction along the valleys of the Mlalazi and Ntuze Rivers and marks the down-faulted southern boundary of the Ngoye Horst. The displacement along the fault decreases from east to west.
- The Matigulu Group and Buhleni Gneiss are juxtaposed and repeated as a series of nappes along northeast-southwest aligned thrust faults towards the west and south, known as the Ngoye Horst. These rocks dip steeply (~70°) towards the south.
- The Mlalazi and Mhlatuze faults underlie the mineralized sands of the Zulti South lease area. As a result of the geological structures, groundwater is localized along faults and weathered zones towards the west. At Tronox and the area along the coast, the more recent thick sedimentary rocks post-date and cover these geological structures.

3.4.4.4 Mining

It is understood that mining will occur within the sands that form the ore body present on site. The Port Durnford deposit (~20 to 25 m thick) is covered by Berea-type red sands has been de-calcified by leaching and the feldspars have been kaolinized. The red colour of the sands is a result of pigmentation due to the decomposition of the ferromagnesian minerals. Mineralization in the dune is erratic (vertically and laterally) but is more concentrated in the upper horizons of red sands. The ore body is reasonably large by mineral sands standards (1 billion tons of mineral resources) (WSP, 2024d).

3.4.5 Hydrogeology

3.4.5.1 General

The hydrogeological units can be characterized by a primary intergranular aquifer which is hosted within the coastal dune deposits as well as a secondary intergranular and fractured aquifer within the sedimentary and metamorphic rocks. Both aquifers are low to moderate yielding with yields between 0.5 to 2 $L.s^{-1}$ (WSP, 2024d).

The unsaturated zone is thin closer along the drainage lines where the depth to the groundwater table is shallow (1.39 m thick in W11), compared to 58.55 m thick in W2. There is limited hydraulic information available for the unsaturated zone. The saturation within the intergranular aquifer is high relating to the porosity of the overburden compared to the fractured aquifer. Within the fractured secondary aquifer, water saturation is limited to the fractures (WSP, 2024d).

3.4.5.2 Hydraulic Conductivity

The primary intergranular aquifer is unconfined and hosted in undifferentiated coastal deposits of the Maputaland Group and alluvium deposited within the Mlalazi and Mhlathuze River systems. This aquifer is a source of water for rivers, lakes and most wetlands during dry periods and is recharged by these systems in wet periods. Groundwater discharge zones in areas below 50 mamsl support permanent wetlands and swamps. Hydraulic conductivities of this aquifer can range between 0.1 to 10 $m.day^{-1}$ whilst transmissivity values up to 100 $m^2.day^{-1}$ have been recorded. The shallow and deep aquifers noted within the study area are characterised as the primary intergranular aquifer (WSP, 2024d).

The secondary intergranular and fractured aquifer is hosted within mainly argillaceous rocks of the Karoo Supergroup and mainly meta-arenaceous rocks of the Natal Metamorphic Province. The weathered and intergranular portion of the aquifer is ~10 to 15 m thick, whilst the fractured portion is ~ 150 to 170 m thick. The thrust faults in the western and southern portions of the site play an important role in terms of storage and flow of groundwater given their potential to act as preferential flow pathways or barriers. This is also anticipated from dolerite intrusions with the Karoo Supergroup. The saturated hydraulic conductivity for this aquifer within the study area varies between 0.001 to 0.1 $m.day^{-1}$, with higher values anticipated for the dolerite contact and fault zones. Hydraulic conductivities in the order of 3.7 $m.day^{-1}$ are noted (WSP, 2024d).

3.4.5.3 Groundwater Levels

The groundwater level ranges and borehole depths vary from artesian conditions to 58.55 meters below ground level (mbgl), with a median of 8.2 mbgl. The water level (0 to 4 mbgl) and borehole depth (1.5 to 35 mbgl) are generally shallower (< 4 mbgl) in the boreholes in or near the sensitive estuarine zones and on the coastline with water levels otherwise generally <25 mbgl (8 to 24.5 mbgl).

Figure 3.15 presents a groundwater level map generated based on water level data recorded from the hydrocensus survey to illustrate the inferred groundwater flow direction distribution of the water level data. The groundwater flow direction is towards the rivers and ocean, mimicking the surface topography.

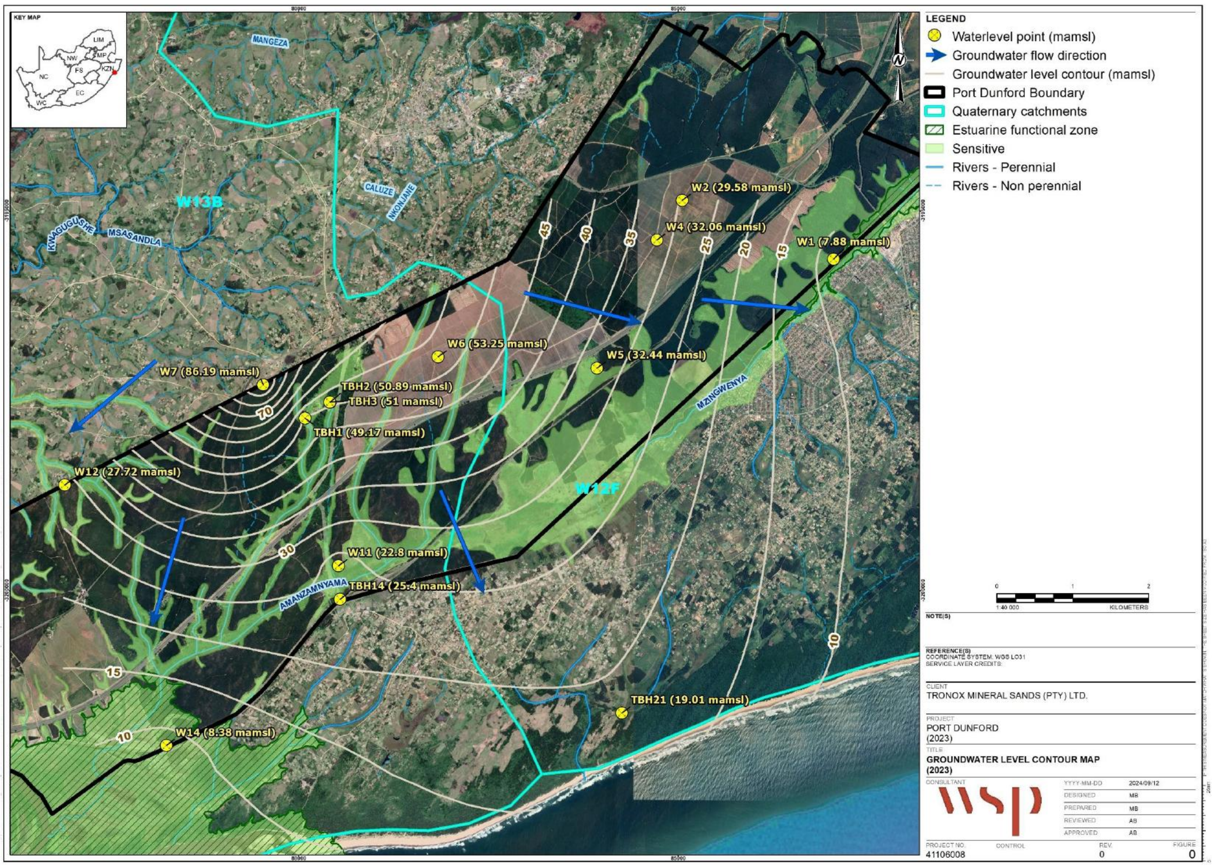

Figure 3.15 **The groundwater flow direction as inferred from the water levels recorded during the hydrocensus (WSP, 2024d).**

Figure 3.16 confirms a strong correlation between the water levels and topography at the lower elevations (shallow boreholes). However, the boreholes at higher elevations (W2, W4, W6. W7 and W12, which represent the deeper aquifer) do not show a strong correlation).

3.4.6 Meteorological Conditions

3.4.6.1 General

Since meteorological conditions affect how pollutants emitted into the air are directed, diluted, and dispersed within the atmosphere, the incorporation of reliable data into an air quality assessment is of the utmost importance. Dispersion comprises vertical and horizontal components of motion. The stability of the atmosphere and the depth of the atmospheric mixing layer control the vertical component. The horizontal dispersion of pollution in the boundary layer is primarily a function of the wind field. The wind speed determines both the distance of downwind transport and the rate of dilution as the plume 'stretches'. Mechanical turbulence is influenced by wind speed, in combination with surface roughness. The meteorological conditions for the Project area presented here were sources from the Air Quality Impact Assessment for the Port Dunford Mine presented in WSP (2024b).

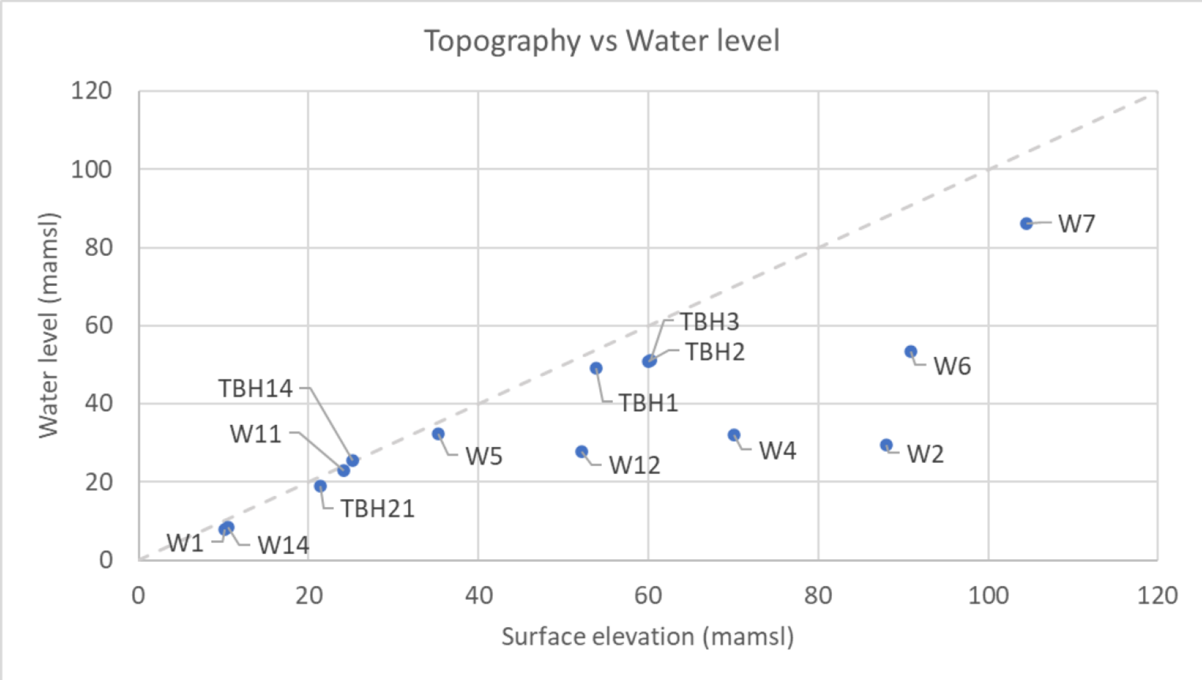

Figure 3.16 Topographical elevation vs. groundwater elevation correlation graph of the area associated with the Port Dunford Mine (WSP, 2024d).

3.4.6.2 Surface Data Used

Parameters that need to be taken into account in the characterisation of dispersion potential include wind speed, wind direction, atmospheric stability, ambient air temperature and mixing depth. To accurately represent meteorological conditions for the Project area, site-specific data from the South African Weather Service (SAWS) Mtunzini weather station for the period January 2020 to December 2022, at a height of 41 m, was obtained. Meteorological data was also sourced from the South African Air Quality Information Systems (SAAQIS) for the nearest station to the site, with the best data recovery, namely the eSikhawini-Richards Bay Clean Air Association (RBCAA) station for the period January 2019 to December 2021. Additionally, modelled AERMET-Ready Weather Research and Forecasting (WRF)-Mesoscale Model Interface Program (MMIF) data was purchased from Lakes Environmental for comparison of the data and use in the dispersion model. An AERMET-ready WRF dataset for the period January 2019 to December 2021 centred in the middle of the Project site and covering a domain of 50 km x 50 km was utilised.

3.4.6.3 Wind Field

Wind roses summarize wind speed and directional frequency at a location. Each directional branch on a wind rose represents wind originating from that direction, with each branch divided into segments of colour, representative of different wind speeds. Calm conditions are defined as wind speeds less than 0.5 $m.s^{-1}$, although it is noted the SAWS wind sensor only records winds from 1 $m.s^{-1}$.

Wind roses were developed using Lakes Environmental WRPlot Freeware (Version 8.0.2) for the full period of available data; diurnally for early morning (00h00 to 06h00), morning (06h00 to 12h00), afternoon (12h00 to 18h00) and night (18h00 to 00h00); and seasonally for summer (December, January and February), autumn (March, April and May), winter (June, July and August) and spring (September, October and November). Wind roses for the SAWS Mtunzini and eSikhawini-RBCAA meteorological stations and WRF data are presented below in Figure 3.17, Figure 3.18 and Figure 3.19, respectively. The following key items are highlighted:

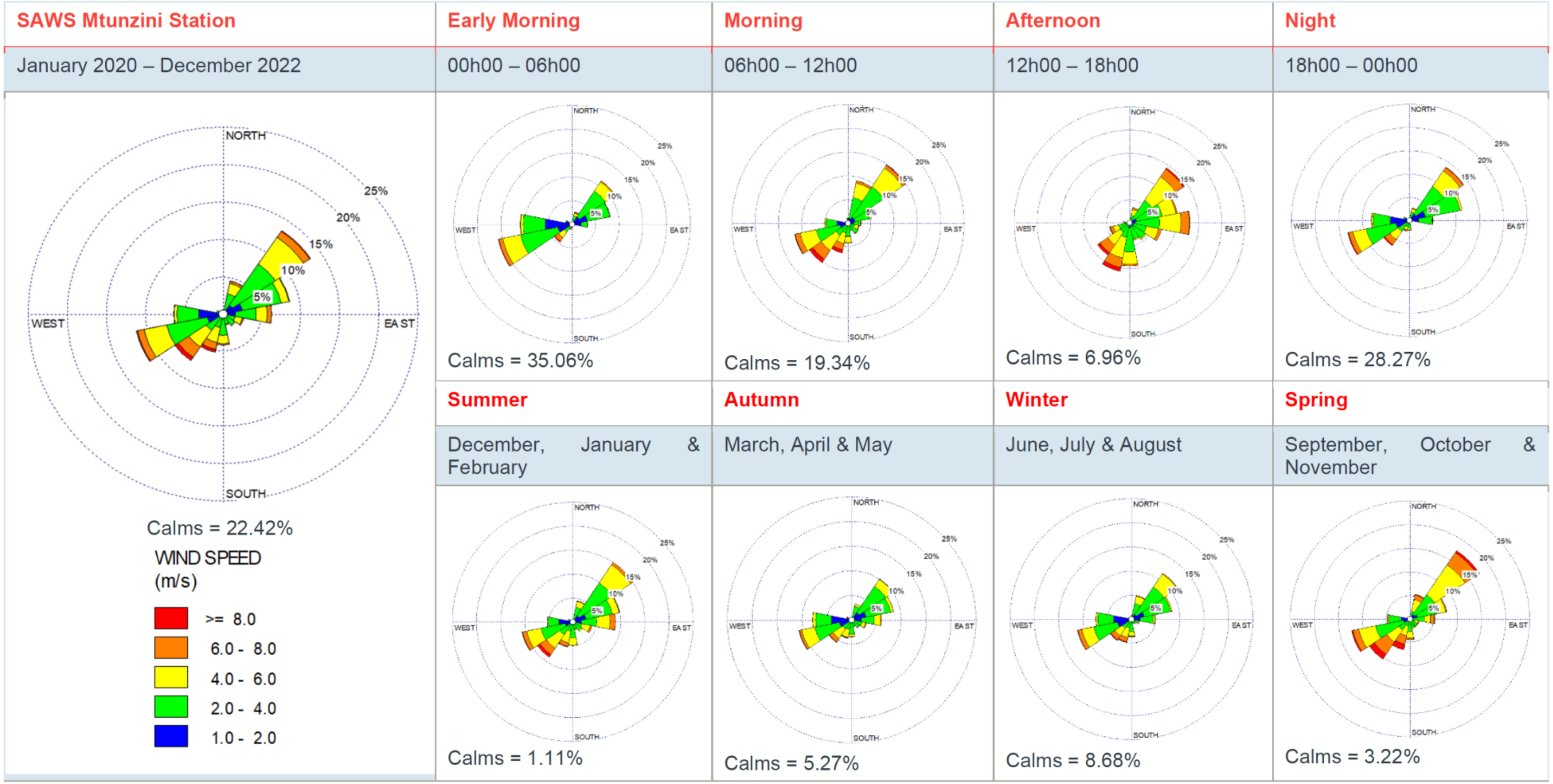

Figure 3.17 Local wind conditions at the SAWS Mtunzini meteorological station for the period 2020 – 2022 (WSP, 2024b).

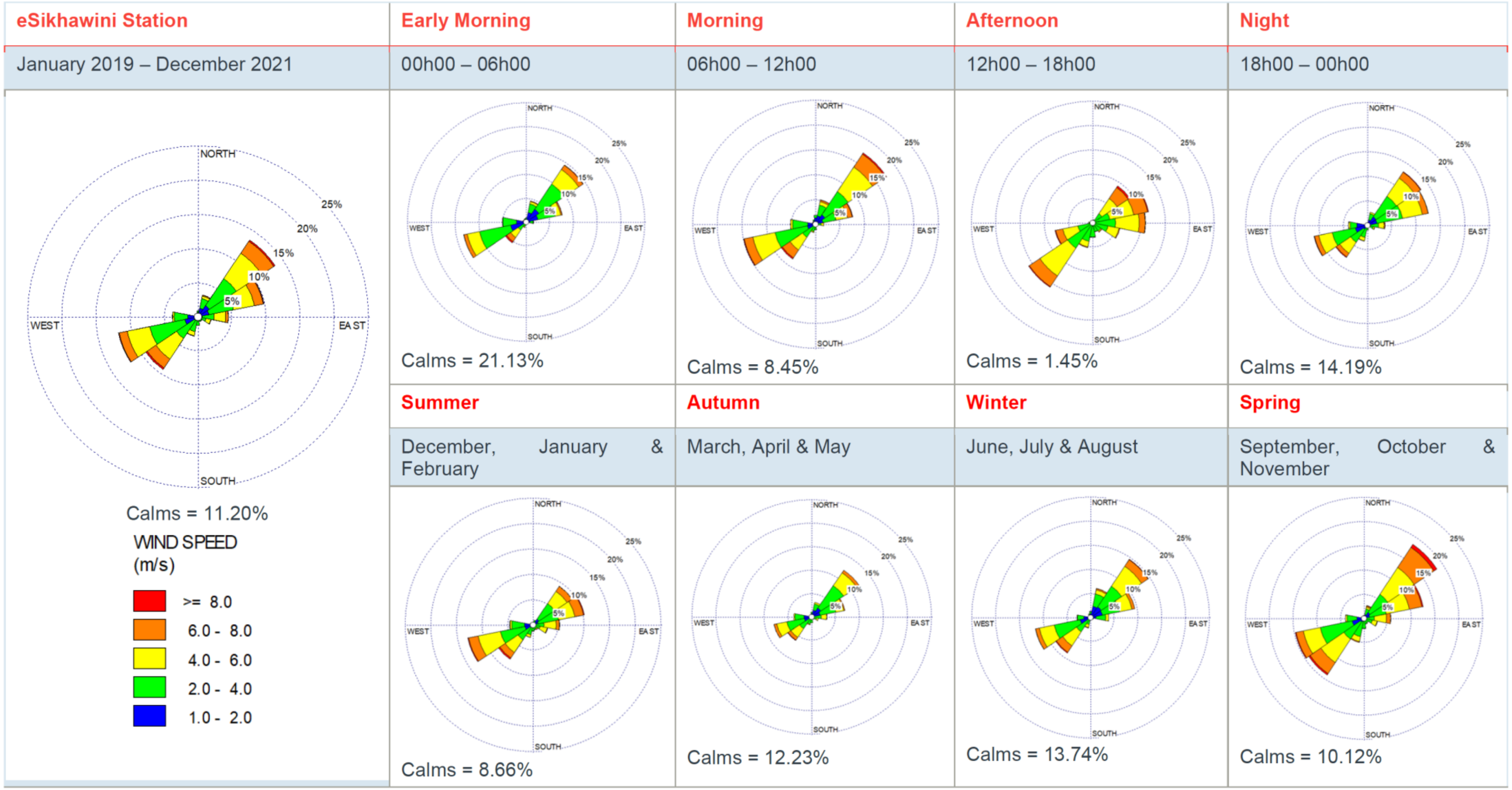

Figure 3.18 Local wind conditions at the eSikhawini-RBCAA meteorological station for the period 2019 – 2021 (WSP, 2024b).

<table>
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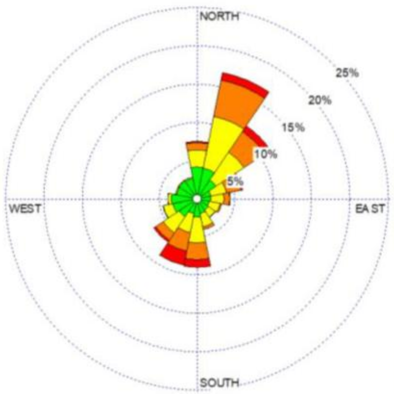
<tr><td>January 2019 – December 2021</td><td>00h00 – 06h00</td><td>06h00 – 12h00</td><td>12h00 – 18h00</td><td>18h00 – 00h00</td></tr>
<tr><td rowspan="4">
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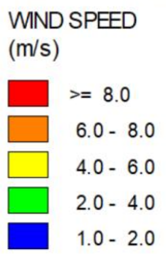
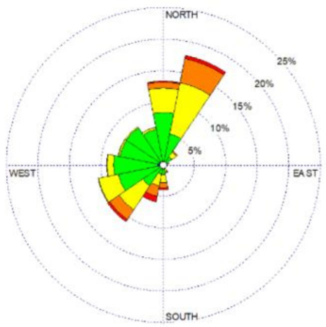
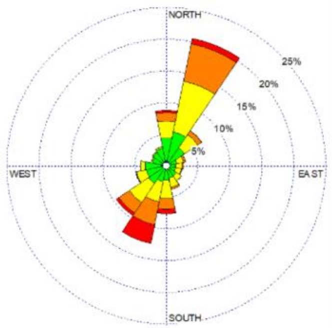
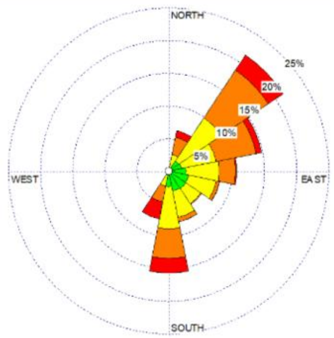
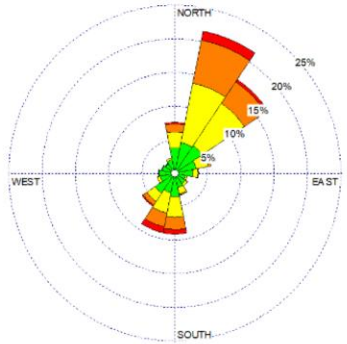
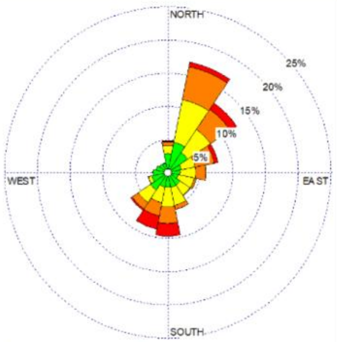
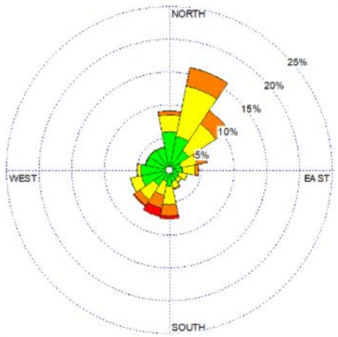
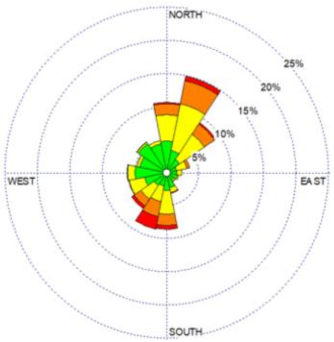
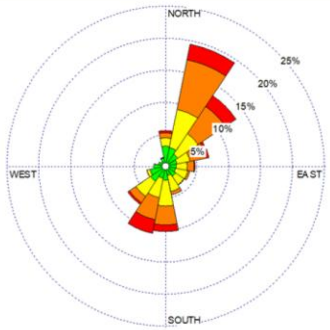
</td><td>
Calms = 0.98%</td><td>
Calms = 1.76%</td><td>
Calms = 0.18%</td><td>
Calms = 1.29%</td></tr>
<tr><td>Summer</td><td>Autumn</td><td>Winter</td><td>Spring</td></tr>
<tr><td>December, January & February</td><td>March, April & May</td><td>June, July & August</td><td>September, October & November</td></tr>
<tr><td>
Calms = 1.40%</td><td>
Calms = 1.12%</td><td>
Calms = 0.85%</td><td>
Calms = 0.96%</td></tr>
</table>

Figure 3.19 Local wind conditions at the WRF AERMET data for the period 2019 – 2021 (WSP, 2024b).

Mtunzini Station Data

- North-easterly and west-south-westerly winds prevail in the region for the entire period, with calm conditions occurring ~22% of the time and an average wind speed of 3 $m.s^{-1}$ recorded.
- West-south-westerly winds prevail during the early morning hours (00h00-06h00).
- From the morning and into the night (06h00 to 00h00) north-easterly winds prevail.
- North-easterly winds prevail during summer and spring, whilst west-south-westerly winds prevail during autumn and winter. The strongest wind speeds are observed during spring.

eSikhawini Station Data

- North-easterly and west-south-westerly winds prevail in the region for the entire period, with calm conditions occurring ~11% of the time and an average wind speed of 3 $m.s^{-1}$ recorded.
- North-easterly and west-south-westerly winds prevail during the early morning hours (00h00 to 06h00) into the late morning (06h00 to 12h00) and again at night (18h00 to 00h00), with an east-south-easterly wind also introduced at night.
- In the afternoon/ early evening (12h00 to 18h00) south-westerly winds prevail.
- Seasonal winds from the northeast and west-southwest prevail throughout the year with the strongest wind speeds observed during spring.

WRF Modelled Meteorological Data

- North-north-easterly winds prevail in the region for the entire period, with calm conditions occurring ~1% of the time and an average wind speed of 5 $m.s^{-1}$ recorded.
- North-north-easterly winds prevail during the early morning hours (00h00 to 06h00) into the late morning (06h00 to 12h00) and again at night (18h00 to 00h00).
- In the afternoon (12h00 to 18h00) north-easterly winds prevail, with a strong southerly component also evident.
- Seasonal winds from the north-northeast prevail throughout the year with the strongest wind speeds observed during spring.

When comparing all meteorological data, it was observed that winds from the north-northeast prevailed using the modelled WRF data, whilst the Mtunzini station and eSikhawini station indicated a slight shift in winds with prevailing winds from the northeast. As such, similar trends in wind directions were observed. The slight changes in data can be associated with the height of the stations, the data recovery of the stations and the location of the stations.

3.4.6.4 Temperature and Rainfall

Ambient air temperature influences plume buoyancy as the higher the plume temperature is above the ambient air temperature, the higher the plume will rise. Further, the rate of change of atmospheric temperature with height influences vertical stability (i.e. formation of mixing or inversion layers), while rainfall is an effective removal mechanism of atmospheric pollutants and thus also relevant in the assessment of pollution potential

Figure 3.20 presents the average, maximum and minimum temperatures, whilst Figure 3.21 presents the humidity and total monthly rainfall recorded using the Mtunzini station data for the 2020 to 2022 period. The region typically receives the highest levels of rainfall during the warmer, summer (December to February) months, with drier conditions during the cooler, winter months (June, July and August). The total rainfall received for 2020, 2021 and 2022 was 1,037 mm, 1,591 mm and 1,208 mm, respectively.

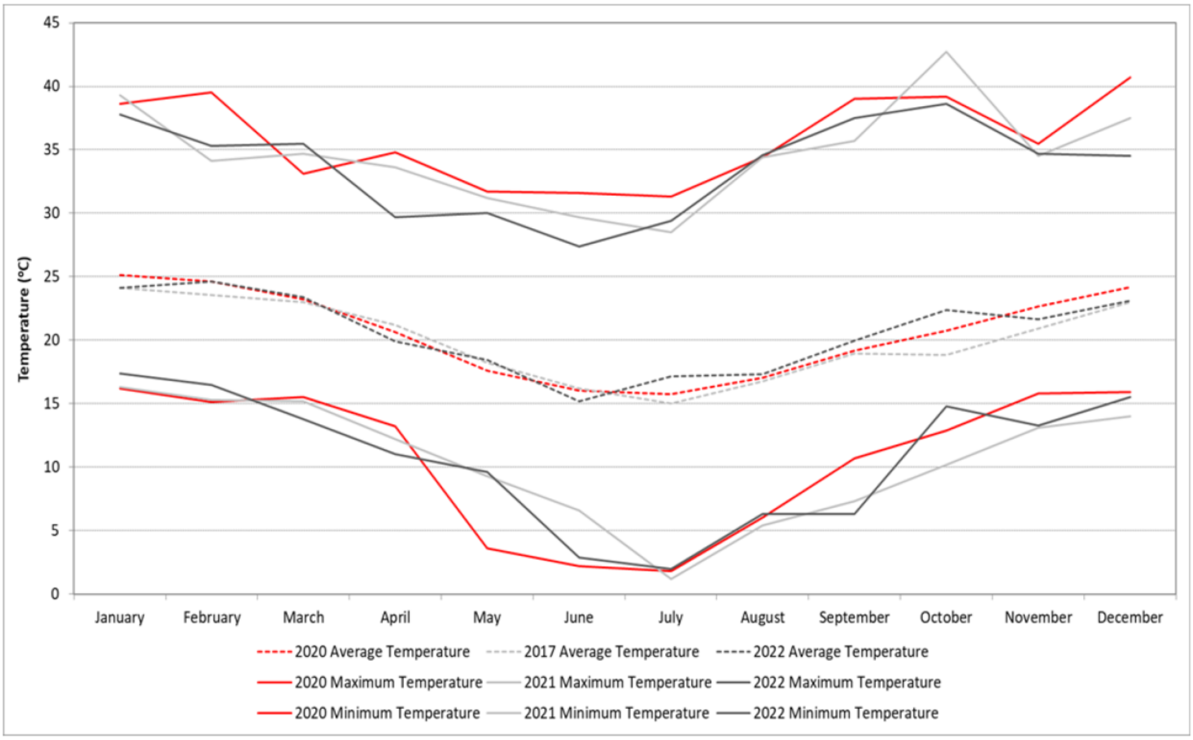


Figure 3.20 **Average, maximum and minimum monthly temperatures for the Port Dunford region for the period January 2020 to December 2022 using the Mtunzini meteorological station data (WSP, 2024b).**

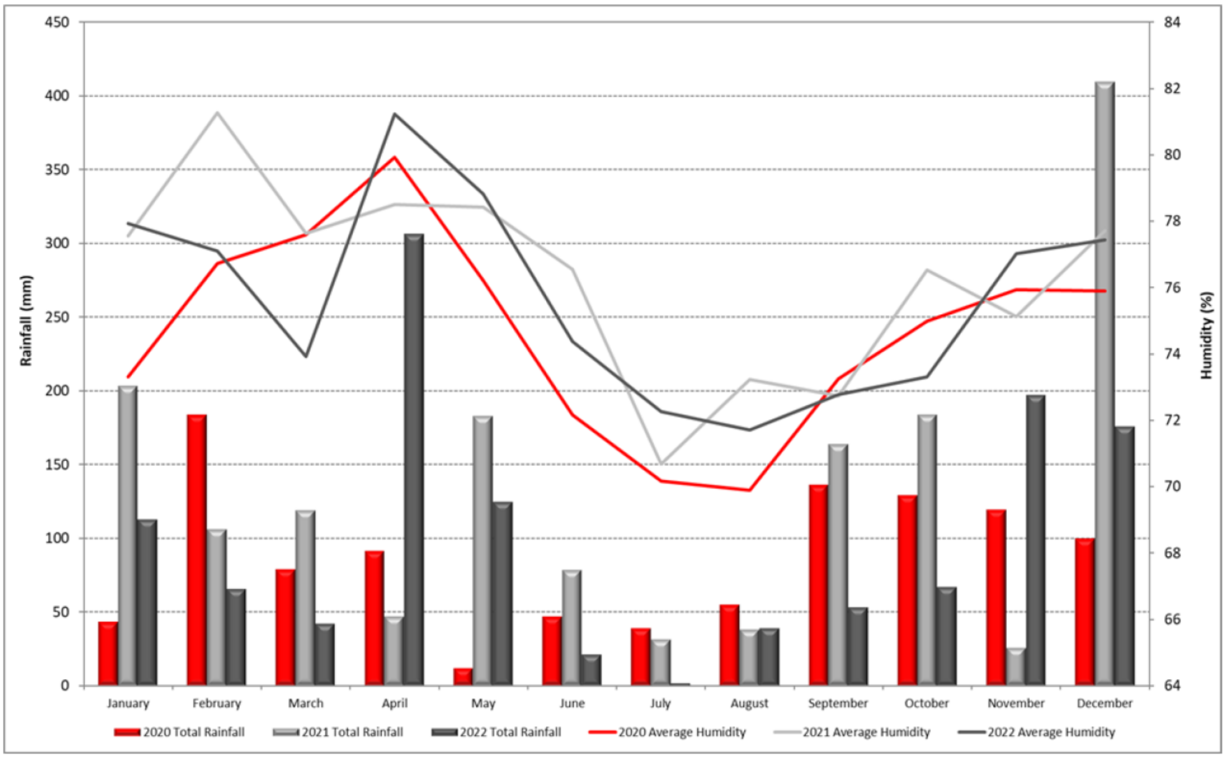


Figure 3.21 **Total monthly rainfall and average humidity for the Port Dunford region for the period January 2020 to December 2022 using the Mtunzini meteorological station data (WSP, 2024b).**

Temperatures ranged from a low of 2°C, 1°C and 2°C in 2020, 2021 and 2022, respectively in winter to a high of 41°C, 43°C and 39°C in 2020, 2021 and 2022, respectively in summer. The average temperature for 2019, 2020 and 2021 recorded was 25°C, 24°C and 24°C, respectively. The average relative humidity for 2020, 2021 and 2022 recorded was 75%, 76% and 76%, respectively.

Figure 3.22 presents the average, maximum and minimum temperatures, whilst Figure 3.23 presents the humidity and total monthly rainfall recorded using WRF-modelled data for the 2019 to 2021 period. Clear seasonal variations are evident in the temperature and rainfall values for the area. The region typically receives the highest levels of rainfall during the warmer, summer (December to February) months, with drier conditions during the cooler, winter months (June, July and August).

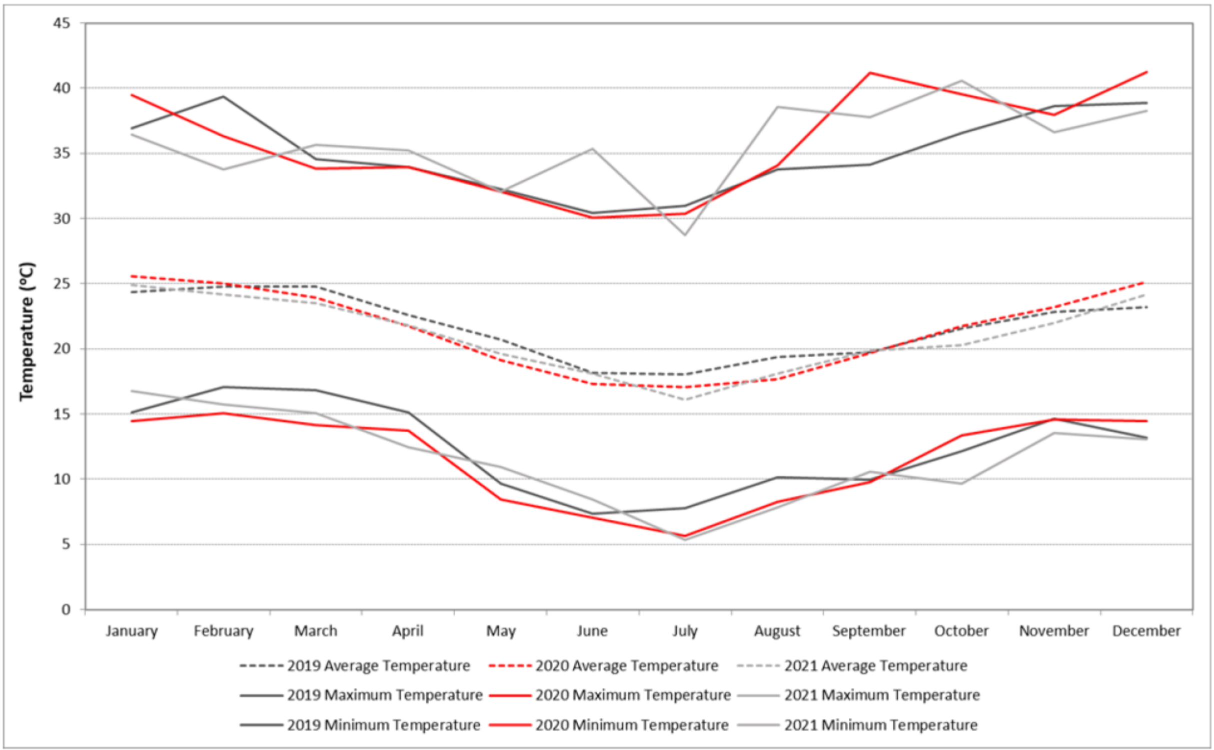


Figure 3.22 Average, maximum and minimum monthly temperatures for the Port Dunford region for the period January 2019 to December 2021 using modelled WRF data (WSP, 2024b).

The total rainfall received for 2019, 2020 and 2021 was 1596 mm, 946 mm and 1636 mm, respectively. Temperatures ranged from a low of 7°C, 6°C and 5°C in 2019, 2020 and 2021, respectively in winter to a high of 39°C, 41°C and 40°C in 2019, 2020 and 2021, respectively in summer. The average temperature for 2019, 2020 and 2021 recorded was 25°C, 26°C and 25°C, respectively. The average relative humidity for 2019, 2020 and 2021 recorded was 73%, 71% and 73%, respectively.

Due to the missing data from the eSikhawini station, no graphs have been displayed but a discussion has been provided. Clear seasonal variations were also evident in the temperature values for the area. Temperatures ranged from a low of 12°C, 8°C and 9°C in 2019, 2020 and 2021, respectively in winter to a high of 38°C, 40°C and 43°C in 2019, 2020 and 2021, respectively in summer. The maximum average temperature for 2019, 2020 and 2021 recorded was 24°C, 26°C and 26°C, respectively. The average relative humidity for 2019, 2020 and 2021 recorded was 67%, 72% and 77%, respectively.

Both data sets produced similar ranged results and are thus deemed representative of the site.

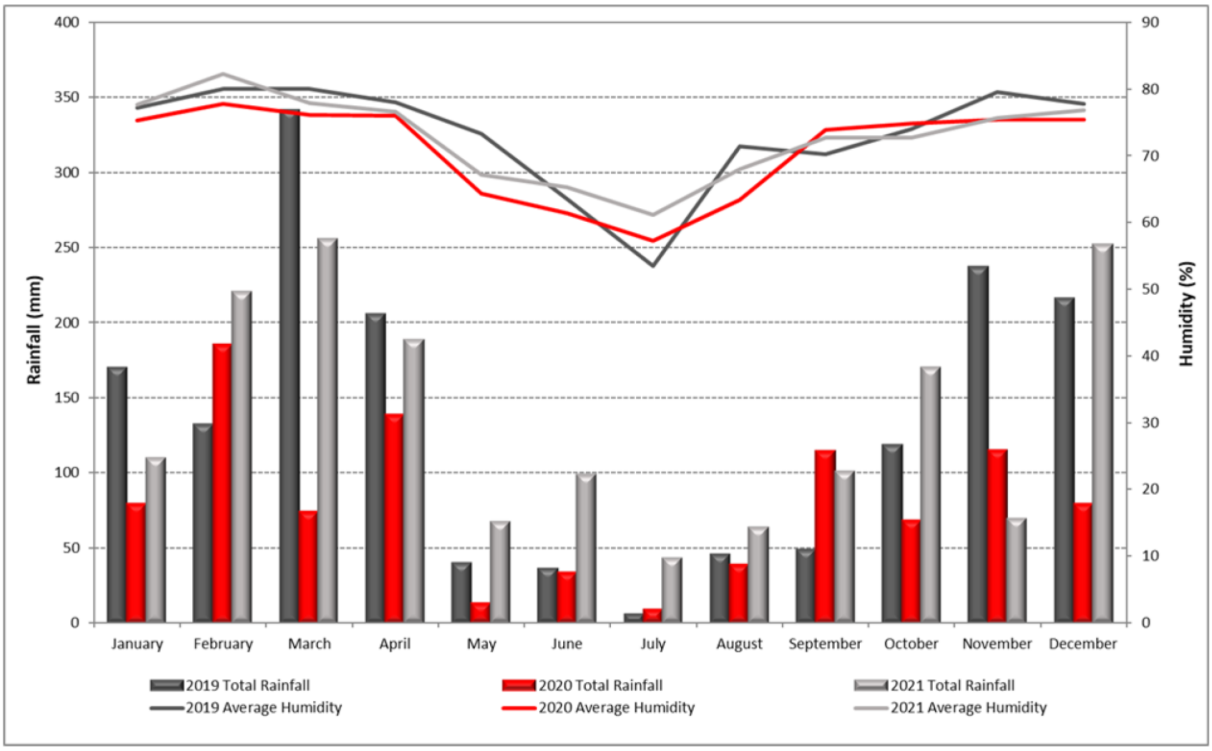


Figure 3.23 Total monthly rainfall and average humidity for the Port Dunford region for the period January 2019 to December 2021 using modelled WRF data (WSP, 2024b).

3.4.6.5 Ambient Particulate Matter Concentrations

Ambient-measured PM_{10} concentrations were sourced from the eSikhaleni RBCAA station and from the South African Air Quality Information System (SAAQIS) eSikhawini monitoring station, which are the closest stations to the site with suitable data recovery (both located ~6 km from the Port Durnford site). Data was obtained for the January 2020 to December 2023 period for both monitoring stations. Data for the 2023 period, however, was not assessed due to the poor data recovery for both stations.

Figure 3.24 presents the 24-hour average PM_{10} concentrations measured at the eSikhaleni monitoring station for the period January 2020 to December 2022. For this period, two exceedances of the 24-hour National Ambient Air Quality Standard (NAAQS) (75 $\mu g.m^{-3}$) were recorded, occurring in June 2021 and July 2021, remaining compliant as four exceedances of the standard are permitted per calendar year. An annual average concentration of 25.30 $\mu g.m^{-3}$, 23.29 $\mu g.m^{-3}$ and 12.90 $\mu g.m^{-3}$ was measured in 2020, 2021 and 2022, respectively. These concentrations remain below the annual average NAAQS (40 $\mu g.m^{-3}$).

Figure 3.25 presents the 24-hour average PM_{10} concentrations measured at the eSikhawini monitoring station for the period January 2020 to December 2022. For this period, two exceedances of the 24-hour NAAQS (75 $\mu g.m^{-3}$) were recorded in June 2021 and July 2021, remaining compliant as four exceedances of the standard are permitted per calendar year. An annual average concentration of 23.35 $\mu g.m^{-3}$, 22.84 $\mu g.m^{-3}$ and 12.50 $\mu g.m^{-3}$ was measured in 2020, 2021 and 2022, respectively. These concentrations remain below the annual average NAAQS (40 $\mu g.m^{-3}$).

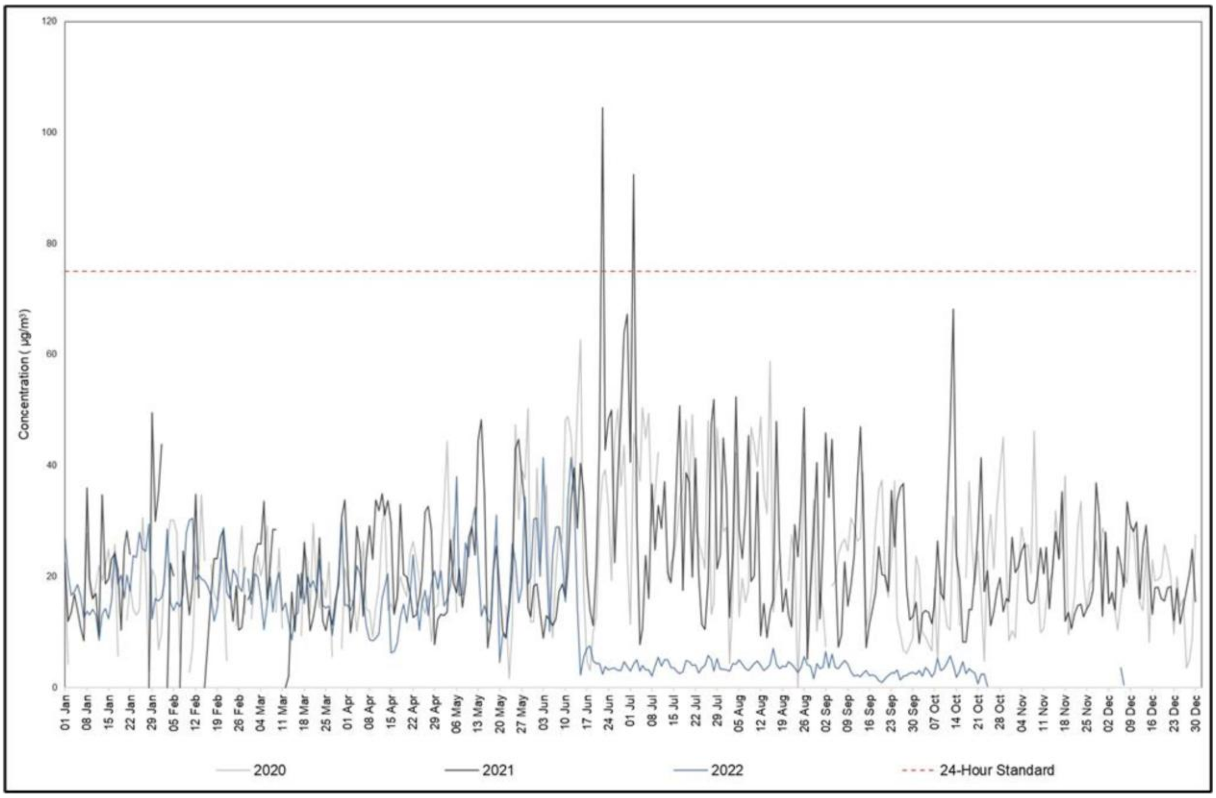


Figure 3.24 **Daily average PM_{10} concentration at the eSikhaleni monitoring station from January 2020 to December 2022 (WSP, 2024b).**

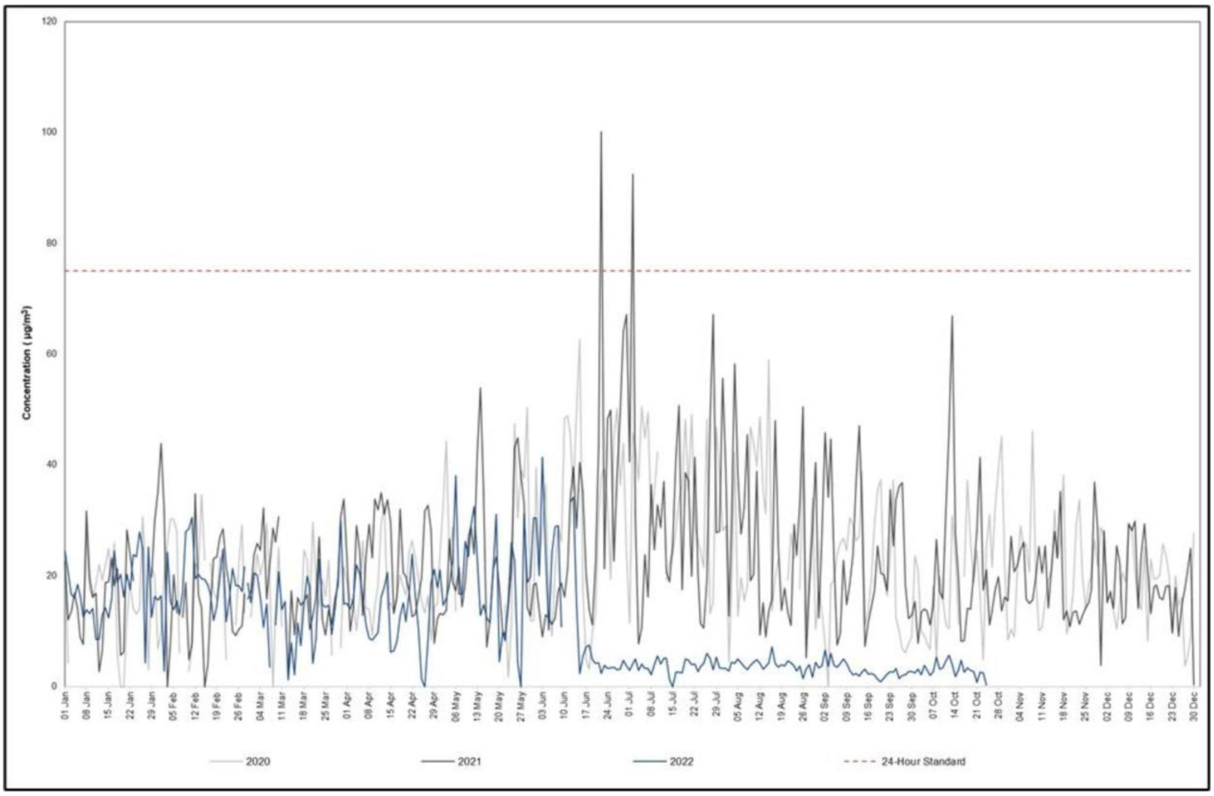


Figure 3.25 **Daily average PM_{10} concentrations at the eSikhawini monitoring station from January 2020 to December 2022 (WSP, 2024b).**

3.4.7 Socio-Economic Baseline Conditions

3.4.7.1 General

The socio-economic baseline conditions are described in (WSP, 2024c). Presented here is a summary of the conditions that serve as a basis for human behavioural conditions and their interaction with the environment. Within the conceptual assessment framework presented in Figure 1.4, this information provides input into the definition of receptor groups and their behaviour within the public exposure conditions (see Section 4.7).

The Port Dunford Mine is located in the uMhlathuze Local Municipalities (LM) in the King Cetshwayo District Municipality (DM) of the KwaZulu-Natal (KZN) Province of South Africa. KZN is one of the nine (9) provinces in the Republic of South Africa. It is the third smallest province (in geographic size) and covers approximately 94,361 km^2 or 7.7% of South Africa's land mass. The province has the second largest population in the country, with about 12.4 Million.

The King Cetshwayo DM is located in the KZN province's north-eastern region on the eastern South African seaboard. It covers an area of 8,213 km^2, from the agricultural town of Gingindlovu in the south to the uMfolozi River in the north and inland to the Nkandla Mountains.

The uMhlathuze LM is situated on the northeast coast of KZN, about 180 kilometres northeast of Durban. The uMhlathuze land area currently covers 123,359 ha. It incorporates Richards Bay, Empangeni, eSikhaleni, Ngwelezane, eNseleni, Felixton, Vulindlela, Bhucanana, Hendersonville, as well as the rural areas under Traditional Councils, namely, Dube, Mkhwanazi, Khoza, Zungu (Madlebe), Somopho, Obizo and a small portion of Obuka. The municipality borders a coastline that spans approximately 45 kilometres. The N2 highway traverses the uMhlathuze LM in a northeast direction towards the Swaziland border and southwest towards Durban. The R34 Provincial Main Road passes through Empangeni towards Melmoth.

3.4.7.2 Population Dynamics

Table 3.2 presents the population density in the King Cetshway DM for 2011, 2016 and 2022, broken down per municipality, which indicates that the population increased over this period. The population rank shows where a significant increment in population lies within KCD. Umhlathuze is ranked 1st in terms of population size.

Table 3.2 Population increases of municipalities within King Cetshwayo District Municipality.

	King Cetshway DM	IMFOLOZI	UMHLATHU ZE	UMLALAZI	MTHONJA NENI	NKANDLA
2011	907,519	122,889	334,459	213,601	47,818	114,416
2016	971,135	144,363	410,465	233,140	78,883	114,284
2022	1,021,344	159,668	412,075	241,416	99,289	108,896
Population rank		3	1	2	5	4

3.4.7.3 Households

The average household size in uMhlathuze is 3.95; in 2011, there were about 94,010 households. The average household size increased to 4.1, and there were about 100,441 households in 2022. If an increase of 1.5% is applied (using data from previous years), the IDP estimated households to be 115,330. If the population grows by 5%, 146,219 households will be reached in 2023 and 205,745 in 2030.

3.4.7.4 Population Gender and Age

In 2016, females numbered 187,287 and males numbered 177,175 within the uMhlathuze LM. Female-headed households increased in 2001 from 36.29 % to 40.70% in 2011. Table 3.3 shows that the population age cohort <15 has been declining at the district and uMhlathuze LM level, while the population cohort for the 15 to 64 age group has shown an increase at both the district and local municipality level between 2001 and 2011.

Table 3.3 Population Age Structure.

Municipality	Population				Age Structure (Percentage % of Population)			
			≤15		15-64		65+	
	2001	2011	2022	2011	2022	2011	2022	2011
KCD	885,965	907,519	29.9	34.8	57.3	60.7	4.4	4.5
uMhlathuze	289,190	334,459	25.9	29.9	69.4	66.8	4.7	3.3

Source: (Statistics SA, Census 2022)

3.4.7.5 Education

In 2022, matric was the highest qualification for 46.5% of the population in uMhlathuze, whereas only 36.9 % had matric in 2011. King Cetshwayo DM had 8.4% of its population having matric and a postgraduate qualification in 2011, 39.5 % of the population passed matric, and only 9.5 % obtained higher qualifications in 2022.

3.4.7.6 Employment

In 2017, 24.6% of the uMhlathuze population was employed. This is slightly lower than the KCD percentage of 26.5%. Figure 3.26 shows the percentage of employment per ward in uMhlathuze in 2011. Ward 23 had the highest employment at 50% and Ward 30 the lowest, below 10%.

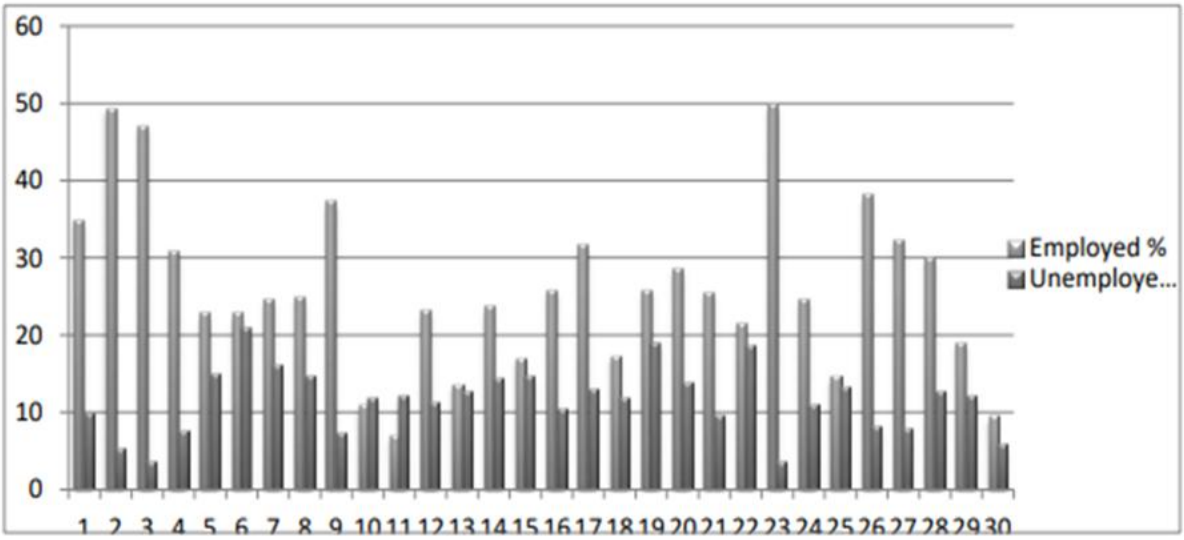


Figure 3.26 Percentage of Employment per ward in Umhlathuze.

3.4.7.7 Economy

The King Cetshwayo DM consists of excellent agricultural conditions. The agricultural sector is a dual economy with commercial agriculture and traditional agriculture. The most significant contributing local municipality is the uMhlathuze LM (44% of the GDP of the diuMfolozi follows this Umfolozi at 25.7% and uMlalazi at 21.3%).

According to, 80.6% of the King Cetshwayo DM municipality's population have an income of less than R76,400 p.a. or R6,366.66 monthly. Moreover, 41.3% of the population falls in the income bracket of R9,601 to R38,200 p.a. or R800 to R3,183.33 monthly. In uMhlathuze, many persons in Wards 5, 6, 13, 15, 18, 25 and 29 earn less than R1,600 monthly. Functional age groups indicate the level of the potential workforce in a region. Therefore, the critical age group relates to individuals aged 15 years.

3.5 Radiological Conditions

3.5.1 General

The purpose of this section is to provide a summary overview of the currently available radiological information for the Port Dunford Mine. Since the Port Dunford Mine is yet operational, the available site-specific radiological data represent and define the radiological baseline conditions of the area. Where necessary and justified, data and information from nearby mining operations will be used as analogues for the Port Dunford Mine.

3.5.2 Radiological Baseline Conditions

3.5.2.1 General

In terms of Requirement 6 of IAEA GSR Part 1 (Rev. 1) (IAEA, 2014), an operating organization is required to comply with all national legal and regulatory requirements, which include collecting baseline data before site development and preparing a safety case and supporting safety assessment (IAEA, 2021). As a minimum, these may include the following:

- Establish the airborne environmental radon concentration near the Project area;
- Establish the existing levels of naturally occurring radionuclides at the site (e.g., surface water, groundwater, soil, sediment and dust), for comparison with later monitoring results. This is especially important concerning NORM residues because the same radionuclides are already present in nature; and
- Spatial gamma radiation survey of the areas that might be disturbed and used to implement the mining and mineral processing activities.

The process of establishing the radiological baseline for the Port Dunford Mine is still in progress. Presented here is the data currently available and what has been done to complete the baseline site characterisation process.

3.5.2.2 Spatial Gamma Radiation and Dose Rate Survey

No spatial gamma radiation or dose rate surveys have been conducted in the potentially affected areas around the Port Dunford Mine due to accessibility challenges. However, these surveys will be carried out before construction begins to establish the pre-operational conditions.

3.5.2.3 Environmental Airborne Radon Concentration

Radon Gas Monitors supplied by ParcRGM are used to monitor the ambient environmental radon concentration in the air. For this purpose, 4 RGM were deployed at the end of February 2024 and were recovered by the end of May 2024 (i.e., for 3 months). Table 3.4 summarises the description and coordinates of the RGM deployed at the Port Dunford Mine area.

Table 3.4 Description and coordinates of the RGMs deployed at the Port Dunford Mine area.

RGM No.	Description	Latitude	Longitude
L110393	The northern boundary of RSF Site 9, on the lowest point in the neighbouring Indigenous forest (very sensitive environmental area)	-28.9030	31.7939
L110401	Centre of the proposed PWP site	-28.8889	31.8389
L110388	RSF Site C, between cell 2 and cell 3	-28.8823	31.8613
RGM 4	Nearby community less than 200m away from the mining area planned for 2042	-28.8739	31.8473

Table 3.5 summarises the results for the 3 months, showing that the airborne radon concentration varies between 8 and 14 $Bq.m^{-3}$. No further results are available yet for these locations or other results for the Port Durnford community. The intention is to continue with these RGM monitoring points at the mine site for another 3 quarters.

Table 3.5 Summary of the RGM results listed in Table 3.4, for the period February 2024 to May 2024 (Second Quarter).

RGM No.	Hours	Location	Concentration	Concentration
			$Bq.m^{-3}.hour^{-1}$	$Bq.m^{-3}$
L110393	2,208	RSF Site 9,	1.90E+04	8.61E+00
L110401	2,208	PWP site	2.80E+04	1.27E+01
L110388	2,208	RSF Site C	3.10E+04	1.40E+01
RGM 4	No data			

3.5.2.4 Radioanalysis Results for Environmental Media

No site-specific full-spectrum radioanalysis results for environmental media are available for the Port Dunford Mine area at present. However, several sampling locations for surface water, groundwater, sediment and soil were identified that will be sampled for full-spectrum analysis before construction commenced. It is expected that the analysis results will be available in 2025.

3.5.3 Raw Materials, Products and By-products

As the Port Dunford Mine is not yet operational, there are currently no site-specific or operational full-spectrum radioanalysis results available for its products, by-products, and residue materials. The best and most recent analysis results that are available that could be considered as representative, are 2024 results from the Fairbreeze Mine.

Table 3.6 summarises some of the product and residue materials from Fairbreeze for which full-spectrum analysis results are available and that can be used as analogues for the Port Dunford Mine The Necsa Radioanalytical Laboratory results are included in Appendix E. This is justified since the mineral suite in the Port Durnford ore body closely matches that of the Fairbreeze ore bodies, as indicated in Section 3.3.2.

Table 3.8 summarises the full-spectrum analysis results for the Faibreeze samples. These results were used for the Port Dunford Mine. For this purpose, it is assumed that secular equilibrium exists between the parent radionuclides and their progeny for which analysis results are not available (see Section 2.3.4.5). Consequently, the following assumptions were made for the assessment:

Table 3.6 Summary of product and residue materials from Fairbreeze for which full-spectrum analysis results are available and that can be used as analogues for the Port Dunford Mine.

Product or Residue Material	Application or Endpoint
Zircon Prime	Sold as products
Zircon Standard	
Zirkwa	
Rutile Prime	
Rutile Standard	
Zircon Magnetic Concentrate	Reject materials that are being sold to one customer.
Zircon Magnetic Rejects	
Zircon Rutile Concentrate	
Ilmenite Zircon Concentrate	
Final Ilmenite Zircon Concentrate	
MSP Sand Tails	Transported back from the MSP to the mine as backfilling material in the mining void
MSP Slimes	Transported back from the MSP to the mine for disposal in the RSF
MSP Gypsum	Transported back from the MSP to the mine for disposal in the mining void as waste
PWP Heavy Mineral Concentrate	Transport to the MSP for further processing
PWP Sand Sails	Currently put back into the mining void as backfill material.
PWP Slimes	Currently pumped into the Residue Storage Facility (RSF)

- The orebody material for the Port Dunford Mine is represented by the average of the PWP Slimes, PWP Sand Tails and the PWP Heavy Mineral Concentrate samples in Table 3.8 (see Table 3.7).
- The backfill material for the Port Dunford Mine void is represented by the average of the MSP sand tails, the PWP sand tails and the MSP Gypsum samples in Table 3.8 (see Table 3.9). The MSP Gypsum analysis results were included as an option to dispose of the material in the mine void as opposed to the RSFs.
- The RSF material for the Port Dunford Mine is represented by the average of the MSP Slimes, PWP Slimes and the MSP Gypsum samples in Table 3.8 (see Table 3.10).
- The topsoil material is represented by the PWP sand tails samples in Table 3.8 since no radioanalysis results for topsoil are available at present (see Table 3.11).

Table 3.7 The orebody radionuclide composition for the Port Dunford Mine, as derived from the results in Table 3.8.

Sampling Point	PWP Heavy Mineral Concentrate	PWP Sand Sails	PWP Slimes	Average
Radionuclide	Activity Concentrations ($Bq.kg^{-1}$)			
U-238	621	15.4	41.2	225.9
U-234	626	15.6	41.6	227.7
Ra-226	499	19	29	182.3
Pb-210	726	19	29	258.0
U-235	28.6	0.71	1.9	10.4
Th-232	552	13.3	49.1	204.8
Ra-228	595	13.3	117	241.8
Th-228	558	13.3	75.5	215.6

Table 3.8 Full-spectrum radioanalysis results of products, byproducts and residue material from the Tronox KZN Operations.

Sampling Date	10/04/2024					
Necsa Report No.	RS2014-0909					
Sampling Point	Zircon Prime	Zircon Standard	Zirkwa	Rutile Prime	Rutile Standard	Zircon Magnetic Concentrate
Radionuclide	Activity Concentrations (Bq.kg^{-1})					
U-238	4,480	5,110	5,800	751	906	7,740
U-234	4,520	5,150	5,850	757	914	7,810
Ra-226	3,360	3,980	400	710	708	7,180
Pb-210	957	3,920	5,180	547	785	6,030
U-235	206	235	267	34.6	41.7	356
Th-232	527	653	1010	175	245	18,500
Ra-228	401	517	159	235	260	22,300
Th-228	424	510	148	240	215	22,000
K-40	< 340	< 370	< MDA	< 310	< 270	< 860
Gross alpha	33,800	42,400	51,900	5,400	9,910	330,000
Gross beta	4,480	17,800	21,400	2,610	3,210	73,000

Sampling Date	10/04/2024					
Necsa Report No.	RS2014-0909					
Sampling Point	Zircon Magnetic Rejects	Zircon Rutile Concentrate	Ilmenite Zircon Concentrate	Final Ilmenite Zircon Concentrate	MSP Sand Tails	MSP Slimes
Radionuclide	Activity Concentrations (Bq.kg^{-1})					
U-238	12,100	728	801	1,370	130	236
U-234	12,200	735	808	1,380	131	238
Ra-226	12,000	571	772	925	112	229
Pb-210	10,300	637	777	957	< 96	226
U-235	557	33.5	36.9	63.1	5.97	10.9
Th-232	35,800	310	1,520	3,330	71.8	446
Ra-228	43,900	285	1,870	2,710	89.7	513
Th-228	42,500	299	1,860	2,700	117	516
K-40	< 1,100	< 240	309	< 240	< 350	< 440
Gross alpha	707,000	5,110	15,800	41,400	1,080	5,380
Gross beta	136,000	2,930	6,700	13,300	670	1,900

Sampling Date	10/04/2024					
Necsa Report No.	RS2014-0909					
Sampling Point	MSP Gypsum	Crude Ilmenite (Tronox KZN)	Crude Ilmenite (Australia)	PWP Heavy Mineral Concentrate	PWP Sand Tails	PWP Slimes
Radionuclide	Activity Concentrations (Bq.kg^{-1})					
U-238	337	123	64.8	621	15.4	41.2
U-234	350	124	65.4	626	15.6	41.6
Ra-226	173	103	61.6	499	19	29
Pb-210	453	< 180	< 130	726	< 71	< 110
U-235	16	5.66	2.98	28.6	0.711	1.9
Th-232	605	224	118	552	13.3	49.1
Ra-228	551	224	116	595	< 61	117
Th-228	487	275	139	558	< 31	75.5
K-40	< 820	< 200	< 210	< 260	< 320	< 470
Gross alpha	16700	16300	2910	2430	7930	979
Gross beta	11500	2450	971	550	3640	400

Table 3.9 The mine void backfill material radionuclide composition for the Port Dunford Mine, as derived from the results in Table 3.8.

Sampling Point	PWP Sand Tails	MSP Sand Tails	MSP Gypsum	Average
Radionuclide	Activity Concentrations (Bq.kg^{-1})			
U-238	15.4	130	337	160.8
U-234	15.6	131	350	165.5
Ra-226	19	112	173	101.3
Pb-210	19	112	453	194.7
U-235	0.7	6	16	7.6
Th-232	13.3	71.8	605	230.0
Ra-228	13.3	89.7	551	218.0
Th-228	13.3	117	487	205.8

Table 3.10 The RSF material radionuclide composition for the Port Dunford Mine, as derived from the results in Table 3.8.

Sampling Point	MSP Slimes	PWP Slimes	MSP Gypsum	Average
Radionuclide	Activity Concentrations (Bq.kg^{-1})			
U-238	236	41.2	337	204.7
U-234	238	41.6	350	209.9
Ra-226	229	29	173	143.7
Pb-210	226	29	453	236.0
U-235	10.9	1.9	16	9.6
Th-232	446	49.1	605	366.7
Ra-228	513	117	551	393.7
Th-228	516	75.5	487	359.5

Table 3.11 The topsoil material radionuclide composition for the Port Dunford Mine, as derived from the results in Table 3.8.

Sampling Point	PWP Sand Tails
Radionuclide	Activity Concentrations (Bq.kg^{-1})
U-238	15.4
U-234	15.6
Ra-226	19
Pb-210	19
U-235	0.7
Th-232	13.3
Ra-228	13.3
Th-228	13.3

3.5.4 Radon Exhalation Rate

Radon gas may be emitted from material containing naturally occurring Ra-226, which decays into the naturally occurring radon isotope, Rn-222. Not all radon atoms originating in the crystal structure of the material will escape the lattice into the pore space of the material. Radon atoms located within solid grains are unlikely to become available for release to the atmosphere, owing to their very low diffusion coefficients in solids. However, if they are located in the interstitial space between grains, they may diffuse to the surface. Therefore, releases of radon from the surface of materials containing Ra-226 into the atmosphere take place by the following series of processes (see Figure 3.27) (IAEA, 2013):

- Emanation — radon atoms formed from the decay of radium escape from the grains (mainly because of recoil) into the interstitial space between the grains. The process is represented by the radon emanation coefficient.
- Transport — diffusion and advective flow cause the movement of the emanated radon atoms through the residue or soil profile to the ground surface. The process is represented by the radon diffusion coefficient.
- Exhalation — radon atoms that have been transported to the ground surface and then exhaled into the atmosphere. The process is represented by the radon exhalation rate or radon flux.

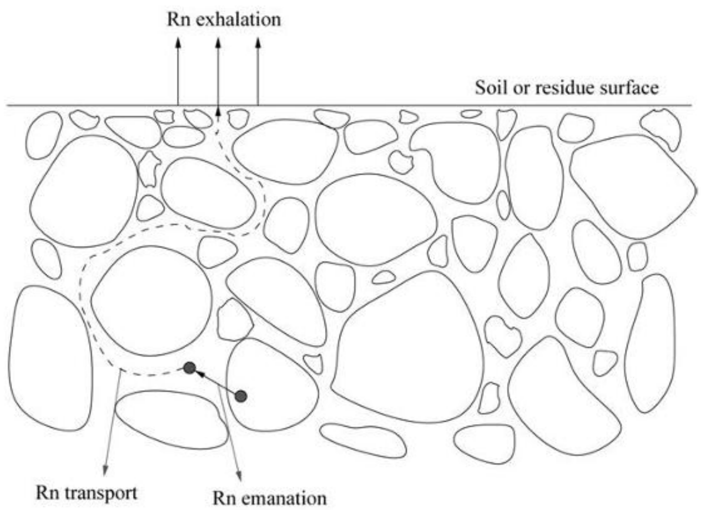


Figure 3.27 Process leading to radon gas released into the atmosphere (IAEA, 2013).

The emanation coefficient is defined as the fraction of radon atoms generated that escape the solid phase in which they are formed and become free to migrate through the bulk medium. In practice, the emanation coefficient has to be measured for each material being studied since it may be affected by the Ra-226 distribution and particle size of the material, the moisture content and the uranium mineralogy of the material (IAEA, 2013).

The molecular diffusion coefficient of radon is defined by Fick's first law, which states that radon flux density is linearly proportional to its concentration gradient. In a porous medium such as soil, radon moves by diffusion in the pore space between the soil particles. The rate of radon movement or flux through soil may be slower than by diffusion in a homogeneous medium such as pure air for two main reasons: smaller fluid volume limiting flow (porosity, n) and tortuous flow path around particles (tortuosity, τ).

No site-specific radon exhalation rates are available for sources of radiation exposure associated with the Port Dunford Mine or for any of the other sources at Fairbreeze or the CPC. Parc Scientific (2015) determined the radon exhalation rate for a range of area sources at Richards Bay Minerals. The values range from 0.01 $Bq.m^{-2}.s^{-1}$ to 0.1 $Bq.m^{-2}.s^{-1}$, with an average of 0.04 $Bq.m^{-2}.s^{-1}$.

Another approach that can be followed to derive radon exhalation rates for the source material is to use the correlation between the Ra-226 and the radon exhalation rate as presented in Parc Scientific (2006). Parc Scientific (2006) summarised radon exhalation rates measured from residue storage facilities in the South

African gold mining industry and reported coefficients, derived from regression lines fitted through these data points. These diffusion coefficients are used with concentrations of Ra-226 measured in the tailings material to estimate the radon exhalation rate in units of $Bq.m^{-2}.s^{-1}$. Parc Scientific (2006) presented the measured data as ‘average’ and ‘maximum’ values based on the statistical distribution of the data. The derived diffusion coefficients, therefore, also represent average and maximum values. The equations and coefficients used for deriving radon exhalation rates for TSFs are as follows (Parc Scientific, 2006):

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

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

Table 3.12 presents the average and maximum radon exhalation rates, estimated from the measured radium concentration in some of the materials listed in Table 3.8. Except for the HMC, the results vary between 0.01 and 0.13 $Bq.m^{-2}.s^{-1}$ on average.

Table 3.12 Radon exhalation rated derived from the Ra-226 content of some materials for which full-spectrum analysis results are available in Table 3.8, using the equations presented in Parc Scientific (2006).

Source Material	Ra-226 ($Bq.kg^{-1}$)	Rn Exhalation Rate Range ($Bq.m^{-2}.s^{-1}$)	
		Average	Maximum
PWP Heavy Mineral Concentrate	499	0.28	0.30
PWP Sand Sails	19	0.01	0.01
PWP Slimes	29	0.02	0.02
MSP Sand Tails	112	0.06	0.07
MSP Slimes	229	0.13	0.14
MSP Gypsum	173	0.10	0.11

4 Development and Justification of Public Exposure Conditions

4.1 Introduction

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

Consistent with the assessment framework presented in Figure 1.4, the radiological public impact is evaluated through the development of site-specific public exposure conditions. As used here, an exposure condition is defined as follows:

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

The purpose of this section is to use the current understanding of the Port Dunford Mine and its surroundings (see Section 3), bounded by the conditions and assumptions defined in the assessment context (see Section 2), to develop relevant site-specific public exposure conditions. Different approaches can be used to derive a discrete set of public exposure conditions. A Source-Pathway-Receptor (SPR) analysis approach was judged appropriate for the assessment (see Figure 1.4). 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 Port Dunford Mine are evaluated and discussed in Section 4.3 to Section 4.5. Section 4.6 introduces the way conceptual models are represented in the definition of the exposure conditions. The outcome of the SPR analysis approach is then used for the definition and justification of the public exposure conditions in Section 4.7.

4.2 Key Concepts used in the SPR Analysis Approach

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

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

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

4.3 Source Identification

4.3.1 General

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

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

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

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

4.3.2 Primary and Secondary Sources of Radiation Exposure

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

- Stockpile facility used to store ore, products, waste or other residue material on the surface, from which naturally occurring radionuclides may be dispersed in solid (dust), liquid (seepage), or gaseous (radon gas) form;
- An open pit that developed following open cast mining to extract minerals from the orebody, from which naturally occurring radionuclides may be dispersed in solid (dust), liquid (seepage), or gaseous (radon gas) form;
- Mineral processing activities, where radioactive gasses and dust may be released from the beneficiation of ore containing naturally occurring radionuclides;
- Water management facilities (e.g., process or return water dams), used to manage excess water generated through the mining, mineral processing and residue disposal activities, and where water may be released to the environment; and

- Materials handling activities (e.g., loading and hauling to the transfer of material containing naturally occurring radionuclides from one point to another), during which radioactive dust may be generated and released into the environment.

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

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

Members of the public may potentially be subject to radiation exposure from both primary and secondary sources at a mining and mineral processing operation, with expected differences in modes and duration of exposure. The purpose of Section 4.3.3 and Section 4.3.4 is to provide a brief description of the potential primary and secondary sources of radiation exposure associated with the Port Dunford Mine. Note that the significance of these sources may vary and may change over time during the LoM.

4.3.3 Primary Sources Associated with the Port Dunford Mine

4.3.3.1 General

Facilities, activities and associated surface infrastructure of the Port Dunford Mine that are known to contain or emit ionising radiation were presented in Section 3.3. It was noted that these facilities and activities are diverse and physically widespread. Table 4.1 summarises the facilities and activities that have the potential to serve as sources of radiation exposure.

The *Assessment Context* defined in Section 2 made a distinction between the pre-operational, the operational and the post-operational (closure) periods. The nature of the Port Dunford Mine is such that the facilities and activities relevant as sources of radiation exposure during the operational period will vary during the LoM, while only some of the facilities and activities will remain during the post-closure period. The operational period is divided into two phases with Phase 1 stretching from 2025 to 2035 (10 years) and Phase 2 stretching from 2036 to 2069 (33 years). During these phases, the significance of facilities and activities as sources of radiation exposure will vary, while at mine closure and during the post-closure period, only some of the facilities will remain at the surface and continue to serve as sources of radiation exposure. The operational period, therefore, represents the ‘worst case’ as it has the highest number of identified sources associated with it and serves as the basis for the development of public exposure conditions for the Port Dunford Mine radiological public safety and impact assessment.

Table 4.1 Summary of Port Dunford Mine surface infrastructure and features Importance to the radiological public safety and impact assessment.

Feature	Description
Mined-out areas	The mined-out areas will emit dust particulates (PM_{10} and TSP), as well as radon gas into the atmosphere for as long as the areas are open and during the load and haul processes. The leaching of contaminants from the mined-out areas to the underlying aquifer serves as a source for the groundwater pathway. The mined-out areas will also continuously emit gamma radiation to the immediate surroundings.
RSFs	The RSFs will emit dust particulates (PM_{10} and TSP), as well as radon gas into the atmosphere for as long as the residues are exposed to the elements, and during any material handling activities at the RSF. The leaching of contaminants to the underlying aquifer serves as a source for the groundwater pathway. The fine tails material will also continuously emit gamma radiation to the immediate surroundings.
HMC, RoM and topsoil stockpiles	The stockpile facilities associated with the Port Dunford Mine include the HMC, RoM and topsoil stockpiles. These stockpiles will emit dust particulates (PM_{10} and TSP), as well as radon gas into the atmosphere. The leaching of contaminants to the underlying aquifer serves as a source for the groundwater pathway. The stockpile facilities will also continuously emit gamma radiation to the immediate surroundings. However, because of their limited sizes, their contribution is expected to be less than that of the RSFs and open pit areas, for example. Note that these stockpiles may vary in size during the mining and processing stages. However, for the assessment, these facilities are assumed to be constant in size during the LoM.
Infrastructure for mine water management	The water control dams will be used for the management of water between the plant and the return water from the mine infrastructure. The leaching of contaminants to the underlying aquifer serves as a source for the groundwater pathway. Water may also be released from the water control dams under certain authorised conditions.
Pipelines	The Port Dunford Mine make use of a pipeline system to transfer water or solids such as coarse sand tails, fine tails and RoM material between surface infrastructure. Any spillages from these pipelines may result in the potential contamination of surface soils within the ming rights area.

Other surface infrastructure such as roads, offices and laboratories does not release naturally occurring radionuclides to the environment and is not considered a source of radiation exposure to members of the public *per se*.

4.3.3.2 Mined Out Areas

The position of the Port Dunford Mine mined-out areas during the different phases and stages of mining is presented in Section 3.3.4 and Section 3.3.5 (see Figure 3.2 and Figure 3.6). Dust generation can be expected since this is the area where the orebody is exploited and the ore is transferred from the mining areas to the plant using load and haul methods.

Mined-out areas may generally serve as a source of radiation exposure through solid-, gas- and water-mediated release of contaminants in the following manner:

- Windblown dust emitted from the area and dust generated during loading and hauling activities contain long-lived alpha-radiating isotopes, which may be dispersed into the atmosphere (solid-mediated release of contaminants, resulting in an increased concentration of airborne radioactivity). This dust is generally referred to as long-lived radioactive dust (LLα). The heavier particulates (greater than 10 microns in size) are generally deposited into the environment (solid-mediated release of contaminants, resulting in an increased concentration of radioactivity in surface soil).
- The radionuclide content of the orebody and Ra-226 specifically, is likely to result in the emission of radon gas into the air (gas-mediated release of contaminants, increasing the airborne concentration of radon).

- Infiltration and subsequent percolation of water from the mined-out areas may induce the leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing radioactivity concentrations in groundwater).
- Water erosion of the mined-out areas may induce the solid-mediated release, dispersion and deposition of dust particles, increasing the radioactivity concentration in surface soil.

Although not a contaminant in the usual sense, the inherent radiological properties of the orebody may result in the continuous emission of gamma radiation from mined-out areas (*external gamma radiation*).

4.3.3.3 Residue Storage Facilities

There are two residue storage facilities (RSFs) that will be developed over the LoM, the location and characteristics of which are presented in Section 3.3.9. The surface of operational or dormant RSFs is generally amenable to wind erosion. Rehabilitation efforts on unused sections of an operational RSF can reduce the formation of windblown dust. As Class 3 waste facilities, the RSFs will require lining. The design assumes that a double-layer containment barrier, made up of a 1,500-micron geomembrane and a geosynthetic clay liner will be installed in the RSFs to prevent environmental contamination. An RSF generally serves as a source of radiation exposure through solid-, gas- and water-mediated release of contaminants in the following manner:

- Windblown dust emitted from the RSFs, or dust generated during activities performed at the RSFs is likely to contain long-lived alpha-radiating isotopes, which could be dispersed into the atmosphere (solid-mediated release of contaminants, resulting in an increased concentration of airborne radioactivity). This dust is generally referred to as long-lived radioactive dust (LLα). The heavier particulates (greater than 10 microns in size) are generally deposited into the environment (solid-mediated release of contaminants, resulting in an increased concentration of radioactivity in surface soil).
- The radionuclide content of the fine tails material and Ra-226 specifically, may result in the emission of radon gas into the air (gas-mediated release of contaminants, increasing the airborne concentration of radon).
- Infiltration and subsequent percolation of water through RSFs may induce the leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing radioactivity concentrations in groundwater).
- Water erosion of the RSFs induces the solid-mediated release, dispersion and deposition of dust particles, increasing the radioactivity concentration in surface soil.

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

4.3.3.4 Stockpiles

The position of the Port Dunford Mine stockpiles during the different phases and stages of mining is presented in Section 3.3.4 and Section 3.3.5 (see Figure 3.2 and Figure 3.6). These include stockpiles of topsoil, sand tailings, RoM material, or HMC produced at the PWP. Generally, a stockpile serves as a source of radiation exposure through solid-, gas- and water-mediated release of contaminants in a similar manner as RSFs (see Section 4.3.3.2). The radioactivity content associated with the HMC, RoM, sand tailings and topsoil stockpiles may vary and may be higher or lower than that of the RSFs. This results in stockpile facilities being less or more significant sources of public radiation exposure.

4.3.3.5 Water Management Infrastructure

It follows from the *System Description* (see Section 3.3) that water control dams will be implemented at the RSF 9 Site and the PWP. The position of these dams is shown in Figure 3.1.

The nature of these water management facilities is such that the only contribution as a source is through water infiltration and subsequent leaching of radionuclides to the underlying geosphere (water-mediated release of contaminants, increasing *groundwater activity concentrations*). While the water control dams are within the mining authorization of the Port Dunford Mine, public access to these facilities cannot be excluded.

4.3.3.6 Pipelines

It follows from the *System Description* (see Section 3.3) that the Port Dunford Mine will make use of an extensive pipeline surface infrastructure to transfer raw water and slurried solid materials between surface infrastructure. These include RoM, Sand tailings and fine tails material. Under normal operating conditions, these pipelines do not serve as a significant source of radiation exposure. It is only under accident and incident conditions (e.g., pipeline bursts) that these pipelines may serve as a potential secondary source of radiation exposure (see Section 4.3.4.4).

4.3.4 Secondary Sources Associated with the Port Dunford Mine

4.3.4.1 General

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

4.3.4.2 Natural Processes and Events

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

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

4.3.4.3 Normal Operating Conditions

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

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

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

4.3.4.4 Secondary Sources Due to Events Outside Normal Operating Conditions

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

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

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

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

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

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

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

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

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

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):

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

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

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

4.4.2 Atmospheric Pathway

4.4.2.1 General

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

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

Airborne particulates and radon gas concentrations are expected to be the highest close to the source and decrease with distance from the source depending on meteorological conditions, the physical characteristics of the contaminants and facilities from which the contaminants are released. The contribution of the atmospheric pathway for the Port Dunford Mine is documented in WSP (2024b). For this purpose, WSP (2024b) made a distinction was made between Phase 1 and Phase 2. For Phase 2, mining was assumed to progress across the site (from 2036 to 2069) and as such, the modelling scenarios have been split into key periods (based on location of emission sources) for ease of assessment. For the dispersion modelling, WSP (2024b) considered the following scenarios (operational years are indicated in brackets):

- Phase 2 Scenario 1 Operations (2036 to 2047);
- Phase 2 Scenario 2 Operations (2048 to 2053); and
- Phase 2 Scenario 3 Operations (2054 to 2069).

Presented here are the resulting PM_{10}, TSP and radon gas dispersion modelling results that form the basis for evaluating the radiological impact of the atmospheric pathway for the Port Dunford Mine. The unit release rates used to model the gas release pathway were corrected for material-specific radon exhalation rates (see Section 3.5).

4.4.2.2 Phase 1

The atmospheric pathway sources for Phase 1 are limited to the mined-out area for Phase 1, associated material handling activities (removal and loading haul trucks) and the transport of the material on roads. Figure 4.1 shows a graphical representation of the PM_{10} concentrations in air attributed to the Port Dunford Mine (in units of $\mu g.m^{-3}$). A similar representation of the annual quantity of dust deposited onto topsoil (in units of $mg.m^{-2}.day^{-1}$) is presented in Figure 4.2. The estimated airborne radon concentration is presented in Figure 4.3. The radon dispersion estimate is based on corrected radon exhalation rates for the relevant facilities and activities (see Section 3.5).

4.4.2.3 Phase 2: Scenario 1

The atmospheric pathway sources for Phase 2 Scenario 1 include the Topsoil Stockpile, Site 9 RSF, the Sand Tailings Stockpiles (A1 to A3), Site RSF C (Pit 1 to Pit 3), material handling activities (removal and loading and offloading of haul trucks, processing plant) and the transport of material on roads. Figure 4.4 shows a graphical representation of the PM_{10} concentrations in air attributed to the Port Dunford Mine (in units of $\mu g.m^{-3}$). A similar representation of the annual quantity of dust deposited onto topsoil (in units of $mg.m^{-2}.day^{-1}$) is presented in Figure 4.5. The estimated airborne radon concentration is presented in Figure 4.6. The radon dispersion estimate is based on corrected radon exhalation rates for the relevant facilities and activities (see Section 3.5).

4.4.2.4 Phase 2: Scenario 2

The atmospheric pathway sources for Phase 2 Scenario 2 are limited to the mined-out area for Scenario 2, associated material handling activities (removal and loading haul trucks) and the transport of the material on roads. Figure 4.7 shows a graphical representation of the PM_{10} concentrations in air attributed to the Port Dunford Mine (in units of $\mu g.m^{-3}$). A similar representation of the annual quantity of dust deposited onto topsoil (in units of $mg.m^{-2}.day^{-1}$) is presented in Figure 4.8. The estimated airborne radon concentration is presented in Figure 4.9. The radon dispersion estimate is based on corrected radon exhalation rates for the relevant facilities and activities (see Section 3.5).

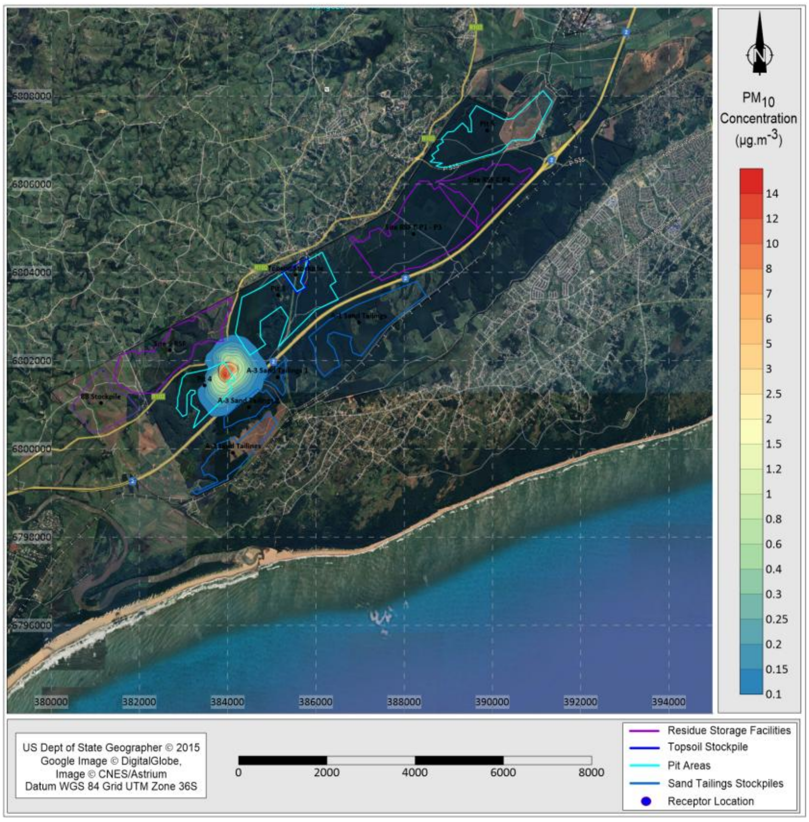


Figure 4.1 **The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to Phase 1 of the Port Dunford Mine.**

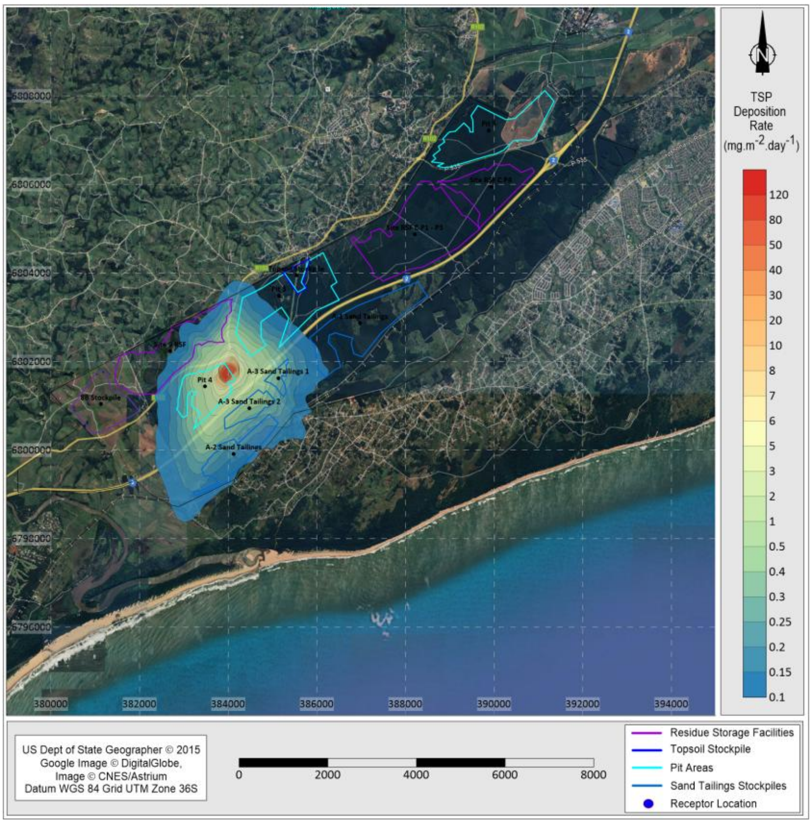


Figure 4.2 **The simulated annual average airborne TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to Phase 1 of the Port Dunford Mine.**

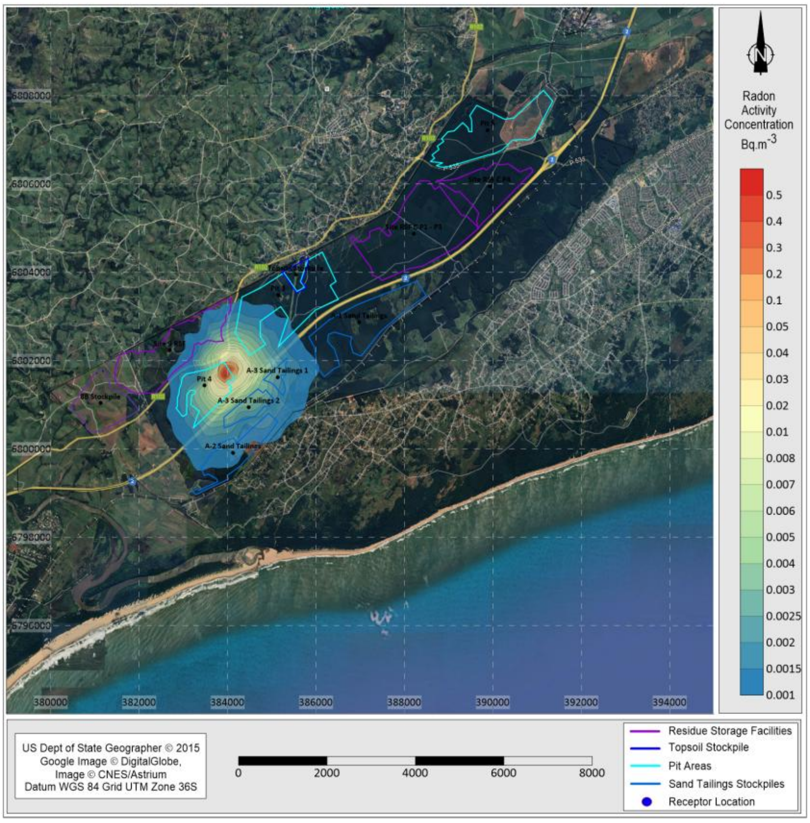


Figure 4.3 The simulated airborne radon concentration (in units of Bq.m^{-3}) attributed to Phase 1 of the Port Dunford Mine.

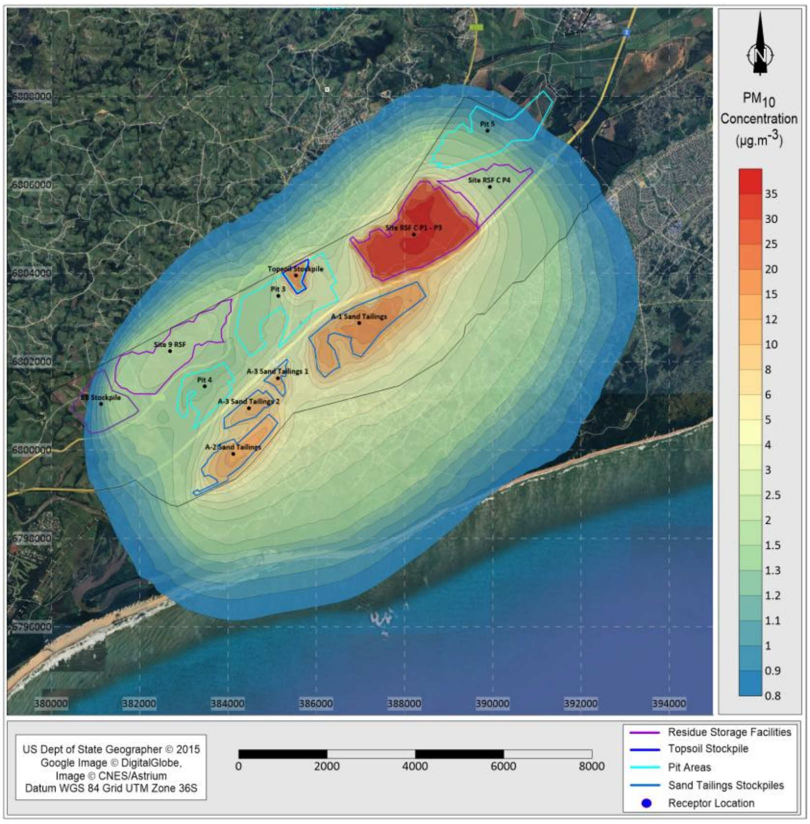


Figure 4.4 The simulated annual average airborne PM_{10} concentrations (in units of µg.m^{-3}) attributed to Phase 2 Scenario 1 of the Port Dunford Mine.

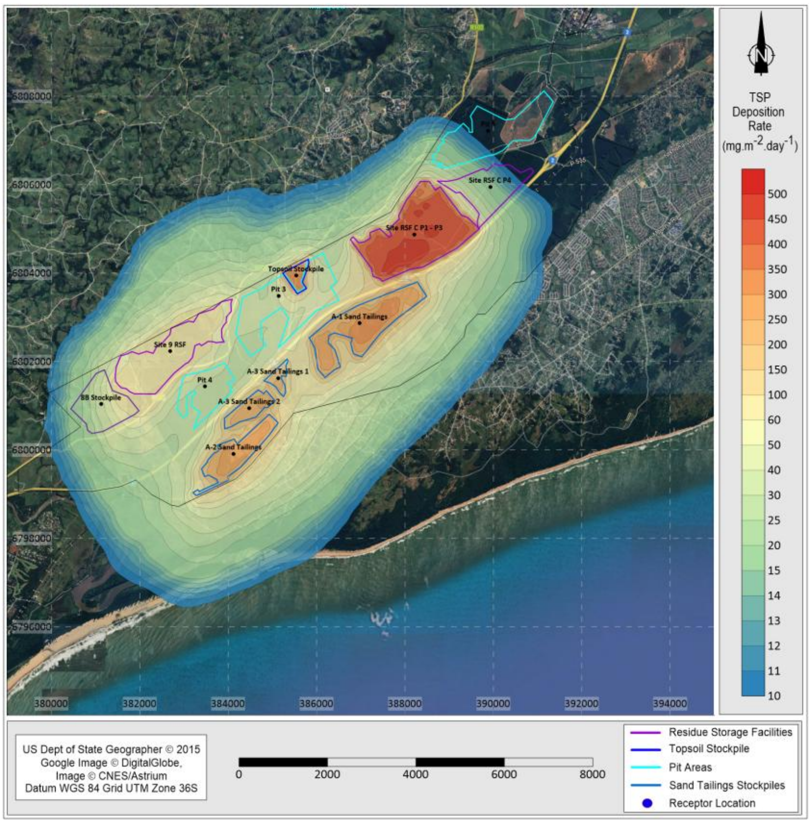


Figure 4.5 **The simulated annual average airborne TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to Phase 2 Scenario 1 of the Port Dunford Mine.**

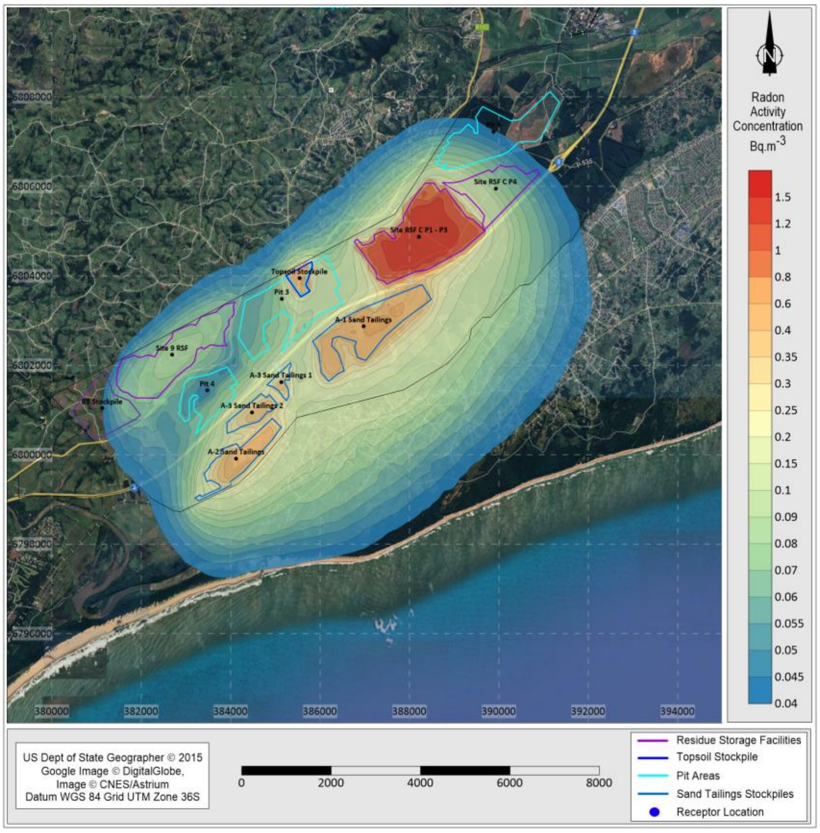


Figure 4.6 **The simulated airborne radon concentration (in units of $Bq.m^{-3}$) attributed to Phase 2 Scenario 1 of the Port Dunford Mine.**

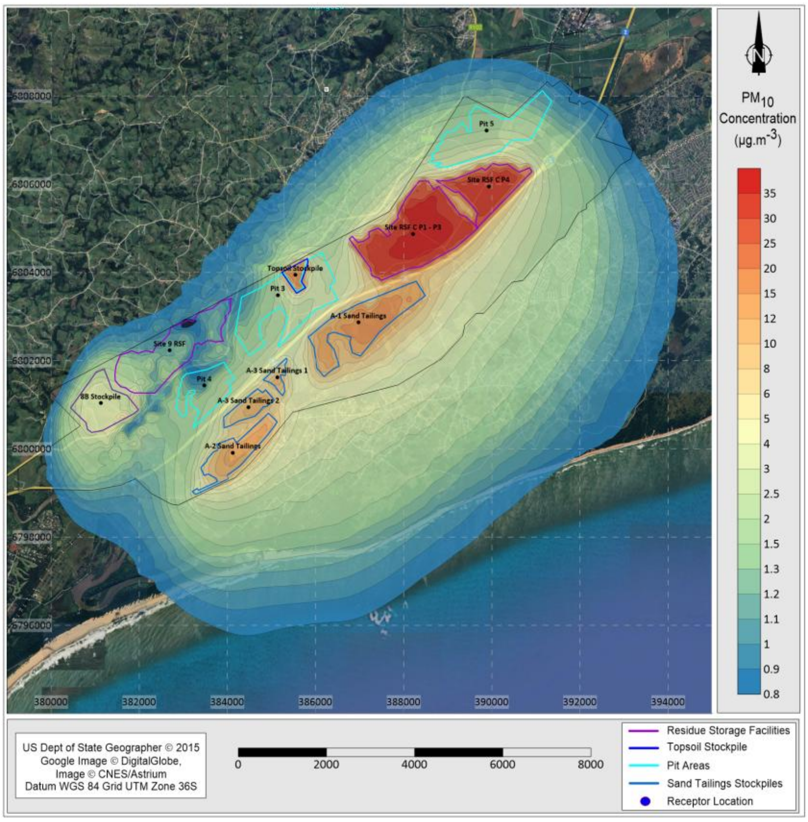


Figure 4.7 **The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to Phase 2 Scenario 2 of the Port Dunford Mine.**

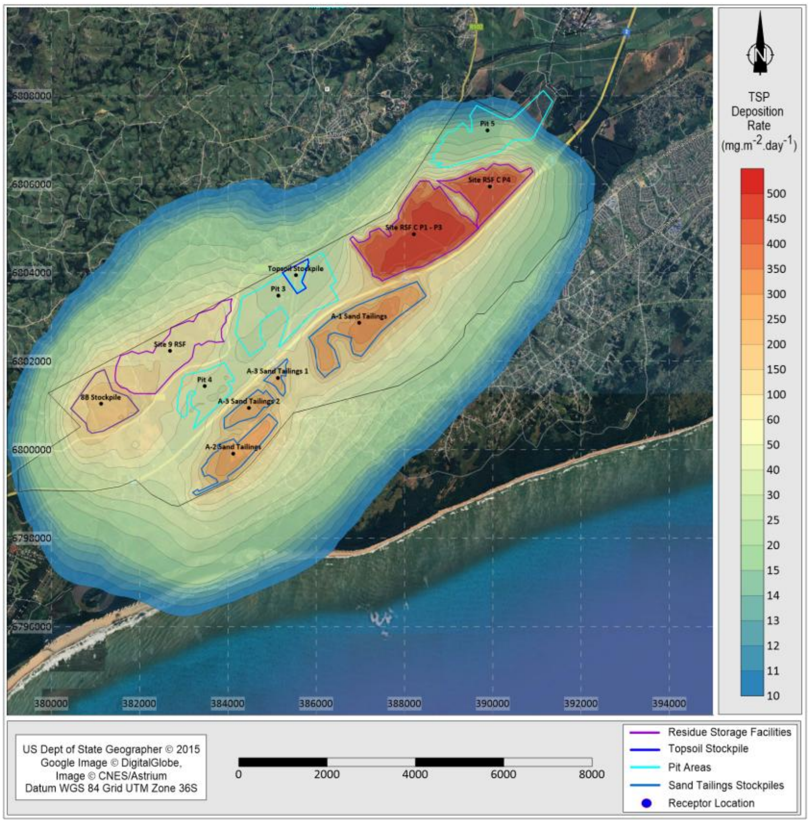


Figure 4.8 **The simulated annual average airborne TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to Phase 2 Scenario 2 of the Port Dunford Mine.**

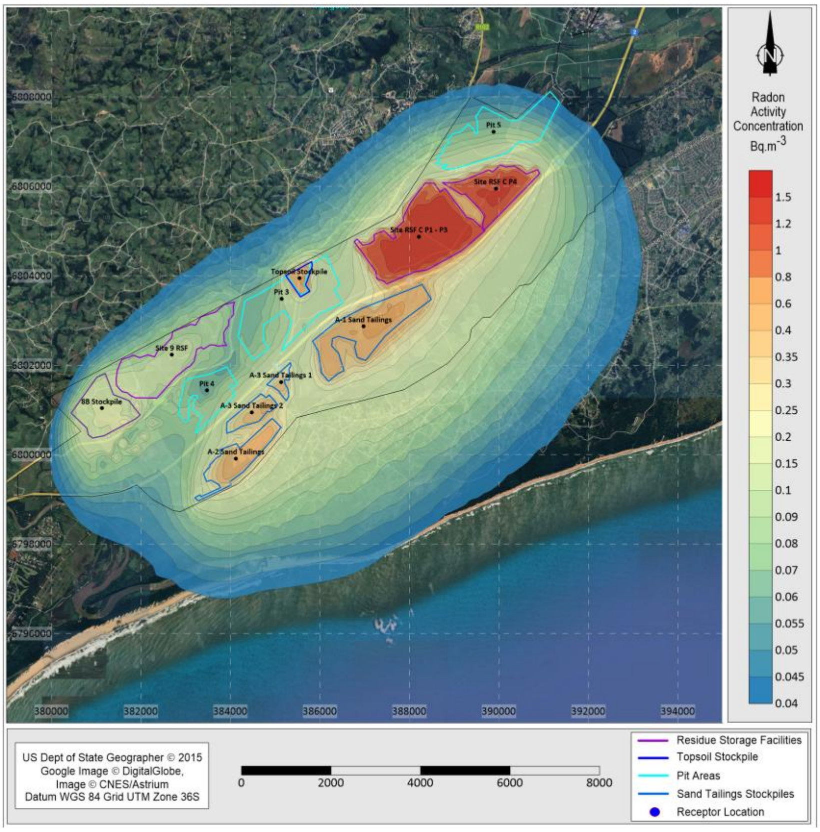


Figure 4.9 **The simulated airborne radon concentration (in units of Bq.m^{-3}) attributed to Phase 2 Scenario 2 of the Port Dunford Mine.**

4.4.2.5 Phase 2: Scenario 3

The atmospheric pathway sources for Phase 2 Scenario 3 are limited to the mined-out area for Scenario 3, associated material handling activities (removal and loading haul trucks) and the transport of the material on roads. Figure 4.10 shows a graphical representation of the PM_{10} concentrations in air attributed to the Port Dunford Mine (in units of µg.m^{-3}). A similar representation of the annual quantity of dust deposited onto topsoil (in units of mg.m^{-2}.day^{-1}) is presented in Figure 4.11. The estimated airborne radon concentration is presented in Figure 4.12. The radon dispersion estimate is based on corrected radon exhalation rates for the relevant facilities and activities (see Section 3.5).

4.4.2.6 Contribution of the Atmospheric Pathway

The flow diagram in Figure 4.13 can be used to evaluate the contribution of the atmospheric pathway to a quantitative total effective dose for Phase 1 and each scenario for Phase 2. It follows from the source description in Section 4.3 that airborne radioactivity near the Port Dunford Mine can be attributed to the emissions of dust that contain LLα and radon gas. Note that the airborne contaminant plume will contribute to the external gamma radiation dose (plume immersion) and inhalation of the airborne radioactivity contributes to the inhalation dose.

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

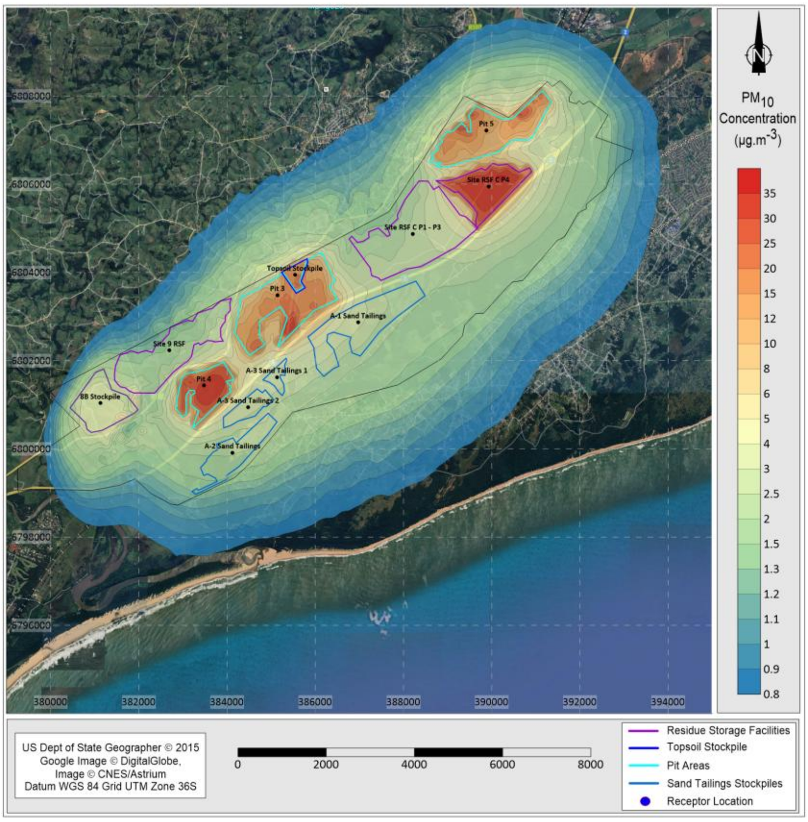


Figure 4.10 **The simulated annual average airborne PM_{10} concentrations (in units of $\mu g.m^{-3}$) attributed to Phase 2 Scenario 3 of the Port Dunford Mine.**

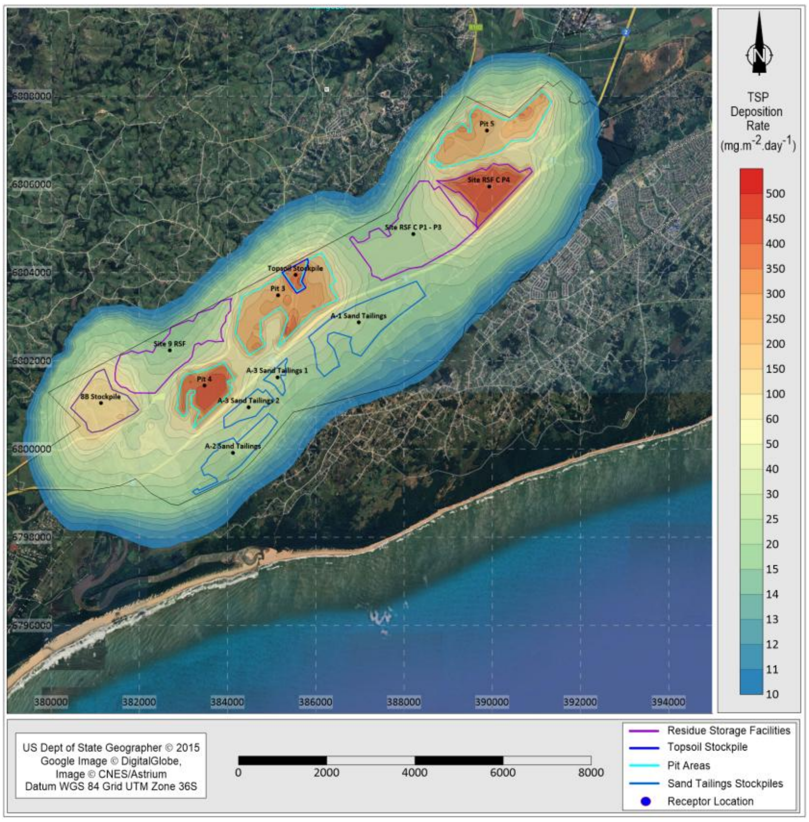


Figure 4.11 **The simulated annual average airborne TSP deposition rate (in units of $mg.m^{-2}.day^{-1}$) attributed to Phase 2 Scenario 3 of the Port Dunford Mine.**

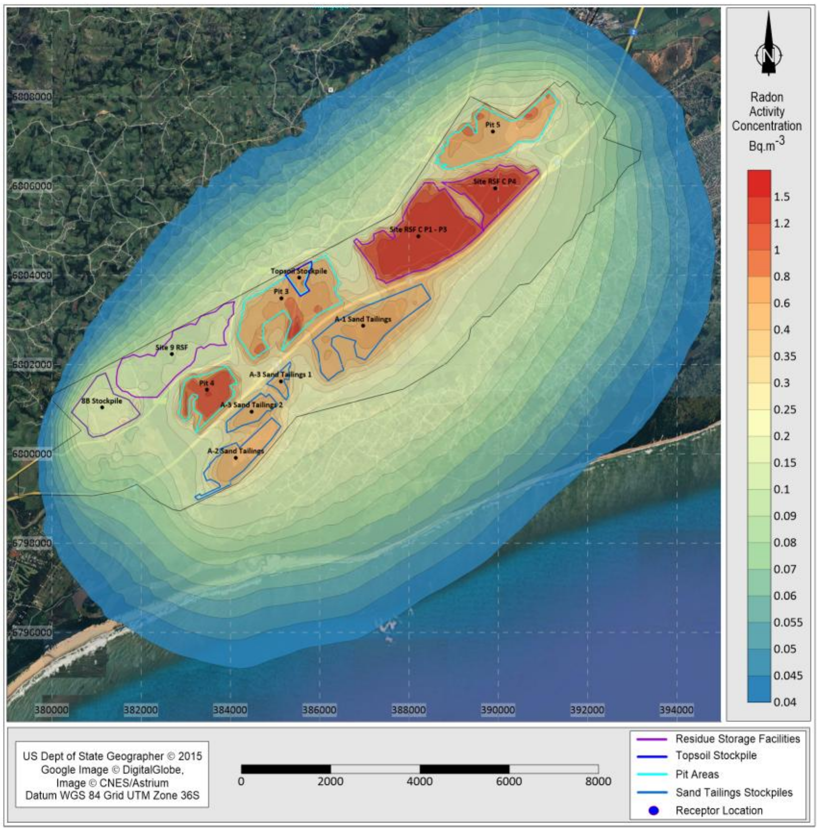


Figure 4.12 The simulated airborne radon concentration (in units of Bq.m^{-3}) attributed to Phase 2 Scenario 3 of the Port Dunford Mine.

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

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

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

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

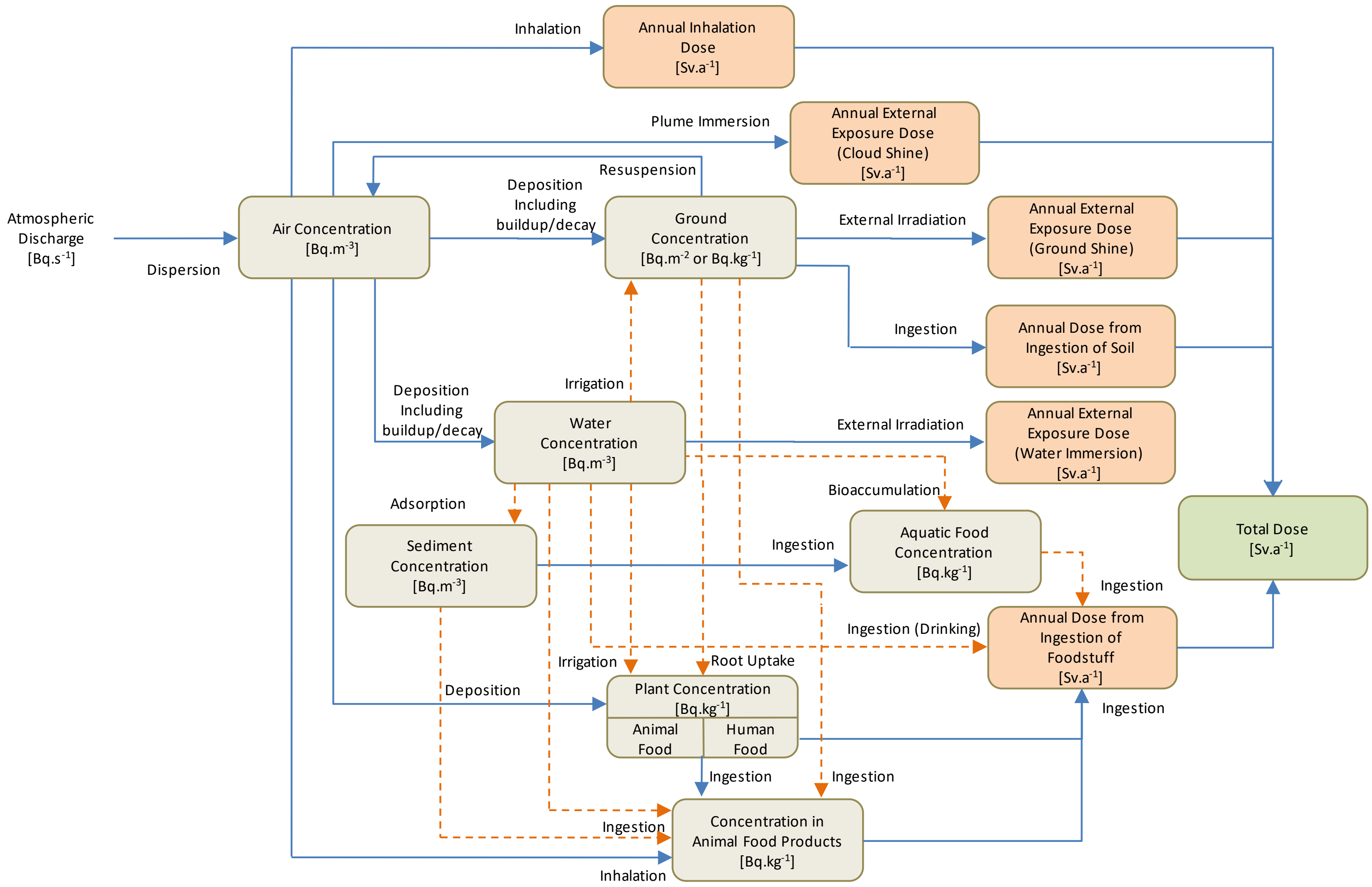


Figure 4.13 Features, processes and associated exposure modes that should be considered to calculate the contribution of the atmospheric pathway to a total dose.

4.4.3 Groundwater Pathway

The primary sources of radiation exposure (see Section 4.3) for the groundwater pathway associated with the Port Dunford Mine are the RSFs, the mined-out areas, HMC and sand tails stockpiles and the water control dams at the RSF and PWP. These sources and their contribution will vary with time as the Port Dunford Mine progresses through the mining schedule. The significance of these sources from a radiological perspective depends on the activity concentration associated with the source material and the resulting leachate to the underlying aquifer.

WSP (2024d) developed a hydrogeological conceptual and numerical model for the Port Dunford Mine. Figure 4.14 presents the simulated head distribution for the LoM (2069), which shows that flow is towards the coast and the low-lying areas of the surface water bodies. Figure 4.15 is a cross-section through RSF C and the Mzingwenya River, as an illustration, to indicate how the concentrations build up in the base rock (WSP, 2024d).

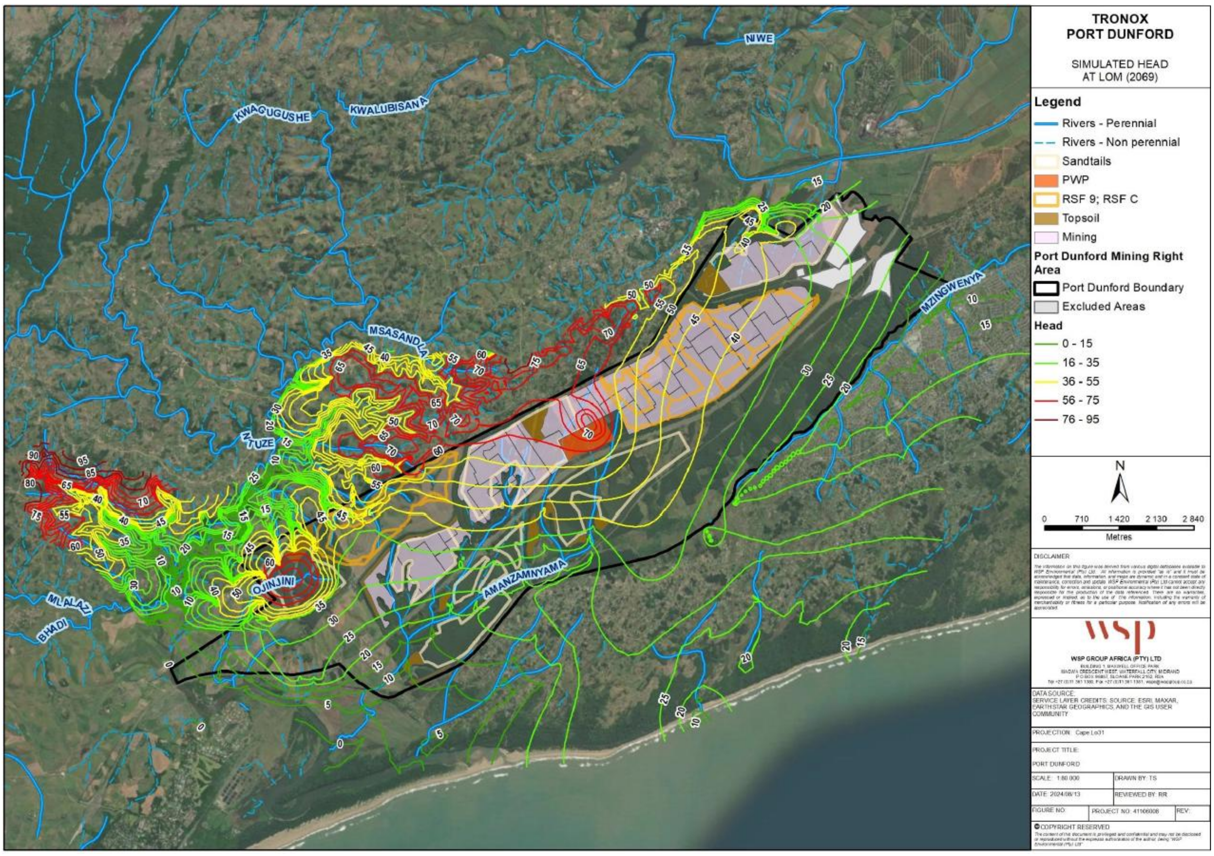


Figure 4.14 The simulated head distribution for the LoM (2069), which shows that flow is towards the coast and the low-lying areas of the surface water bodies (WSP, 2024d).

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

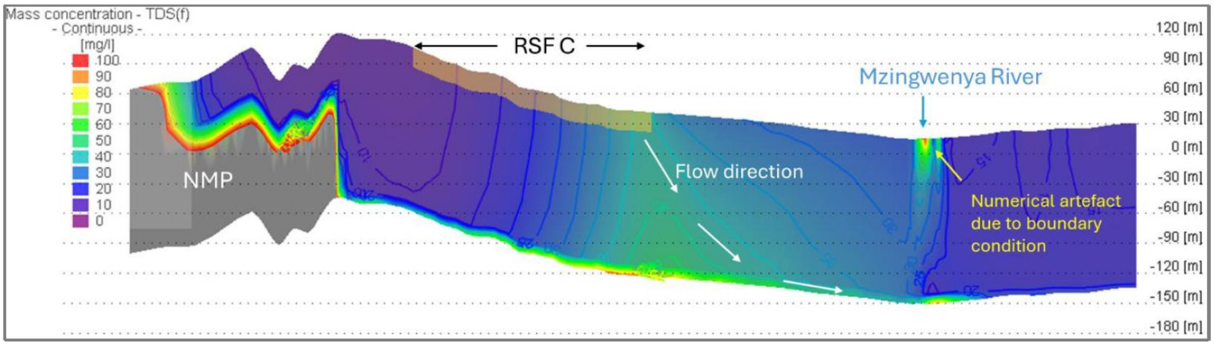


Figure 4.15 A cross-section through RSF C and the Mzingwenya River, as an illustration, to indicate how the concentrations build up in the base rock (NMP) (WSP, 2024d).

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

The flow diagram in Figure 4.16 can be used to calculate the contribution of the groundwater pathway to a quantitative total effective dose. Depending on the radionuclide concentration of the groundwater as well as human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.16. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation of water contributes to the concentrations of radionuclides in crops or soil.

4.4.4 Surface Water Pathway

Under normal conditions, the surface water pathway is an extension of the groundwater pathway and to a lesser extent the atmospheric pathway. However, the controlled or uncontrolled release of contaminated water or mine residue material may serve as a direct source of radiation exposure associated with the surface water pathway. Once discharged into the surface watercourse, radionuclides are subject to a series of physical and chemical processes that affect their transport from the point of discharge. These processes illustrated in Figure 4.17, 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, such as radionuclide decay and other mechanisms that will reduce concentrations in water, such as radionuclide volatilization (if any).

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

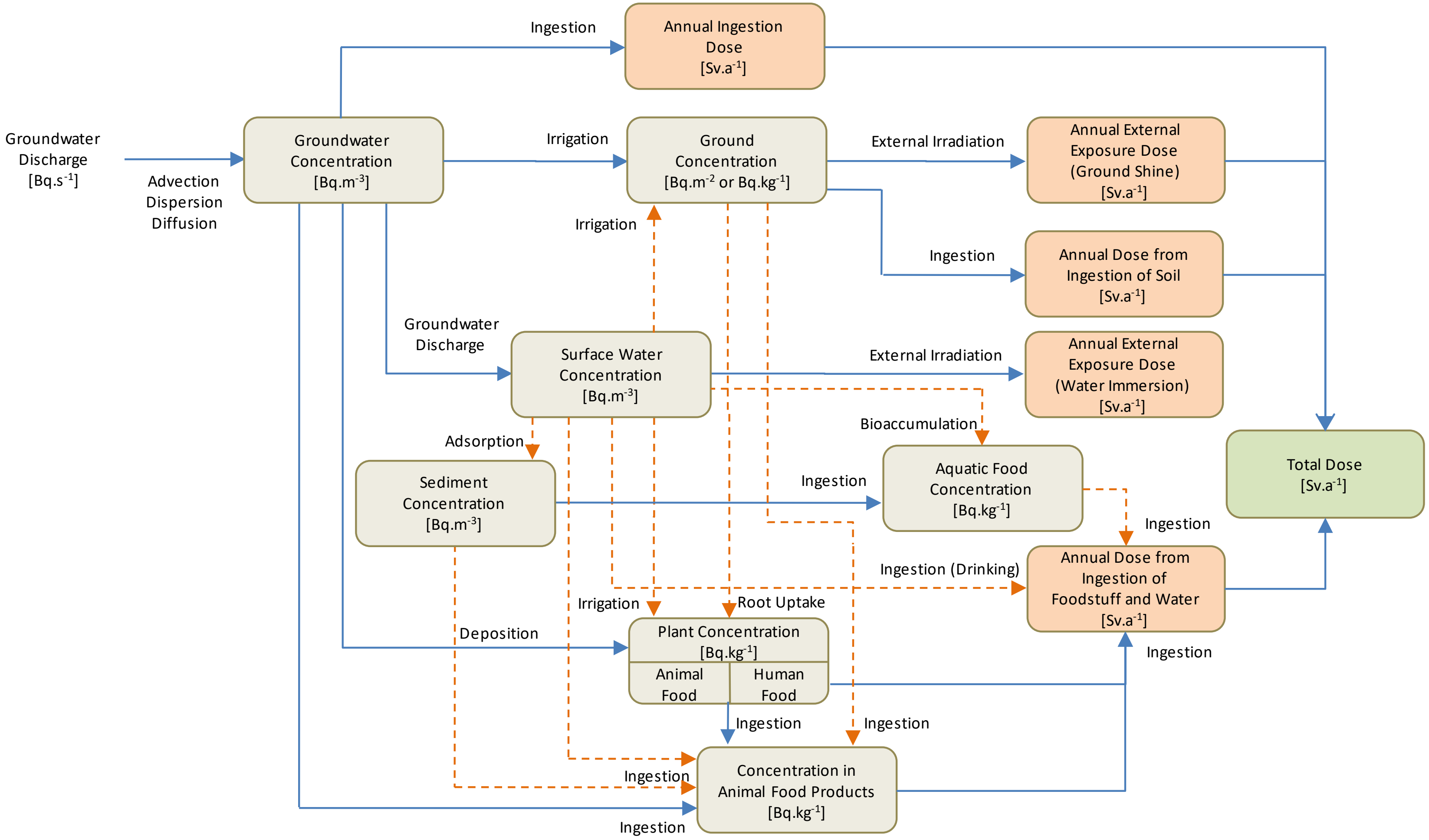


Figure 4.16 **Features, processes and associated exposure modes that should be considered to calculate the contribution of the groundwater pathway to a total dose.**

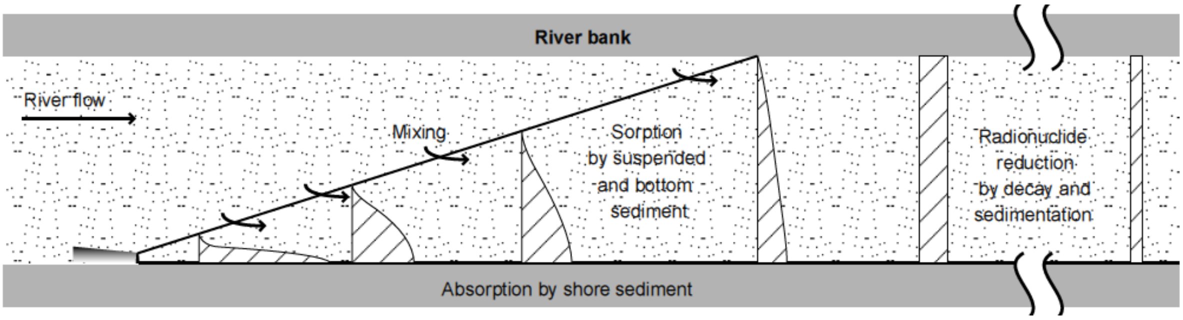


Figure 4.17 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001**).**

Section 3.4.3 provides a summary overview of the hydrological conditions in the Port Dunford Mine area, which indicates that the surface water bodies that are of importance are (see Figure 3.13) (WSP, 2024d):

- Within the W12F quaternary catchment, the perennial Mhlathuze River flows past the northern boundary and its tributaries drain the north-western areas. The perennial Mzingwenya River and its associated tributaries flow along the eastern site boundary from southwest to northeast where it drains into Lake Qhubu.
- Within the W13B quaternary catchment, the perennial Amanzamnyama and Ojinjini Rivers and their associated tributaries flow from north-east to south-west within the site boundary and confluences with the Mlalazi River. Another tributary of the Mlalazi River runs further south of this site boundary. The Mlalazi River runs along the southwestern site boundary and eventually drains into the Indian Ocean.

Contaminated groundwater originating from the Port Dunford Mine area will discharge into these rivers, which may contribute to a radiological impact in addition to any possible direct releases to the surface water body itself.

The flow diagram in Figure 4.18 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 and the human habits and behavioural characteristics, various secondary pathways can contribute to a total effective dose, as illustrated in Figure 4.18. These pathways are similar to those described for the atmospheric pathway, except that instead of deposition of airborne contaminants onto crops or soils, irrigation with contaminated water contributes to radionuclide concentrations in crops or soil.

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

4.4.5 External Gamma Radiation

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

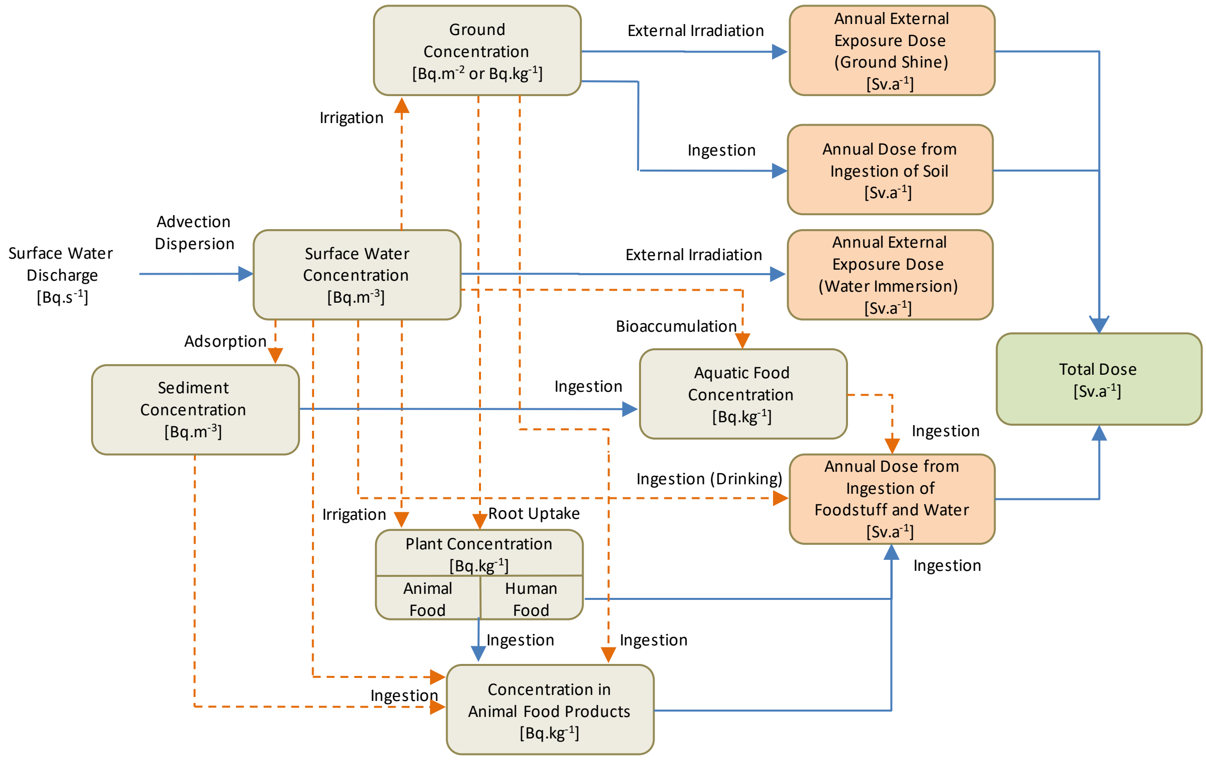


Figure 4.18 Features, processes and associated exposure modes that should be considered to calculate the contribution of the surface water pathway to a total dose.

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

4.5 Receptors

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

The information presented in Section 3.4.7 indicates that the communities closest to the Port Dunford Mine include the residents of the formal and information residential areas of Port Durnford (60 m), Mtunzini (200 m), Gobandlovu (200 m), eSikhawini (200 m), Vulindlela and Felixton. Sensitive receptors identified as part of the air quality impact assessment in WSP (2024b) are presented in Figure 4.19 (see Table 4.2). Selecting these receptor locations for detailed radiological impact assessment analysis provides insight into the potential contribution of the Port Dunford Mine to nearby communities. The consequence analysis results presented in Section 5.4 present the total dose contribution from each exposure route as a contribution of the atmospheric pathway to the total effective dose at each of these receptor points (see Figure 5.9 to Figure 5.13 for Phase 1, for example).

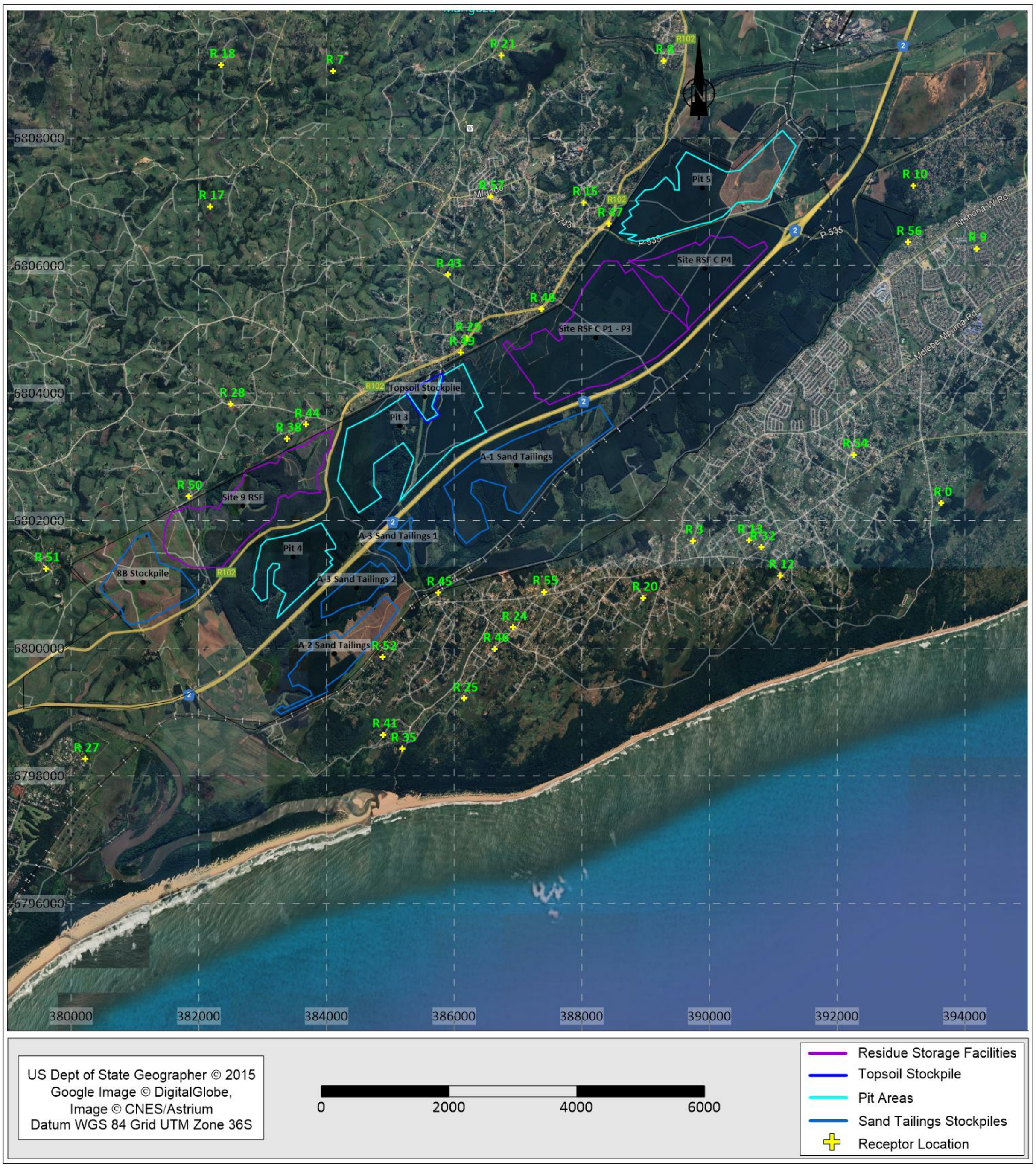


Figure 4.19 **Locality map showing the sensitive receptor locations identified for the air quality impact assessment presented in WSP (2024b) (see Table 4.2).**

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).

Table 4.2 Summary of the sensitive receptor locations used in air quality impact assessment and the dose assessment calculations (WSP, 2024b).

ID	Receptor Name	Receptor Type	Distance from Site Boundary (km)	Direction	Latitude (°S)	Longitude (°E)
R 0	Africa Christian Ministries	Residential	3.4	South-southeast	28.903	31.909
R 1	Amadaka	Residential	2.7	East	28.864	31.934
R 2	Bhiliya	Residential	5.4	East	28.831	31.945
R 3	Church of Jesus Christ of Latter Day Saints	Residential	1.1	South	28.908	31.869
R 4	Dube	Residential	2	East	28.861	31.928
R 5	Empembeni	Residential	6.5	East	28.875	31.971
R 6	Empembeni Primary School	Residential/ School	7.4	East	28.862	31.982
R 7	Engunjini	Residential	5.1	North	28.841	31.812
R 8	Eniwe	Residential/School	0.9	North-northeast	28.84	31.865
R 9	Esikhawini H	Residential	1	East	28.867	31.915
R 10	Gobandlovu	Residential	0.6	East	28.858	31.905
R 11	Gubhethuka	Residential	7.9	East	28.855	31.985
R 12	Injabuloyesizwe Primary School	Residential/School	2.4	South	28.913	31.883
R 13	Isikhalasenkosi High School	Residential/School	1.8	South	28.908	31.878
R 14	Izingeni	Residential	5	West	28.928	31.705
R 15	Khandisa	Residential	0.6	North-northeast	28.86	31.852
R 16	Kuleka	Residential	7.7	North-northeast	28.783	31.902
R 17	Kwashodlisa	Residential	4	North	28.86	31.792
R 18	Lubisana	Residential	5.9	North	28.84	31.794
R 19	Mabuyeni	Residential	4.9	East	28.862	31.954
R 20	Mahunu	Residential	1.2	South	28.916	31.861
R 21	Mangeza	Residential	3.6	North-northeast	28.839	31.839
R 22	Mankunzana	Residential	5.8	North	28.857	31.757
R 23	Manzamnyama Primary School	Residential/School	5.7	North	28.864	31.747
R 24	Mhlanga Primary School	Residential/School	0.9	South	28.92	31.84
R 25	Mntokhona Primary School	Residential/School	1.7	South	28.93	31.832
R 26	Msasandla	Residential	2.5	North-northwest	28.891	31.758
R 27	Mtunzini	Residential	0.7	Southwest	28.938	31.771
R 28	Muntonokudla Secondary School	Residential/School	1	North	28.888	31.795
R 29	Mvuzemvuze Primary School	Residential/School	0.3	North	28.879	31.833

ID	Receptor Name	Receptor Type	Distance from Site Boundary (km)	Direction	Latitude (°S)	Longitude (°E)
R 30	Ncombo	Residential	5.7	East	28.877	31.962
R 31	Ndabayakhe Full Gospel Church	Residential	5.1	North-northeast	28.806	31.851
R 32	Ndabenkulu Temple	Residential	2	South	28.909	31.88
R 33	Ndindima	Residential	4.4	Southeast	28.888	31.936
R 34	Ndleleni	Residential	3	East	28.847	31.929
R 35	Nelisiwe Temple	Residential	1.4	South	28.937	31.822
R 36	Ngwelezana Hospital	Residential	8.2	North-northeast	28.774	31.866
R 37	Ngwelezane	Residential	6.6	North-northeast	28.789	31.87
R 38	Njomane Home	Residential	0.1	North	28.893	31.804
R 39	Nqutshini	Residential	6.6	North-northeast	28.794	31.847
R 40	Nqutshini Primary School	Residential/School	6.8	North-northeast	28.802	31.83
R 41	Nyembe	Residential	0.9	South	28.935	31.819
R 42	Obanjeni Primary School	Residential/School	4.7	West	28.926	31.709
R 43	Ongoye	Residential	1.3	North	28.87	31.83
R 44	PD Seventh Day Adventist Church	Residential	0.3	North	28.891	31.807
R 45	Port Dunford	Residential	0.07	South	28.915	31.828
R 46	Qantayi High School	Residential/School	1.1	South	28.923	31.837
R 47	Residential Area 1	Residential	0.05	North	28.863	31.856
R 48	Residential Area 2	Residential	0.01	North	28.875	31.845
R 49	Residential Area 3	Residential	0.03	North	28.881	31.832
R 50	Residential Area 4	Residential	0.1	North	28.901	31.788
R 51	Residential Area 5	Residential	0.4	West	28.911	31.765
R 52	Residential Area 6	Residential	0.1	South	28.924	31.819
R 53	Sbhamu	Residential	3.2	West	28.921	31.729
R 54	Sikhalasenkosi	Residential	1.9	South	28.896	31.895
R 55	The Church of Jesus Christ (uMhlathuze City)	Residential	0.4	South	28.915	31.845
R 56	Uzimgwenya	Residential	0.07	East	28.866	31.904
R 57	Vulindlelaa	Residential	2	North	28.859	31.837
R 58	Zenzeleni Mashamase Secondary School	Residential/School	3.9	Northwest	28.901	31.73
R 59	Zimeme High School	Residential/School	5.8	North	28.867	31.74

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

As applied in other fields of science, conceptual models are extensively used in radiological public safety assessments. The use of conceptual models in the development of exposure conditions is captured in Figure 1.4 and Figure 4.20.

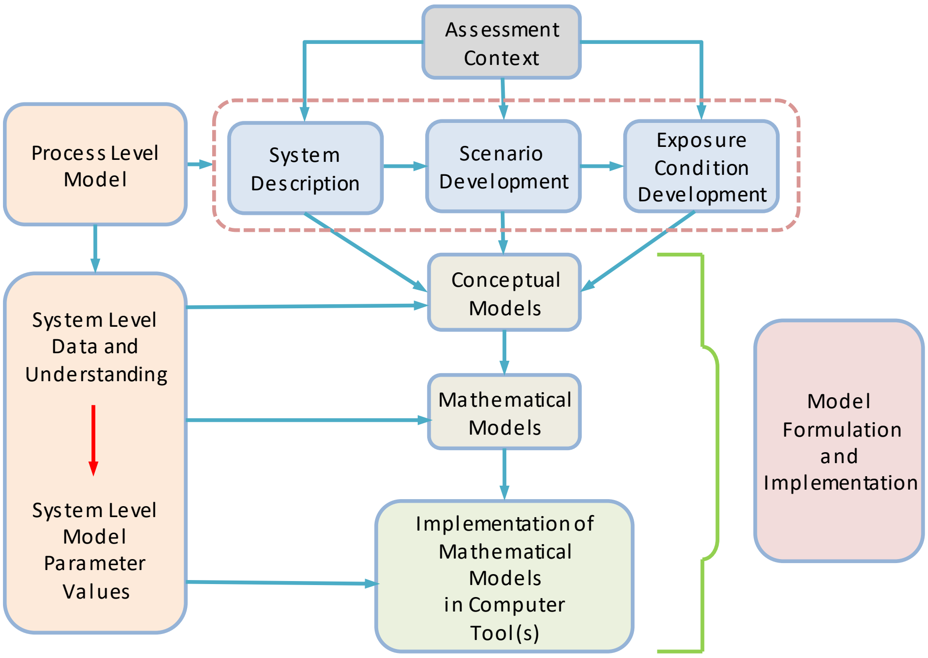


Figure 4.20 **The model development process relative to other elements of the assessment framework as presented in Figure 1.4.**

4.6.2 Conceptual Models for Environmental Pathway Analysis

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

Specialist studies to quantify the behaviour of some of these environmental pathways have been done as part of the S&EIR process for the Port Dunford Mine (WSP, 2024b). Conceptual models developed as part of these studies that were performed on a Process Level, will not be repeated here.

4.6.3 Representation of Conceptual Models for Exposure Conditions

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

Two methods are used to represent the exposure conditions conceptually: a process flow diagram and a RES Matrix or Interaction Matrix (Kozak and Zhou, 1998). In an Interaction matrix, the main variables or parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. A simple example of a 2x2 matrix is illustrated in Figure 4.21, 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.

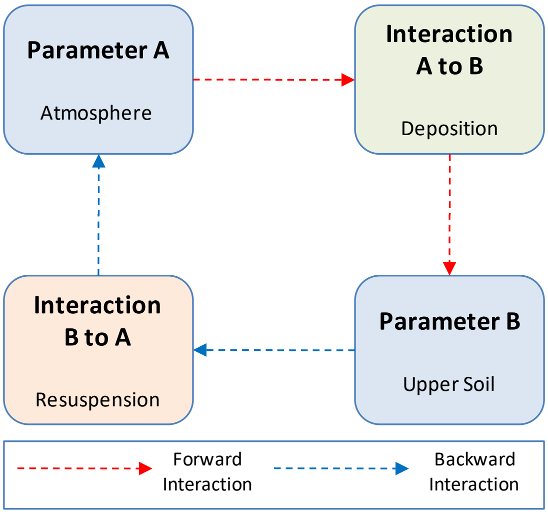


Figure 4.21 A simple 2x2 Interaction Matrix, showing the interaction between features, events and processes in a safety assessment.

It is thus clear that the different elements of the system can be included in the Interaction Matrix and analysed in detail by creating one or more sub-matrices. This approach suggests that the elements on the main diagonal can be represented by a specific theme, such as the migration pathway of radionuclides from the sources to receptors. The off-diagonal elements represent the interaction of events and processes that cause or influence the migration of the radionuclides from one diagonal element (system feature) to another along the identified pathway. Those above the diagonal represent the influence on forwarding motion, while those below influence the backward moment. This is illustrated in Figure 4.22, 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 4.23 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.

4.7 Public Exposure Conditions for the Port Dunford Mine

4.7.1 General

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

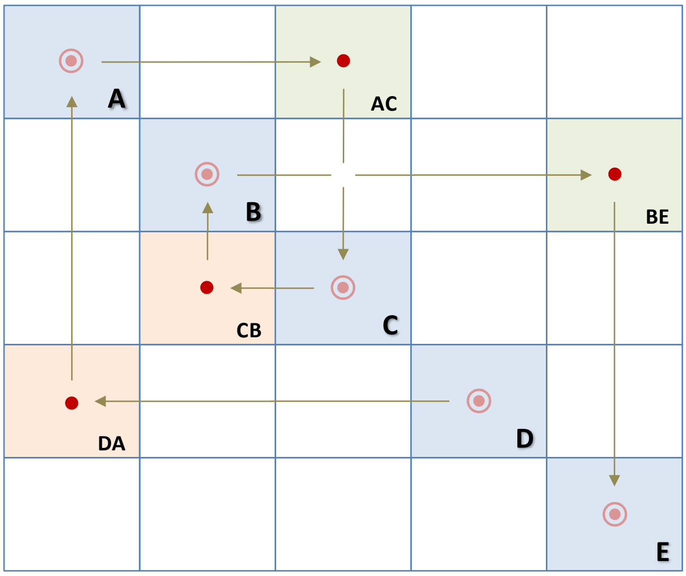


Figure 4.22 Principle of a radionuclide migration path through the Interaction Matrix.

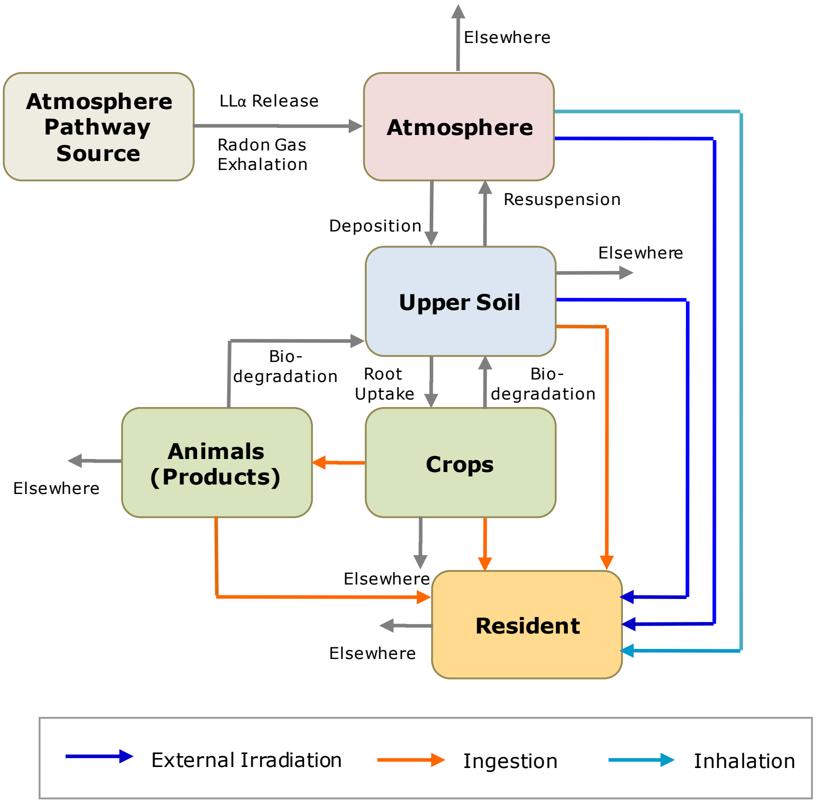


Figure 4.23 A flow diagram is an example of a conceptual model for a specific exposure condition, showing the exposure pathways and the relationship between the different compartments of the system.

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

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

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

The receptors identified in Section 3.4 around the Port Dunford Mine area mainly consist of formal and informal residential areas and forestry areas, with limited other agricultural activities. Given the proximity to the surface infrastructure and available social and land use data, these population groups could cause them to receive a higher radiological dose than the rest of the exposed population. These groups are assumed to consist of members of the public of all ages.

4.7.2 Criteria Used to Define the Discrete Set of Exposure Conditions

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

- Different exposure conditions may be of importance during different phases of the mining and mineral processing operation;
- Exposure conditions may vary depending on variations in the operational conditions on a site-specific basis;
- Different sources of radiation exposure (e.g., a point or diffuse sources) may result in different exposure conditions to receptors;
- The importance of environmental (e.g., atmospheric, surface water or groundwater) or direct exposure pathways depends on the characteristics of sources and human behavioural characteristics; or
- Variations in human behavioural conditions near the mining and mineral processing operation may result in different exposure conditions of concern.

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

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

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

Where justified, a set of alternative and more hypothetical exposure conditions are defined. These hypothetical conditions tend to be more conservative and have the benefit that a wide range of conditions can be postulated. Often these exposure conditions would be representative of the most exposed individual, albeit hypothetical. The key point of judgment on whether the discrete set of exposure conditions is representative of the radiological public safety and impact assessment is whether potential receptors of radiation exposure can relate to at least one of these exposure conditions.

4.7.3 Definition and Justification of Public Exposure Conditions for the Port Dunford Mine Area

Based on the criteria above and with due consideration of the sources, pathways and receptors defined for the Port Dunford Mine, the following two public exposure conditions can be defined to evaluate the potential radiological impact on members of the public under normal operating conditions:

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

Additional exposure conditions relevant to the area can be identified. The critical factor in determining whether the defined set of exposure conditions adequately represents the radiological public safety and impact assessment is ensuring that all potential receptors of radiation exposure can identify with at least one of these conditions. Moreover, it must be verified that their potential radiation exposure is equal to or lower than the levels defined for the identified exposure conditions.

For instance, the potential radiation exposure to nearby Mondi forestry workers is expected to be lower than that of residents in nearby residential areas. Likewise, small-scale agricultural farmers on smallholdings would experience radiation exposure levels lower than those defined under the conservatively estimated Agricultural Area Exposure Condition. Sugar cane farming, on the other hand, represents a single ingested commodity that would result in lower radiation exposure compared to several fruits and vegetables included in the Agricultural Area Exposure Condition. Finally, forestry activities would require assessing radionuclide transfer to trees and their potential use for firewood, construction, or furniture manufacturing in the future. Annual radiation exposure from inhalation or external exposure related to forestry is thus expected to be lower than the direct ingestion of fruits and vegetables grown on the land and consumed exclusively as a food source, as outlined in the Agricultural Area Exposure Condition.

4.7.4 Residential Area Exposure Condition

The purpose of the Residential Area Exposure Condition is to evaluate the radiological consequences to members of the public residing in formal and less formal structures (houses) in the affected residential areas near the Port Dunford Mine. This includes areas such as Mtunzini, Port Dunford, Esikhawini, Gobandlovu; and KwaDlangezwa but is equally relevant to any of the nearby urban and residential areas for the conditions and assumptions presented below.

Residents from these areas can be divided further into those living in formal structures and those living in informal structures. However, it follows from Section 3.4.7 that in terms of potential radiological exposure, their behavioural characteristics are not too different, especially in terms of what they eat. The main differences lie in their socio-economic structures. These differences (e.g., occupancy factors, time spent indoors and outdoors, shielding factors) could be catered for using sensitivity analysis (parameter variation).

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. The aquatic pathways (surface water and groundwater) are excluded for the following reasons:

- Members of the public living in the residential areas receive municipal water as their only source of water. They are not dependent on surface water or groundwater as their source of water for household purposes. However, how much of the municipal water is supplemented with especially surface water, is unknown and uncertain (if any).
- Therefore, the contribution of the aquatic pathways will be evaluated more realistically as a cautious assumption as part of sensitivity and uncertainty analysis, and not as part of a predefined exposure condition.

In addition to the conditions and assumptions presented above, the following are assumed for the Residential Area Exposure Condition:

- The exposure groups consist of members of the public from all age groups.
- The exposure group maintain a small household garden consisting of fruits and vegetables (leafy and root), which fulfil 50% of their annual fruit and vegetable consumption rates.
- The exposure group keep some free-roaming chickens as a source of protein in the form of meat and eggs. A consumption rate equal to 50% of the annual consumption rate is assumed.
- As a conservative assumption, the rate of incidental soil ingestion is maintained at 100% of the value published in RG-002 (NNR, 2013).
- Some food preparation methods are used (e.g., peeling or boiling) that may contribute to a reduction in radioactivity concentrations in fruits, vegetables, or reared poultry. However, for this assessment, it is assumed that no food preparation takes place.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.3 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.
- The exposure condition assumes a TSP deposition period of 100 years, which is conservative given the history of the mining activities in the area.

The conceptual model for the Residential Area Exposure Condition is presented in Figure 4.24 and Figure 4.25 using a flow diagram and Interaction Matrices, respectively.

Table 4.3 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

Figure 4.24 shows that airborne radioactivity in the form of radon gas and particle-associated, LLα are released from the atmospheric pathway sources and are dispersed into the environment. The released radionuclides firstly contribute to an increased concentration of radioactivity in the air, from where the LLα containing dust may deposit onto the upper soil surface or directly onto any fruit or vegetables that may be grown in the back gardens of residential plots. Root uptake processes may transfer some of the radionuclides deposited on the soil surface to the fruits and vegetables. The chickens kept by the residents may consume contaminated crops and soil, which leads to the contamination of animal products such as meat and eggs.

As illustrated in Figure 4.24 and Figure 4.25, backwards interactions such as the biodegradation of contaminated plant material may contribute to the accumulation of radionuclides in the upper soil layer.

Exposure routes for the Residential Area Exposure Condition include radon gas and LLα inhalation, as well as ingestion of contaminated crops (fruits and vegetables).

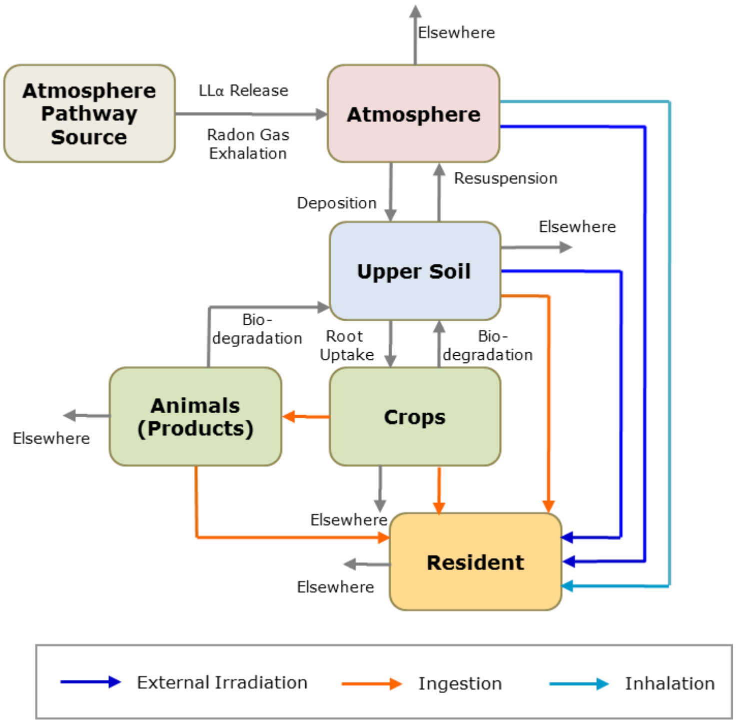


Figure 4.24 Conceptual flow diagram of the exposure pathways associated with the Residential Area Exposure Condition.

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

Figure 4.25 Conceptual Interaction Matrix of the atmospheric exposure pathways Residential Area Exposure Condition.

Inadvertent soil ingestion is also assumed to occur. 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 4.24 and Figure 4.25, biodegradation of crop material may also contribute to the radionuclide contamination of the upper soil, while resuspension of deposited dust may contribute to the airborne activity concentration. Also illustrated in Figure 4.24 and Figure 4.25, is the transfer of some of the radioactivity released from the atmospheric pathway sources, to "elsewhere" through processes such as dispersion, leaching, washing, weathering and excrement. "Elsewhere" as used here refers to a place where humans will not be affected by the radionuclides of concern.

4.7.5 Agricultural Area Exposure Condition

The purpose of the Agricultural Area Exposure Condition is to evaluate the radiological consequences to members of the public practising farming near the Port Dunford Mine. However, the exposure condition is equally relevant to any other agricultural activities practices anywhere near the Port Dunford Mine (e.g., subsistence or small-scale farming on smallholdings). 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 Agricultural Area Exposure Condition:

- The exposure groups consist of members of the public from all age groups.
- The exposure group maintain a farm system consisting of fruits and vegetables (leafy and root), which fulfil 100% of their annual fruit and vegetable consumption rates.
- As a conservative assumption, the rate of incidental soil ingestion is maintained at 100% of the values presented in RG-002 (NNR, 2013).
- Some food preparation methods are used (e.g., peeling or boiling) that may contribute to a reduction in radioactivity concentrations in fruits, vegetables, or reared poultry. However, for this assessment, it is assumed that no food preparation takes place.
- The indoor and outdoor occupancy factors assumed for the assessment are those presented in RG-002 (NNR, 2013), which for adult members of the public are 7,050 and 1,710 hours per annum, respectively.
- Consistent with RG-002 guidelines (NNR, 2013), Table 4.3 lists the age group-specific indoor and outdoor occupancy factors assumed for the assessment.
- The exposure condition assumes a TSP deposition period of 100 years, which is conservative given the history of the mining activities in the area.

The conceptual model for the Agricultural Area Exposure Condition is presented in Figure 4.26 and Figure 4.27 using a flow diagram and Interaction Matrix, respectively.

Exposures associated with the atmospheric pathway are similar to those discussed for the Residential Area Exposure Condition. Some of the airborne radionuclides are deposited onto the upper soil surface, contributing to the radionuclide concentration of the soil. Root uptake processes transfer some of the radionuclides from the soil to crops in the field or household garden as well as grass consumed by cattle.

The concentration of radionuclides in the upper soil will steadily increase over time as more and more dust-containing radionuclides are deposited from the air. Note that, as illustrated in Figure 4.26 and Figure 4.27, biodegradation of plant material (such as crops or animal fodder or grazing) may also contribute to the concentration of radionuclides in the upper soil, while re-suspension of deposited dust may contribute to the airborne activity concentration. Physical processes such as the mixing of the soil through tilling will lead to the redistribution of the radioactive elements and the re-suspension of deposited dust, which may contribute to the airborne activity concentration.

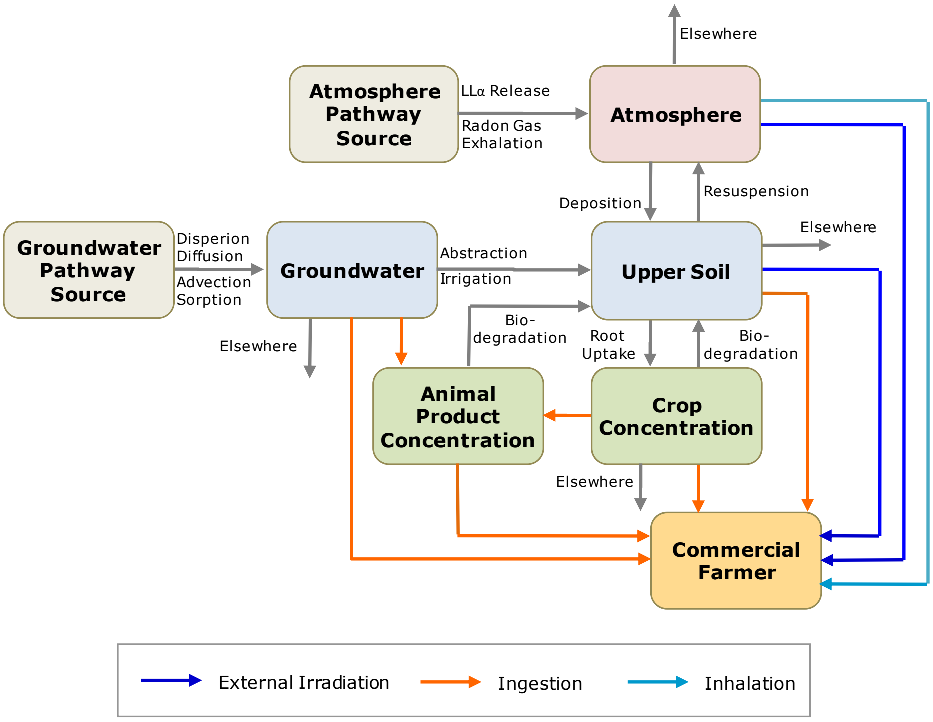


Figure 4.26 Conceptual flow diagram of the exposure pathways associated with the Agricultural Area Exposure Condition.

Humans, in this case, represented by the yellow block labelled 'Commercial Farmer' in Figure 4.27, may be exposed to the radioactivity distributed through the atmospheric and aquatic pathways by inhalation, ingestion and external exposure routes.

Irrigation with contaminated groundwater or surface water contributes to the contamination of the upper soil layers and the distribution of the contamination via the associated secondary pathways (e.g., crops and animal products). Backwards interactions redistribute the radioactivity, initially introduced through the water pathways, within the upper soil as well as to the atmospheric pathway. The distribution and redistribution of the contaminants originating from the atmospheric and water pathways as well as the exposure associated with the Agricultural Area Exposure Condition are illustrated in the flow diagram presented in Figure 4.27. Animals that consume the grass consume a portion of dust or soil with the plant materials they take in. The radioactivity in the upper soil can, therefore, also contribute to the radionuclide contamination of animal products. The expected exposures associated with each route include:

- Inhalation of radon gas and dust containing LLα;
- Ingestion of contaminated produce (fruit, leafy and root vegetables) picked from gardens (100% annual consumption rate);
- Inadvertent ingestion of contaminated soil;
- External exposure to radionuclides deposited in the upper soil layer (ground shine);

- External exposure to airborne LLα (cloud shine);
- Ingestion of contaminated water;
- External exposure to contaminated water (bathing); and
- Ingestion of contaminated produce irrigated with contaminated water.

	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 4.27 Conceptual Interaction Matrix of the exposure pathways associated with the Agricultural Area Exposure Condition.

5 Consequence Analysis

5.1 Introduction

The purpose of the consequence analysis is to assess the potential radiological consequences of the public exposure conditions defined for the Port Dunford Mine in Section 4.7. Consistent with the safety assessment framework and technical approaches therein (see Figure 1.4), the assessment results are then interpreted in terms of the total annual effective dose as compliance criteria (boundary conditions) as defined in the *Assessment Context* (see Section 2). The methodological approach used to calculate the total effective dose is described in Appendix B.

The section is structured as follows. Section 5.2 evaluates the potential contribution of the groundwater pathway included in the definition of the Commercial Agricultural Area Exposure Condition. Section 5.3 evaluates the contribution of the atmospheric pathway included in the definition of all three exposure conditions, while Section 0 then evaluates the radiological consequences of all the exposure conditions defined in Section 4.7 in terms of the total effective dose.

5.2 Contribution from Groundwater Pathway

5.2.1 General

The use of groundwater as a source of water for agricultural use cannot be excluded with confidence. In principle, the groundwater abstracted from a borehole may be contaminated following leaching from facilities associated with the Port Dunford Mine. Similarly, the discharge of groundwater into a surface water body may contaminate the water used for irrigation or general consumption. However, because of associated retardation processes, the leaching and subsequent lateral migration of radionuclides are a slow process. This is because the radionuclides migrate at a much slower rate than the advective flow due to isotope-specific adsorption properties of the fine tails, coarse sand tails or the orebody materials, as well as the similar properties of the underlying aquifer most medium.

5.2.2 Conceptual Model and Implementation

The hydrogeological flow regime was described in Section 3.4.5 and Section 4.4.3 based on the groundwater impact assessment that was done for the Port Dunford Mine (WSP, 2024d). It follows from Section 4.3.3 that several facilities at the Port Dunford Mine may serve as sources of radiation exposure through the groundwater pathway (e.g., RSFs, stockpiles, return water dams, water control dams and from the open pits areas). The radiological properties of these facilities will differ as well as the release mechanisms of contaminated water to the underlying aquifer (i.e., the source terms release rate to the aquifer). However, once released, the contaminant migration processes are similar (e.g., advection, dispersion, diffusion, etc).

To evaluate the contribution of the groundwater pathway, some assumptions were made to assess the radiological consequences, albeit for illustrative purposes. Presented here is a simplified one-dimensional numerical groundwater model using a compartmental modelling approach to represent the migration and fate of contaminants in the environment with an RSF as the source of contamination. As Class 3 waste facilities, the RSFs at the Port Dunford Mine will require lining but will remain a potential source of contamination during the operational and post-closure periods. The conceptual representation of the *System Level* compartmental model implemented in AFRY Intelligent Scenario Modelling (Version 8.5) (https://www.intelligentscenariomodelling.com/) is presented in Appendix D.

The groundwater pathway consists of several compartments that need to be considered in an integrated manner to evaluate the potential contribution to a total effective dose. Figure 5.1 is a simplified schematic diagram of the RSF C facility relative to system components that depict the relevant compartments and the interaction between them. Figure 5.2 presents the AFRY Intelligent Scenario Modelling implementation of Figure 5.1, which can be used to evaluate the contribution of the groundwater pathway.

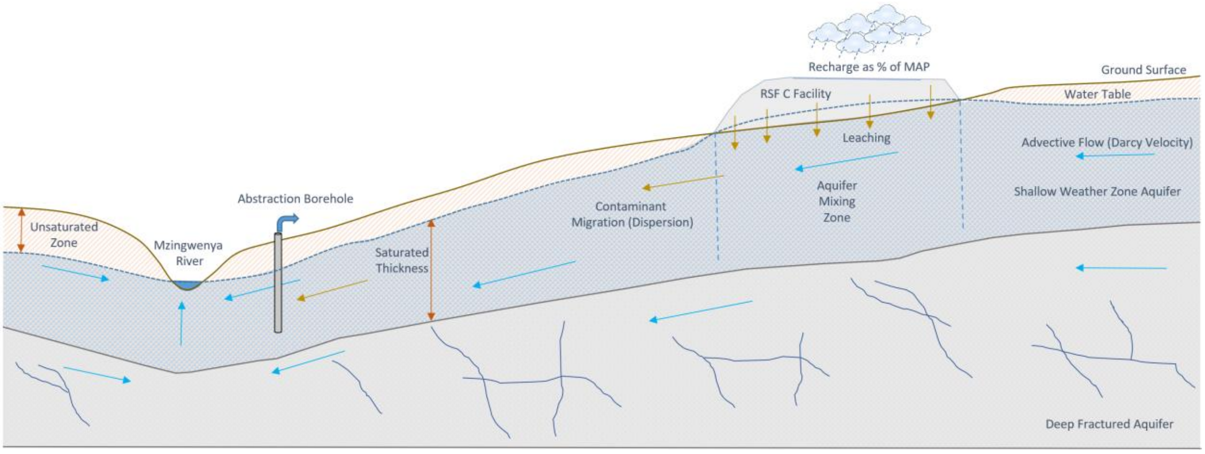


Figure 5.1 Conceptual representation of the model compartment included in the System Level modelling of the groundwater pathway (Not to Scale).

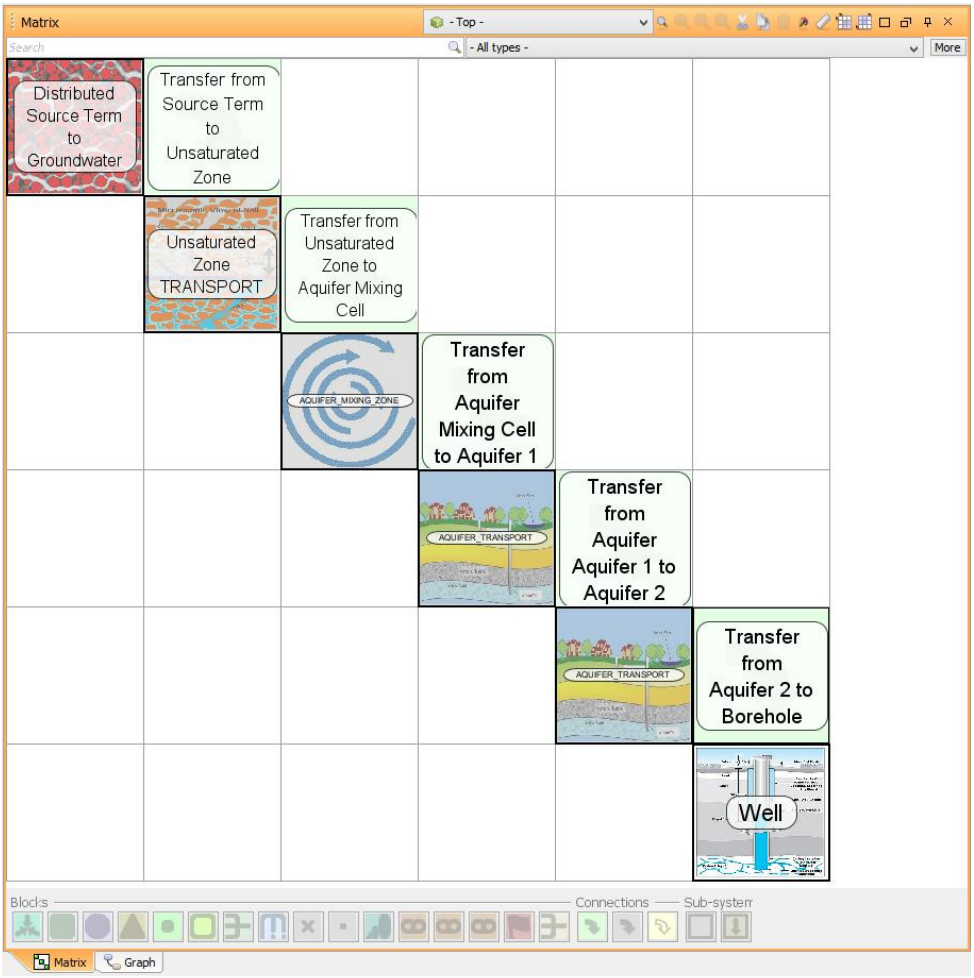


Figure 5.2 The model implementation in AFRY Intelligent Scenario Modelling used to evaluate the contribution of the groundwater pathway for the Port Dunford Mine.

5.2.3 Parameter Values

To evaluate the potential radionuclides concentration in groundwater and the subsequent ingestion dose, hypothetical conditions complemented with site-specific conditions were used to illustrate the relative insignificance of the groundwater pathway over a brief period (e.g., operational period). The activity concentration of the RSF material is made up of the PWP Slimes, MSP Slimes and MSP Gypsum samples as listed in Table 3.10. The average of the two samples is listed in Table 5.1. The activity concentration of radionuclides in the decay chains not presented in Table 3.10 was estimated assuming secular equilibrium[2] between parent radionuclides and their progeny. The following assumptions were consequently applied to the radioanalytical data available for the Port Dunford Mine:

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

Table 5.1 The activity concentrations for the RSF material of the Port Dunford Mine (values in red were assumed to be in secular equilibrium with the parent radionuclide).

Radionuclide	Average of MSP and PWP Slimes Activity Concentration ($Bq.kg^{-1}$)
U-238	204.7
U-234	209.9
Th-230	209.9
Ra-226	143.7
Pb-210	236.0
Po-210	236.0
U-235	9.6
Pa-231	9.6
Ac-227	9.6
Th-232	366.7
Ra-228	393.7

Table 5.2 summarises a few additional parameter values assumed for the leaching analysis. Note that these parameter values are selected to be conservative.

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

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

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[2] *Secular equilibrium is a steady state condition of equal activities between a long-lived parent radionuclide and its short-lived daughter, which is applied to estimate nuclide concentrations in the absence of radioanalytical data. The criterion upon which secular equilibrium depends is given in L'Annunziata (1998).*

Table 5.2 Summary of facility-specific parameter values necessary to calculate the leaching of radionuclides from the Port Dunford Mine TSF.

Parameter		Units	Port Dunford Mine TSF
Mean Annual Precipitation (MAP)		[mm]	1,224
Recharge (Infiltration) Rate Through TSF as % of MAP	< 50 years	[m.y^{-1}]	1.84E-01 (15% of MAP)
	50 to 75 years		1.22E-01 (10% of MAP)
	75 to 100 years		6.12E-02 (5% of MAP)
	> 100 years		3.67E-02 (3% of MAP)
Volumetric Moisture Content		[m^3.m^{-3}]	3.0E-01
The density of RSF Material		[kg.m^{-3}]	1.400E+03
Average Height		[m]	50
Average Area		[m^2]	4.360E+06
Assumed Length and Width (√Area)		[m]	2.088E+03
Volume		[m^3]	2.180E+08

The approach adopted for the analysis presented here is to use a conservative range of K_d values from the literature for illustrative purposes. Table 5.3 lists soil distribution coefficients for selected radionuclides published in RG-002 (NNR, 2013), as well as the range of values from the literature for different soil types as published by the Argonne National Laboratory (Yu *et al.*, 1993). The comparison shows that the values of the distribution coefficients found in the literature can vary significantly.

Table 5.3 Distribution coefficients from literature for the elements of concern, as well as the K_d values in the analysis for illustrative purposes (NNR, 2013; Yu *et al.*, 1993).

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

Table 5.4 lists additional aquifer parameters needed for the calculations. The unsaturated zone underneath the RSF is conservatively assumed to be only 1 m thick, with a dry bulk density of 1,400 kg.m^{-3} and a volumetric moisture content of 0.3 m^3.m^{-3}. A thicker unsaturated zone will retard the migration of radionuclides to the point of abstraction even further. Assuming an effective porosity of 0.02 (2%), an average hydraulic conductivity in the order of 10 m.day^{-1} and a hydraulic gradient of 0.01, the actual groundwater flow velocity is 5 m.day^{-1}. Using these values, the advective potential plume migration rate would be in the order of 1.83E+03 m.year^{-1} for the area as listed in Table 5.2.

5.2.4 Results

Figure 5.3 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 200,000 years (the Th-232 decay chain only becomes visible after 1,000,000 years). If one assumes the RG-002 (NNR, 2013) water ingestion rates for the different age groups, then the groundwater activity concentrations in Figure 5.3 translate to water ingestion doses shown in Figure 5.4. It illustrates that for the assumed conditions, the potential contribution from the groundwater pathway at a borehole located 500 m from the RSF is only visible in tens of thousands of years, and potentially at doses between 200 and 250 µSv.year^{-1}.

Table 5.4 Aquifer parameters assumed for the TSFs and areas of concern to calculate the advective flow and migration of radionuclides.

Parameter	Units	Value
Depth to Water Table	m	1
Aquifer Thickness		20
Hydraulic Conductivity	m.day^{-1}	10
Effective Porosity	-	0.02
Hydraulic Gradient		0.01
Darcy Velocity	m.day^{-1}	1.00E-01
Actual Velocity		5.00E+00
Longitudinal dispersivity (α_L)	m	50
Dry Bulk Density	kg.m^{-3}	1,800
Distance to Borehole	m	500
Borehole Fraction in Contaminant Plume	-	1

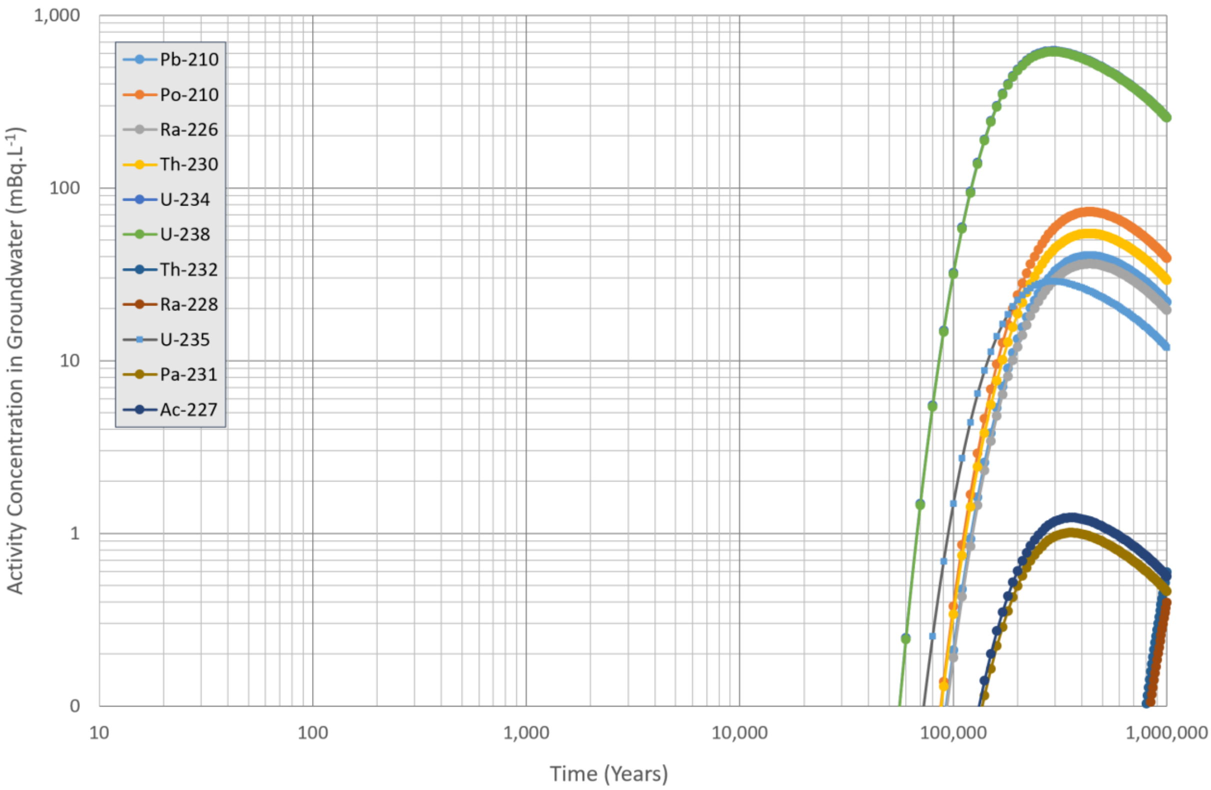

Figure 5.3 The simulated activity concentration in groundwater abstracted from a borehole 500 m from the RSF C.

It is thus clear that the contribution of the groundwater pathway to a total effective dose is only possible in the far future. The contribution of the atmospheric pathway is from the day of commissioning. Therefore, care must be taken to combine the contribution of the two pathways to calculate the total effective dose.

5.2.5 Discussion of Results

The consequence analysis results for the groundwater pathway using the RSF C as the source were to illustrate the potential contribution of the groundwater pathway. For this purpose, conservative assumptions were used (e.g., no solubility limits, no liner, with little sorption).

The results confirmed that the contribution of the groundwater pathway is expected in the distant future. Although site-specific conditions may influence the results, this will in all likelihood be similar got all potential sources. The disposal of the MSP Gypsum with the fines does not pose a significant impact. The average between the three waste streams was used. Using the actual volume ratio between the fines and Gypsum will reduce the peak doses. Even more so if the Gypsum is disposed of in the mine void areas.

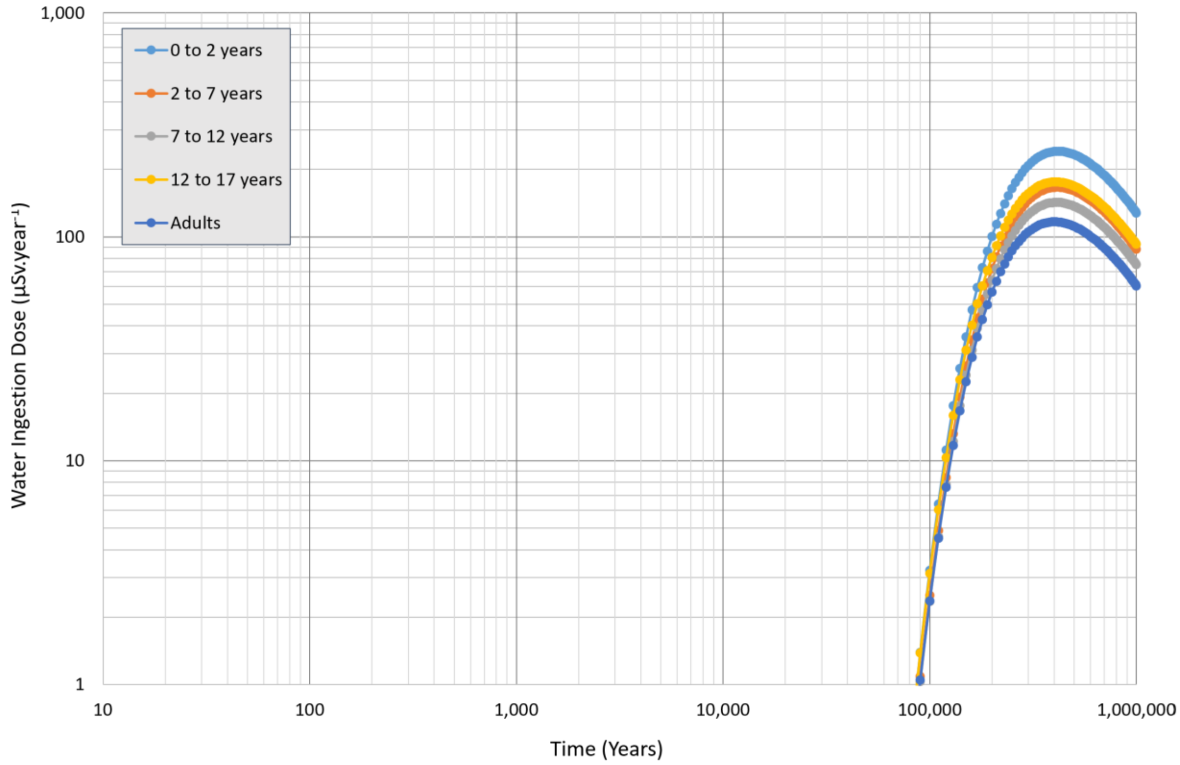

Figure 5.4 The simulated water ingestion dose to the different age groups 500 m from the Port Dunford Mine RSF C, using the activity concentrations in Figure 5.3.

5.3 Dose Contribution from the Atmospheric Pathway

5.3.1 General

The purpose of this section is to present the potential contribution of the atmospheric pathway to a total effective dose for the Port Dunford Mine. This is a function of the sources of airborne contaminants associated with the atmospheric pathway, as well as the radioactivity concentration in the airborne and deposited dust. The dose contribution presented here is in terms of LLα dust inhalation, radon gas inhalation, as well as the contribution of cloud shine and ground shine (following deposition) to external gamma radiation.

Consistent with the mine schedule and the characterisation of the atmospheric pathway in Section 4.4.2.1, a distinction was made between Phase 1 and the three scenarios of Phase 2. The activity concentration of radionuclides in the decay chains not presented in Section 3.5.3 was estimated assuming secular equilibrium between parent radionuclides and their progeny. The following assumptions were consequently applied to the radioanalytical data available for the Port Dunford Mine:

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

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

5.3.2 Phase 1

5.3.2.1 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2.2 represent the consolidated concentrations from all atmospheric pathway sources of concern for Phase 1. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well.

The Port Dunford Mine orebody that will be mined during Phase 1 is represented by the average of the PWP HMC, the PWP sand tails and the PWP slimes in Table 3.8 (see Table 3.7). Using the average values and the assumptions for equilibrium in Section 5.3.1, the activity concentrations listed in Table 5.5 were used as the activity concentrations for the PM_{10} and TSP for the Phase 1 sources (i.e., the orebody).

5.3.2.2 Radon Inhalation Dose

The radon inhalation dose is based on the airborne radon concentration presented in Section 4.4.2 (see Figure 4.3) and the corrected radon exhalation rate calculated in Section 3.5.4. Figure 5.5 presents the resulting radon inhalation dose using the dose conversion factor listed in Table B 2.

Table 5.5 The nuclide-specific activity concentrations in materials associated with the orebody for Phase 1 of the Port Dunford Mine (values in red were assumed to be in secular equilibrium with the parent radionuclide).

Radionuclide	Activity Concentration (Bq.kg^{-1})
U-238	225.9
U-234	227.7
Th-230	227.7
Ra-226	182.3
Pb-210	258.0
Po-210	258.0
U-235	10.4
Pa-231	10.4
Ac-227	10.4
Th-232	204.8
Ra-228	241.8

Figure 5.5 shows that the radon inhalation dose is most significantly close to the facilities associated with Phase 1 and decreases with distance away from the facilities due to dispersion. The maximum radon inhalation dose outside the Port Dunford Mine boundary is trivial, with a maximum radon inhalation dose of less than 20 µSv.year^{-1}.

5.3.2.3 LLα Inhalation Dose

Figure 4.1 presents the annual average PM_{10} concentration. Multiplication of these dust concentrations with the relevant activity concentrations in Table 5.5 and the dose conversion factors will result in the dust inhalation dose to members of the public. As expected, the inhalation dose distribution is consistent with the PM_{10} distribution in Figure 4.1. However, the maximum calculated dust inhalation dose for Phase 1 is trivial and less than 4 μSv.year^{-1}.

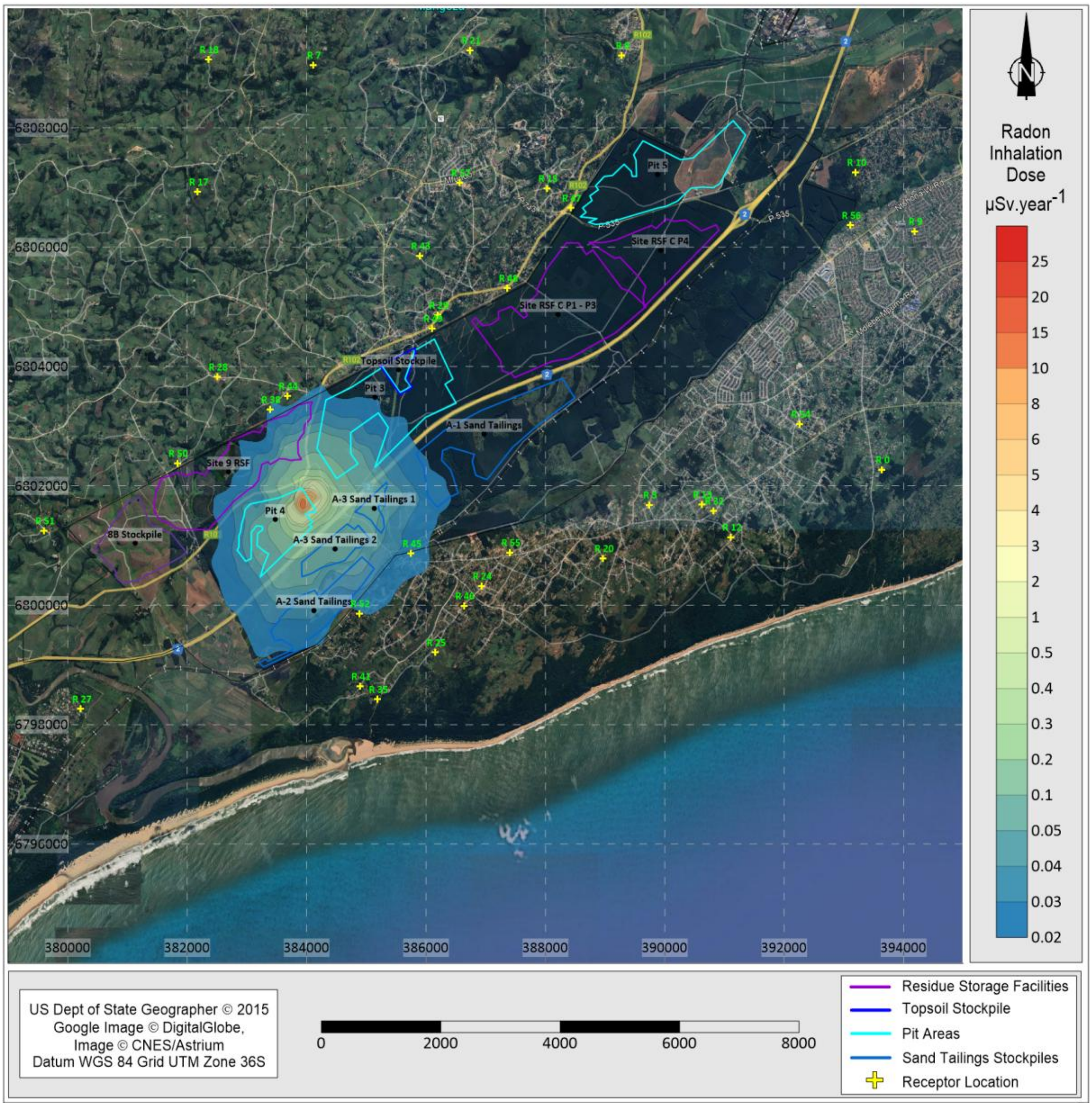

Figure 5.5 The distribution of the radon inhalation dose induced by the facilities associated with Phase 1 of the Port Dunford Mine, based on the airborne radon concentration presented in Figure 4.3.

5.3.2.4 External Gamma Radiation

The potential contribution from external gamma radiation (cloud shine) to the total effective dose is induced by the PM_{10} cloud of dust. These values are insignificantly small (less than 1 μSv.year^{-1}) where PM_{10} concentrations typical of mining and mineral processing activities are observed. For Phase 1 the Port Dunford Mine, the contribution of cloud shine to the total effective dose is zero (less than 4E-6 μSv.year^{-1}). Similarly, the deposition of TSP in the environment and the subsequent build-up of radionuclides may also contribute to external gamma radiation (ground shine). These values are a function of the deposition period, but typically also tend to be low where deposition rates and deposition periods (i.e., assumed to be 75 years) are typical of most mining and mineral processing activities. As expected, the external gamma radiation distribution is consistent with the TSP distribution in Figure 4.2. However, the maximum calculated dust inhalation dose for Phase 1 is trivial and less than 3 µSv.year^{-1}.

5.3.2.5 Dose Due to Deposition

The atmospheric pathway may also contribute to the total effective dose following deposition and subsequent build-up of radioactivity on the surface soil. This results in the transfer of radioactivity to plants and animal products, which introduces secondary pathways. The contribution of deposition to the total effective dose is, therefore, a function of the deposition period and the exposure conditions defined for the assessment. The contribution of deposition to the total effective dose is discussed in Section 5.4.

5.3.3 Phase 2: Scenario 1

5.3.3.1 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2.3 represent the consolidated concentrations from all atmospheric pathway sources of concern for Phase 2 Scenario 1. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well.

The atmospheric pathway sources for Scenario 1 include the Topsoil Stockpile, Site 9 RSF, the Sand Tailings Stockpiles (A1 to A3) and Site RSF C (Pit 1 to Pit 3). These facilities have different radiological properties. Using the radiological data in Table 3.8, the following assumptions were made to derive the activity concentrations listed in Table 5.6 for the PM_{10} and TSP in Scenario 1:

- The Topsoil Stockpile is represented by the PWP Sand Tails sample in Table 3.8 (see Table 3.11);
- Site 9 RSF is represented by the represented by the average of the MSP Slimes, PWP Slimes and the MSP Gypsum samples in Table 3.8 (see Table 3.10);
- The Sand Tailings Stockpiles (A1 to A3) are represented by the average of the PWP Sand Tails, the MSP Sand Tails and the MSP Gypsum samples in Table 3.8 (see Table 3.9); and
- The Site RSF C (Pit 1 to Pit3) is represented by the average of the PWP Slimes, PWP Sand Tails and the PWP Heavy Mineral Concentrate samples in Table 3.8 (see Table 3.7).

Table 5.6 The activity concentrations for Phase 2 Scenario 1 of the Port Dunford Mine (values in red were assumed to be in secular equilibrium with the parent radionuclide).

Radionuclide	Topsoil Stockpile	Site 9 RSF	A-1 Sand Tailings	A-2 Sand Tailings	A-3 Sand Tailings	Site RSF C P1 - P3
	Activity Concentration (Bq.kg^{-1})					
U-238	15.4	204.7	160.8	160.8	160.8	225.9
U-234	15.6	209.9	165.5	165.5	165.5	227.7
Th-230	15.6	209.9	165.5	165.5	165.5	227.7
Ra-226	19.0	143.7	101.3	101.3	101.3	182.3
Pb-210	19.0	236.0	194.7	194.7	194.7	258.0
Po-210	19.0	236.0	194.7	194.7	194.7	258.0
U-235	0.7	9.6	7.6	7.6	7.6	10.4
Pa-231	0.7	9.6	7.6	7.6	7.6	10.4
Ac-227	0.7	9.6	7.6	7.6	7.6	10.4
Th-232	13.3	366.7	230.0	230.0	230.0	204.8
Ra-228	13.3	315.0	218.0	218.0	218.0	241.8

5.3.3.2 Radon Inhalation Dose

The radon inhalation dose is based on the airborne radon concentration presented in Section 4.4.2 (see Figure 4.3) and the corrected radon exhalation rate calculated in Section 3.5.4. Figure 5.6 presents the resulting radon inhalation dose using the dose conversion factor listed in Table B 2. Figure 5.6 shows that the radon inhalation dose is most significantly close to the facilities associated with Scenario 1 of the Port Dunford Mine and decreases with distance away from the facilities due to dispersion. The maximum radon inhalation dose outside the Port Dunford Mine boundary is trivial, with a maximum radon inhalation dose of less than 40 µSv.year^{-1}.

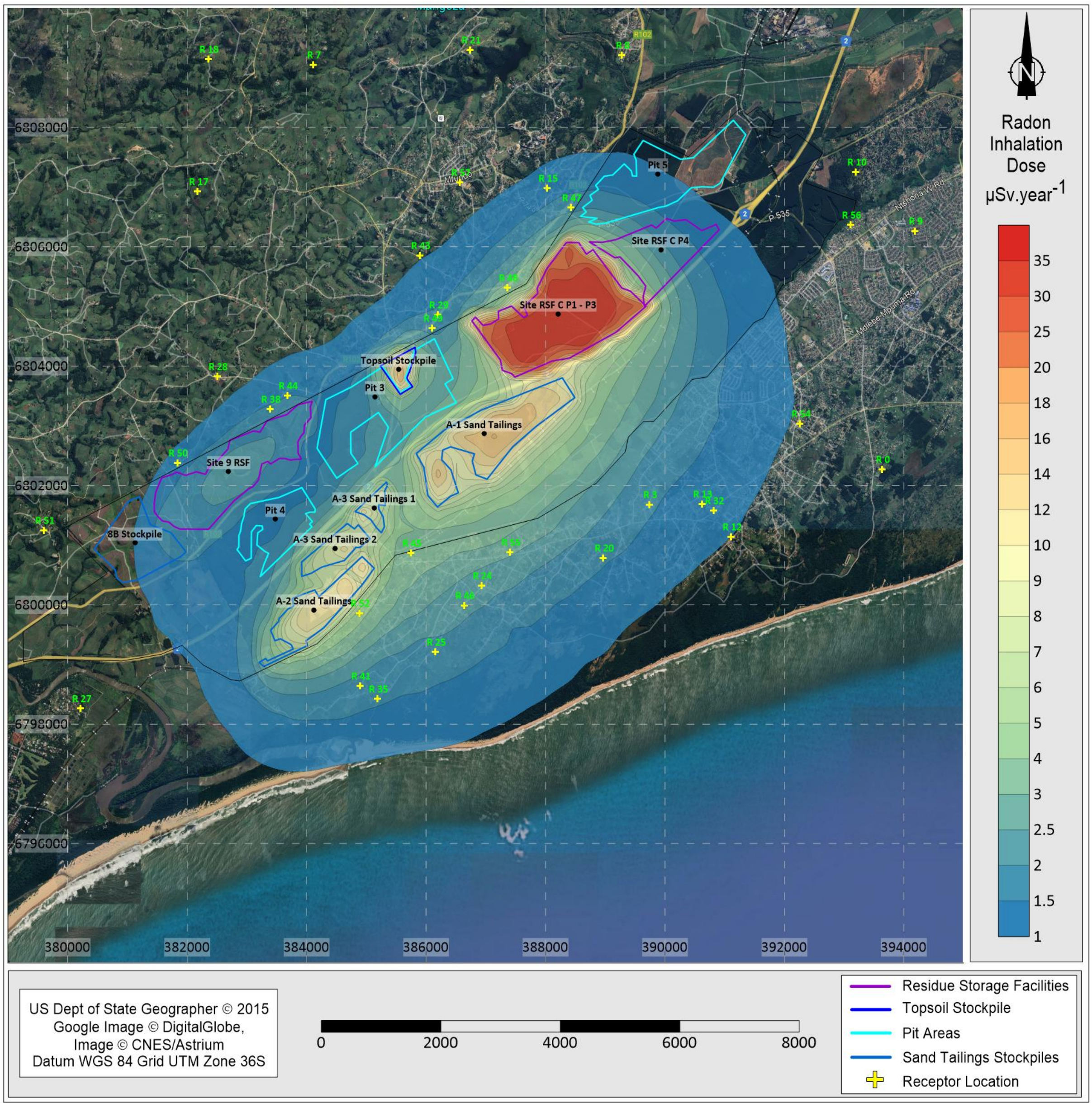

Figure 5.6 The distribution of the radon inhalation dose induced by the facilities associated with Phase 2 Scenario 1 of the Port Dunford Mine, based on the airborne radon concentration presented in Figure 4.3.

5.3.3.3 LLα Inhalation Dose

Figure 4.1 presents the annual average PM_{10} concentration. Multiplication of these dust concentrations with the relevant activity concentrations in Table 5.5 and the dose conversion factors will result in the dust inhalation dose to members of the public. As expected, the inhalation dose distribution is consistent with the PM_{10} distribution in Figure 4.1. The maximum calculated dust inhalation dose for Scenario 1 of the Port Dunford Mine is low and less than 25 µSv.year^{-1}.

5.3.3.4 External Gamma Radiation

The potential contribution from external gamma radiation (cloud shine) to the total effective dose is induced by the PM_{10} cloud of dust. These values are insignificantly small (less than 1 µSv.year^{-1}) where PM_{10} concentrations typical of mining and mineral processing activities are observed. For Scenario 1 of the Port Dunford Mine, the contribution of cloud shine to the total effective dose is zero (less than 3E-5 µSv.year^{-1}).

Similarly, the deposition of TSP in the environment and the subsequent build-up of radionuclides may also contribute to external gamma radiation (ground shine). These values are a function of the deposition period, but typically also tend to be low where deposition rates and deposition periods (i.e., assumed to be 75 years) are typical of most mining and mineral processing activities. As expected, the external gamma radiation distribution is consistent with the TSP distribution in Figure 4.2. However, the maximum calculated dust inhalation dose for Scenario 1 of the Port Dunford Mine is low and less than 10 µSv.year^{-1}.

5.3.3.5 Dose Due to Deposition

The atmospheric pathway may also contribute to the total effective dose following deposition and subsequent build-up of radioactivity on the surface soil. This results in the transfer of radioactivity to plants and animal products, which introduces secondary pathways. The contribution of deposition to the total effective dose is, therefore, a function of the deposition period and the exposure conditions defined for the assessment. The contribution of deposition to the total effective dose is discussed in Section 5.4.

5.3.4 Phase 2: Scenario 2

5.3.4.1 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2.4 represent the consolidated concentrations from all atmospheric pathway sources of concern for Phase 2 Scenario 2. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well.

The atmospheric pathway sources for Scenario 2 include the same sources as for Scenario 1, with the addition of Site RSF C (P4) and the 8B Stockpile. These facilities have different radiological properties. However, the Topsoil Stockpile, Site 9 RSF and the Sand Tailings Stockpiles (A1 to A3) have the same activity concentration for Scenario 2 as for Scenario 1 (see Table 5.6). Using the radiological data in Table 3.8, the following assumptions were made to derive the activity concentrations for Site RSF C (Pit 1 to Pit3), Site RSF C (P4) and 8B Stockpile listed in Table 5.7 for the PM_{10} and TSP in Scenario 2:

- The Site RSF C (Pit 1 to Pit3) is not a mined-out area anymore and is now represented by the average of the MSP Slimes, PWP Slimes and the MSP Gypsum samples in Table 3.8 (see Table 3.10);
- Site RSF C (P4) is represented by the average of the PWP Slimes, PWP Sand Tails and the PWP Heavy Mineral Concentrate samples in Table 3.8 (see Table 3.7); and
- The 8B Stockpile is represented by the average of the PWP Sand Tails, the MSP Sand Tails and the MSP Gypsum samples in Table 3.8 (see Table 3.9).

Table 5.7 The activity concentrations for Phase 2 Scenario 2 of the Port Dunford Mine (values in red were assumed to be in secular equilibrium with the parent radionuclide).

Radionuclide	Site RSF C P1 - P3	Site RSF C (P4)	8B Stockpile
	Activity Concentration (Bq.kg^{-1})		
U-238	204.7	225.9	160.8
U-234	209.9	227.7	165.5
Th-230	209.9	227.7	165.5
Ra-226	143.7	182.3	101.3
Pb-210	236.0	258.0	194.7
Po-210	236.0	258.0	194.7
U-235	9.6	10.4	7.6
Pa-231	9.6	10.4	7.6
Ac-227	9.6	10.4	7.6
Th-232	366.7	204.8	230.0
Ra-228	315.0	241.8	218.0

5.3.4.2 Radon Inhalation Dose

The radon inhalation dose is based on the airborne radon concentration presented in Section 4.4.2 (see Figure 4.3) and the corrected radon exhalation rate calculated in Section 3.5.4. Figure 5.7 presents the resulting radon inhalation dose using the dose conversion factor listed in Table B 2. Figure 5.7 shows that the radon inhalation dose is most significantly close to the facilities associated with Scenario 2 of the Port Dunford Mine and decreases with distance away from the facilities due to dispersion. The maximum radon inhalation dose outside the Port Dunford Mine boundary is trivial, with a maximum radon inhalation dose of less than 40 µSv.year^{-1}.

5.3.4.3 LLα Inhalation Dose

Figure 4.1 presents the annual average PM_{10} concentration. Multiplication of these dust concentrations with the relevant activity concentrations in Table 5.5 and the dose conversion factors will result in the dust inhalation dose to members of the public. As expected, the inhalation dose distribution is consistent with the PM_{10} distribution in Figure 4.1. The maximum calculated dust inhalation dose for Scenario 2 of the Port Dunford Mine is low and less than 23 µSv.year^{-1}.

5.3.4.4 External Gamma Radiation

The potential contribution from external gamma radiation (cloud shine) to the total effective dose is induced by the PM_{10} cloud of dust. These values are insignificantly small (less than 1 µSv.year^{-1}) where PM_{10} concentrations typical of mining and mineral processing activities are observed. For Scenario 2 of the Port Dunford Mine, the contribution of cloud shine to the total effective dose is zero (less than 3E-5 µSv.year^{-1}).

Similarly, the deposition of TSP in the environment and the subsequent build-up of radionuclides may also contribute to external gamma radiation (ground shine). These values are a function of the deposition period, but typically also tend to be low where deposition rates and deposition periods (i.e., assumed to be 75 years) are typical of most mining and mineral processing activities. As expected, the external gamma radiation distribution is consistent with the TSP distribution in Figure 4.2. However, the maximum calculated dust inhalation dose for Scenario 2 of the Port Dunford Mine is low and less than 12 µSv.year^{-1}.

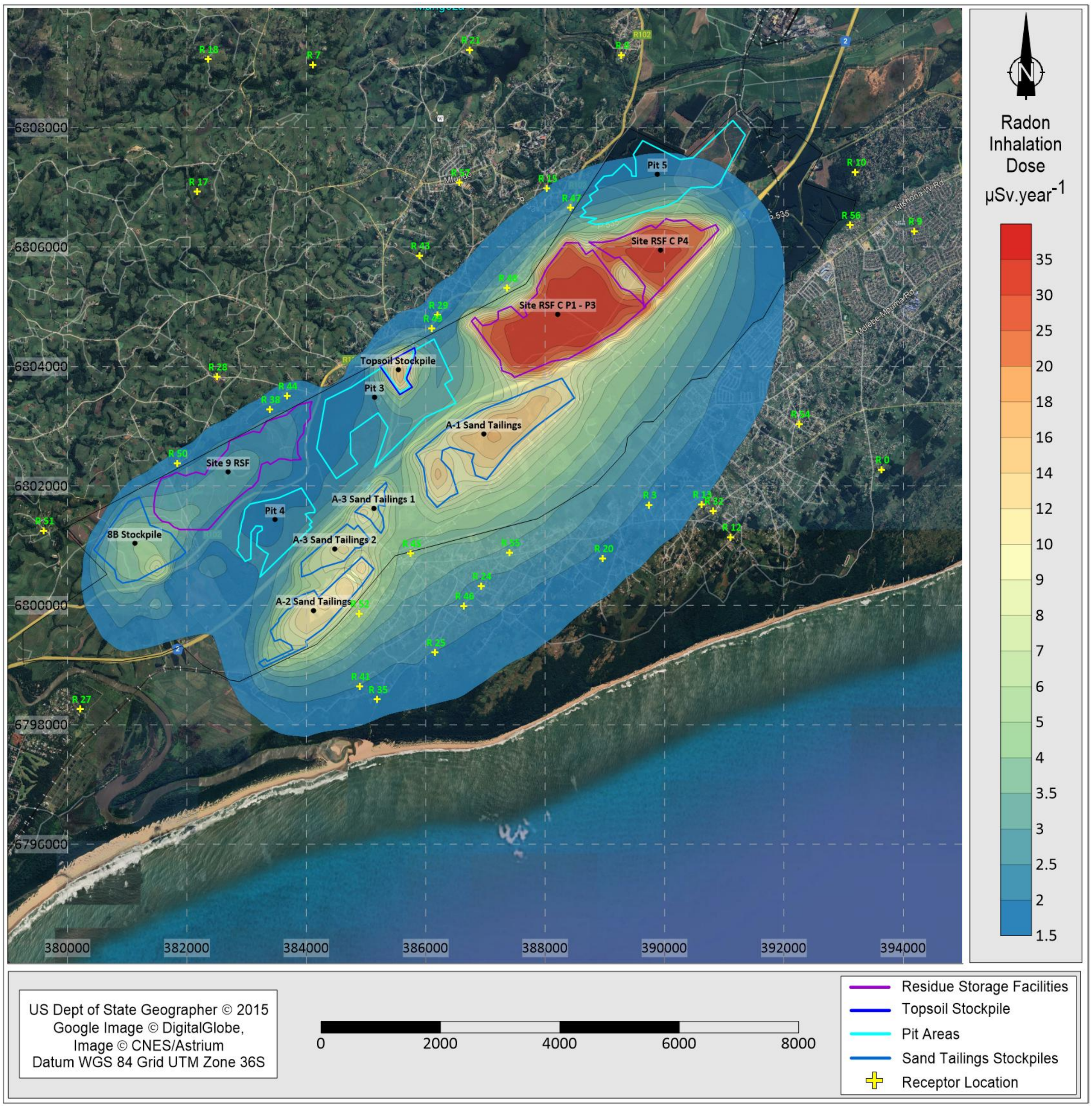

Figure 5.7 The distribution of the radon inhalation dose induced by the facilities associated with Phase 2 Scenario 2 of the Port Dunford Mine, based on the airborne radon concentration presented in Figure 4.3.

5.3.4.5 Dose Due to Deposition

The atmospheric pathway may also contribute to the total effective dose following deposition and subsequent build-up of radioactivity on the surface soil. This results in the transfer of radioactivity to plants and animal products, which introduces secondary pathways. The contribution of deposition to the total effective dose is, therefore, a function of the deposition period and the exposure conditions defined for the assessment. The contribution of deposition to the total effective dose is discussed in Section 5.4.

5.3.5 Phase 2: Scenario 3

5.3.5.1 Radionuclide Concentration in Airborne and Deposited Dust

The airborne dust concentrations (PM_{10} and TSP) presented in Section 4.4.2.4 represent the consolidated concentrations from all atmospheric pathway sources of concern for Phase 2 Scenario 3. These sources have different radiological properties, which means that the radioactivity concentrations of the dust released from each source differ as well.

The atmospheric pathway sources for Scenario 3 include the same facilities as for Scenario 2, with the addition of Pit 3, Pit 4 and Pit 5. These facilities have different radiological properties. Except for RSF C (P4), the activity concentrations for the Scenario 2 facilities remain the same (see Table 5.7). Using the radiological data in Table 3.8, the following assumptions were made to derive the activity concentrations for Site RSF C (P4), as well as Pit 3, Pit 4 and Pit 5 listed in Table 5.8 for the PM_{10} and TSP in Scenario 3:

- Site RSF C (P4) is not a mined-out area anymore and is now represented by the average of the MSP Slimes, PWP Slimes and the MSP Gypsum samples in Table 3.8 (see Table 3.10); and
- Pit 3, Pit 4 and Pit 5 are represented by the average of the PWP Slimes, PWP Sand Tails and the PWP Heavy Mineral Concentrate samples in Table 3.8 (see Table 3.7).

Table 5.8 The activity concentrations for Phase 2 Scenario 3 of the Port Dunford Mine (values in red were assumed to be in secular equilibrium with the parent radionuclide).

Radionuclide	Site RSF C (P4)	Pit 3, Pit 4 and Pit 5
	Activity Concentration (Bq.kg^{-1})	
U-238	138.6	225.9
U-234	139.8	227.7
Th-230	139.8	227.7
Ra-226	129.0	182.3
Pb-210	127.5	258.0
Po-210	127.5	258.0
U-235	6.4	10.4
Pa-231	6.4	10.4
Ac-227	6.4	10.4
Th-232	247.6	204.8
Ra-228	315.0	241.8

5.3.5.2 Radon Inhalation Dose

The radon inhalation dose is based on the airborne radon concentration presented in Section 4.4.2 (see Figure 4.3) and the corrected radon exhalation rate calculated in Section 3.5.4. Figure 5.8 presents the resulting radon inhalation dose using the dose conversion factor listed in Table B 2. Figure 5.8 shows that the radon inhalation dose is most significantly close to the facilities associated with Scenario 3 of the Port Dunford Mine and decreases with distance away from the facilities due to dispersion. The maximum radon inhalation dose outside the Port Dunford Mine boundary is trivial, with a maximum radon inhalation dose of less than 40 µSv.year^{-1}.

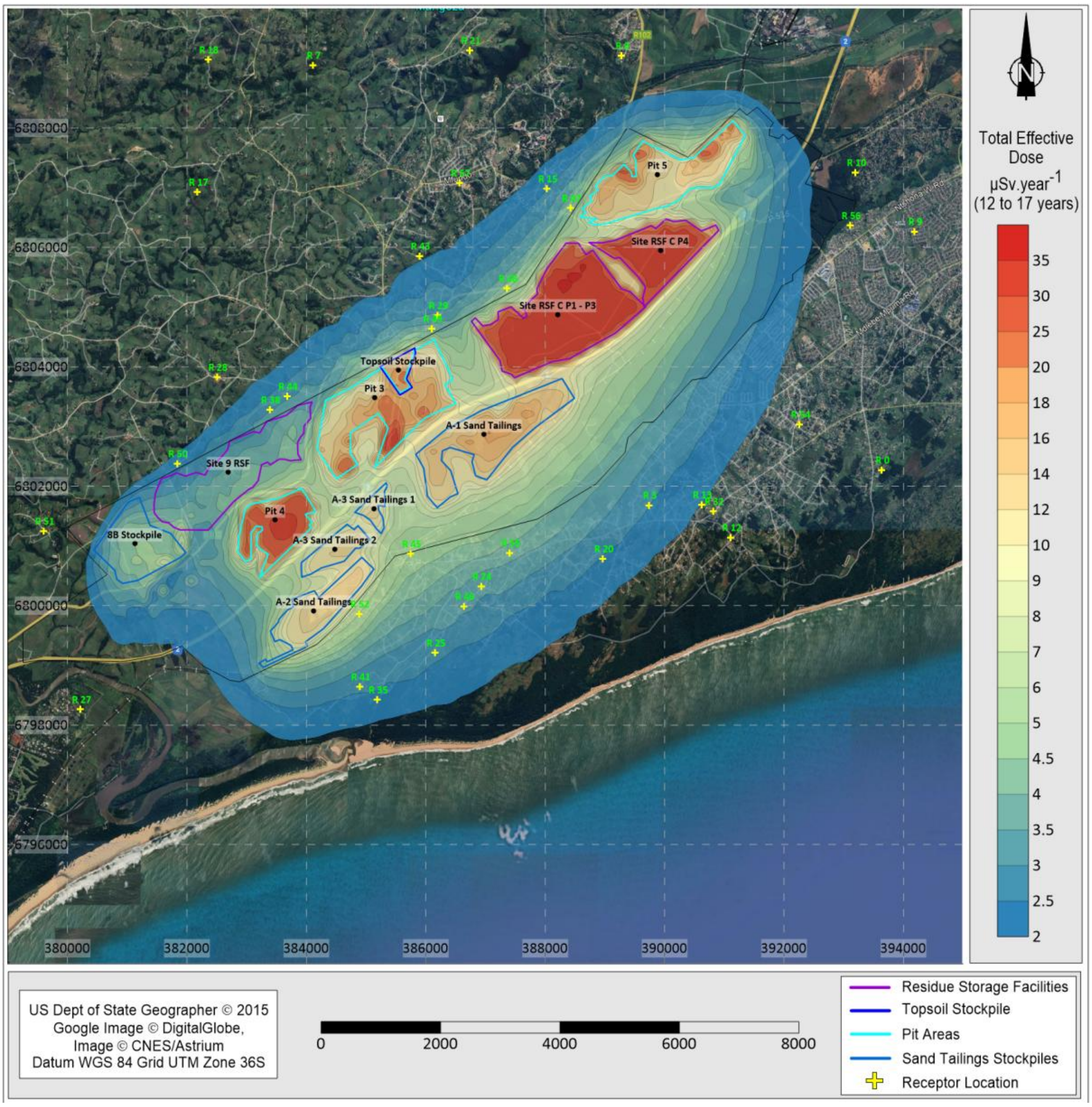

Figure 5.8 The distribution of the radon inhalation dose induced by the facilities associated with Phase 2 Scenario 3 of the Port Dunford Mine, based on the airborne radon concentration presented in Figure 4.3.

5.3.5.3 LLα Inhalation Dose

Figure 4.1 presents the annual average PM_{10} concentration. Multiplication of these dust concentrations with the relevant activity concentrations in Table 5.5 and the dose conversion factors will result in the dust inhalation dose to members of the public. As expected, the inhalation dose distribution is consistent with the PM_{10} distribution in Figure 4.1. The maximum calculated dust inhalation dose for Scenario 3 of the Port Dunford Mine is low and less than 23 μSv.year^{-1}.

5.3.5.4 External Gamma Radiation

The potential contribution from external gamma radiation (cloud shine) to the total effective dose is induced by the PM_{10} cloud of dust. These values are insignificantly small (less than 1 μSv.year^{-1}) where PM_{10} concentrations typical of mining and mineral processing activities are observed. For Scenario 3 of the Port Dunford Mine, the contribution of cloud shine to the total effective dose is zero (less than 2E-5 μSv.year^{-1}).

Similarly, the deposition of TSP in the environment and the subsequent build-up of radionuclides may also contribute to external gamma radiation (ground shine). These values are a function of the deposition period, but typically also tend to be low where deposition rates and deposition periods (i.e., assumed to be 75 years) are typical of most mining and mineral processing activities. As expected, the external gamma radiation distribution is consistent with the TSP distribution in Figure 4.2. However, the maximum calculated dust inhalation dose for Scenario 3 of the Port Dunford Mine is low and less than 10 μSv.year^{-1}.

5.3.5.5 Dose Due to Deposition

The atmospheric pathway may also contribute to the total effective dose following deposition and subsequent build-up of radioactivity on the surface soil. This results in the transfer of radioactivity to plants and animal products, which introduces secondary pathways. The contribution of deposition to the total effective dose is, therefore, a function of the deposition period and the exposure conditions defined for the assessment. The contribution of deposition to the total effective dose is discussed in Section 5.4.

5.4 Total Effective Dose Calculation for Exposure Conditions

5.4.1 General

The purpose of this section is to present the results of the total effective dose calculations for the public exposure conditions defined for the Port Dunford Mine in Section 4.7. Due to the nature of these exposure conditions and the potential contribution of the different environmental pathways to the total effective dose, the focus of the results presented here is the contribution through the atmospheric pathway.

Consistent with the mine schedule and the characterisation of the atmospheric pathway in Section 4.4.2.1, a distinction was made between Phase 1 and the three scenarios of Phase 2. For each phase and scenario, the results for a Residential Area Exposure Condition and an Agricultural Area Exposure Condition are presented.

5.4.2 Residential Area Exposure Condition

The purpose of the Formal Residential Area Exposure Condition is to evaluate the radiological consequences to members of the public residing in formal and informal structures (houses) in the affected residential areas near the Port Dunford Mine. It is assumed that these residents maintain a household garden that contributes to 20% of their annual consumption rate of fruit and vegetables.

The main contributors to a total effective dose for the Formal Residential Area Exposure Condition are the atmospheric and associated secondary pathways. This means that the exposure routes of concern include inhalation, ingestion and external exposure. The expected exposures associated with each route include (see Section 4.7.4):

- Inhalation of radon gas and dust containing LLα;
- Ingestion of contaminated produce (fruit, leafy and root vegetables) harvest from the household garden (20% annual consumption rate);
- Inadvertent ingestion of contaminated soil; and
- External exposure to radionuclides deposited in the upper soil layer (ground shine) and external exposure to airborne LLα (cloud shine).

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

5.4.3 Agricultural Area Exposure Condition

The purpose of the Agricultural Area Exposure Condition is to evaluate the radiological consequences to members of the public practising farming near the Port Dunford Mine. The exposure condition is conservatively defined, which means that this exposure condition relates to any farming activity for the conditions and assumptions included in the definition of the Agricultural Area Exposure Condition (e.g., commercial agricultural, small-scale farming or farming that is performed on a subsistence basis. It is conservatively assumed that the farmer, farm workers and their families are dependent on the land for the annual consumption rate of cereal, fruit and vegetables, as well as animal products that include eggs, milk and meat.

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

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

A dust deposition period of 100 years is assumed to calculate the build-up of radionuclides in the topsoil layer, which is very conservative (see Section 4.7.5). While a contribution of groundwater was realistically included in the definition of the Agricultural Area Exposure Condition, the result presented in Section 5.2 suggests that a possible contribution from the groundwater pathway will only be in thousands of years and, therefore, cannot realistically be added to contributions from the atmospheric pathway.

5.4.4 Phase 1

5.4.4.1 Residential Area Exposure Condition

Figure 5.9 to Figure 5.13 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1 (see Table 4.2 and Figure 5.14 for the receptor locations), which shows that the calculated doses at the receptor locations are trivial (less than 0.08 μSv.year^{-1}). The 12 to 17 years age group will receive the highest total effective dose. The isopleth map is presented in Figure 5.14, which shows that the maximum dose during Phase 1 is less than 100 μSv.year^{-1}.

5.4.4.2 Agricultural Area Exposure Condition

Figure 5.15 to Figure 5.19 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1 (see Table 4.2 and Figure 5.20 for the receptor locations), which shows that the calculated doses at the receptor locations are trivial (less than 0.12 μSv.year^{-1}). The 12 to 17 years age group will receive the highest total effective dose. The isopleth map is presented in Figure 5.20, which shows that the maximum dose during Phase 1 is less than 100 μSv.year^{-1}.

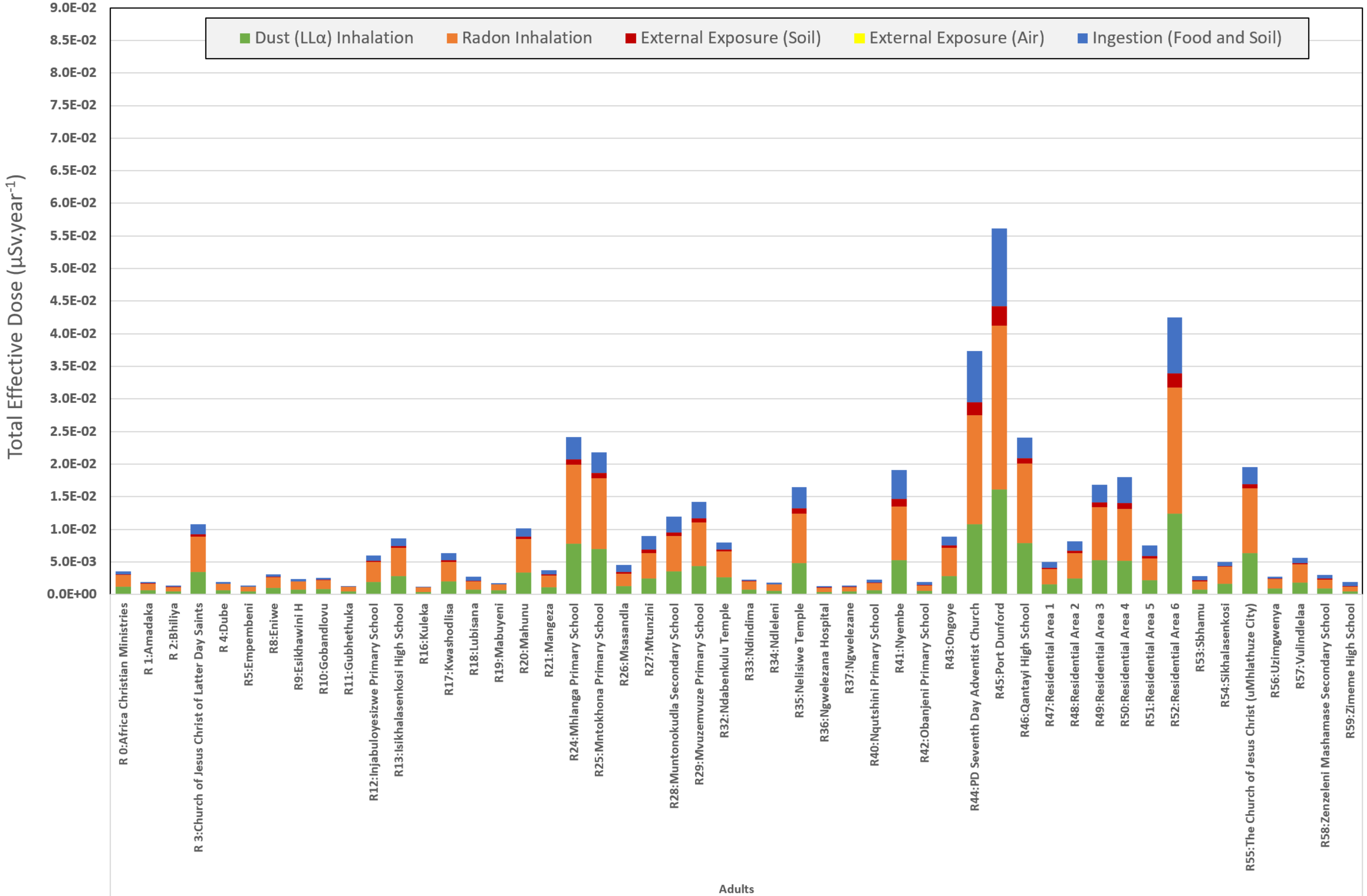

Figure 5.9 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 1 for the Residential Area Exposure Condition (See Figure 5.14 for receptor locations).**

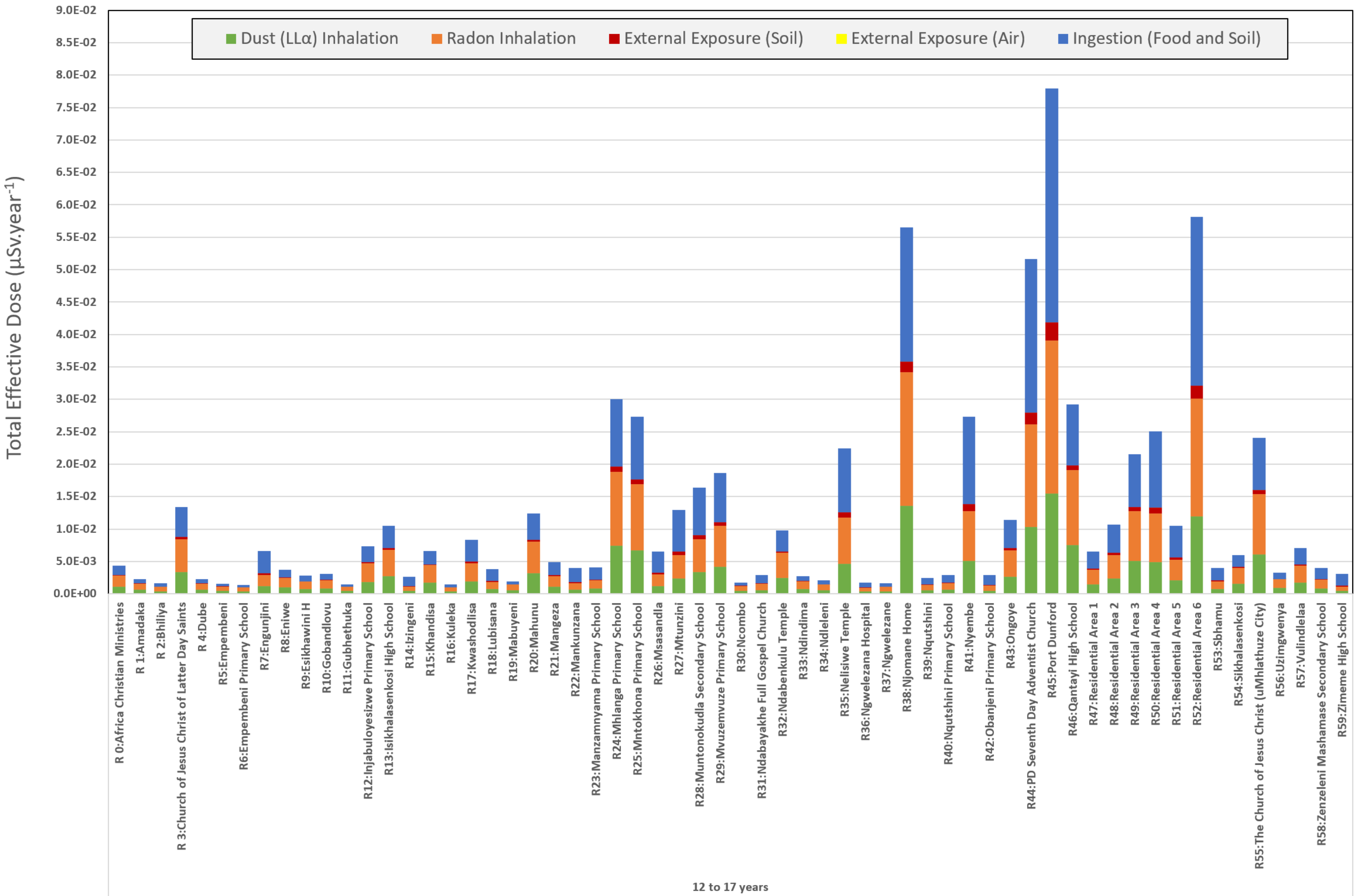

Figure 5.10 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 1 for the Residential Area Exposure Condition (See Figure 5.14 for receptor locations).**

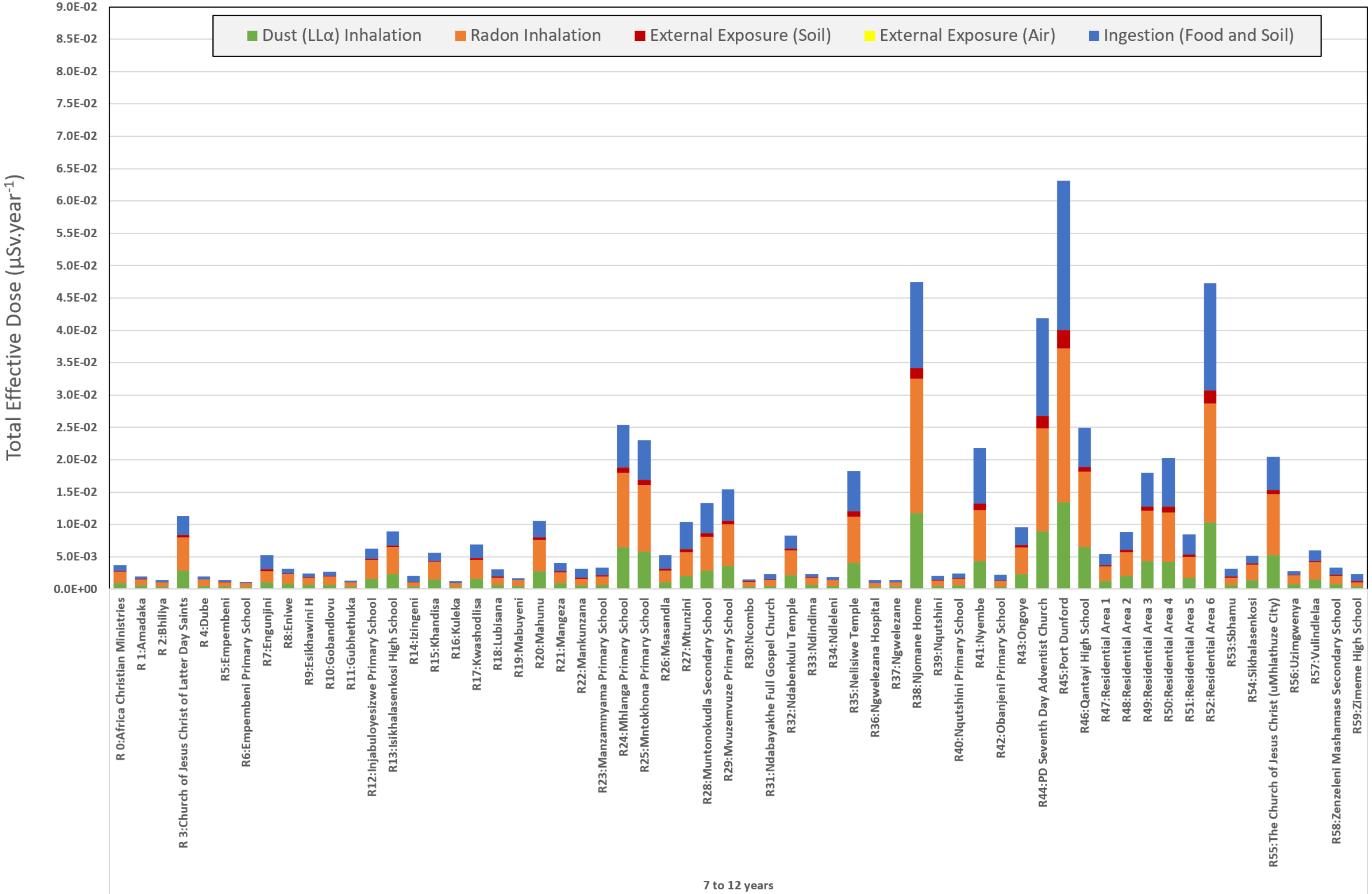

Figure 5.11 Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 1 for the Residential Area Exposure Condition (See Figure 5.14 for receptor locations).

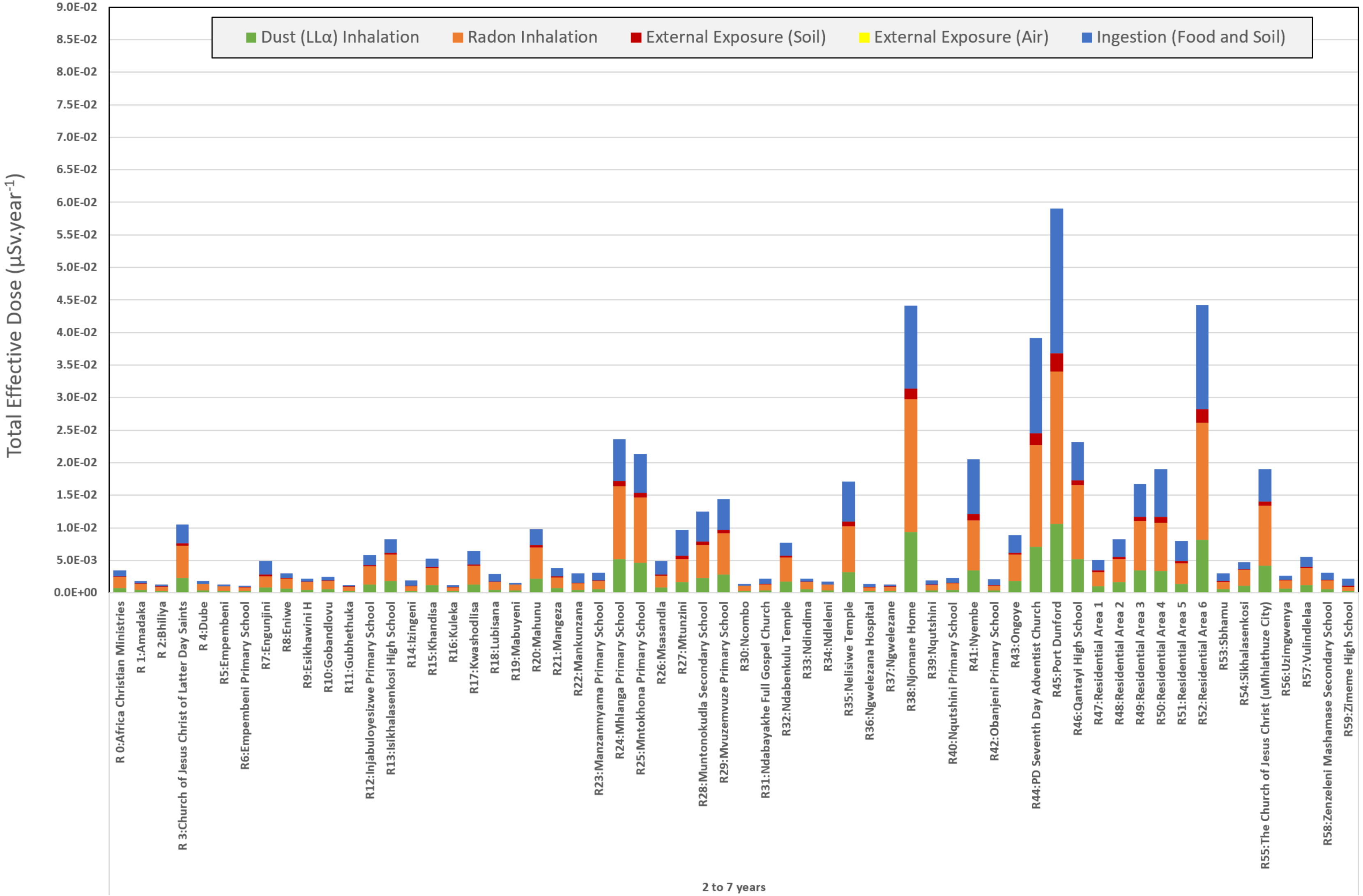

Figure 5.12 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 1 for the Residential Area Exposure Condition (See Figure 5.14 for receptor locations).**

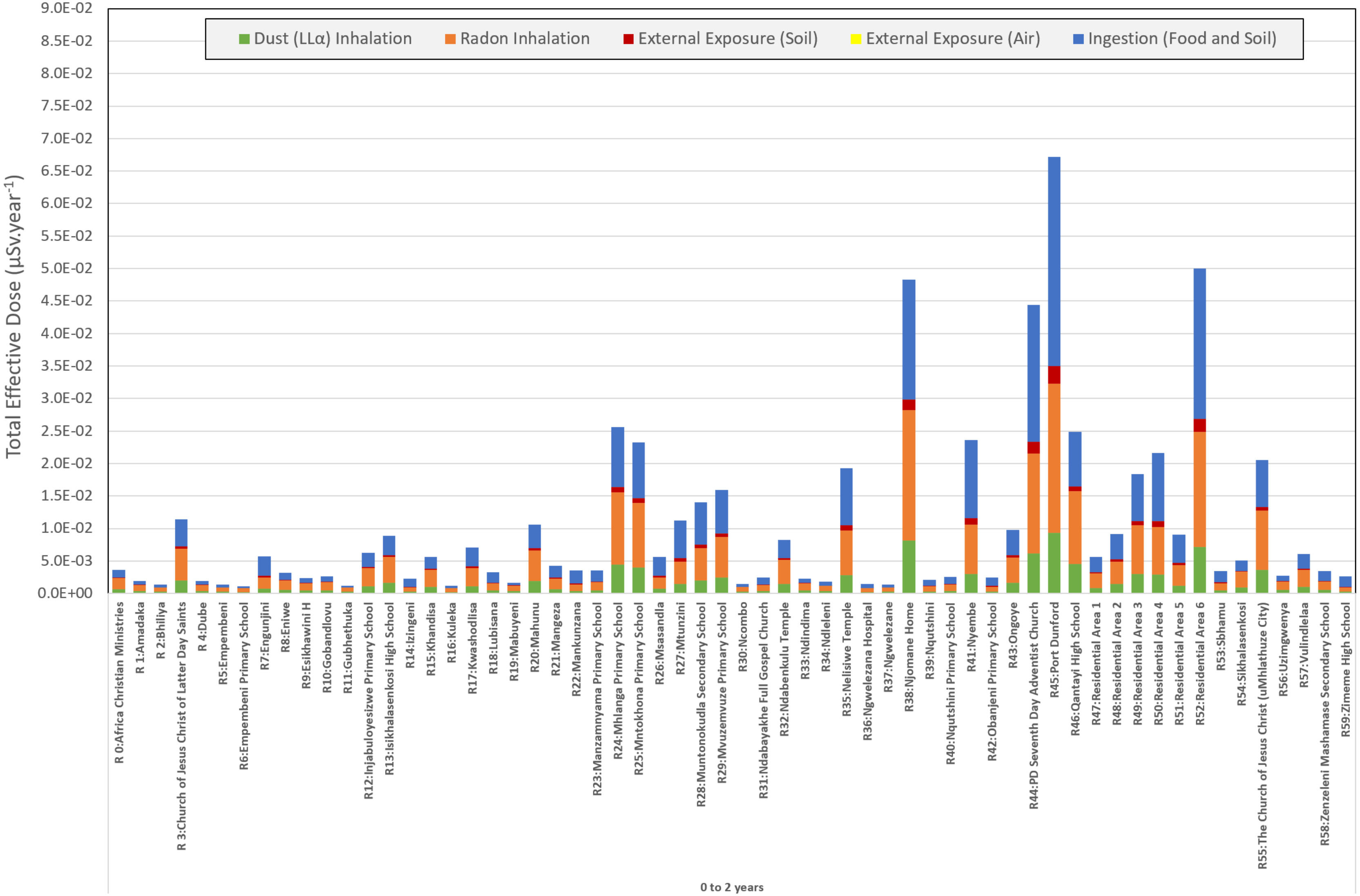

Figure 5.13 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 1 for the Residential Area Exposure Condition (See Figure 5.14 for receptor locations).**

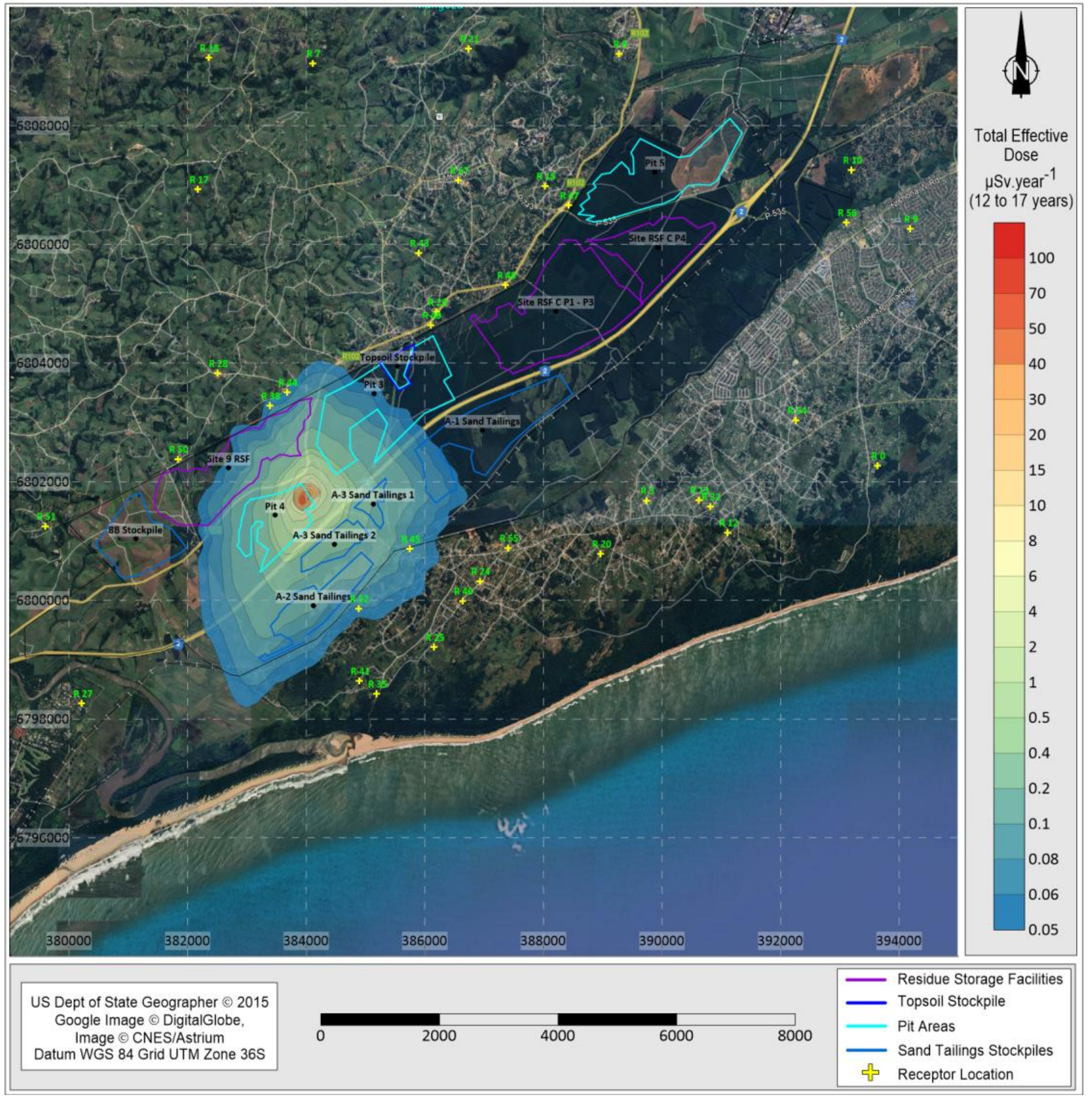

Figure 5.14 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Residential Area Exposure Condition for Phase 1 for the Port Dunford Mine.**

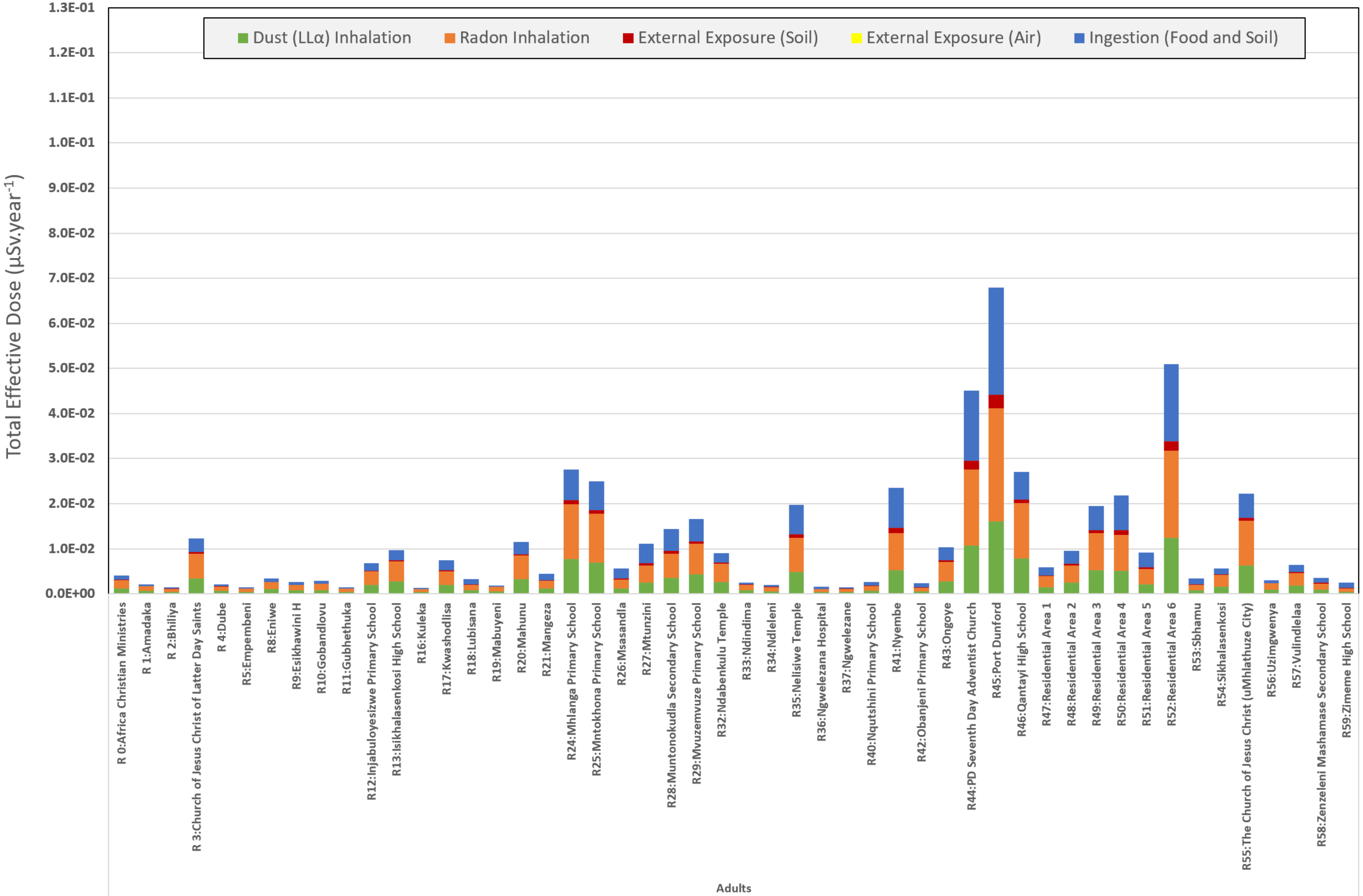

Figure 5.15 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 1 for the Agricultural Area Exposure Condition (See Figure 5.14 for receptor locations).**

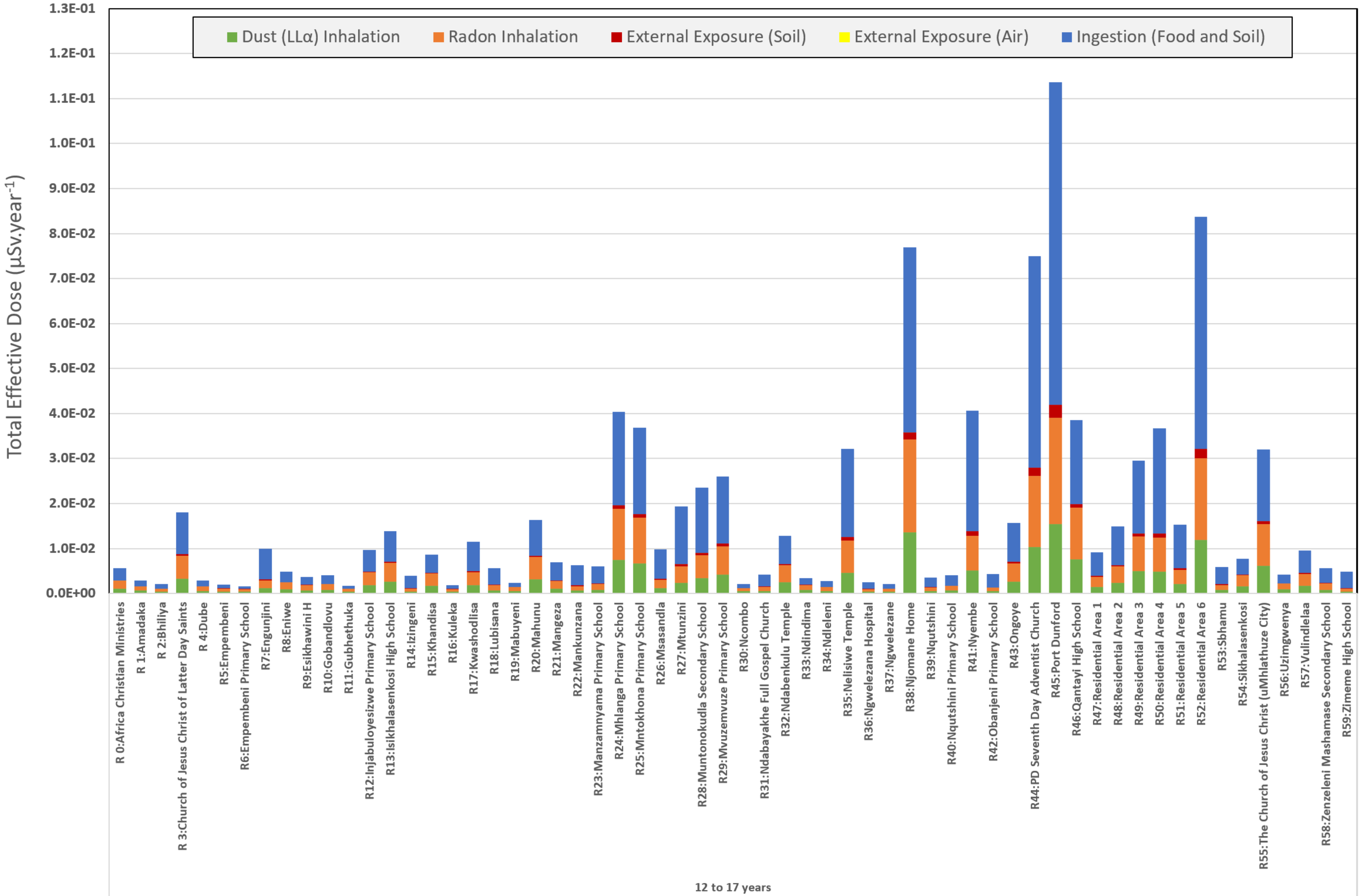

Figure 5.16 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 1 for the Agricultural Area Exposure Condition (See Figure 5.14 for receptor locations).**

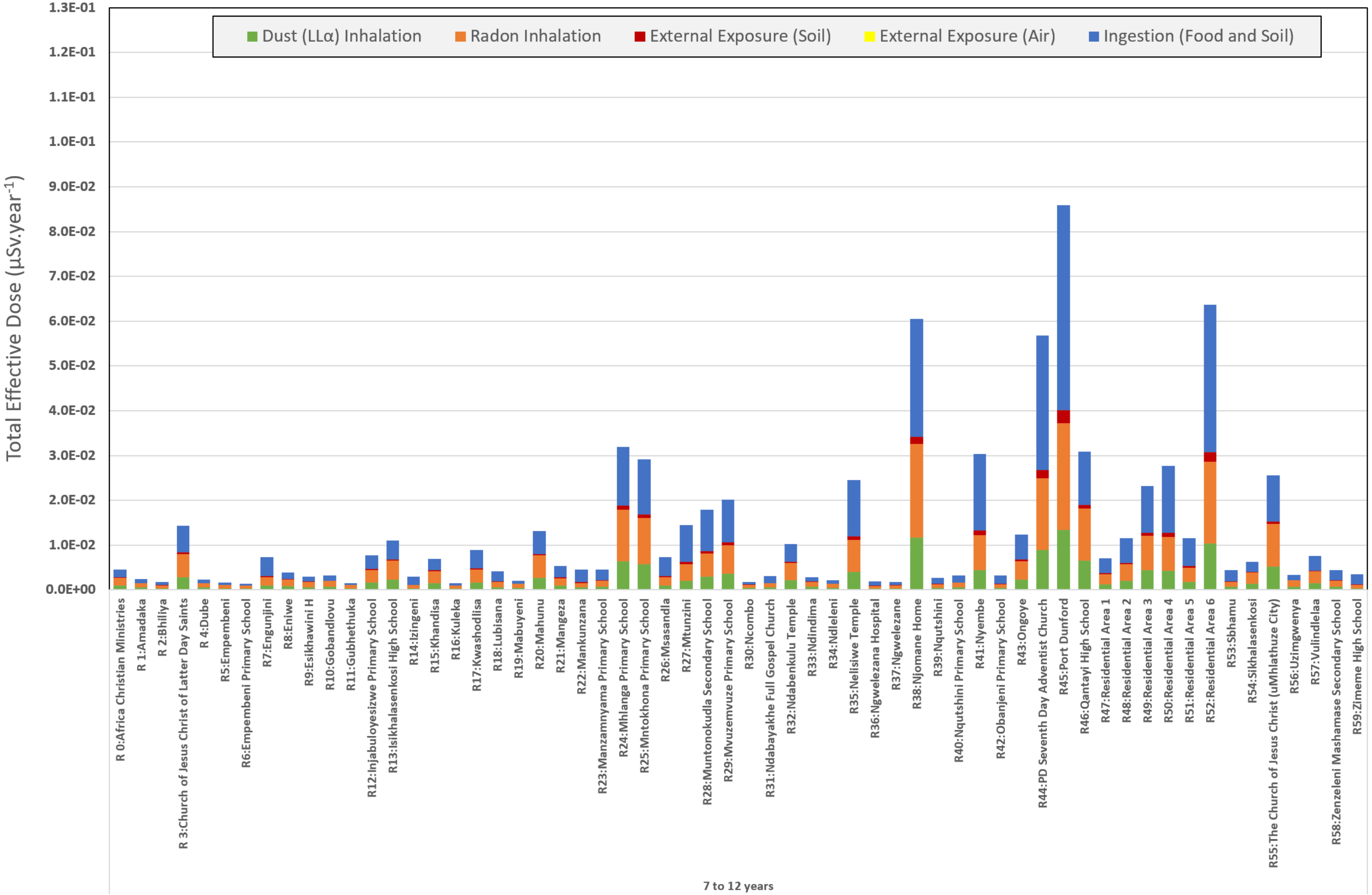

Figure 5.17 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 1 for the Agricultural Area Exposure Condition (See Figure 5.14 for receptor locations).**

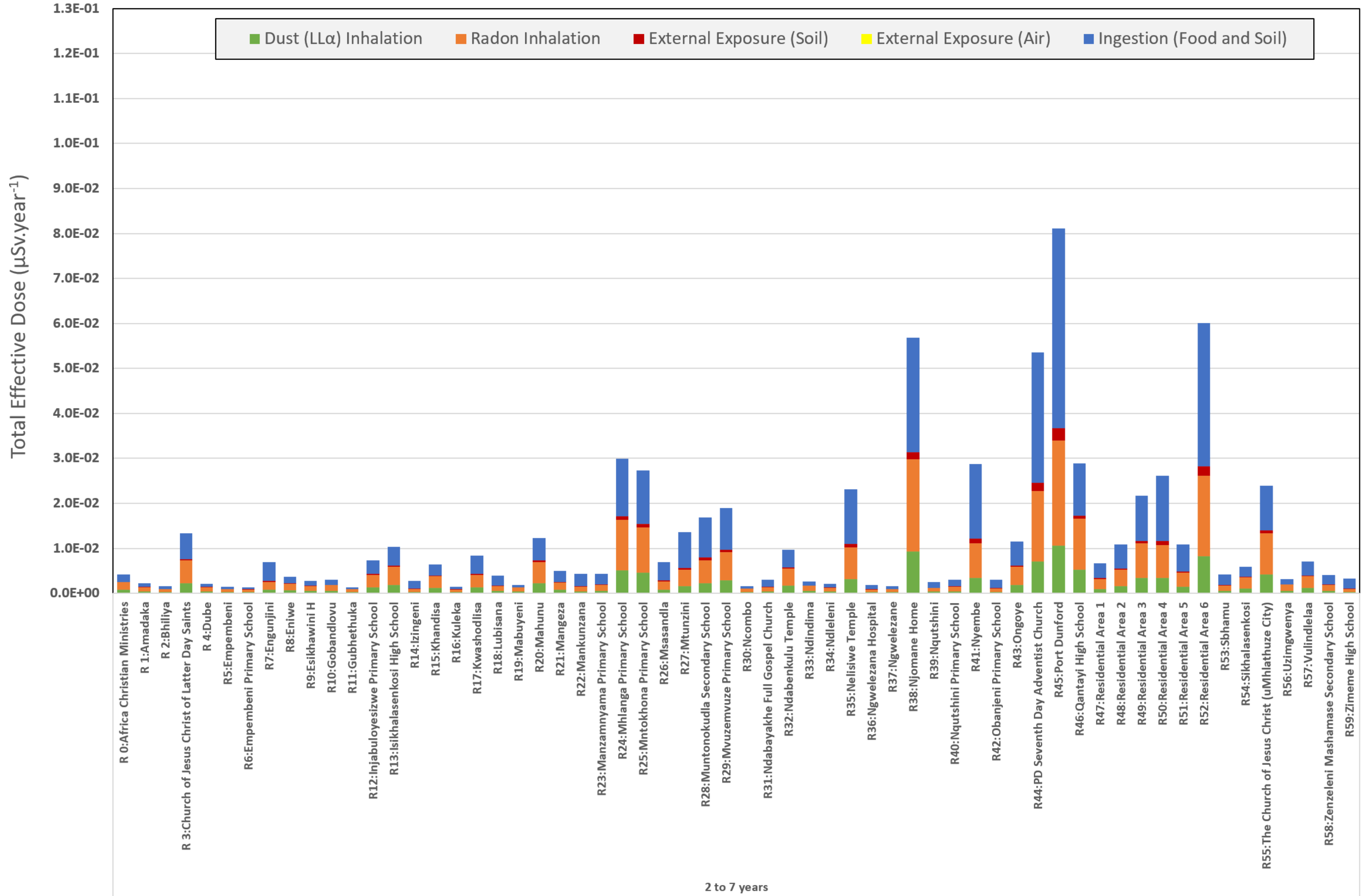

Figure 5.18 Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 1 for the Agricultural Area Exposure Condition (See Figure 5.14 for receptor locations).

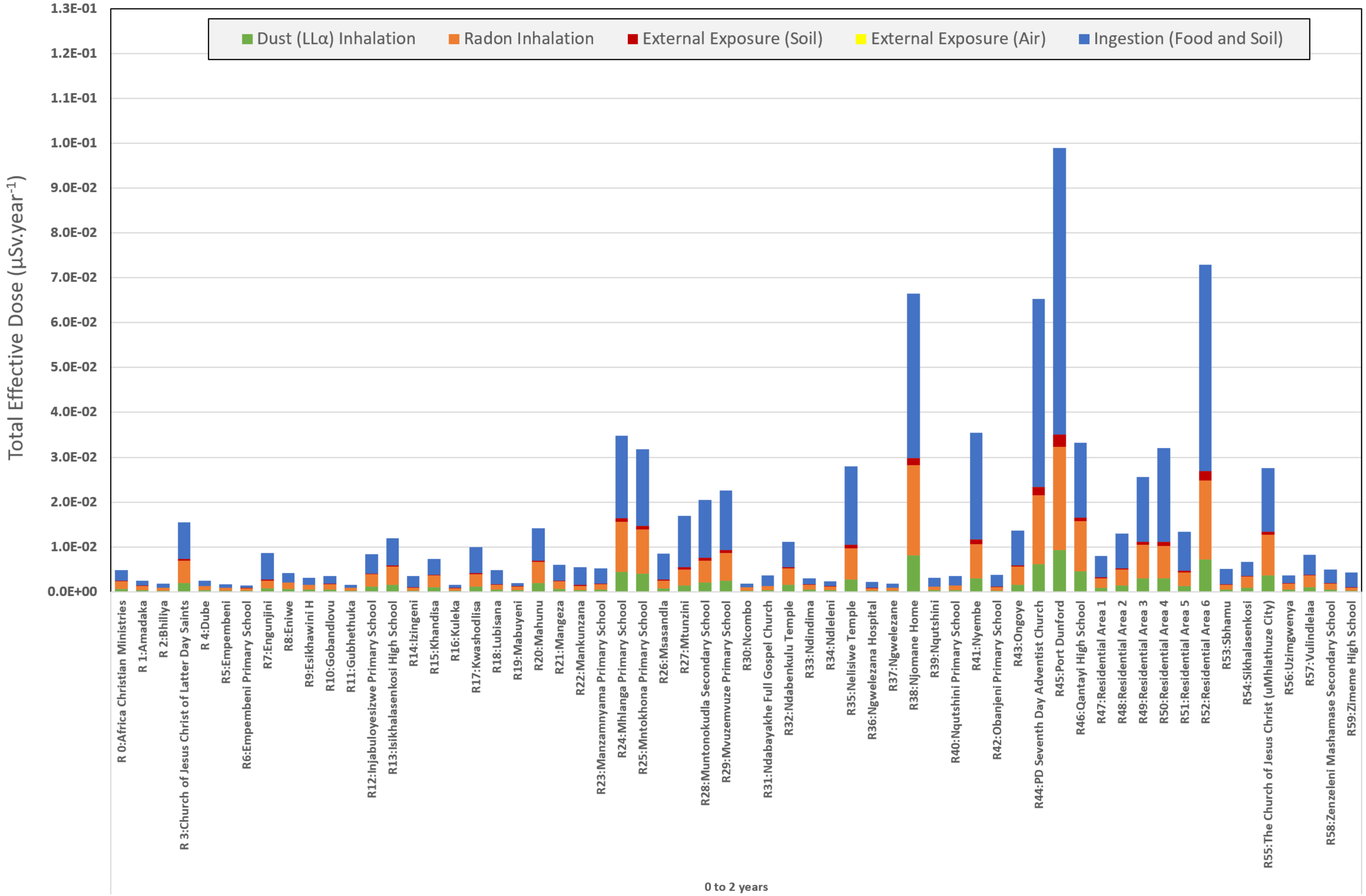

Figure 5.19 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 1 for the Agricultural Area Exposure Condition (See Figure 5.14 for receptor locations).**

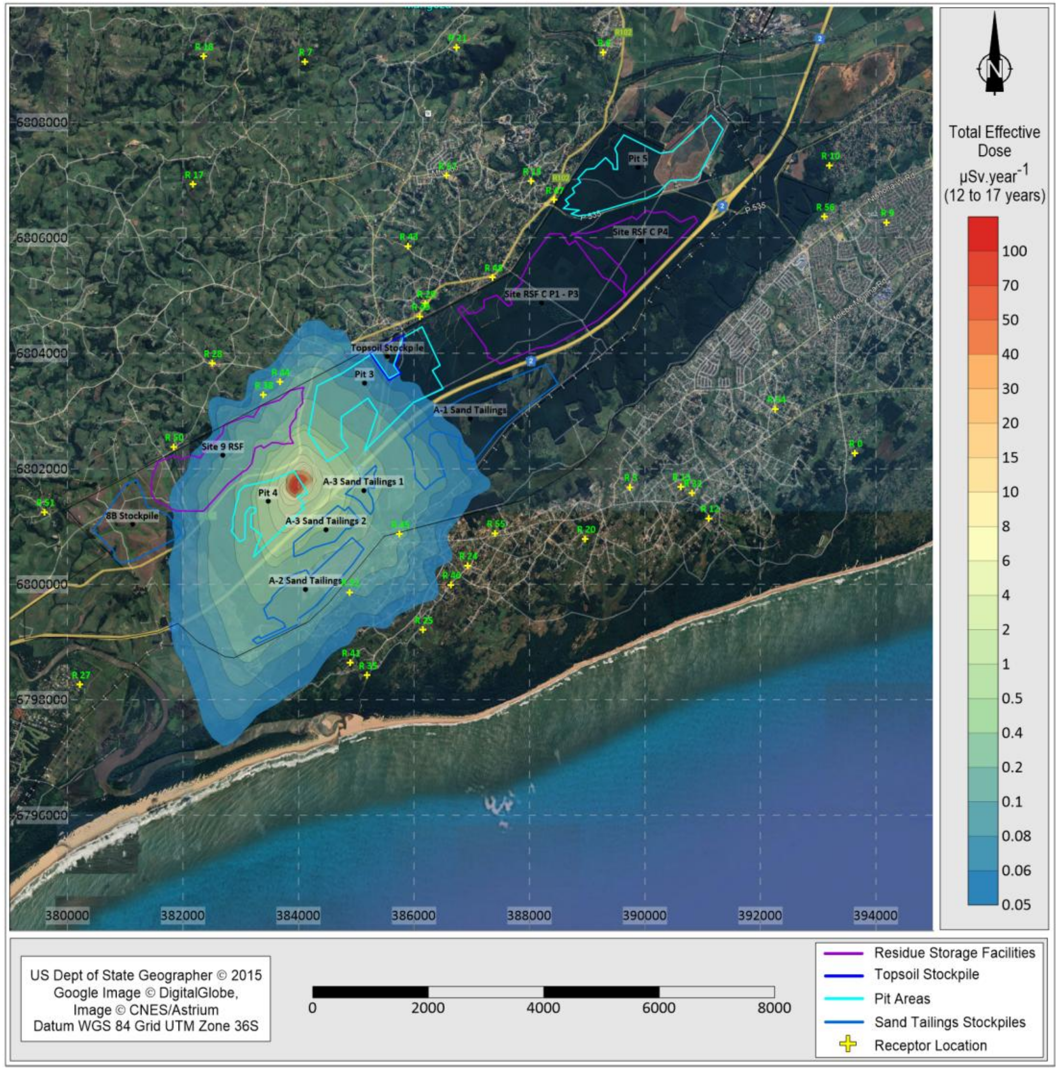

Figure 5.20 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Agricultural Area Exposure Condition for Phase 1 for the Port Dunford Mine.**

5.4.4.3 Interpretation of the Results

The Phase 1 mining operations are limited to a small footprint of 41 ha over a ten (10) year period between 2025 and 2035. The potential radiological exposure to members of the public during this phase is limited, with the main contributor to the dose from the orebody in the mined-out area. However, the maximum dose in this area is still less than 100 μSv.year^{-1}, even for the conservative Agricultural Area Exposure Condition. This is significantly less than the public dose constraint (250 μSv.year^{-1}) or dose limits (1,000 μSv.year^{-1}).

The total effective dose decreases significantly with distance away from the source area, to such an extent that the calculated doses for selected receptor locations are trivial and less than 0.12 μSv.year^{-1}. The main contributors to the total effective dose are radon gas and dust inhalation, as well as ingestion of soil and crops. It can, therefore, be concluded that the impact of Phase 1 will have an insignificant impact on members of the public.

5.4.5 Phase 2: Scenario 1

5.4.5.1 Residential Area Exposure Condition

Figure 5.21 to Figure 5.25 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.26 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 27 μSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 μSv.year^{-1}.

The isopleth map is presented in Figure 5.26, which shows that the maximum total effective dose for Scenario 1 of the Port Dunford Mine is less than 250 μSv.year^{-1}. The maximum calculated total effective dose on top of Site RSF C (P1 to P3) is in the order of 190 μSv.year^{-1}. However, residential developments are not possible on top of the facilities. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 30 μSv.year^{-1}.

5.4.5.2 Agricultural Area Exposure Condition

Figure 5.27 to Figure 5.31 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.32 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 45 μSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 μSv.year^{-1}.

The isopleth map is presented in Figure 5.32, which shows that the maximum total effective dose for Scenario 1 of the Port Dunford Mine only exceeds 250 μSv.year^{-1} on top of Site RSF C (P1 to P3). The maximum calculated total effective dose is in the order of 315 μSv.year^{-1}. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 60 μSv.year^{-1}.

5.4.5.3 Interpretation of the Results

The Phase 2 Scenario 1 mining operations are scheduled for 2036 to 2047, with the Topsoil Stockpile, Site 9 RSF, the Sand Tailings Stockpiles (A1 to A3) and Site RSF C (Pit 1 to Pit 3) as the main contributors (sources) to the atmospheric pathway. The potential radiological exposure to members of the public outside the Port Dunford Mine boundary during this phase is low and less than 60 μSv.year^{-1} for the conservative Agricultural Area Exposure Condition. The 250 μSv.year^{-1} dose constraint is only exceeded on top of the facilities.

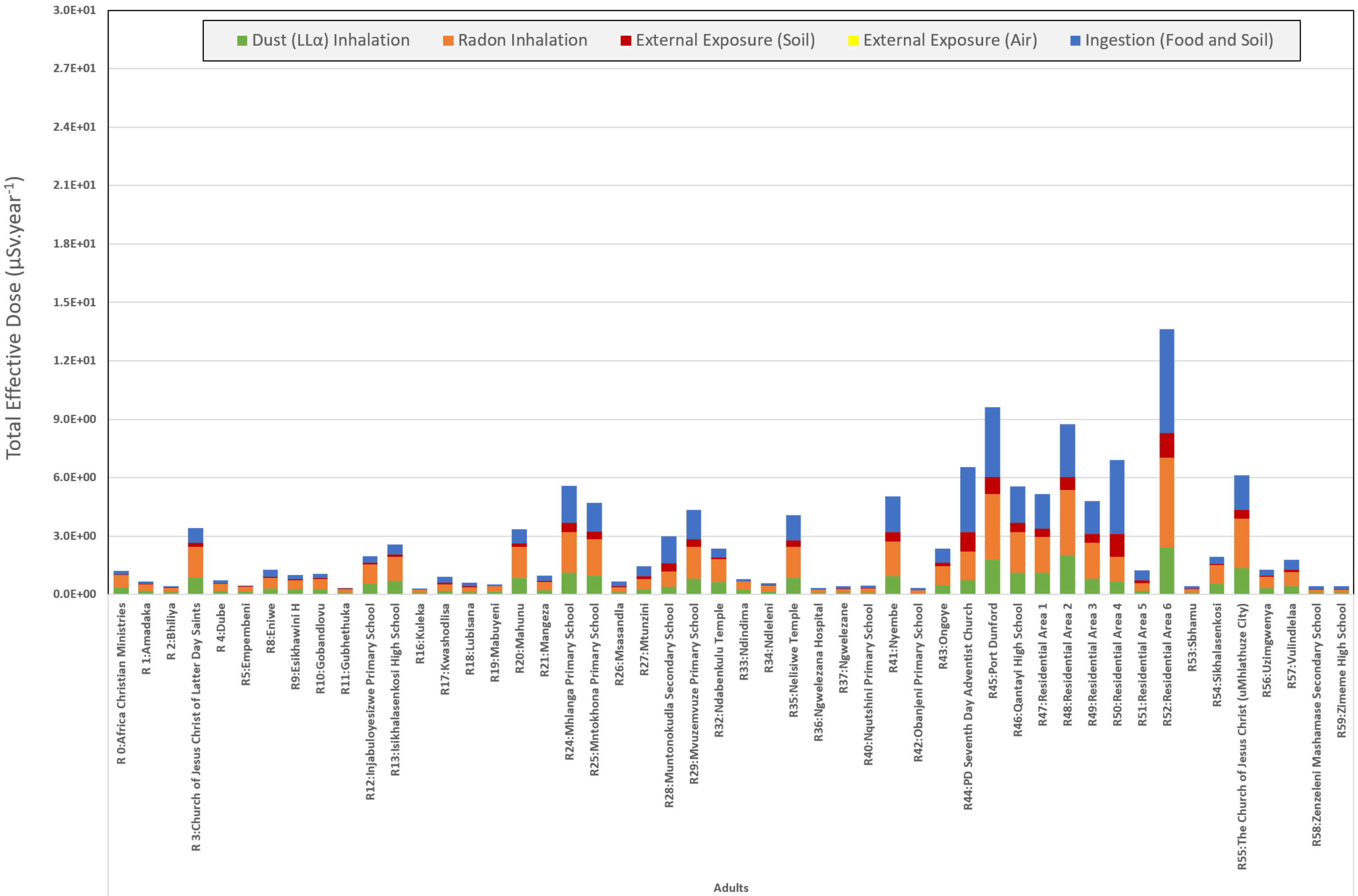

Figure 5.21 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 1 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

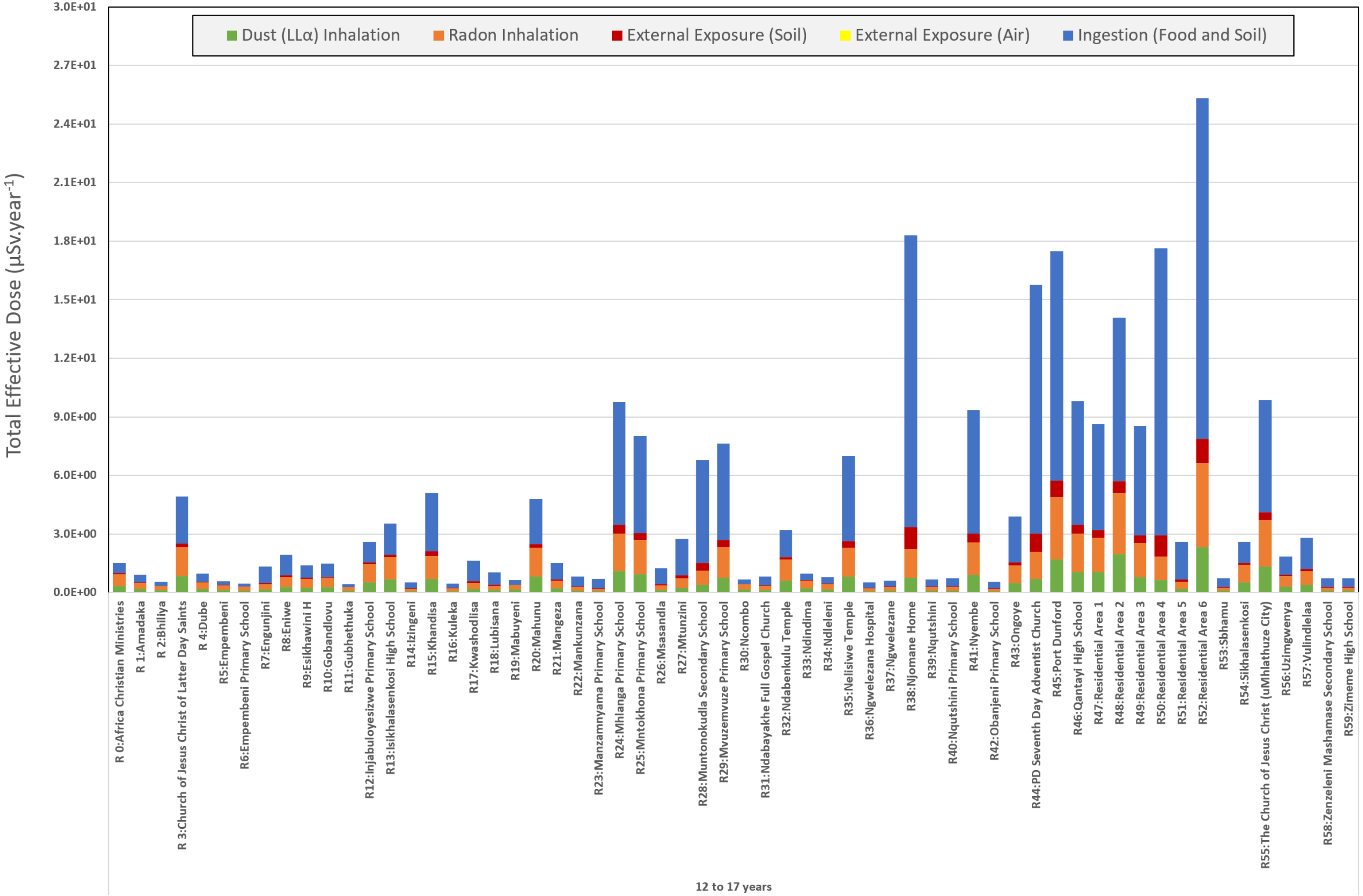

Figure 5.22 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 1 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

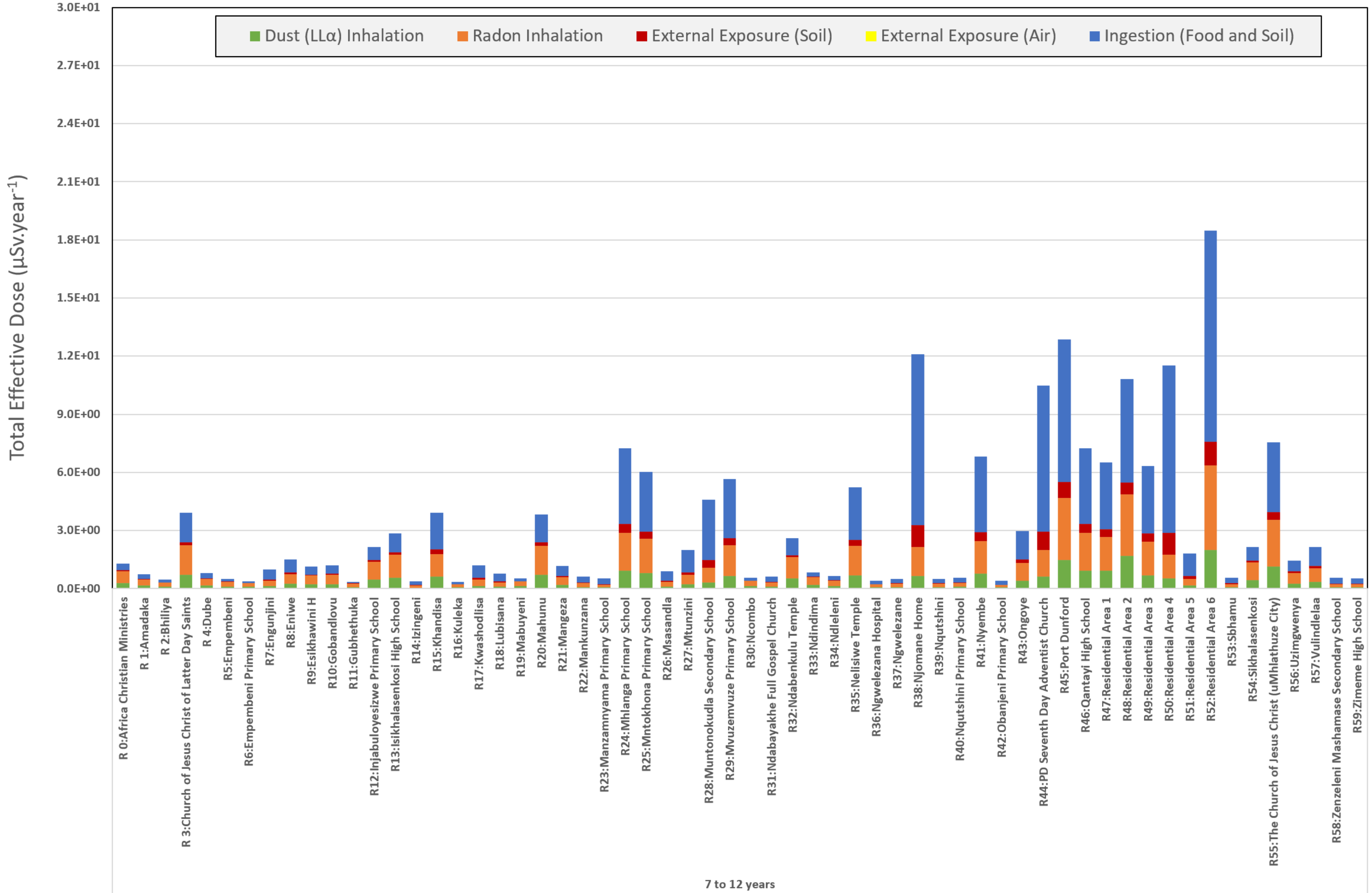

Figure 5.23 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 1 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

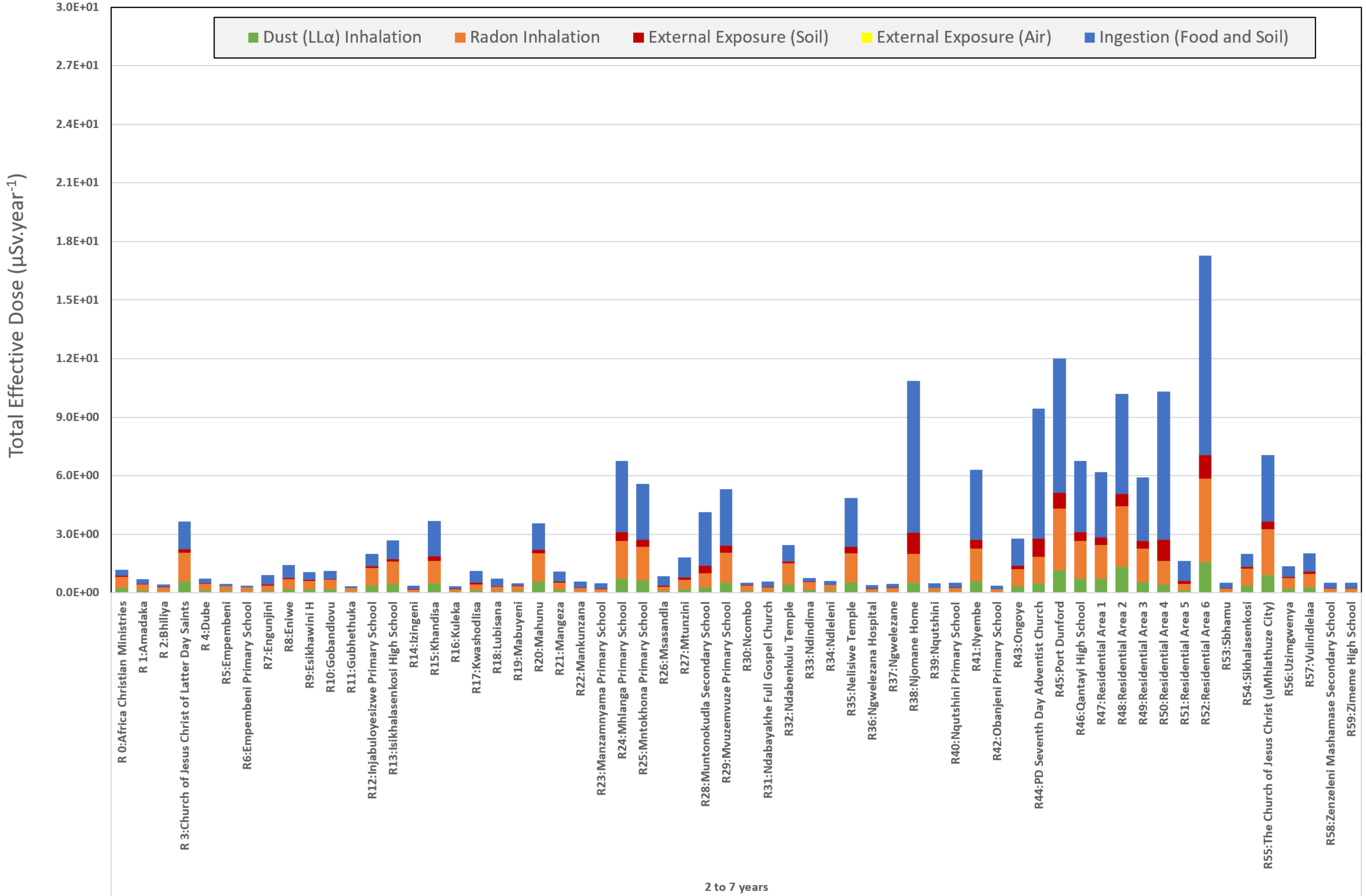

Figure 5.24 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 1 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

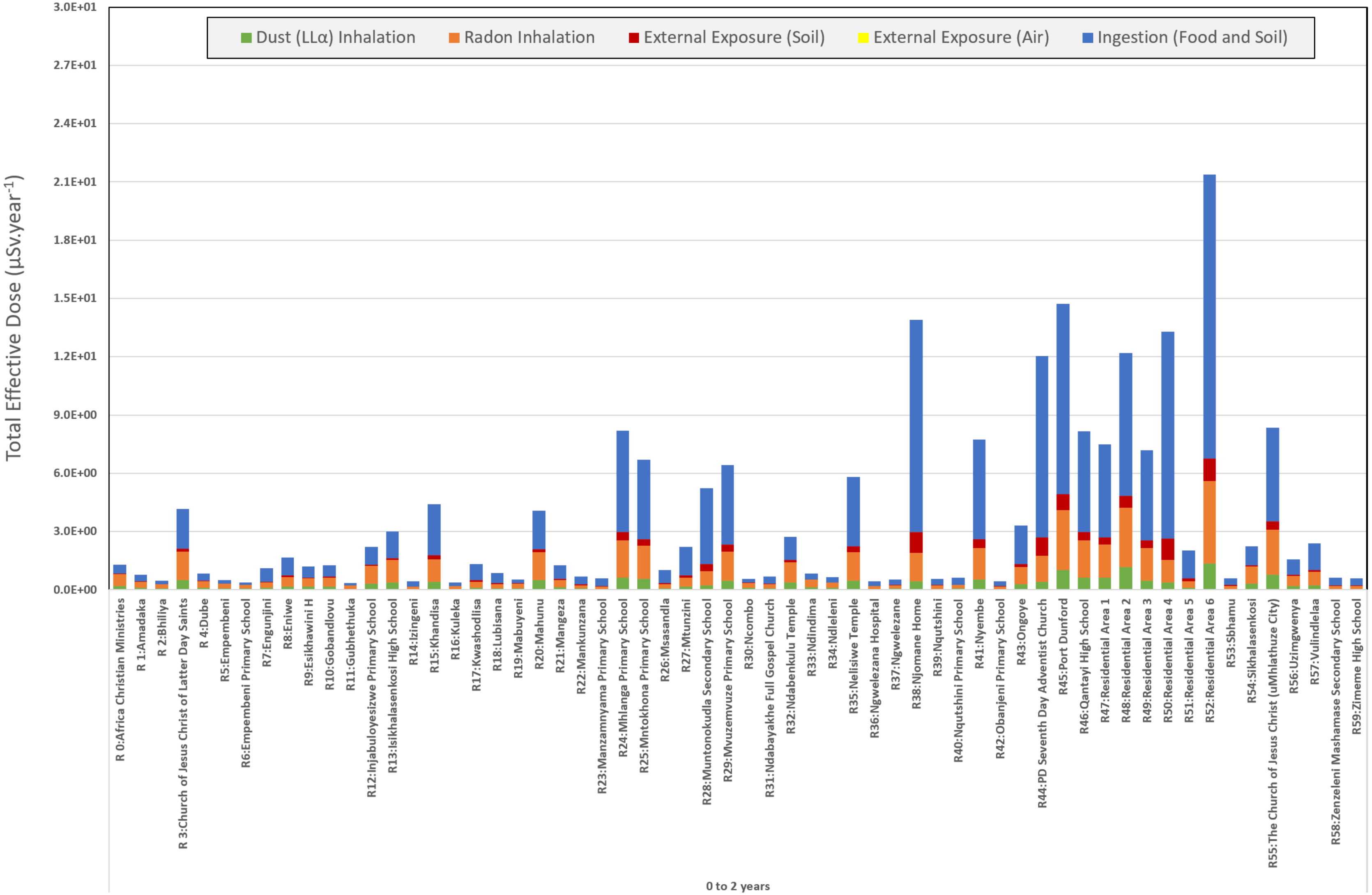

Figure 5.25 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 1 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

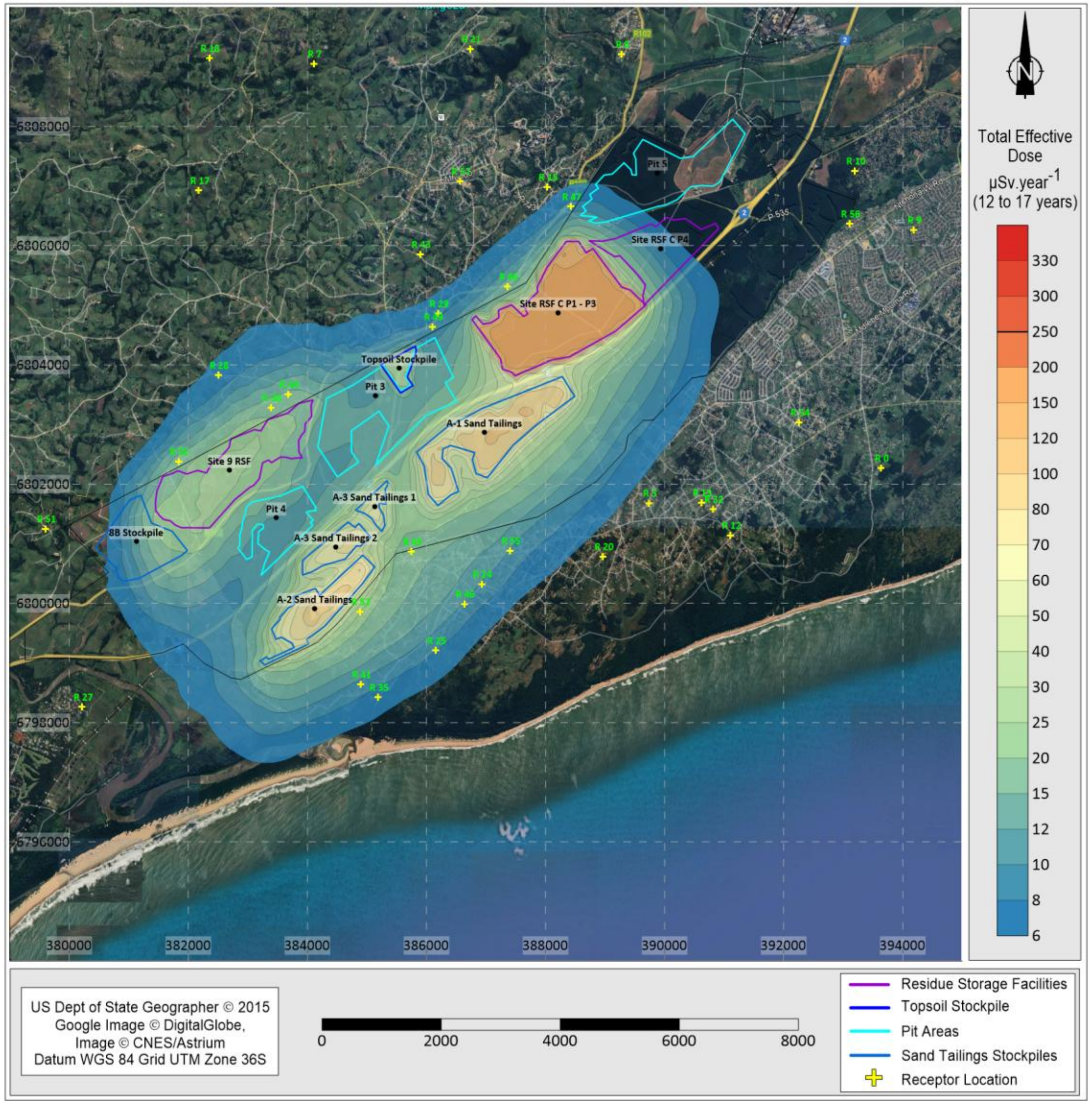

Figure 5.26 Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Residential Area Exposure Condition for Phase 2 Scenario 1 for the Port Dunford Mine.

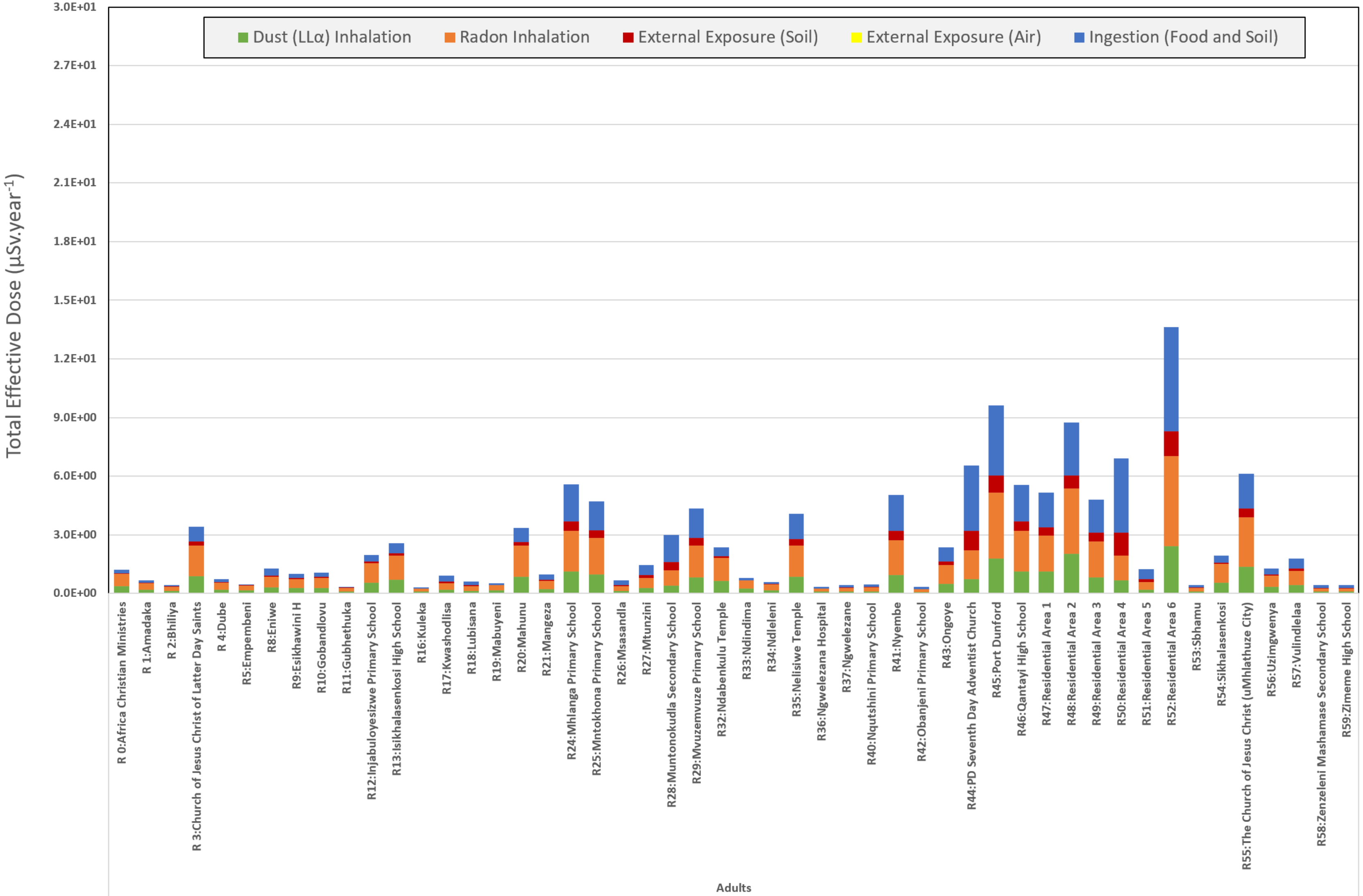

Figure 5.27 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 1 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

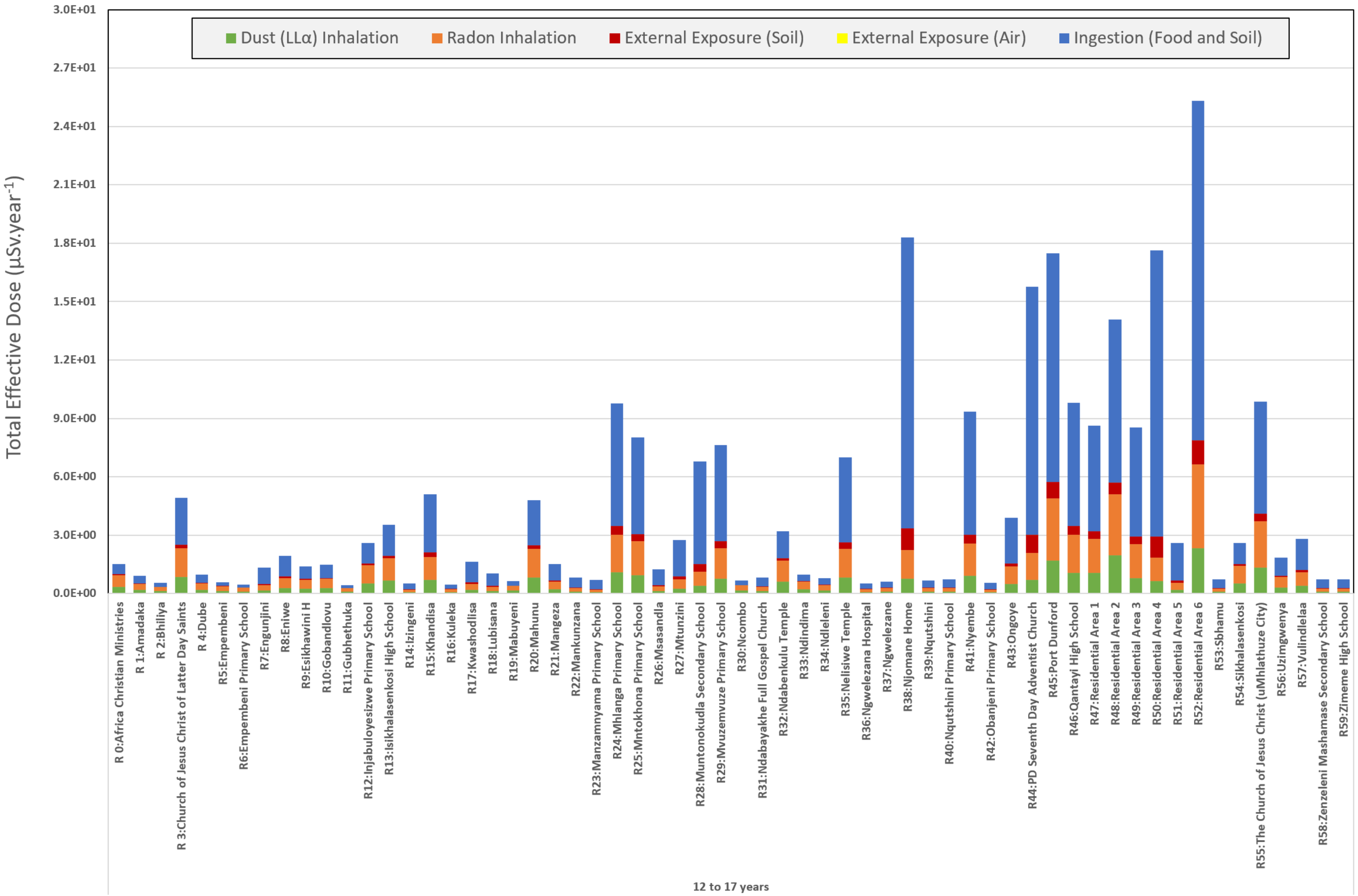

Figure 5.28 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 1 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

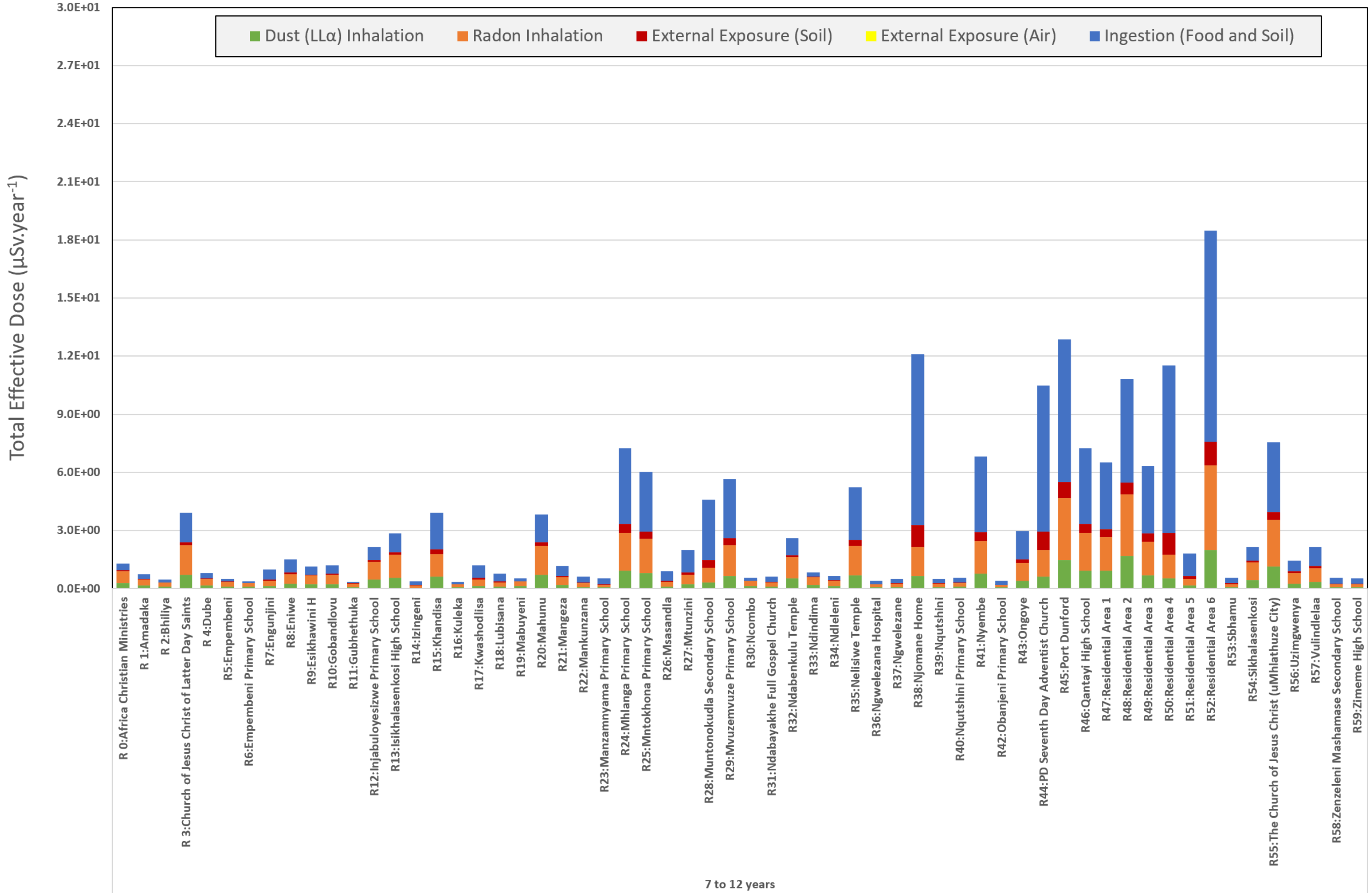

Figure 5.29 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 1 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

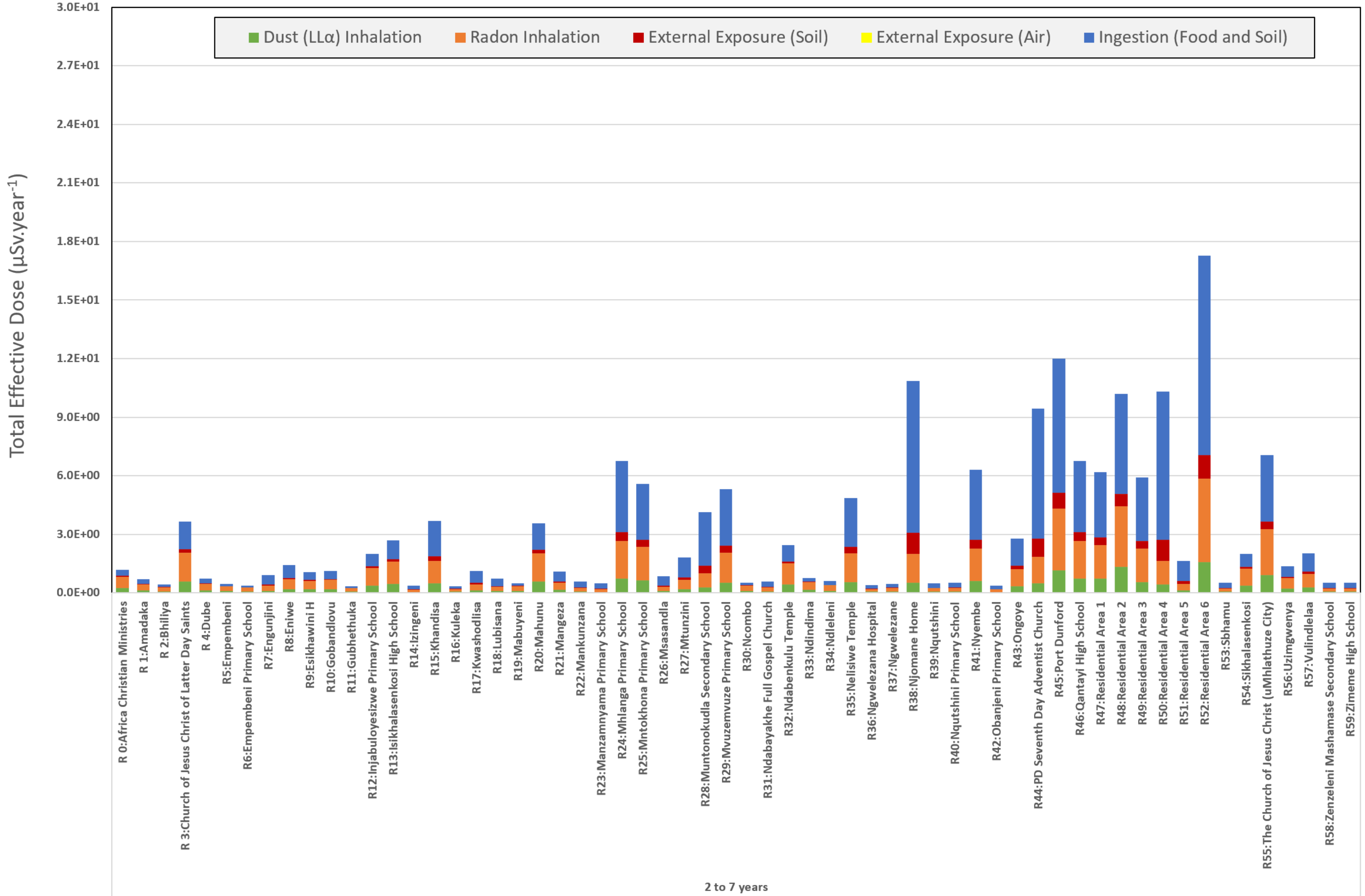

Figure 5.30 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 1 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

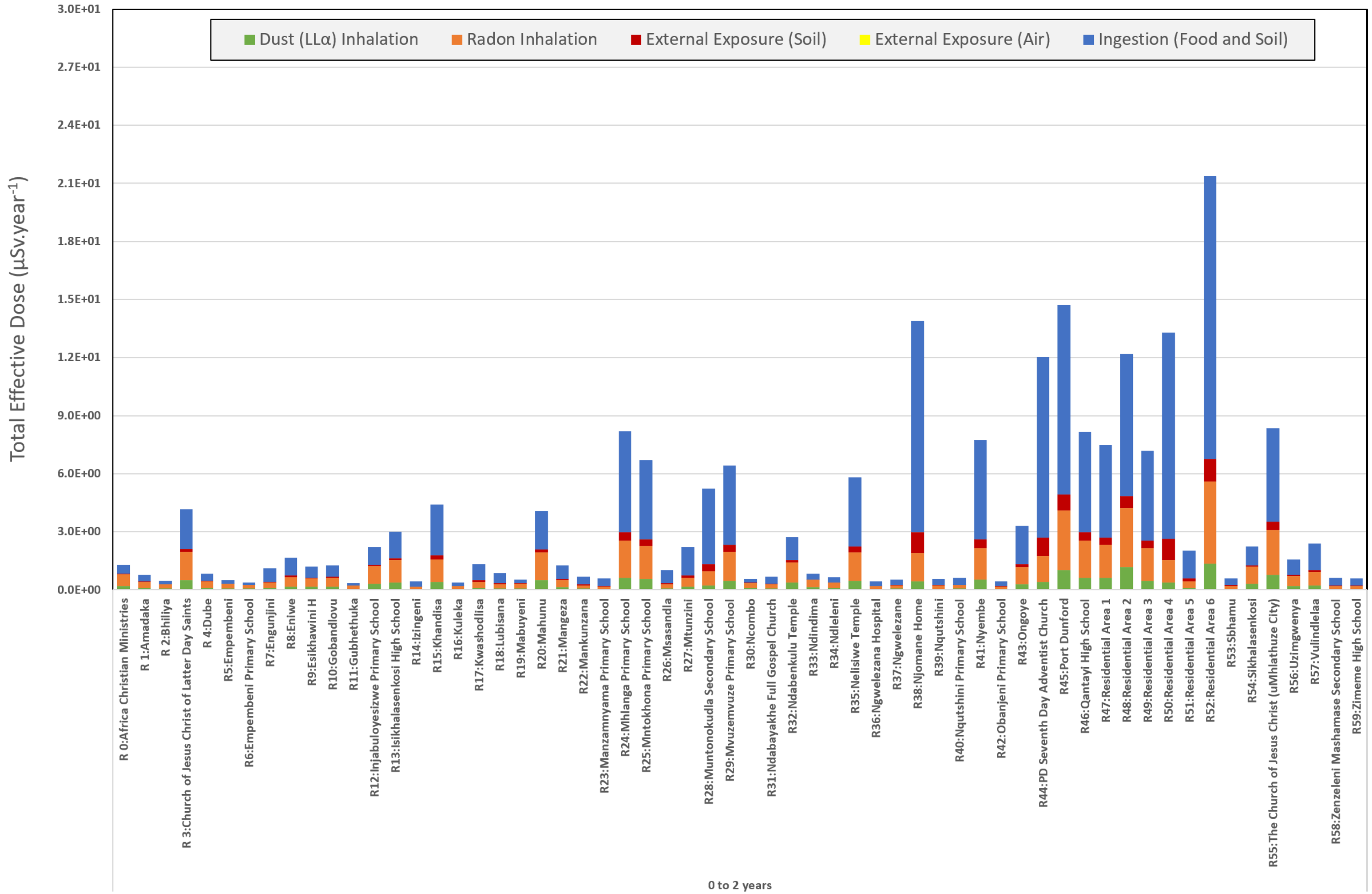

Figure 5.31 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 1 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

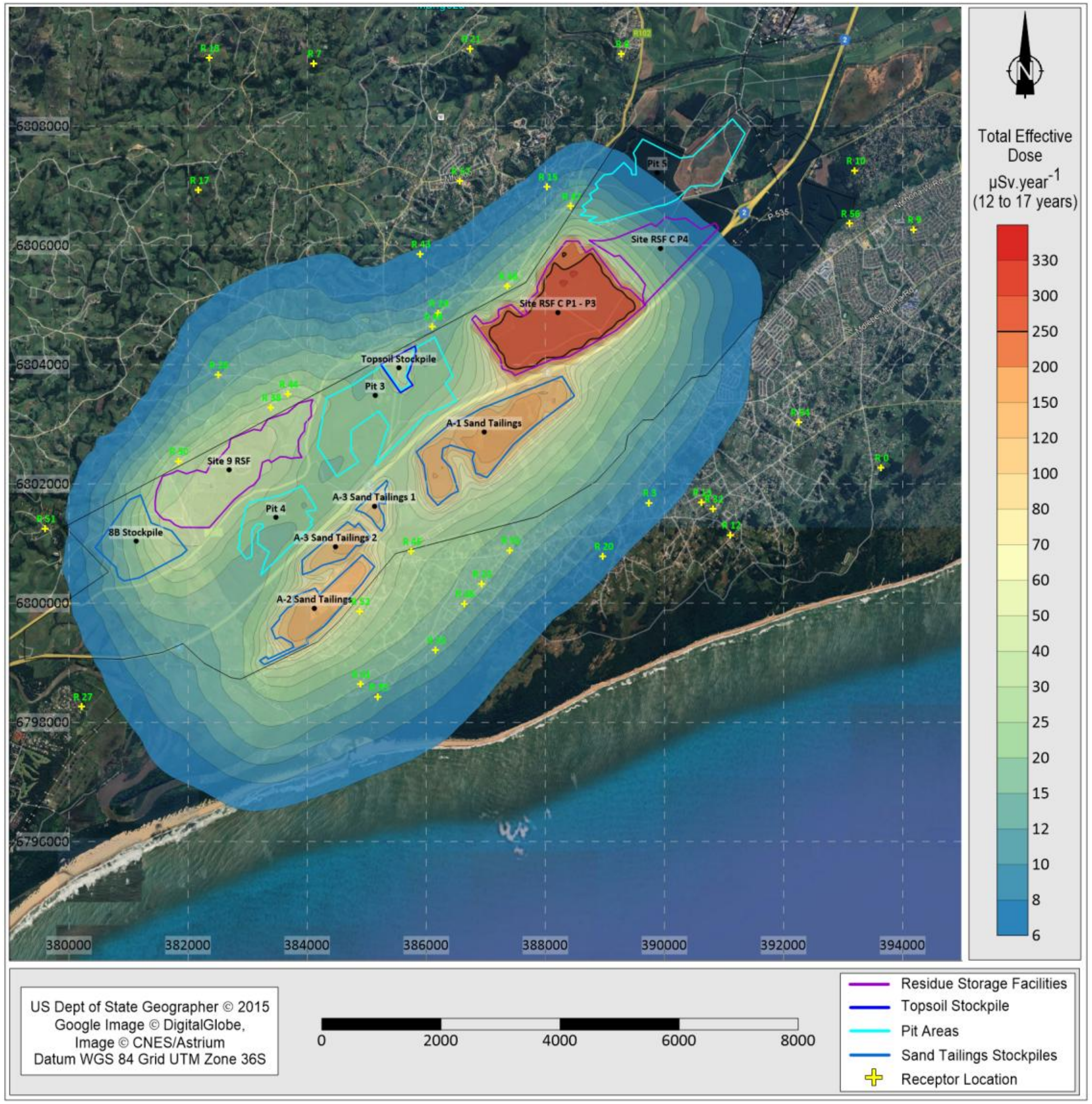

Figure 5.32 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Agricultural Area Exposure Condition for Phase 2 Scenario 1 for the Port Dunford Mine.**

The total effective dose decreases significantly with distance away from the source area, to such an extent that the calculated doses for selected receptor locations are less than 45 µSv.year^{-1}. Site RSF C (Pit 1 to Pit 3) results in the highest dose contribution during this phase, but since it is located further from the site boundary, it does not have the same effect as the Sand Tailings Stockpiles (A2), for example. The main contributors to the total effective dose are the ingestion of soil and crops, which suggest that the deposition of dust (TSP) is more significant than the inhalation of airborne dust (PM_{10}).

It can, therefore, be concluded that the impact of Phase 2 Scenario 1 of the Port Dunford Mine will have a low radiological impact on members of the public.

5.4.6 Phase 2: Scenario 2

5.4.6.1 Residential Area Exposure Condition

Figure 5.33 to Figure 5.37 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.38 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 45 µSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 µSv.year^{-1}.

The isopleth map is presented in Figure 5.38, which shows that the maximum total effective dose for Scenario 2 of the Port Dunford Mine is less than 250 µSv.year^{-1}. The maximum calculated total effective dose on top of Site RSF C (P1 to P3) and Site RSF C (P4) is in the order of 200 µSv.year^{-1}. However, residential developments are not possible on top of the facilities. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 30 µSv.year^{-1}.

5.4.6.2 Agricultural Area Exposure Condition

Figure 5.39 to Figure 5.43 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.44 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 45 µSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 µSv.year^{-1}.

The isopleth map is presented in Figure 5.44, which shows that the maximum total effective dose for Scenario 2 of the Port Dunford Mine only exceeds 250 µSv.year^{-1} on top of Site RSF C (P1 to P3) and Site RSF C (P4). The maximum calculated total effective dose is in the order of 340 µSv.year^{-1}. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 60 µSv.year^{-1}.

5.4.6.3 Interpretation of the Results

The Phase 2 Scenario 2 mining operations are scheduled for 2048 to 2054, with Site RSF C (P4) and the 8B Stockpile in addition to the Scenario 1 atmospheric pathway sources that contribute to the radiological impact. The potential radiological exposure to members of the public outside the Port Dunford Mine boundary during this phase is low and less than 60 µSv.year^{-1} for the conservative Agricultural Area Exposure Condition. The 250 µSv.year^{-1} dose constraint is only exceeded on top of the facilities.

The total effective dose decreases significantly with distance away from the source area, to such an extent that the calculated doses for selected receptor locations are less than 45 µSv.year^{-1}. Site RSF C (Pit 1 to Pit 3) and Site RSF C (P4) result in the highest dose contribution during this phase, but since it is located further from the site boundary, they do not have the same effect as the Sand Tailings Stockpiles (A2), for example.

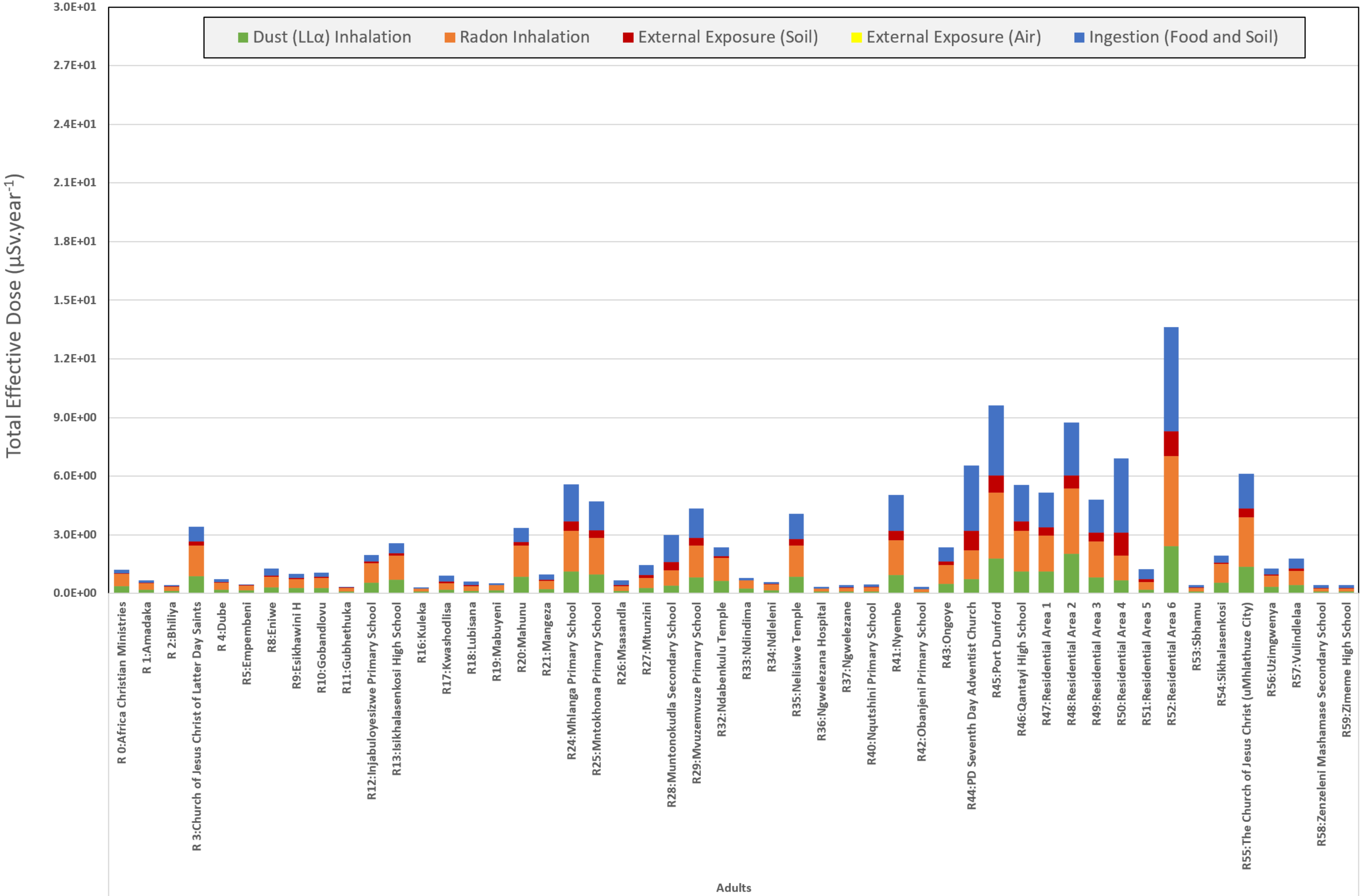

Figure 5.33 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 2 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

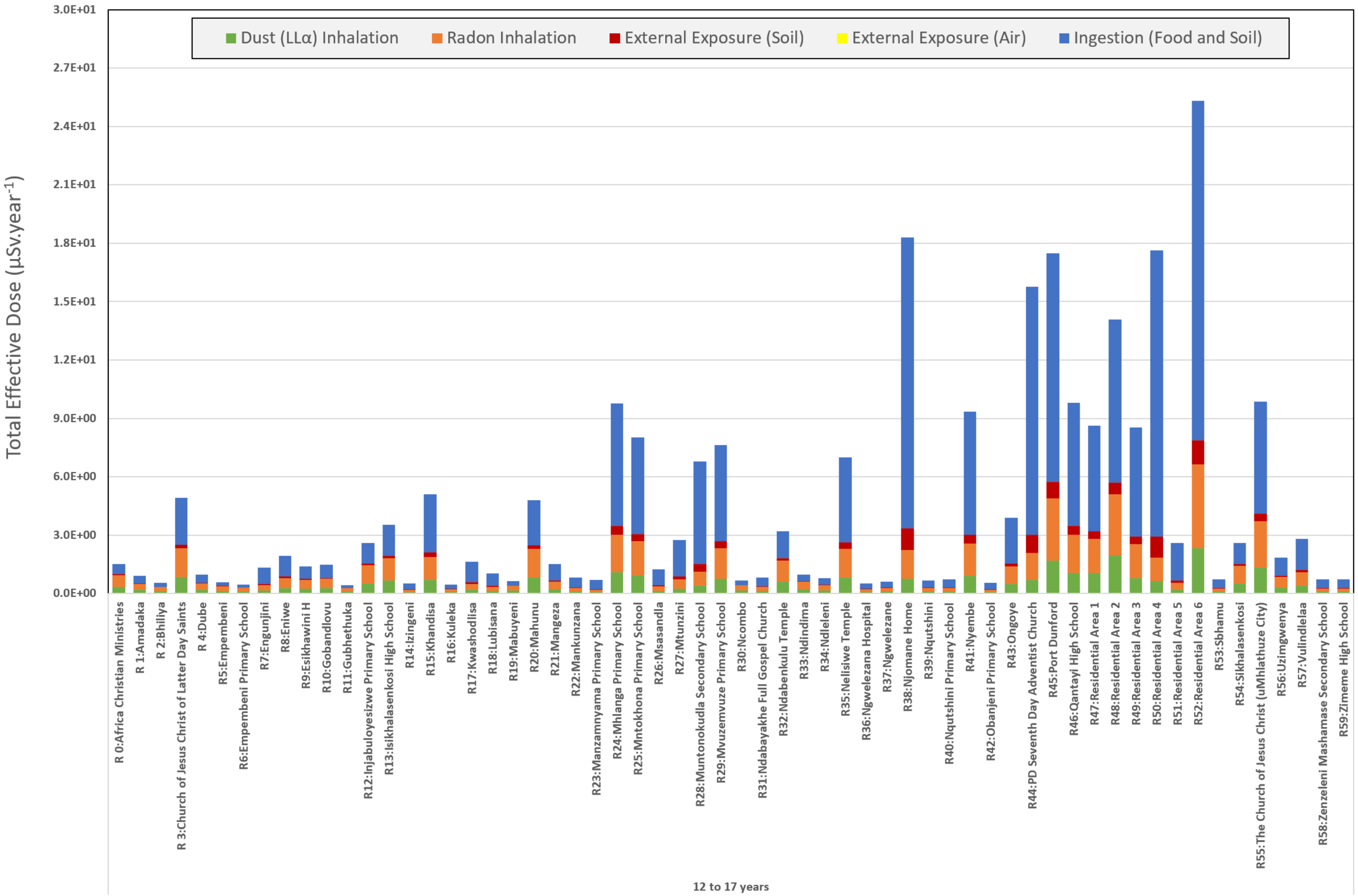

Figure 5.34 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 2 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

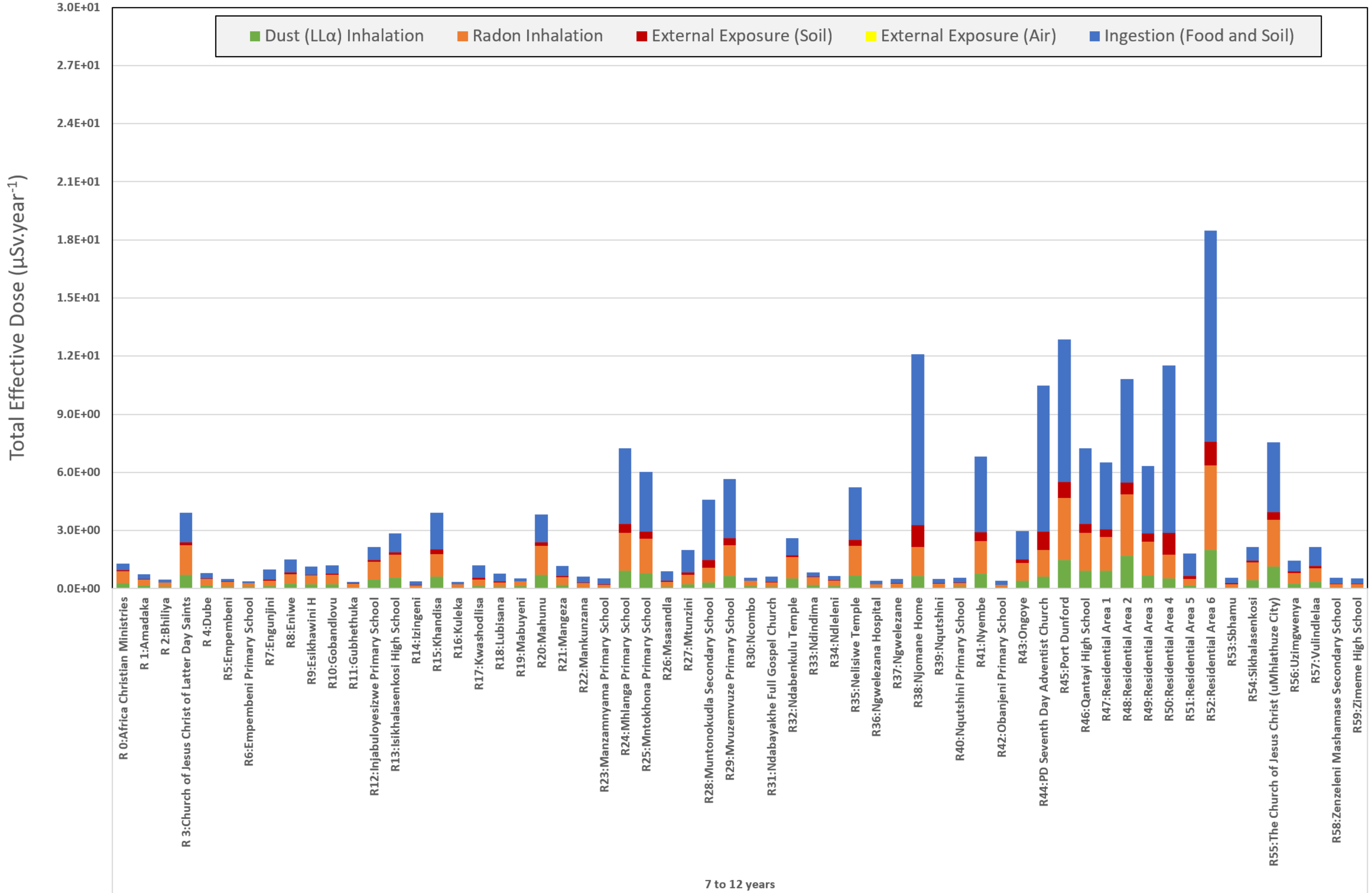

Figure 5.35 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 2 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

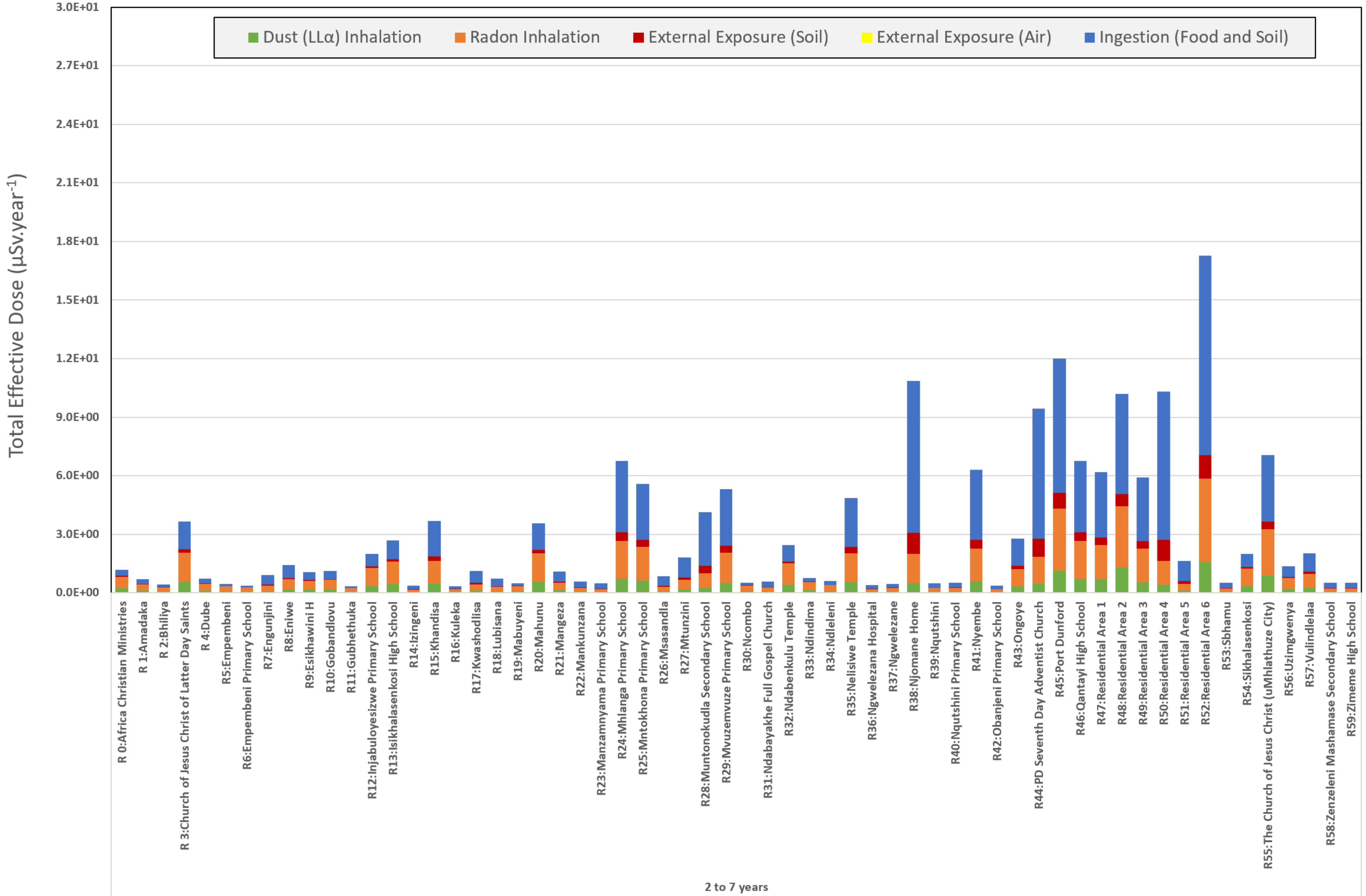

Figure 5.36 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 2 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

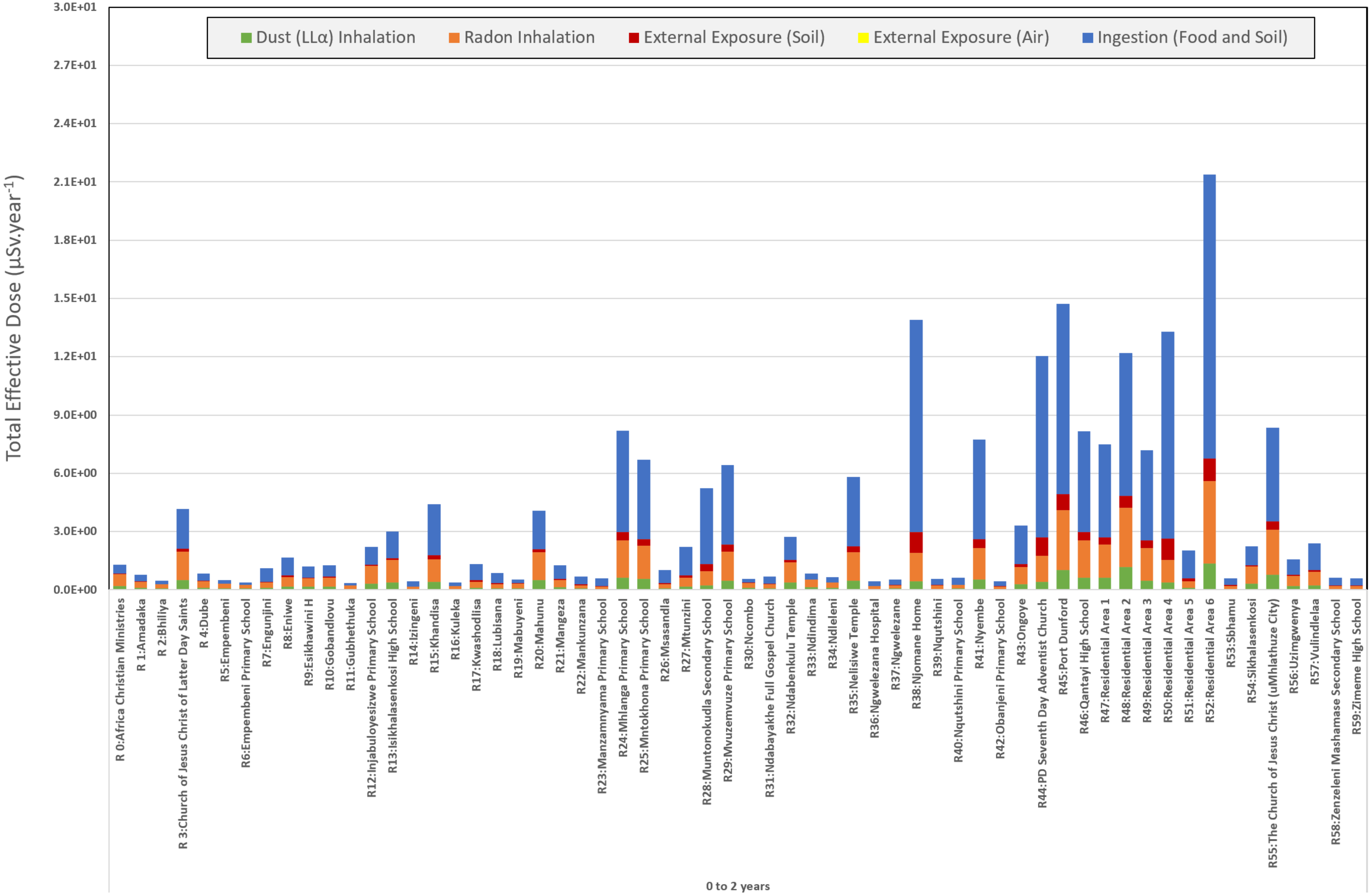

Figure 5.37 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 2 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

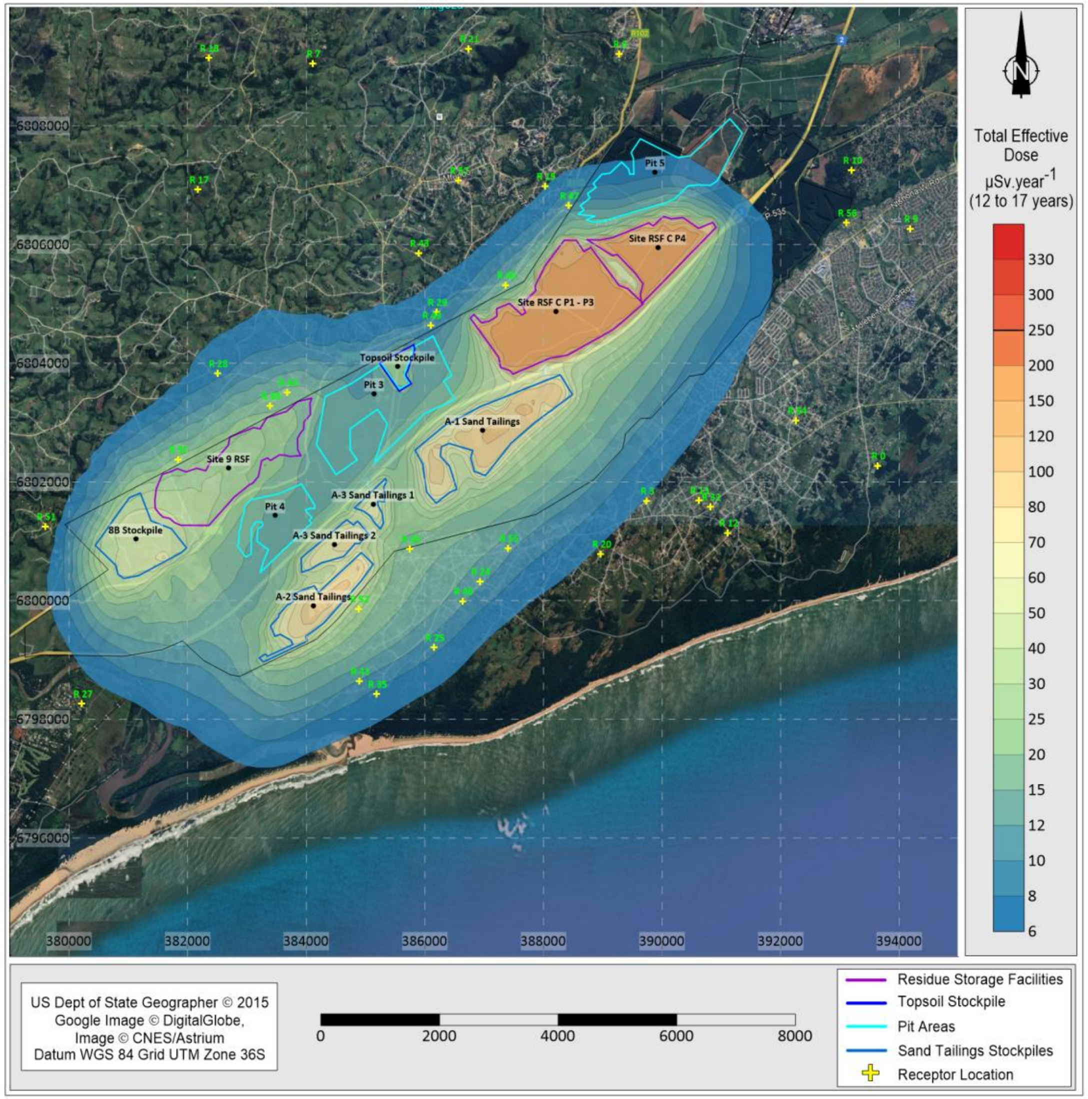

Figure 5.38 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Residential Area Exposure Condition for Phase 2 Scenario 2 for the Port Dunford Mine.**

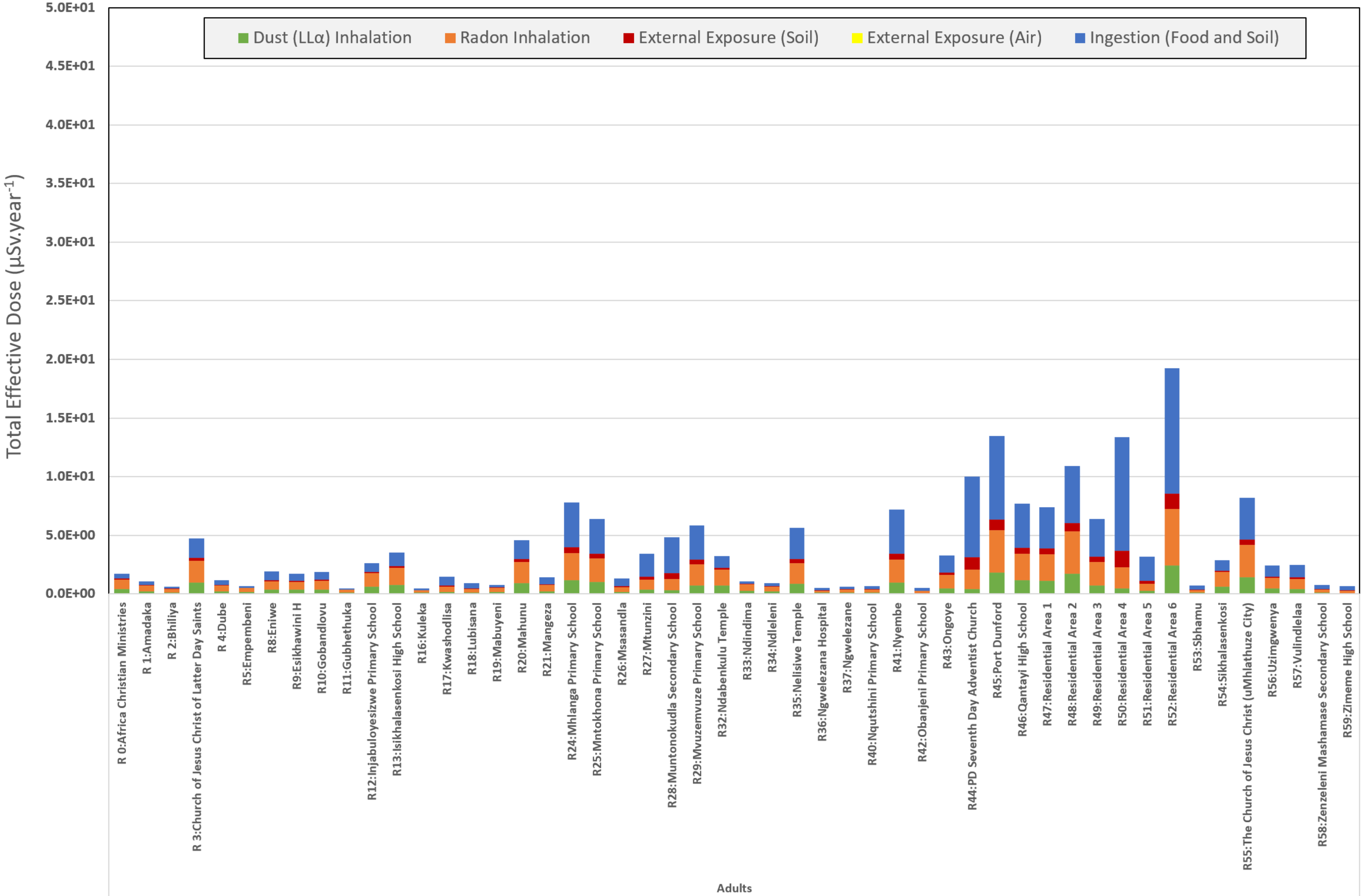

Figure 5.39 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 2 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

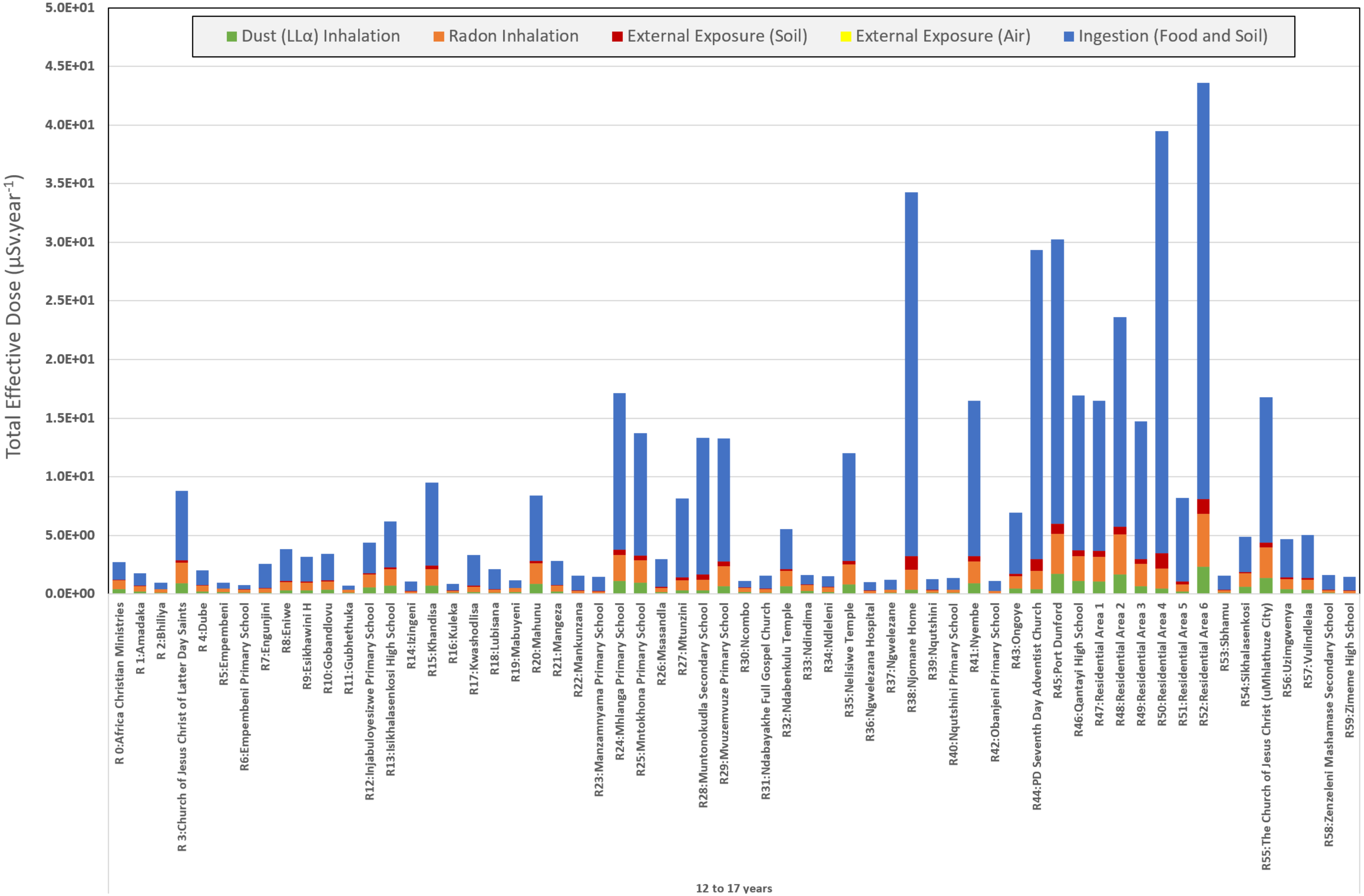

Figure 5.40 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 2 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

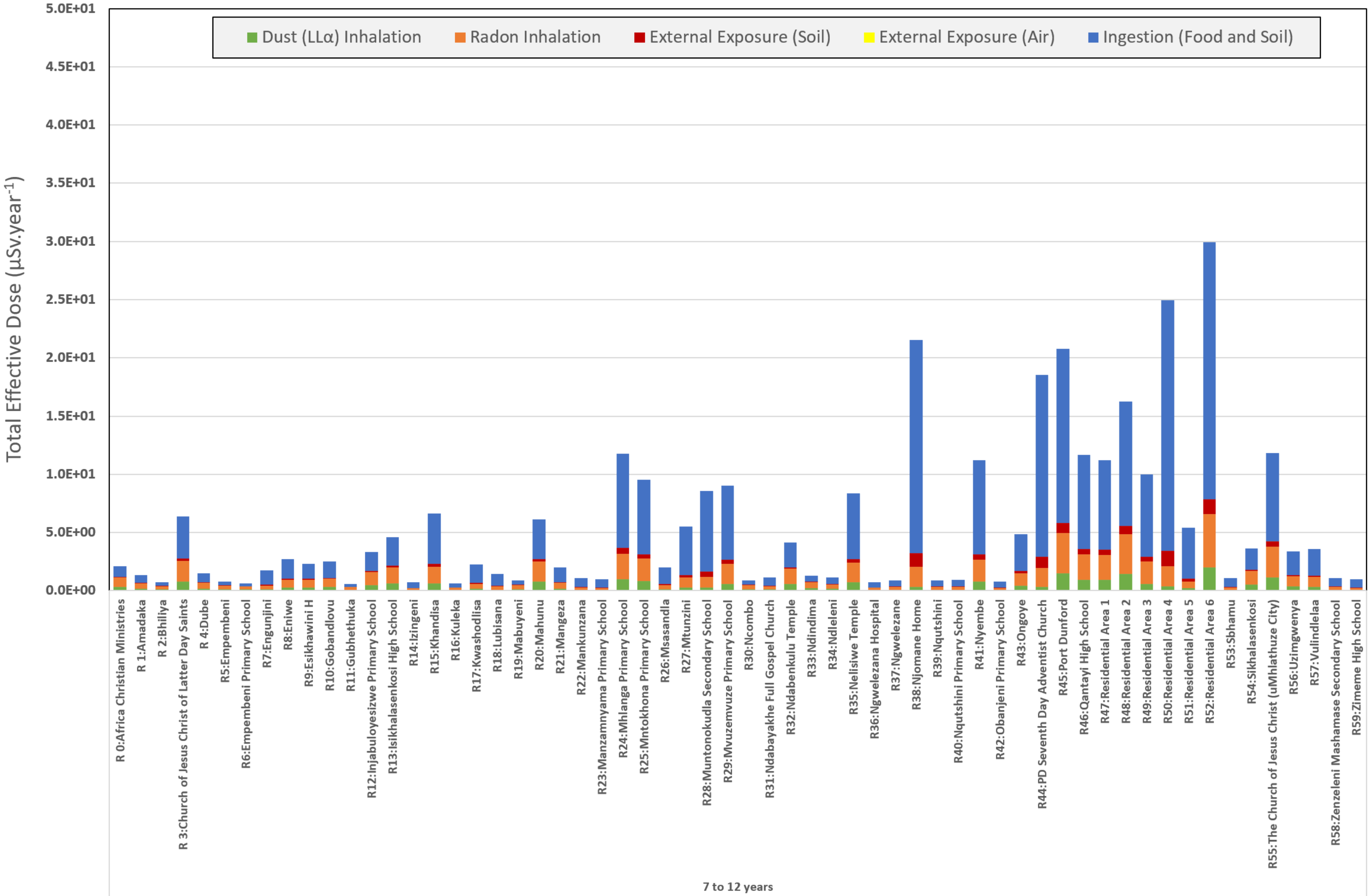

Figure 5.41 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 2 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

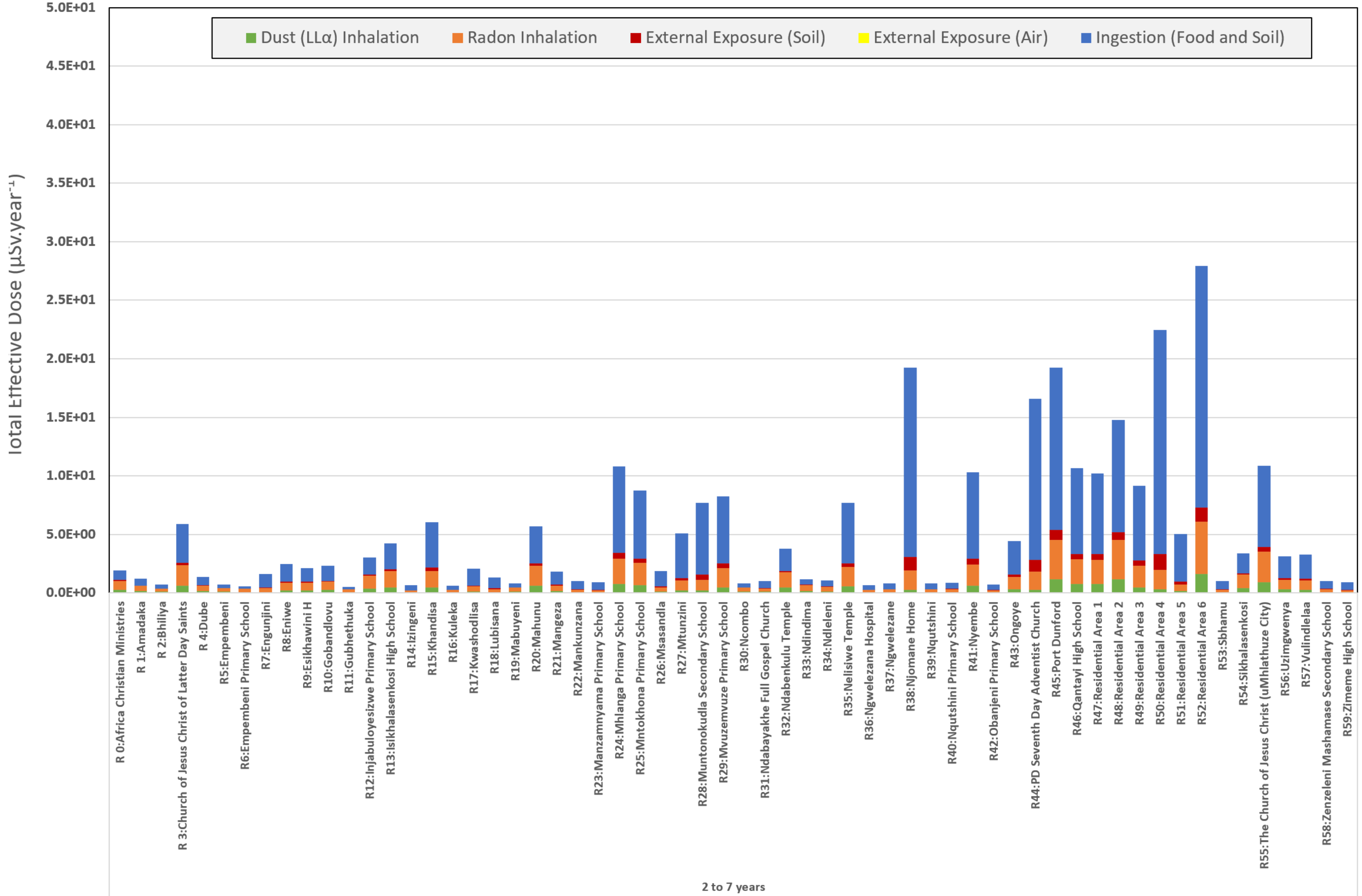

Figure 5.42 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 2 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

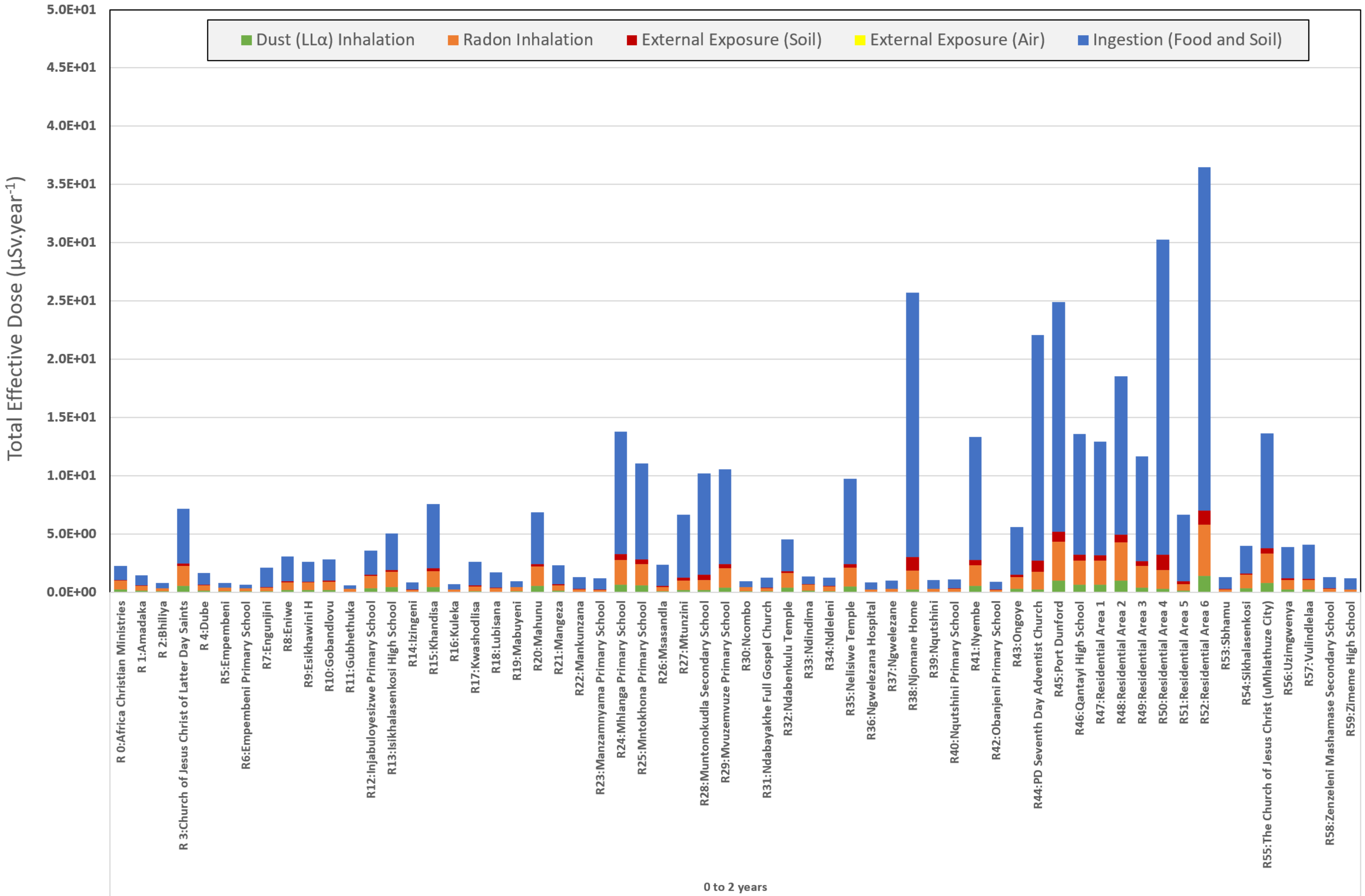

Figure 5.43 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 2 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

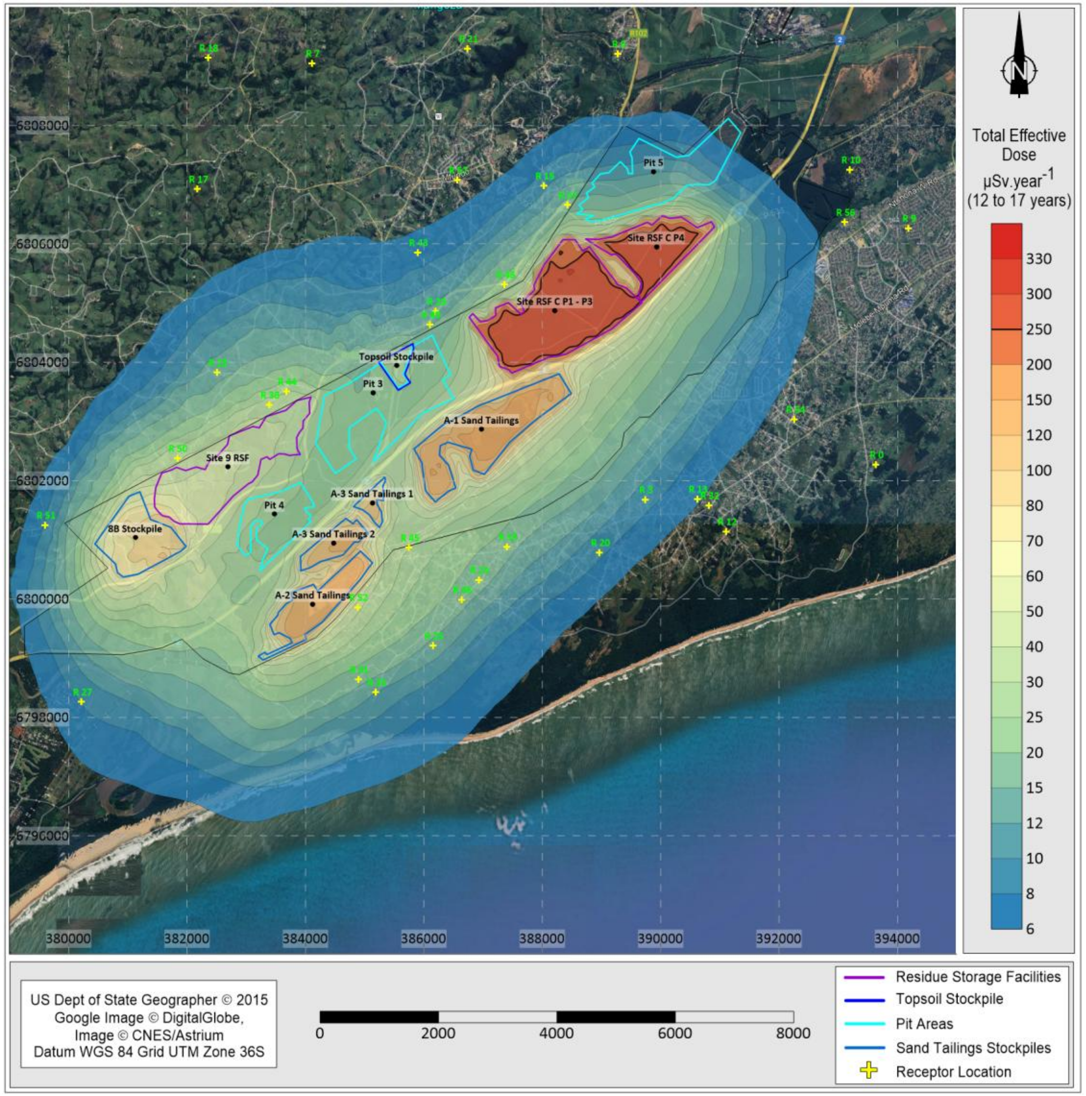

Figure 5.44 Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Agricultural Area Exposure Condition for Phase 2 Scenario 2 for the Port Dunford Mine.

The main contributors to the total effective dose are the ingestion of soil and crops, which suggest that the deposition of dust (TSP) is more significant than the inhalation of airborne dust (PM_{10}).

It can, therefore, be concluded that the impact of Phase 2 Scenario 2 of the Port Dunford Mine will have a low radiological impact on members of the public.

5.4.7 Phase 2: Scenario 3

5.4.7.1 Residential Area Exposure Condition

Figure 5.45 to Figure 5.49 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.50 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 16 µSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 µSv.year^{-1}.

The isopleth map is presented in Figure 5.50, which shows that the maximum total effective dose for Scenario 3 of the Port Dunford Mine is less than 250 µSv.year^{-1}. The maximum calculated total effective dose on top of Site RSF C (P4) is in the order of 190 µSv.year^{-1}. However, residential developments are not possible on top of the facilities. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 30 µSv.year^{-1}.

5.4.7.2 Agricultural Area Exposure Condition

Figure 5.51 to Figure 5.55 presents the dose assessment results for selected receptor locations for the five age group categories listed in Table B 1, respectively (see Table 4.2 and Figure 5.56 for the receptor locations). The results show that the calculated total effective dose doses at the receptor locations are insignificant (less than 24 µSv.year^{-1} for the age group 12 to 17 years, who will receive the highest total effective dose) compared to the public dose constraint of 250 µSv.year^{-1}.

The isopleth map is presented in Figure 5.56, which shows that the maximum total effective dose for Scenario 2 of the Port Dunford Mine only exceeds 250 µSv.year^{-1} on top of Site RSF C (P4). The maximum calculated total effective dose is in the order of 320 µSv.year^{-1}. However, agricultural activities are not possible on top of the facilities. The maximum total effective dose outside the boundary of the Port Dunford Mine is less than 60 µSv.year^{-1}.

5.4.7.3 Interpretation of the Results

The Phase 2 Scenario 3 mining operations are scheduled for 2054 to 2069, with Pit 3, Pit 4 and Pit 5 in addition to the Scenario 2 atmospheric pathway sources that contribute to the radiological impact. The potential radiological exposure to members of the public outside the Port Dunford Mine boundary during this phase is low and less than 60 µSv.year^{-1} for the conservative Agricultural Area Exposure Condition. The 250 µSv.year^{-1} dose constraint is only exceeded on top of some of the facilities.

The total effective dose decreases significantly with distance away from the source area, to such an extent that the calculated doses for selected receptor locations are less than 24 µSv.year^{-1}. Site RSF C (P4) and Pit 3 result in the highest dose contribution during this phase, but since it is located further from the site boundary, it does not have the same effect as Pit 5, for example. The main contributors to the total effective dose are the ingestion of soil and crops, which suggest that the deposition of dust (TSP) is more significant than the inhalation of airborne dust (PM_{10}).

It can, therefore, be concluded that the impact of Phase 2 Scenario 3 of the Port Dunford Mine will have a low radiological impact on members of the public.

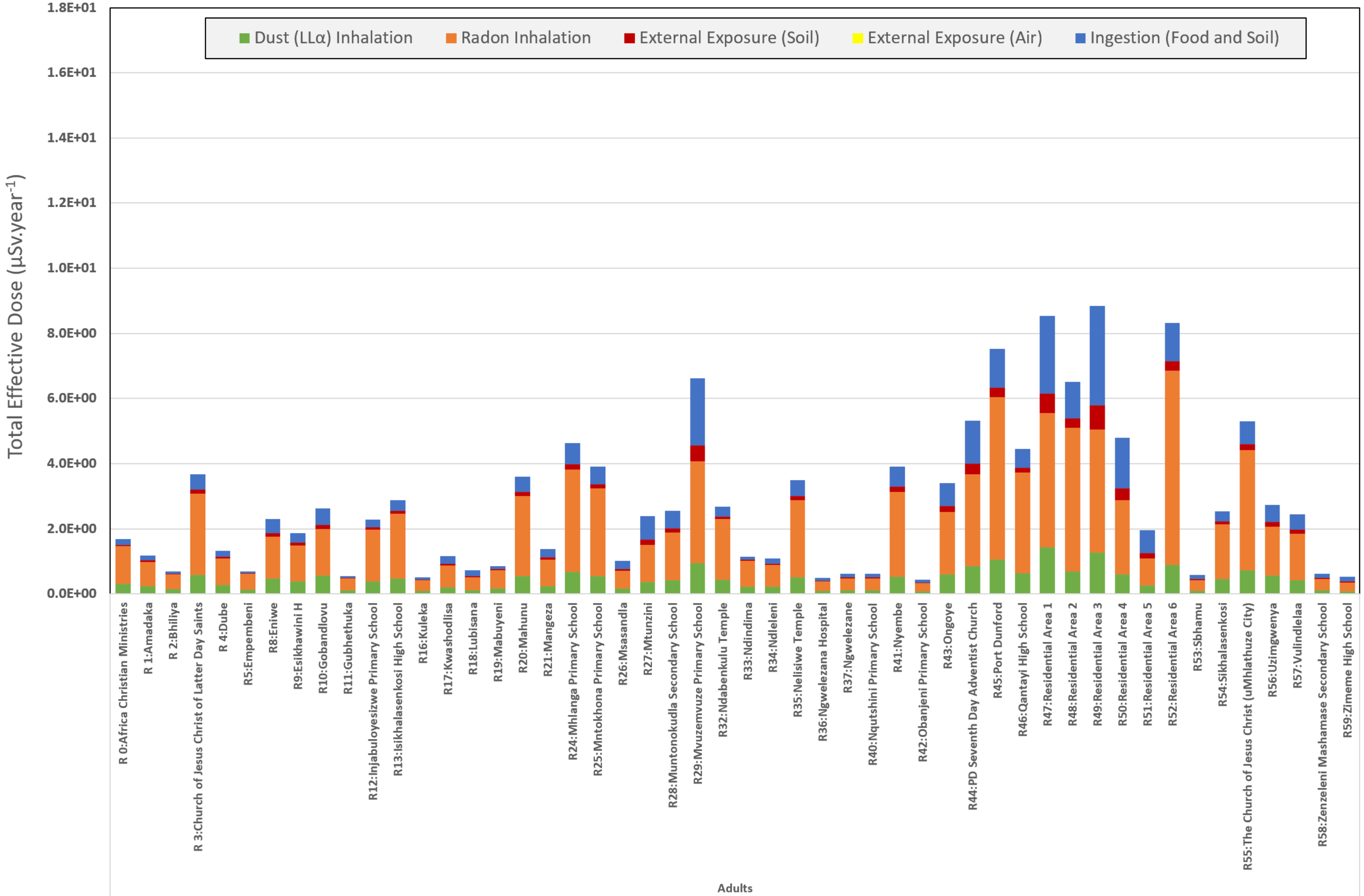

Figure 5.45 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 3 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

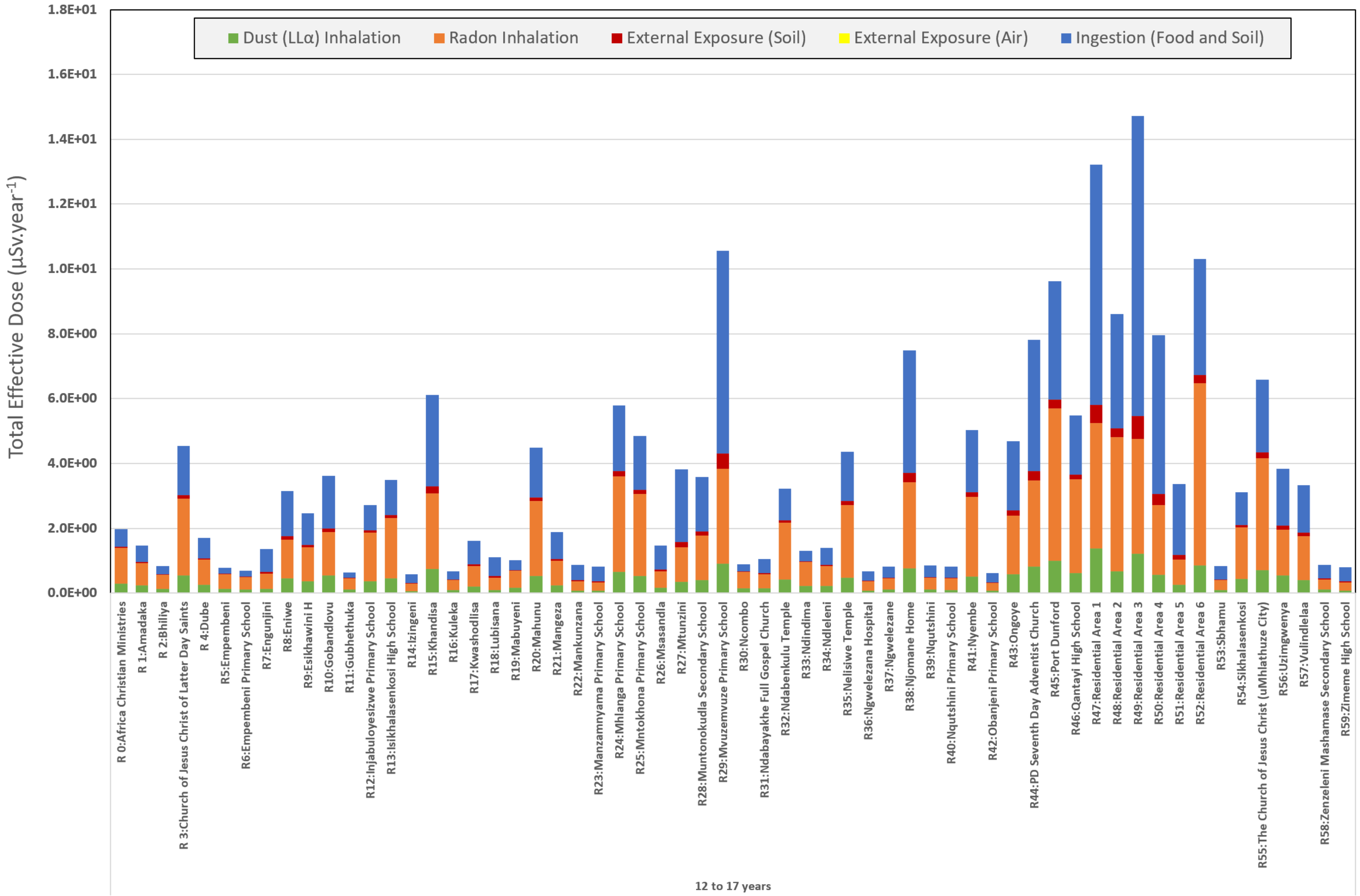

Figure 5.46 **Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 3 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

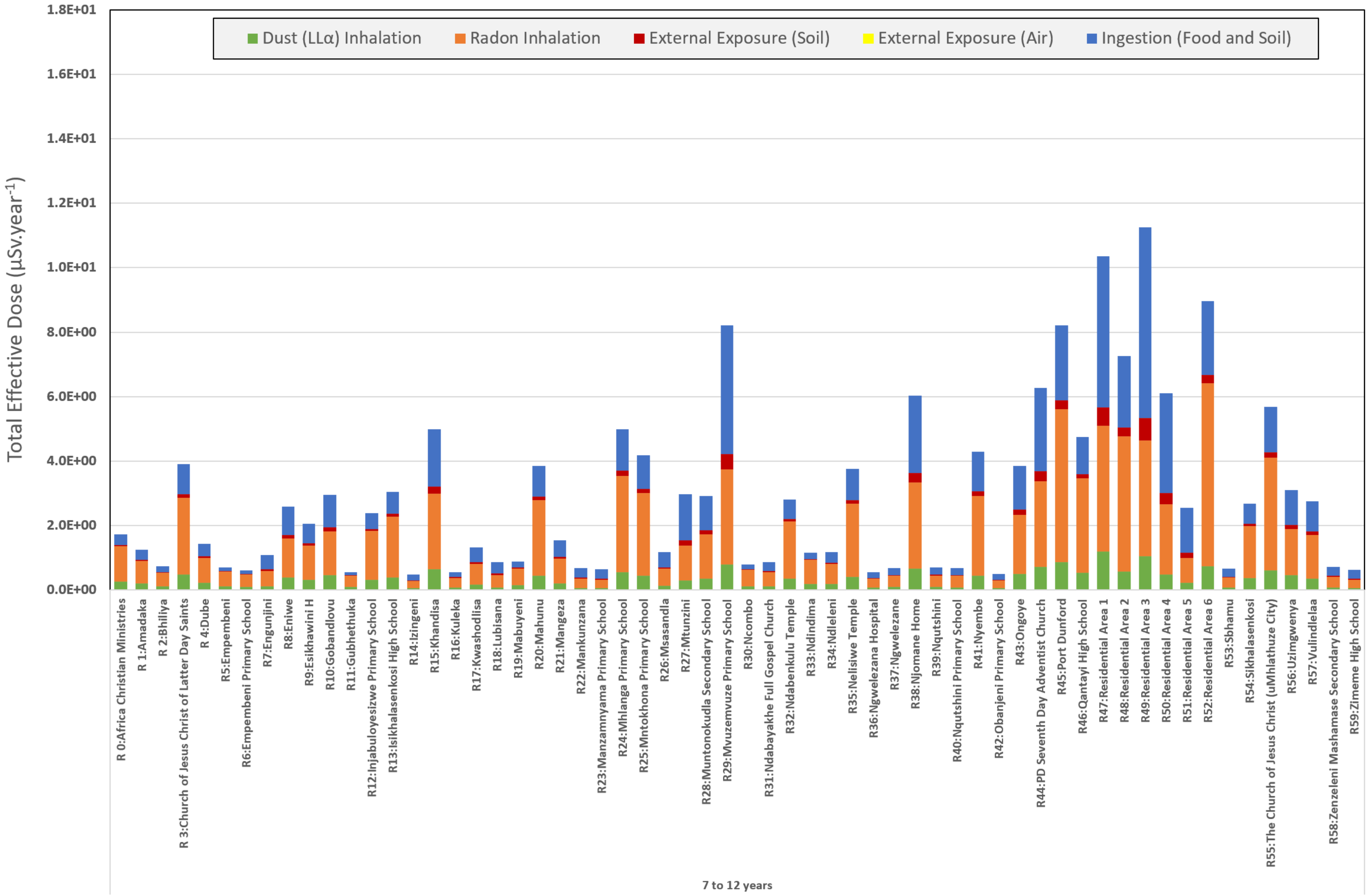

Figure 5.47 **Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 3 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

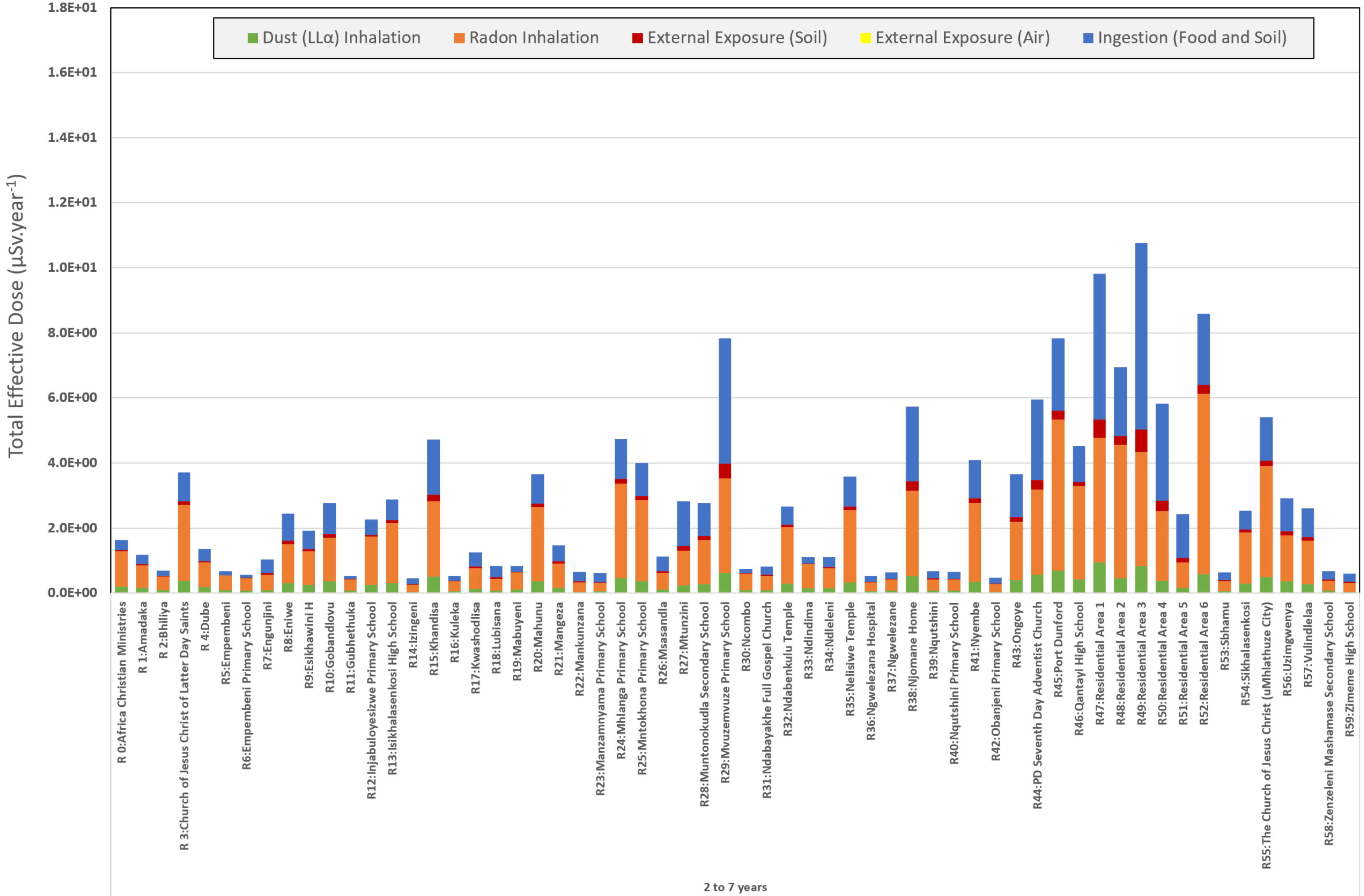

Figure 5.48 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 3 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

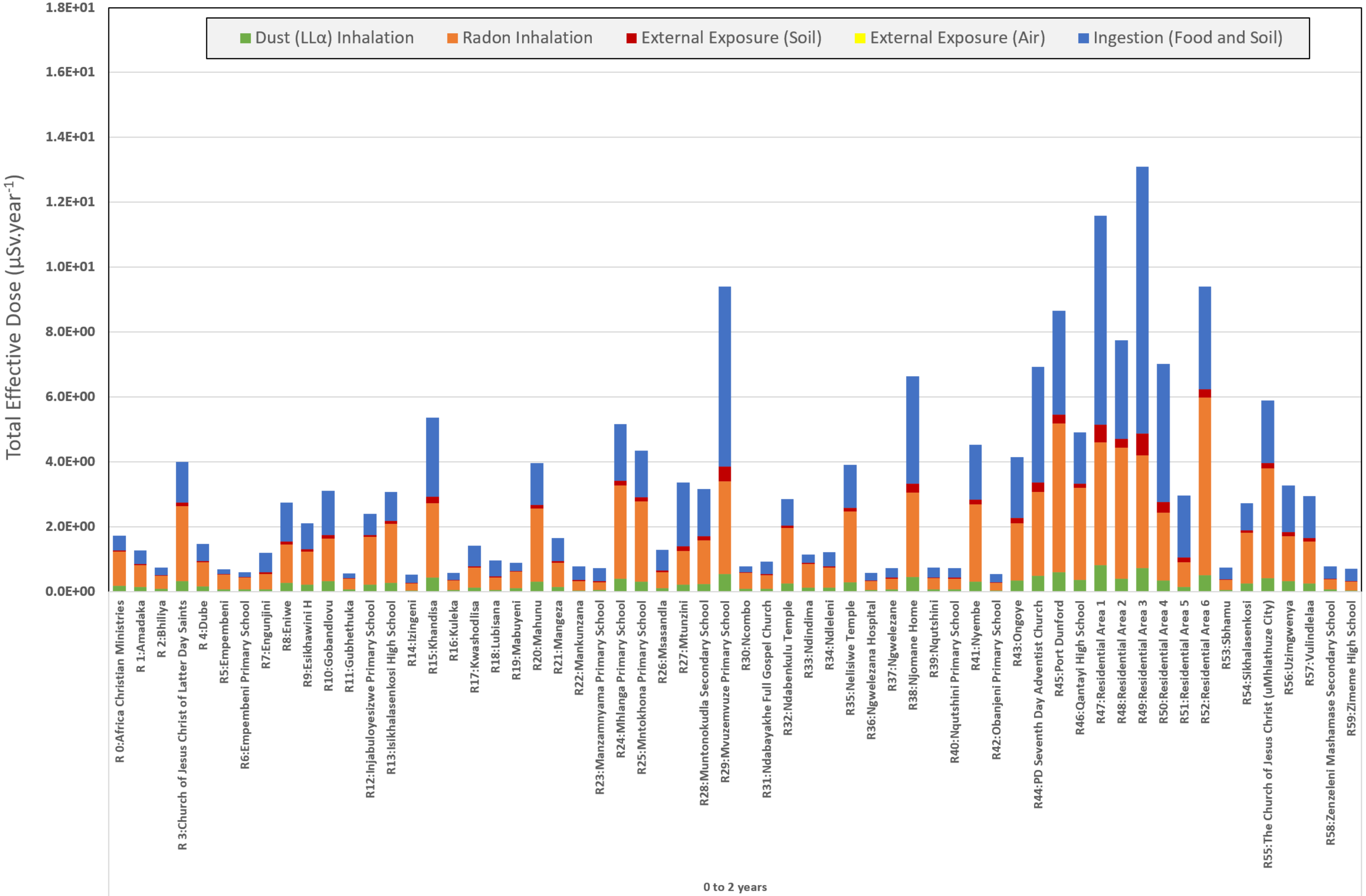

Figure 5.49 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 3 for the Residential Area Exposure Condition (See Figure 5.26 for receptor locations).**

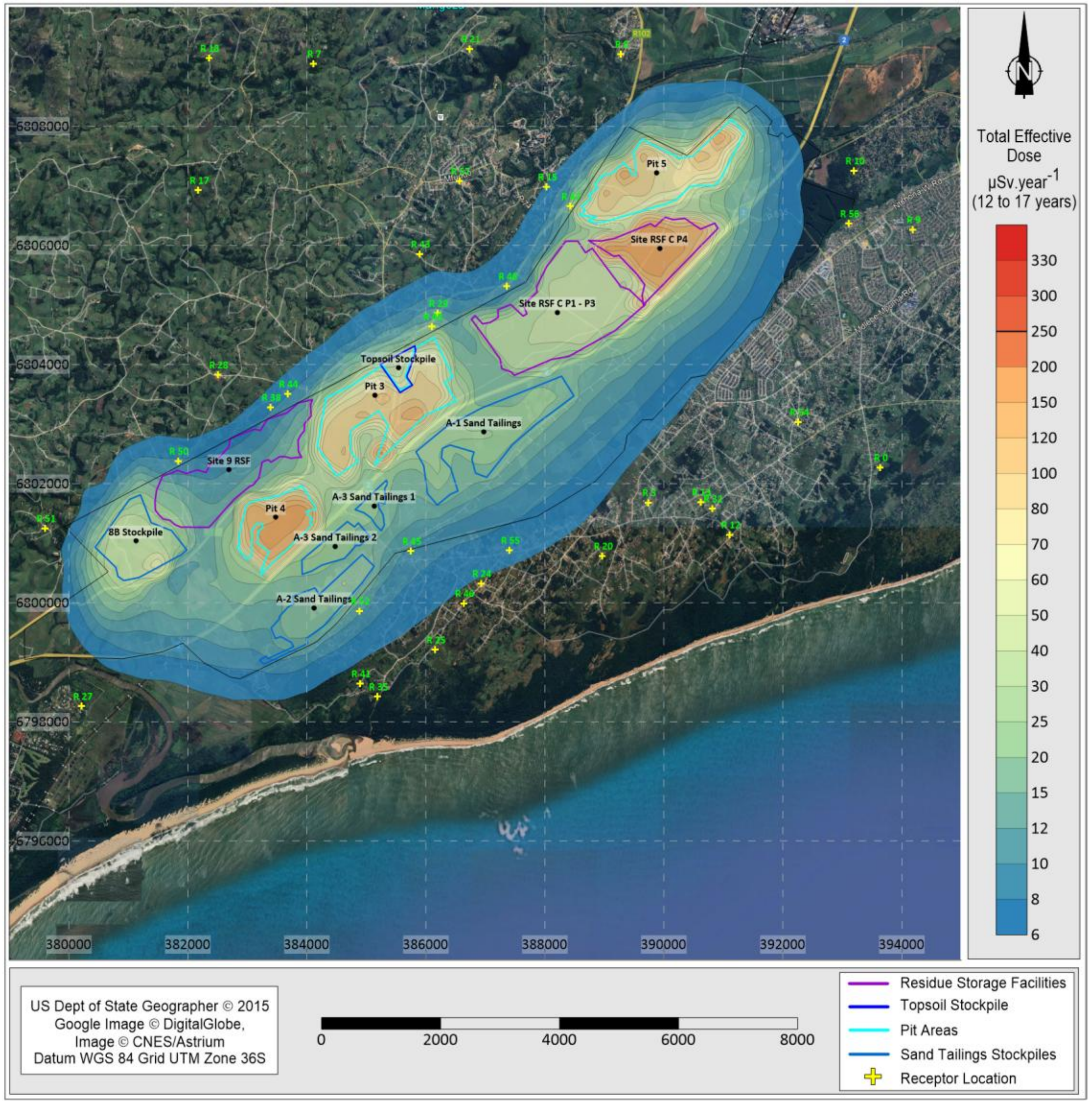

Figure 5.50 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Residential Area Exposure Condition for Phase 2 Scenario 3 for the Port Dunford Mine.**

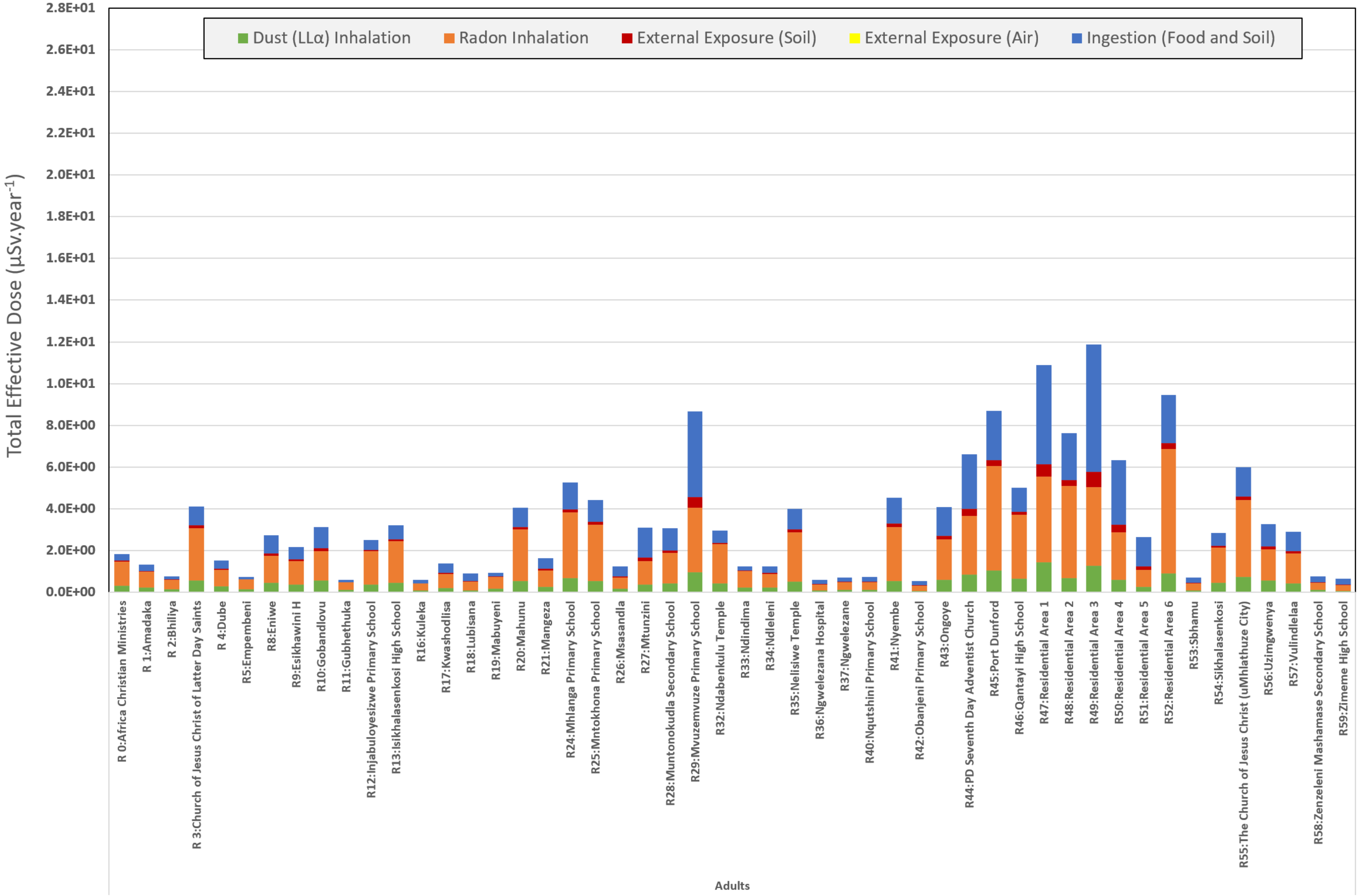

Figure 5.51 **Contribution of the pathway-specific doses to the total dose for adults at receptor locations for Phase 2 Scenario 3 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

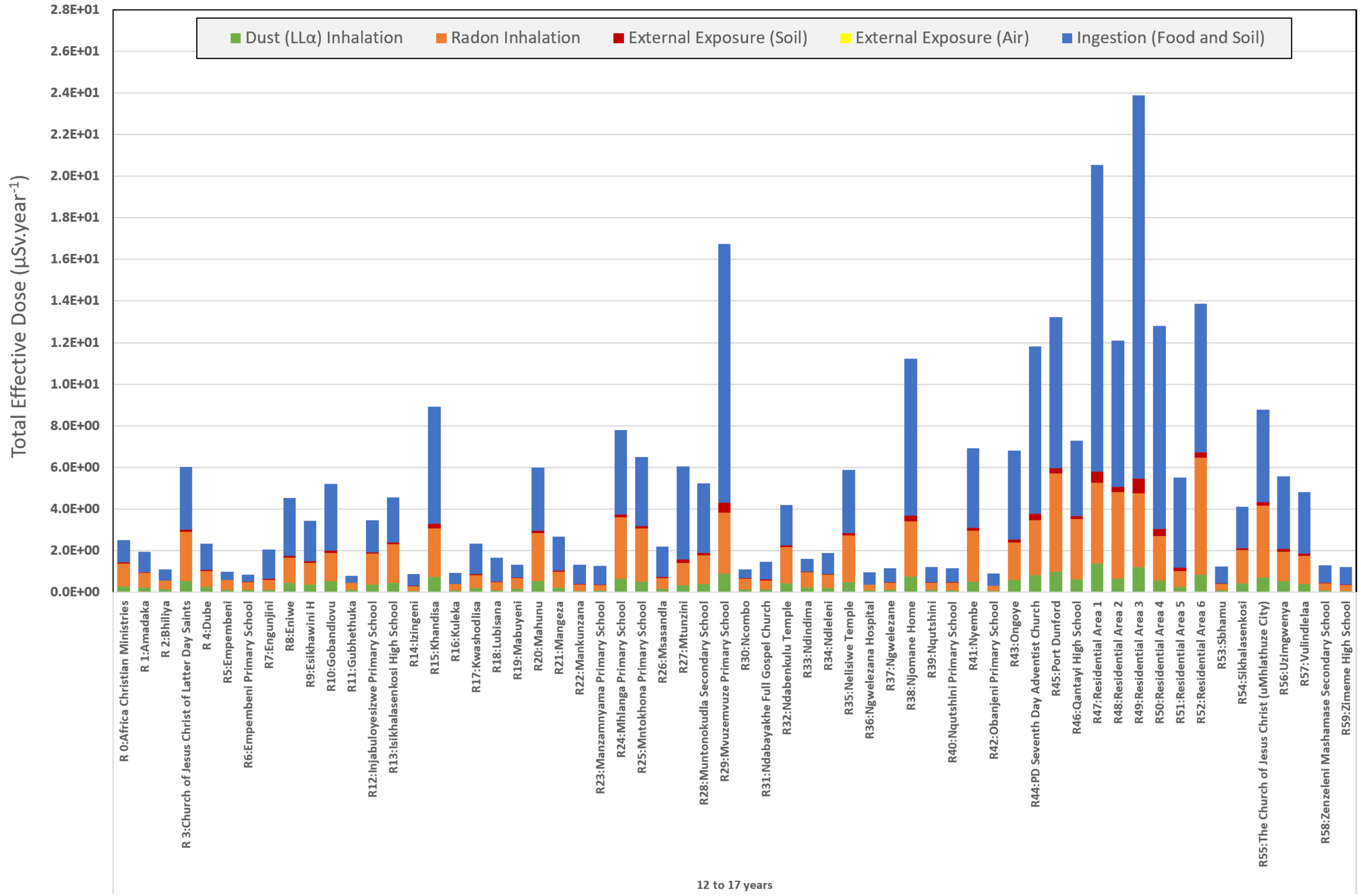

Figure 5.52 Contribution of the pathway-specific doses to the total dose for the 12 to 17 years age group at receptor locations for Phase 2 Scenario 3 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).

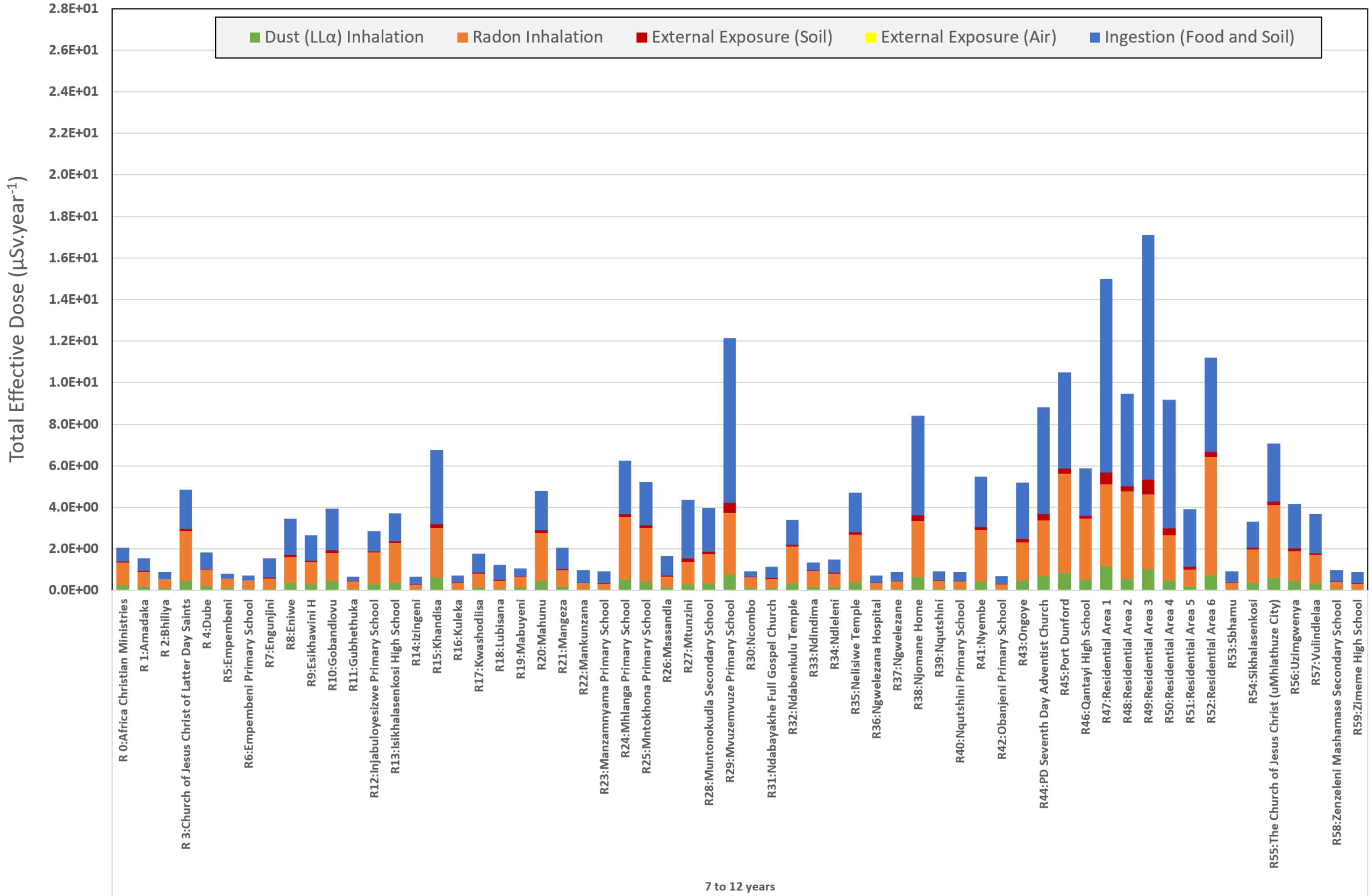

Figure 5.53 Contribution of the pathway-specific doses to the total dose for the 7 to 12 years age group at receptor locations for Phase 2 Scenario 3 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).

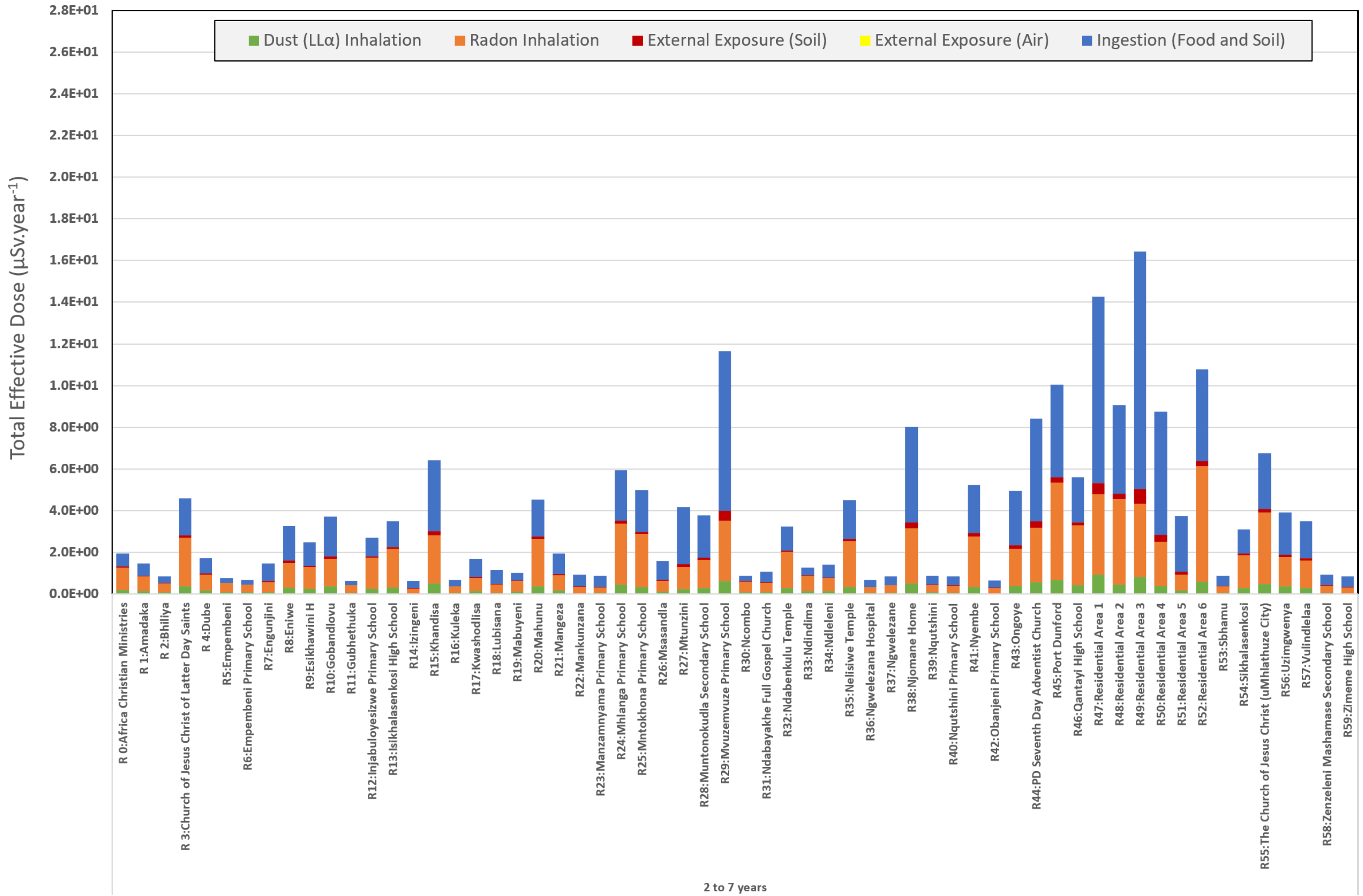

Figure 5.54 **Contribution of the pathway-specific doses to the total dose for the 2 to 7 years age group at receptor locations for Phase 2 Scenario 3 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

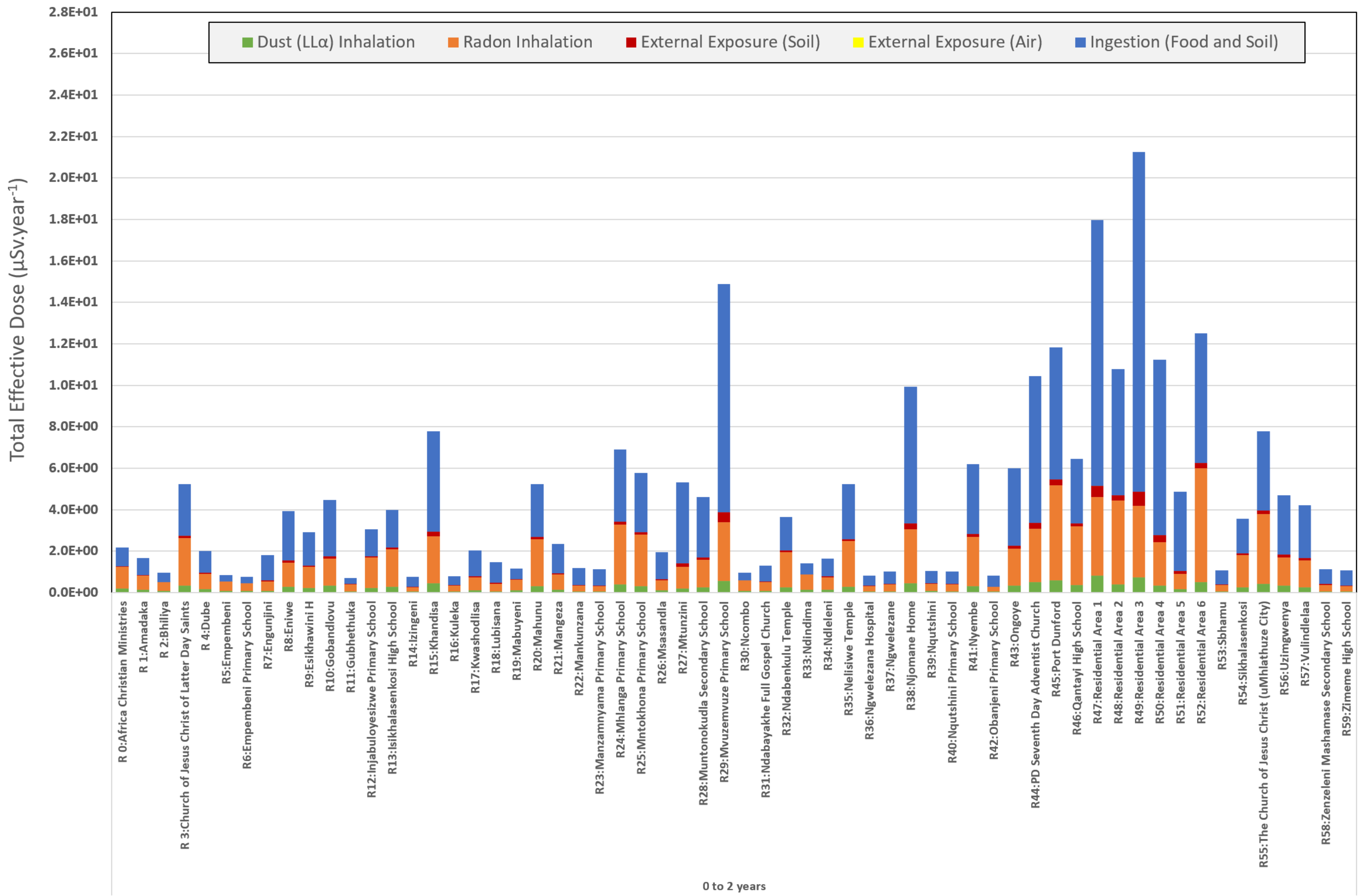

Figure 5.55 **Contribution of the pathway-specific doses to the total dose for the 0 to 2 years age group at receptor locations for Phase 2 Scenario 3 for the Agricultural Area Exposure Condition (See Figure 5.32 for receptor locations).**

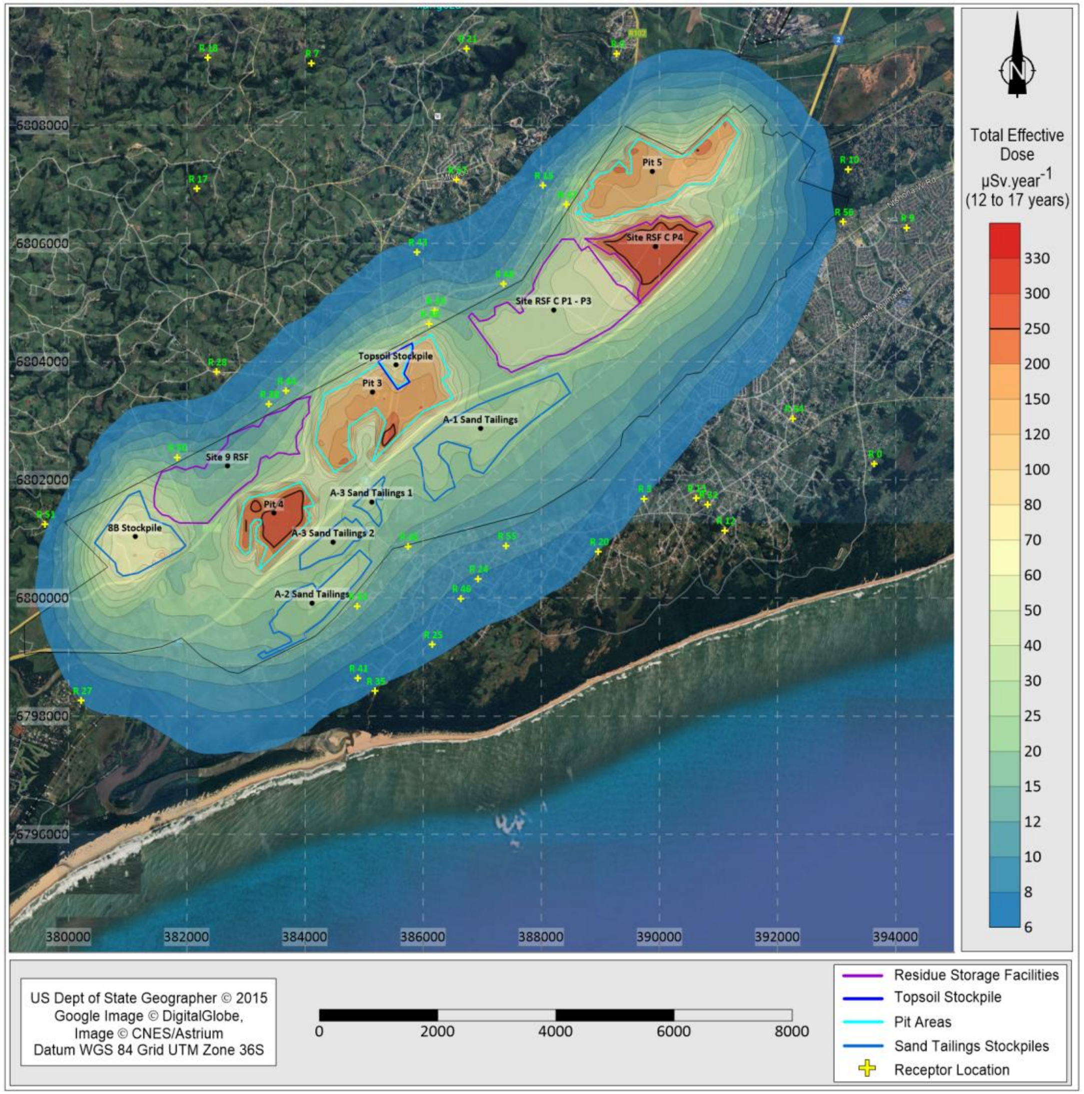

Figure 5.56 **Dose isopleth map representing the total effective dose for the 12 to 17 years age group of the Agricultural Area Exposure Condition for Phase 2 Scenario 3 for the Port Dunford Mine.**

5.4.8 Discussion of Results

The total effective dose calculations presented here were for a Residential Area Exposure Condition and an Agricultural Area Exposure Condition. The two exposure conditions differ in the type of produce that was included in the ingestion route and the associated consumption rates of the produce, with the Agricultural Area Exposure Condition being the more conservative of the two. This resulted in higher ingestion doses and hence higher total effective doses for the Agricultural Area Exposure Condition.

The dose calculations were performed for Phase 1 and Phase 2 (Scenario 1 to Scenario 3) of the Port Dunford Mine, taking into account the introduction of additional facilities as mining progressed as well as the potential variation in radiological properties as the nature of the facilities changes with time. The dose calculations were performed for the age group categories listed in Table B 1. The results were presented as isopleth maps for the age group that resulted in the highest total effective dose, which in this case was the age group 12 to 17 years. The results were also presented at several sensitive receptor locations that correspond to the locations identified in the air quality impact assessment (WSP, 2024b). For these points, the results for all age group categories were presented.

The isopleth maps showed that the highest total effective doses are at the Port Dunford Mine facilities that serve as potential sources of radiation exposure (e.g., RSF, open pit areas, sand tailings stockpiles) but dissipate rapidly with distance away from the sources, to such an extent that none of the selected receptor locations recorded a total effective dose of more than 45 μSv.year^{-1}. The maximum recorded effective dose just outside the Port Dunford Mine boundary for any of the phases or exposure conditions did not exceed 60 μSv.year^{-1}. This is well below the public limit of 1,000 μSv.year^{-1} or even the dose constraint of 250 μSv.year^{-1}.

According to the system description, the MSP Gypsum will be returned to the RSFs and consequently, the activity concentration of the RSF material is represented by the average of the fines and the gypsum. However, the possibility also exists to return it to the mine void. For this reason, it was also included in the mine void material. The results illustrated that both options are acceptable from a radiation exposure perspective.

During the decommissioning and post-closure period, the anticipated land use condition will be to return the land to the landowner once Tronox is satisfied that the facility, and the chosen vegetation cover. This may only be in about 2070 that the land use condition is returned to forestry and possible agricultural activity (e.g., sugar case plantations). The Agricultural Area Exposure condition is very conservative and assumes total dependence on the land to sustain the farm system. Even under these conditions, the maximum dose on top of RSF C is less than 300 μSv.year^{-1}, which is well below the public limit of 1,000 μSv.year^{-1}. This does not take into consideration the reduction of exposure that would be introduced due to a covering layer and the return of the topsoil layer.

It is important to note that the results represent the contribution of the atmospheric pathway to the total effective dose and, consequently, are directly related to the results for PM_{10}, TSP and radon gas produced as part of the air quality impact assessment for the Port Dunford Mine presented in WSP (2024b). Furthermore, the Port Dunford Mine is not operational yet, which means that the results represent a prospective assessment. The radiological properties of the materials used in the assessment are based on the most recent radioanalytical results for materials generated as part of the Fairbreeze mine (see Section 3.5.3). The prospective assessment should be updated with a site-specific assessment once radiological analysis results for the Port Dunford Mine materials become available.

6 Sensitivity and Uncertainty Analysis

6.1 General

The consequence analysis presented in Section 5 is based on several conditions and parameter values that were presented in the *System Description* (see Section 3), the *Definition and Justification of Public Exposure Conditions* (see Section 4) and the *Mathematical Model Development* (see Appendix B). These results are viewed as the most realistic and representative of the potential radiological impact on members of the public residing near the Port Dunford Mine. However, the inherent nature of a safety assessment for a mining and mineral processing operation is such that uncertainties exist, both in the conditions assumed and the parameter values used. It was from this perspective that the inexact nature of safety assessments was highlighted in the *Assessment Context* (see Section 2). The purpose of this section is to address some of these uncertainties and to evaluate the sensitivity of the assessment results to variations in conditions and parameter values. Viewed from this perspective, it serves as a “what if” analysis in support of the overall safety case for the Port Dunford Mine.

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

6.2 Cumulative Radiological Impact

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

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

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

The focus of the assessment is on the contribution of the Port Dunford Mine to the annual effective dose to members of the public. Other potential sources of radiation exposure to members of the public include the now-closed Hillendale Operation and the Fairbreeze Operation of Tronox KZN. However, it follows from Section 5, that the potential total effective dose as a contribution from the Port Dunford Mine will be less than 250 μSv.year^{-1}. This means that similar contributions from the neighbouring operations will most likely still result in a total effective dose of less than the dose limit of 1,000 μSv.year^{-1}.

6.3 Variations in Public Exposure Conditions

6.3.1 General

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

6.3.2 Variation in the Defined Exposure Conditions

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

Members of the public who reside in more formal residential areas with fewer household gardens to supplement their daily consumption of produce will be subject to lower levels of exposure than those considered in the Residential Area Exposure Condition.

The Agricultural Area Exposure Condition is highly conservative, assuming that the exposure group relies entirely on the land for its annual food supply, including protein sources (e.g., poultry, beef, eggs, and milk), vegetables (e.g., leafy and root varieties), and fruit. Therefore, it is unlikely that any variation in land use conditions would result in higher radiation doses than those calculated under this condition. This includes activities such as sugarcane farming or forestry, as forestry does not involve the direct ingestion of produce grown on the affected land.

Furthermore, members of the public who work in the area (e.g., workers in the forestry industries) will only be subject to inhalation and external exposure, which constitute a relatively small contribution to the total effective dose, especially since they will only be exposure during the day and not on a full-time basis.

6.3.3 Alternative Exposure Conditions

6.3.3.1 General

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

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

6.3.3.2 Spillage of Solid materials

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

- What was spilt (i.e., water, sludge, sand tails, or coarse sand tails) and what is the activity concentration of the water or material that was spilt;
- Where the spillage took place (i.e., on a public road, open field or at or nearby surface water body or nearby residential area), how long the spillage lasted and the lateral extent (area) that was contaminated; and
- How long the potential contamination is left unintended before remedial action for the area is instituted and there is a possibility that members of the public have access to the contaminated area?

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

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

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

Figure 6.1 and Table 6.1 show that an exposure period of more than 600 hours to the PWP HMC will result in a total effective dose of more than 250 μSv.year^{-1}. For the MSP Slimes and MSP Gypsum, the exposure limit is in the order of 1,200 hours. For the MSP Sand Tails, the PWP Sand Tails and the PWP Slimes, the exposure limit is more than 3,000 for a dose of 250 μSv.year^{-1}.

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

6.3.3.3 Water Spillage

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

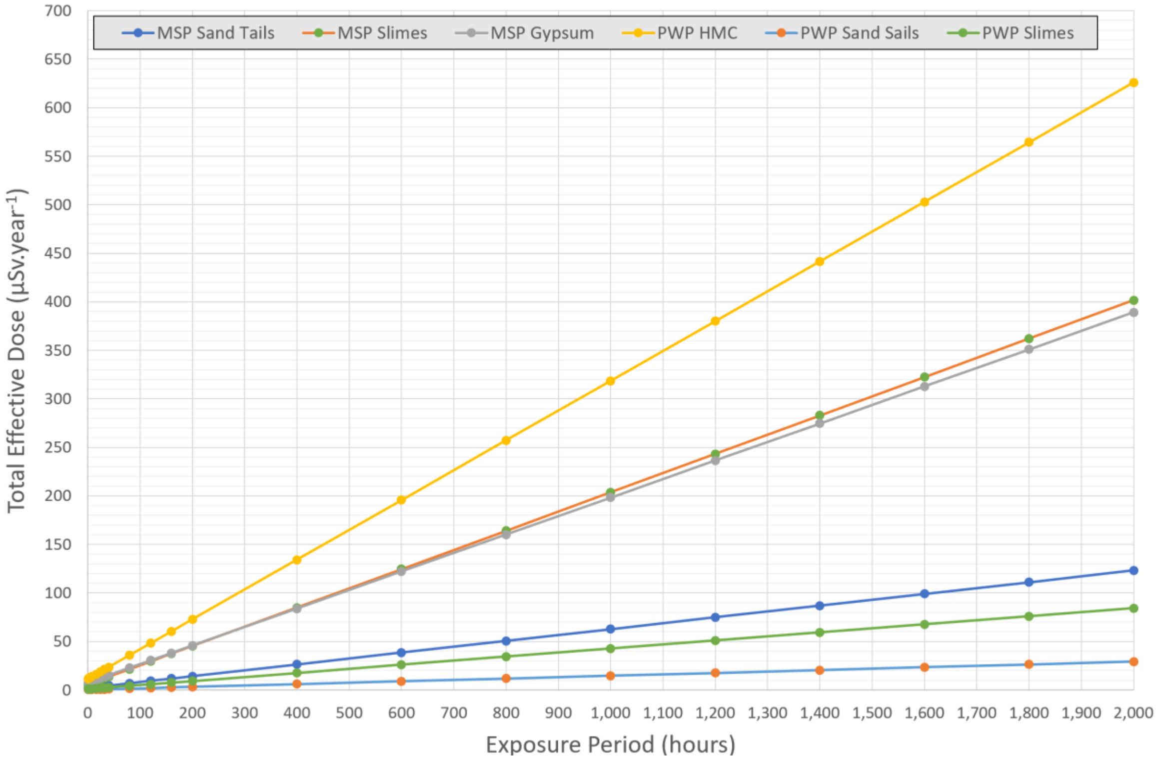

Figure 6.1 **Total effective dose for the six Port Dunford Mine TSFs as a function of the exposure period.**

Table 6.1 **Summary of the exposure period (in hours) for each material to limit the total effective dose to 250 µSv.year^{-1}.**

Solid Material	Exposure Period (hours)
MSP Sand Tails	2,000
MSP Slimes	1,200
MSP Gypsum	1,200
PWP HMC	600
PWP Sand Sails	2,000
PWP Slimes	2,000

6.4 Variation in Parameter Values

6.4.1 Human Consumption Values

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

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

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

6.4.2 Dust Deposition Period

The dose calculations for the different exposure conditions were performed assuming a 75-year deposition period, which was assumed to be realistic given the history of the Port Dunford Mine. The dose assessment models assumed a build-up of activity on the soil surface over this period, which by implication influenced the total effective dose. One can thus assume that the surface soil concentration will continue to increase steadily with time. Experience shows that the rate of build-up increases until about 2,000 years, after which equilibrium is reached with removal processes such as radiological decay and leaching. Over this period, the ingestion doses can potentially increase more than three-fold, but with an accompanying increase in uncertainties.

6.4.3 Parameters Used to Evaluate the Contribution of the Groundwater Pathway

Section 5.2 evaluated the contribution of the groundwater pathway. For this purpose a combination of site-specific and generic parameter values was used to calculate the potential total effective dose from the ingestion of water abstracted downstream from a large area facility (e.g., RSF).

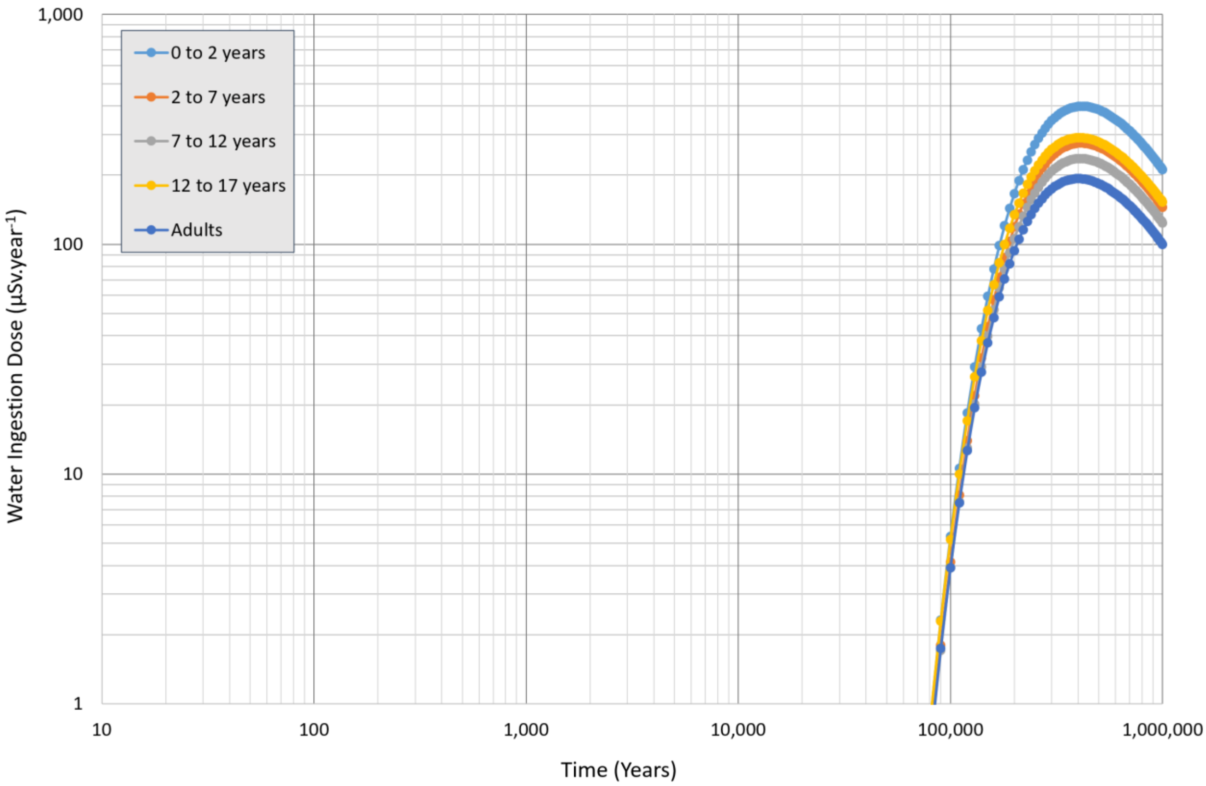

Figure 6.2 The simulated water ingestion dose to the different age groups 500 m from the Port Dunford Mine RSF C, using the Gypsum sample activity concentrations (See Table 3.8).

The selected parameter values have the potential to influence the results: For example:

- The results are directly related to the activity concentration of the source material. The results presented in Section 5.2 assumed the average of the MSP Slimes and PWP Slimes samples in Section 3.5.3. Using the Gypsum sample results, for example, will result in a higher ingestion dose, as illustrated in Figure 6.2 (see Figure 5.4).
- An unsaturated zone thickness of 1 m was assumed. A thicker zone will increase the flow path and the peak dose will take longer to reach the borehole;
- The saturated zone thickness was assumed to be 20 m. If increased to decreased, the dilution and dispersion in the aquifer will be higher or lower and will influence the peak dose at the borehole accordingly.
- The selection of the hydraulic parameters to calculate the Darcy velocity (e.g., hydraulic gradient, hydraulic conductivity and effective porosity) will influence the advective flow rate through the aquifer.
- The results are very sensitive to the sorption properties (Kd-values) assumed for the source material, as well as the unsaturated and saturated zones, which define the retarded migration of contaminants relative to the advective transport.
- It was assumed that the borehole that is used to abstract water only from the contaminant plume and is not diluted by fresh water.

7 Impact Assessment

7.1 General

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

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

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

7.2 Construction Phase

The Port Dunford Mine is a new operation, which means that several construction activities will be required to establish the mine surface infrastructure. The activities involve, amongst others, site clearance and footprint preparation for the open pit areas and the construction/upgrade of access and haul roads.

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

7.3 Operational Phase

7.3.1 General

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

The operational period is further divided into Phase 1 (2025 to 2036) and Phase 2, which is further divided into Scenario 1 (2036 to 2047), Scenario 2 (2048 to 2054) and Scenario 3 (2054 to 2069). The time-dependent nature of the Port Dunford Mine means that the radiological impact will vary from the initial Phase 1 activities towards the closure of the operation at the end of Phase 2. The radiological public safety assessment presented in Section 5 considered this variation in site-specific conditions, which illustrated that the radiological impact on members of the public varies over the LoM.

7.3.2 Activities

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

- Exhalation and dispersion of radon gas from the RSFs (Phase 2), open pit areas and various stockpile facilities; and
- Emission and dispersion of particulate matter containing radionuclides from the RSFs (Phase 2), open pit areas, and the various stockpile facilities, as well as due to relevant loading and hauling activities.

Table 7.1 summarises the activities associated with the operational phase that may have a potential radiological impact on the receptors identified for the Port Dunford Mine.

Table 7.1 Summary of the activities and the impact of the activities during the operational phase of the Port Dunford Mine.

Interaction	Impact
Exhalation and dispersion of radon gas into the atmosphere	Radon gas generated in the area sources (e.g., RSFs, open pit areas and stockpiles) due to the presence of Ra-226 will be exhaled into the atmosphere. Inhalation of the radon gas contributes to the total effective dose.
Emission and dispersion of particulate matter into the atmosphere	Wind erosion at the area sources (e.g., RSFs, open pit areas and stockpiles) will cause particulate matter containing radionuclides to be emitted into the atmosphere. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion and external radiation exposure routes.

7.3.3 Exhalation and Dispersion of Radon Gases

7.3.3.1 Impact Description

During the operational phase and for the duration of the LoM, radon gas is generated in the RSFs and stockpile facilities due to the presence of Ra-226. The same applies to the open pit areas. This means that the radon gas is exhaled continuously from these facilities and areas into the atmosphere. Following the exhalation and subsequent dispersion of the radon gas into the atmosphere, inhalation of the airborne gas contributes to the total effective dose to receptors identified for the Port Dunford Mine.

7.3.3.2 Management/Mitigation Measures

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

On average, the total effective dose calculated at receptor locations varies from 0.01% (Phase 1) to 2.3% (Phase 2) of the public dose constraint of 250 $\mu Sv.year^{-1}$, of which radon inhalation contributes 25% to 40%. This is significantly lower than the regulatory compliance criteria, which means that from a compliance perspective, no additional management or mitigation measures are required for radon inhalation. From a dose optimisation perspective, the following can be noted.

- The radon exhalation rate from the surface facilities (e.g., RSFs, open pit areas and various stockpile facilities) is determined by several factors, of which moisture content is one. This means that by keeping the facilities wet, the exhalation rate will be reduced marginally. However, it is not effective to wet all the surface facilities deep enough (2 to 4 m) to reduce the radon exhalation rates marginally.

- The most effective way to reduce the radon exhalation rates 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 surface.

7.3.3.3 Impact Rating

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

Table 7.2 Impact significant rating for the exhalation and dispersion of radon gas during the operational phase of the Port Dunford Mine.

Impact Description: Exhalation and dispersion of radon gas to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

7.3.4 Emission and Dispersion of Particulate Matter

7.3.4.1 Impact Description

During the operational phase and for the duration of the LoM, the RSF, open pits areas and stockpile facilities will cause particulate matter containing radionuclides to be dispersed into the environment through the atmospheric pathways. Under worst-case conditions, these facilities and activities will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere for the duration of the operational period.

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 Port Dunford Mine include inhalation of the airborne dust, ingestion of contaminated soil, crops and animal products, and external gamma radiation through cloud shine and ground shine.

7.3.4.2 Management/Mitigation Measures

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

On average, the total effective dose calculated at receptor locations varies from 0.01% (Phase 1) to 2.3% (Phase 2) of the public dose constraint of 250 μSv.year^{-1}, of which radon inhalation contributes 9% to 18%. This is significantly lower than the regulatory compliance criteria, which means that from a compliance perspective, no additional management or mitigation measures are required for dust inhalation.

The contribution of external exposure (cloud shine and ground shine) is less than 5% (on average) of the total effective dose for all age groups at selected receptor locations. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for external gamma radiation.

The contribution of animal and crop ingestion is less than 50% (on average) of the total effective dose for all age groups at selected receptor locations, which is an indication of the TSP deposition rate. This means that from a regulatory compliance perspective, no additional management or mitigation measures are required for the ingestion pathways.

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 (WSP, 2024b), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Wetting of material before feeding into the DTMUs.
- Hydraulically transferred material will be deposited wet on relevant stockpiles and pits during backfilling.
- Use of water sprayers in the PWP screening and crushing processes.
- Rehabilitation and vegetation of legacy stockpiles and backfilled areas.
- Develop an air quality management plan for the Port Dunford Mine, including air quality monitoring to ensure compliance at upwind and downwind locations.

7.3.4.3 Impact Rating

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

Table 7.3 Impact significant rating for the particulate matter emission and dispersion that contains radionuclides during the operational phase of the Port Dunford Mine.

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

7.4 Post-Closure Phase

7.4.1 General

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

7.4.2 Activities

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

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

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

Table 7.4 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 regulatory authority. The RSFs and backfilled open pits areas will be covered with a topsoil layer.
Exhalation of radon gas and particulate matter from the remaining surface facilities (e.g., RSF) to the atmosphere	Radon gas generated in the remaining facilities (e.g., RSF material) due to the presence of Ra-226 will be exhaled into the atmosphere. Inhalation of the radon gas contributes to the total effective dose. Wind erosion at the remaining facilities will cause particulate matter containing radionuclides to be emitted into the atmosphere. The airborne dust (PM_{10}) and deposited dust (TSP) contribute to the total effective dose through inhalation, ingestion and external radiation exposure routes.
Leaching and migration of radionuclides from the TSF	Radionuclides will leach from the RSF into the underlying aquifer, after which they will migrate in the general groundwater flow direction. Abstraction and use of the contaminated water contribute to the total effective dose through the ingestion and possible external radiation exposure routes.

7.4.3 Implementation of the Decommissioning Plan

7.4.3.1 Impact Description

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

A gamma radiation survey will be performed at the infrastructure sites, followed by appropriate rehabilitation and clean-up operations for conditional or unconditional clearance from the regulatory authority. In addition, any area that may have become contaminated during or because of operational activities will also be rehabilitation and clean-up for conditional or unconditional clearance. The RSFs and backfilled open pit areas will be covered with a topsoil layer.

7.4.3.2 Impact Rating

Table 7.5 presents the impact significant rating for the implementation of the decommissioning plan of the Port Dunford Mine.

Table 7.5 Impact significant rating for the implementation of the decommissioning plan of the Port Dunford Mine.

Impact Description: Implementation of the NNR-approved decommissioning plan of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Positive	5	1	3	5	4	**56**	**P3**
	Significance	**P3 - Moderate**						

7.4.4 Exhalation of Radon Gas and Particulate Matter

7.4.4.1 Impact Description

During the post-closure phase, some of the facilities (e.g., RSF) will remain at the surface and continue to serve as sources of radiation exposure to members of the public. These facilities will serve as a source of windblown dust (i.e., wind erosion) to the atmosphere during the post-closure period. During the same period, radon gas generated in the RSF materials due to the presence of Ra-226 will continue to be exhaled into the atmosphere. While the RSF is one example, it also depends on what the closure plan for the open pit areas would be. Also, if the decommissioning plan is not implemented to its full extent, then there is a possibility that unrehabilitated footprint areas remain at the surface.

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 Port Dunford Mine include inhalation of the airborne dust, ingestion of contaminated soil, crops and animal products, and external gamma radiation through cloud shine and ground shine.

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

7.4.4.2 Management/Mitigation Measures

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

The total effective dose as a contribution from the windblown dust, as well as radon gas released from the remaining facilities, is well below the regulatory compliance criteria (dose constraint), which means that from a compliance perspective, no additional management or mitigation measures are required. On average, the total effective dose calculated at sensitive receptor locations varies from 0.01% (Phase 1) to 2.3% (Phase 2) of the public dose constraint of 250 $\mu Sv.year^{-1}$.

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 (WSP, 2024b), will contribute to a reduction in the total effective dose if applied for the duration of the operational period:

- Rehabilitation and vegetation of legacy stockpiles and backfilled areas.
- Develop an air quality management plan for the Port Dunford Mine, including air quality monitoring to ensure compliance at upwind and downwind locations.

7.4.4.3 Impact Rating

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

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

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

7.4.5 Leaching and Migration of Contaminants from the RSFs

7.4.5.1 Impact Description

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

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

7.4.5.2 Management/Mitigation Measures

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

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

From 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:

- Develop appropriate strategies to manage potential extraneous water if required.

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

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

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

Impact Description: Leaching and migration of radionuclides from the TSF during the post-closure phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

7.5 Cumulative Impact

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

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

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

Thirdly, the radiological safety assessment process considers the cumulative contribution from all relevant sources of radiation exposure associated with the Port Dunford Mine. These sources may vary for the different exposure pathways and as a function of time but include the TSF, various stockpile facilities and open pit areas. This means that the radiological impact assessment includes the cumulative impact of these sources, as appropriate and justified.

Finally, on a more regional scale, the assessment context makes provision for a cumulative impact from all contributing operations (or practices) in the area that may contribute to the total effective dose to members of the public. This is important since the public dose limit of 1,000 $\mu Sv.year^{-1}$ is from all contributing sources and operations. However, as stated in Section 2.3.4.6, the scope of the assessment was limited to the Port Dunford Mine and did not make provision for a regional assessment to evaluate cumulative effects from all contributing operations. The total effective dose was still below the dose constraint for a single operation, which means that the cumulative impact from all operations will still be below the public dose limit.

Other potential sources of radiation exposure to members of the public include the now-closed Hillendale Operation and the Fairbreeze Operation of Tronox KZN. However, it follows from Section 5, that the potential total effective dose as a contribution from the Port Dunford Mine will be less than 250 μSv.year^{-1}. This means that similar contributions from the neighbouring operations will most likely still result in a total effective dose of less than the dose limit of 1,000 μSv.year^{-1}.

8 Radiation Monitoring Programme

8.1 General

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

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

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

8.2 Baseline Characterisation

The purpose of the radiological baseline characterisation programme is to establish the radiological conditions observed at the site and surroundings before the commissioning of the Port Dunford Mine. Given the timescales and mining schedule, the area of concern at present is where Phase 1 will be implemented.

Some baseline characterisation has been done in the area. The results from an airborne environmental radon survey in the area using RGMs are reported in Section 3.5.2. It is recommended that the monitoring of radon gas should be extended to include more locations and to cover a full year to account for seasonal variations. It is recommended that 10 to 20 RGM be deployed on the boundary of the areas that will be mined during Phase 1. In addition, the closest sensitive receptors to the Phase 1 area listed in Table 8.1 can be included.

Table 8.1 Receptor locations that can be considered for the deployment of RGMs for baseline site characterisation (see Table 4.2).

ID	Receptor Name	Receptor Type	Distance from Site Boundary (km)	Direction	Latitude (°S)	Longitude (°E)
R 38	Njomane Home	Residential	0.1	North	28.893	31.804
R 44	PD Seventh Day Adventist Church	Residential	0.3	North	28.891	31.807
R 45	Port Dunford	Residential	0.07	South	28.915	31.828
R 50	Residential Area 4	Residential	0.1	North	28.901	31.788
R 52	Residential Area 6	Residential	0.1	South	28.924	31.819

The sampling and radioanalysis of environmental media such as dust fallout, soil, surface water, sediment and groundwater are scheduled for 2025 and consequently, are not available yet. It is recommended that the sampling locations be coordinated with the environmental sampling locations and used in the S&EIR process.

In addition to the sampling and analysis of environmental media, it is proposed that a full gamma radiation and dose rate survey on a grid basis be conducted after site preparation and cleaning of the Phase 1 area. Currently, site access is limited due to the overgrowth in the area. Soil samples should again be collected for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains in the affected areas at locations that will be informed by the gamma radiation survey.

It is also proposed that, as soon as samples become available, full-spectrum radioanalysis be conducted on the topsoil, orebody (RoM), coarse tails, fine tails and HMC. These analysis results would feed into the site-specific safety assessment to be conducted after commissioning.

Once the baseline site characterisation for Phase 1 of the Port Dunford Mine is completed, a baseline site characterisation report should be compiled that documents all the results and presents the potential public radiation exposure under baseline conditions.

8.3 Monitoring Programme

Tronox is an existing operation with an approved public Radiation Protection Programme (RPP) for each operation under CoR-43, which makes provision for environmental monitoring and analysis to ensure that members of the public are sufficiently protection from releases into the environment. The responsibility for the implementation and execution of the monitoring programme lies with the Radiation Protection Function (RP Function) which may include legally appointed persons consisting of a Radiation Protection Monitor(s) (RPM), a Radiation Protection Officer (RPO), and a Radiation Protection Specialist (RPS).

Table 8.2 summarises the proposed monitoring programme for the Port Dunford Mine aimed at public radiation protection.

Table 8.2 Summary of the environmental monitoring programme proposed for the Port Dunford Mine aimed at public radiation protection.

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

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

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

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

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

8.4 Proposed Monitoring Points

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

- The surface water monitoring locations should coincide with the existing surface water monitoring points currently included in the public RPP. The principle to be applied is that the monitoring locations should be upstream and downstream of the Port Dunford Mine area in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the monitoring points proposed in WSP (2024d). The principle to be applied is that the monitoring locations should be upstream and downstream of the Port Dunford Mine area, as well as upstream and downstream of specific surface facilities. The exact location will be determined by the availability of water-bearing boreholes in the specific area.
- The dust fallout monitoring locations should coincide with the monitoring points (dust buckets) proposed in (WSP, 2024b).
- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

9 Conclusions and Recommendations

9.1 General

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

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

9.2 Conclusions

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

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

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

- On average, the total effective dose calculated at receptor locations for the atmospheric pathway varies from 0.01% (Phase 1) to 2.3% (Phase 2) of the public dose constraint of 250 μSv.year^{-1}. The most significant contribution from the atmospheric pathway is from the ingestion of crops and animal products, as well as, radon gas and dust inhalation.
- The contribution from the groundwater pathway was evaluated with the RSF C as the main contributing source. It was illustrated that the potential radiological impact is only visible in thousands of years at maximum total effective doses of less than 250 μSv.year^{-1}, which means that it cannot be considered as a contributing pathway for the Agricultural Area Exposure Condition during the operational phase of the Port Dunford Mine;
- The results for the two public exposure conditions were presented as dose isopleths for the most exposed age group (12 to 17 years), with more detailed exposure route-specific results at the sensitive receptor locations selected to be close to the Port Dunford Mine infrastructure. The results show that notwithstanding the proximity of the receptor locations to the surface infrastructure, the doses are still less than the dose limit for all age groups, with a maximum contribution of less than 50 Sv.year^{-1} from the atmospheric pathway.

- The disposal of the MSP Gypsum in the mine void or the RSF was considered for both the groundwater and atmospheric pathways, with the conclusion that both options are acceptable from a radiation exposure perspective.

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

These total effective dose assessment results were used to derive the radiological impact rating during the different phases of the Port Dunford Mine. Table 9.1 summarises the radiological impact significant rating for the operational phase, while Table 9.2 summarises the radiological impact significant rating for the post-closure phase of the Port Dunford Mine.

Table 9.1 Summary of the radiological impact significant rating for the operational phase of the Port Dunford Mine.

Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						
Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Table 9.2 Summary of the radiological impact significant rating for the post-closure phase of the Port Dunford Mine.

Impact Description: Implementation of the NNR-approved decommissioning plan of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Operational	Positive	5	1	3	5	4	**56**	**P3**
	Significance	**P3 - Moderate**						
Impact Description: Emission and dispersion of particulate matter that contains radionuclides to the atmosphere during the operational phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	1	1	3	4	3	**27**	**N2**
	Significance	**N2 - Low**						
Impact Description: Leaching and migration of radionuclides from the TSF during the post-closure phase of the Port Dunford Mine								
Stage	Character	Pre-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

Stage	Character	Post-Mitigation						
		(M+	E+	R+	D)x	P=	S	Rating
Post-closure	Negative	3	2	3	5	3	**39**	**N3**
	Significance	**N3 - Moderate**						

9.3 Recommendations

The radiological impact assessment made use of assumptions for conditions and parameter values required for the dose assessment, which is not ideal. To improve the radiological public safety and impact assessment, Recommendations were made for the baseline site characterisation programme and the radiological monitoring programme.

Based on the outcome of the preliminary baseline site characterisation and the outcome of the radiological public impact and safety assessment, the following is recommended as an extension of the baseline site characterisation programme of the Port Dunford Mine:

- Perform gamma radiation and dose rate surveys on a grid basis of all potentially affected areas for Phase 1;
- Collect soil samples at selected locations that coincide with selected locations that represent potentially hot-spot areas identified during the gamma radiation survey for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains;
- Perform an airborne radon gas survey in the Port Dunford Mine area using RGMs on a campaign basis;

- Collect surface water, groundwater and sediment samples on an upstream and downstream basis that is representative of the Port Dunford Mine area for full-spectrum radioanalysis of the U-238, U-235 and Th-232 decay chains; and
- Perform full-spectrum analysis of an orebody (RoM), HMC, topsoil, and RSF material that will be generated and used as part of the Port Dunford Mine. This will be complementary to the results already available and will only be possible once samples are available.
- Once the baseline site characterisation for Phase 1 of the Port Dunford Mine is completed, a baseline site characterisation report should be compiled that documents all the results and presents the potential public radiation exposure under baseline conditions.

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

- The surface water monitoring locations should coincide with the monitoring points proposed as part of the surface water impact assessment prepared for the S&EIR. The principle to be applied is that the monitoring locations should be upstream and downstream of the Port Dunford Mine in potentially affected surface water streams, as well as upstream and downstream of potential discharge points.
- The sediment monitoring locations should coincide with the surface water monitoring points, applying the same principles.
- The groundwater monitoring points should coincide with the monitoring points proposed in WSP (2024d). The principle to be applied is that the monitoring locations should be upstream and downstream of the Port Dunford Mine area, as well as upstream and downstream of specific surface facilities. The exact location will be determined by the availability of water-bearing boreholes in the specific area.
- The dust fallout monitoring locations should coincide with the monitoring points (dust buckets) proposed in WSP (2024b).
- The environmental radon monitoring locations do not have to coincide with specific locations. The principle to apply is that it should be widespread over the mining rights area, in the dominant wind direction where receptors are located, complemented with monitoring locations in what can be considered as background. The exact location is often influenced by whether a secured location is available to improve the recovery rate of the RGMs.

The RPSA for the Port Dunford Mine took into consideration the different phases of the Project. Phase 1 is for the first 10 years. It is recommended that the different phases that extend to 2069 be evaluated on a site-specific basis as part of the regular updates of the RPSAs that are performed every 5 years. During these updates, the respective groundwater and atmospheric pathway models should be updated with more site-specific information.

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Appendix A: Radionuclide and Element-Dependent Data

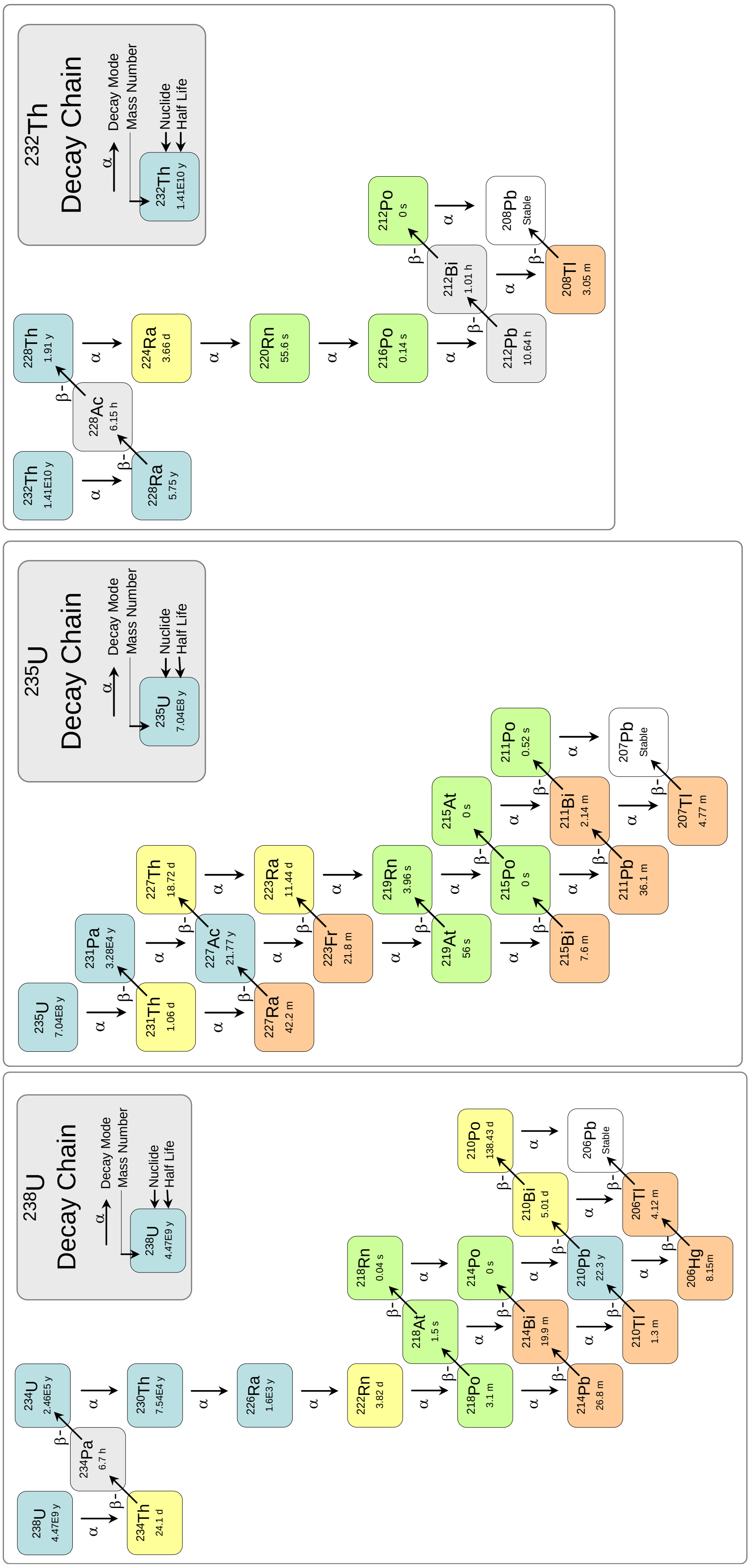

Figure A 1 Schematic illustrations of the U-238, U-235, and Th-232 decay chains.

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

As indicated in Section 2.2, 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 the outside. This situation contrasts with the intake of radionuclides by inhalation or ingestion, where the radiations are emitted inside the body.

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

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

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

Inhalation Exposure (LLα 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})

Parameter	Indoors	Outdoors	At Work	Unit
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 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 the continued deposition of airborne radionuclides. The approach used for estimating activity concentrations in soil (C_{soil}) is presented in Appendix D. The rate at which different age groups inadvertently consume soil on an annual basis is obtained from values published in RG-002.

Ingestion of Contaminated Crops

The soil contaminated with radionuclides could contaminate crops that are grown in it. The effective dose rate from the ingestion of contaminated secondary crops ($ED_{ing,crop}$, in µSv.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

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

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

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

where C_{water} is the radionuclide concentration in the water (Bq.m^{-3}), C_{soil} is the radionuclide concentration in the soil (Bq.kg^{-1}), CF_{crop} is the soil-to-crop concentration factor (Bq.kg^{-1} fresh weight per Bq.kg^{-1} dry soil), S_{crop} is the soil contamination on the crop (kg.kg^{-1}). f_{growth} is the crop growth day per day of the year (unitless), Int_{crop} is the interception fraction (irrigation water and deposition) on the crop (unitless), I_{rate} is the annual depth of irrigation applied to the crop (m.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 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 the deposition of airborne dust, represented by the term $Int_{crop}\, f_{growth}\ Dep_{rate}$; and
- External contamination of the crop due to irrigation of the crops, represented by the term $Int_{crop}\, f_{growth} C_{water}\ I_{rate}$.

A concentration factor (CF_{crop}) defines the transfer of activity from contaminated soil to crops planted in the soil and consumed by humans or animals. The concentration factor reflects only the uptake of radionuclides from the soil via roots and excludes the effects of deposition of radionuclides onto the plant surfaces by re-suspension, deposition, and fallout. Concentration factors prescribed in RG-002 (NNR, 2013) are presented for different soil groups. The RG-002 values are listed in **Error! Reference source not found.** 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 the product), and DC_{ing}.is the dose coefficient for ingestion (µSv.Bq^{-1}). Similarly, the effective dose from the ingestion of milk ($ED_{ing,milk}$, in µSv.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 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 is listed in Table C 6 in Appendix C.

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

Equation 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 the product), C_{past} is the pasture radionuclide concentration (Bq.kg^{-1} fresh weight of the pasture), CR_{past} is the animal pasture consumption rate (kg.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, 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 of 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 remainder of the parameters are listed above. Values for the consumption rates of water, soil and fodder for beef, sheep/goat/pig and poultry respectively, are summarised in Table C 8 in Appendix C.

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

The concentration in the pasture is calculated using an equation similar to Equation 6 but without the food preparation loss term. The activity concentration in the pasture (C_{past}, in Bq.kg^{-1}) can be calculated using the following equation:

Equation 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 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, are summarised in Table C 10 in Appendix C.

External Gamma Irradiation: Soil

The effective dose from external exposure to the contaminated soil of various extents (ED_{Ext_s}, in µSv.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}). The duration of exposure for different age groups is presented in Table C 11 in Appendix C.

External Gamma Irradiation: Water

The effective dose from external exposure to contaminated water (ED_{Ext_w}, in µSv.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}). The duration of exposure for different age groups is presented in Table C 11 in Appendix C.

Time-Dependent Soil Concentration

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

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

Equation 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 the 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 the 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 soil 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 stockpile 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. To simplify the calculation, it is therefore conservatively assumed that the facility will be 5 meters or more. A thinner layer will only have the effect of reducing the radon exhalation rate. Alternatively, a much thicker layer (>10 m) will not significantly increase the radon exhalation rate calculated with an assumed 5 m thickness.

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

Equation 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 by the adult ingestion rates.

Ingestion Pathway	Unit	Ingestion Rates for Different Age Groups				
		0 - 2 Years	2 - 7 Years	7 - 12 Years	12 – 17 Years	Adult
% of Adult Rate	-	40	50	60	85	100
Water	$L.y^{-1}$	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 based on dry weight concentration in the plant to the dry weight concentration in the soil, (2) RG-002 values for fruit are given as wet weight concentration in fruit per dry weight concentration in soil. (3) Values for grain from RG-002 are specifically for maize. (4) Animal feed from grain is for maize stalks and roots, which are commonly used as animal feed.

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

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

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

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

Appendix D:
Conceptual Representation of the Groundwater Model in AFRY Intelligent Scenario Modelling

Figure D 1 to Figure D 3 present simplified representations of the groundwater pathway for different site-specific conditions. Viewed simplistically, the main components of the groundwater system are a source, an unsaturated zone of limited thickness, a saturated zone, a mixing zone between clean and contaminated water in the aquifer, and a receptor of groundwater contamination that could be in the form of an abstraction borehole or a surface water body such as a river or a lake. The source as used here could be a contaminated soil layer with a relatively limited thickness and lateral extent, a surface stockpile facility (e.g., Tailings Storage Facility or Waste Rock Dump) with a relatively large lateral extent and thickness, or a below-grade layer of contaminated waste material.

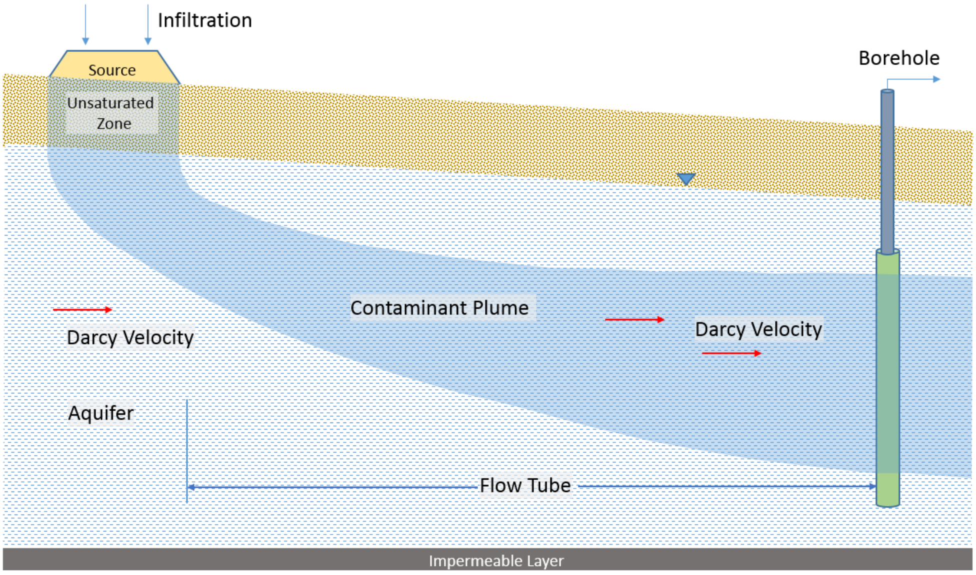

Figure D 1 **Schematic representation of the groundwater system to calculate the migration of radionuclides through a deep (thick) aquifer system and a relatively small lateral extent source term, with an abstraction borehole as a receptor.**

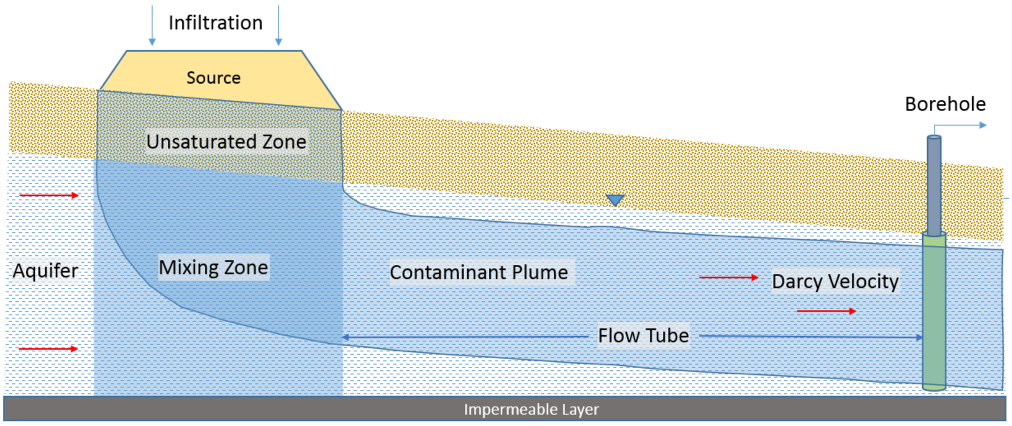

Figure D 2 **Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with an abstraction borehole as a receptor.**

It is assumed that radionuclides contained in the source are released following the infiltration and dissolution of precipitation into and through the source. The radionuclides that leach from the source migrate vertically through the unsaturated zone towards the groundwater table (i.e., an interface between the unsaturated and saturated zone). Upon entering the aquifer (saturated zone), mixing between contaminated and uncontaminated water will occur, after which the radionuclides migrate along with the groundwater flow path towards the downstream borehole or surface water body.

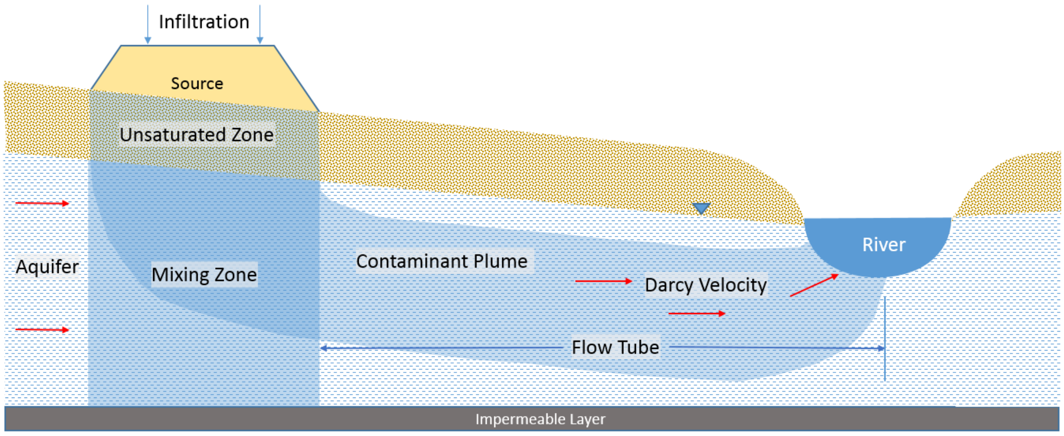

Figure D 3 **Schematic representation of the groundwater system to calculate the migration of radionuclides through a shallow (thin) aquifer system and a relatively large lateral extent source term, with a river as a receptor.**

Steady-state flow conditions are assumed for radionuclide migration. The processes consider advection, hydrodynamic dispersion, radioactive decay, and radionuclide sorption by the soil matrix. For the latter, instantaneous and reversible sorption described by a linear isotherm (also known as a K_d-model or sorption distribution coefficient) is assumed. Figure D 1 is a conceptual representation of a source term with limited thickness and lateral extent, with a thick aquifer system that underlies the source, whereas Figure D 2 and Figure D 3 represent a shallow (thin) aquifer system and a relatively large lateral extent source term.

The *System Level* model that was used to evaluate the contribution of the groundwater pathway was implemented in AFRY Intelligent Scenario Modelling® (Version 8.5) (https://www.intelligentscenariomodelling.com/). A conceptual representation of the different compartments of the *System Level* Model is presented in Figure D 4 to Figure D 8.

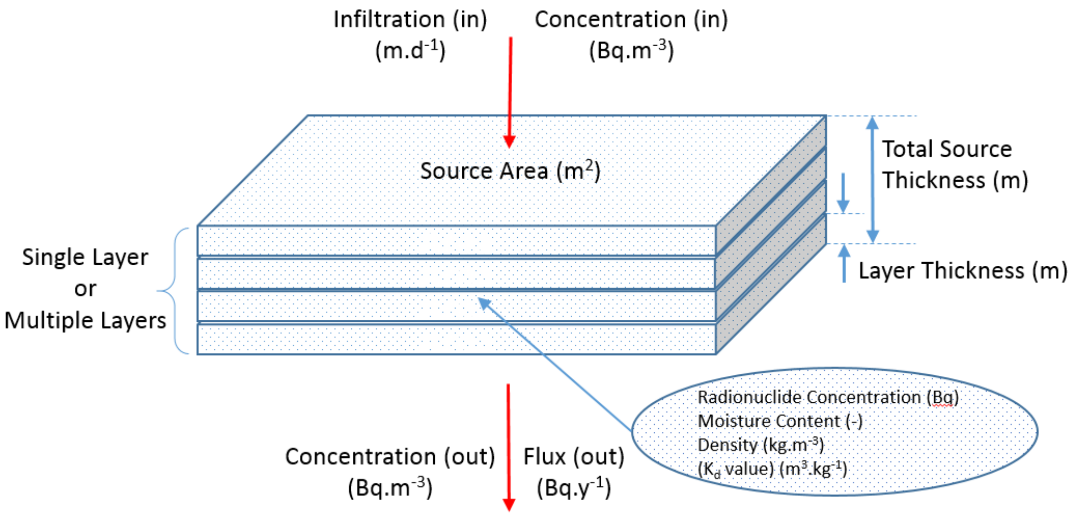

Figure D 4 **Conceptual representation and associated parameter values for the source term model.**

Figure D 4 shows that the source term model is a function of the radionuclide specific activity concentration (Bq), the volumetric moisture content ($m^3.m^{-3}$), the dry bulk density of the source material ($kg.m^{-3}$), and the radio element-specific distribution coefficient or K_d-value ($m^3.kg^{-1}$). The advective transfer coefficient that represents the loss of radionuclides from the total source, or from one layer to the next, is given by the model described in IAEA (2004b) and :

Equation 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 the 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 parameter values. Figure D 4 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 5 shows that the unsaturated zone model is a function of the volumetric moisture content (m^3.m^{-3}) and the dry bulk density of the unsaturated zone (kg.m^{-3}), the radioelement-specific distribution coefficient or K_d-value (m^3.kg^{-1}) for the unsaturated soils, as well as the dispersivity (m). The advective and dispersive transfer coefficients that represent the transfer and loss of radionuclides from the unsaturated zone to the saturated zone (aquifer) are similar to those presented in Equation 34 to Equation 36, except that it is for the unsaturated zone parameter values.

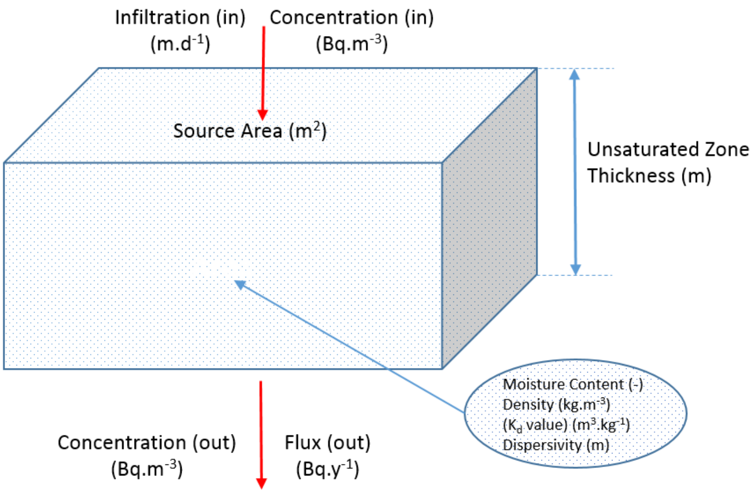

Figure D 5 **Conceptual representation and associated parameter values for the unsaturated zone model.**

Figure D 6 is a simplified representation of the aquifer mixing zone and the most important parameters. The infiltration rate ($m.y^{-1}$) is assumed constant (i.e., steady-state conditions) and equal to the infiltration rate in 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).

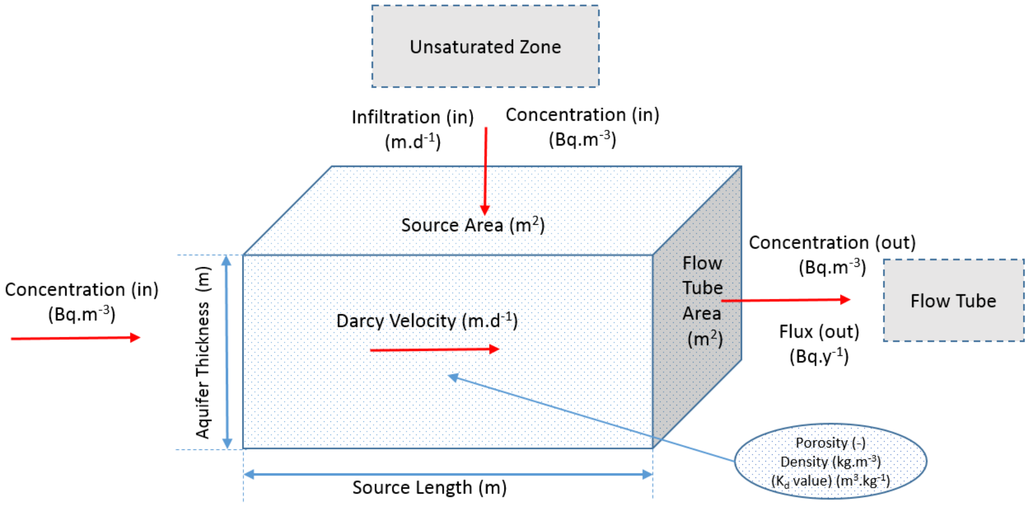

Figure D 6 Conceptual representation and associated parameter values for the aquifer mixing zone model.

Figure D 6 shows that the aquifer mixing zone model is a function of the Darcy velocity ($m.y^{-1}$), 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 7 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 are similar to those presented in Equation 34 to Equation 36, except that it is for the aquifer parameter values.

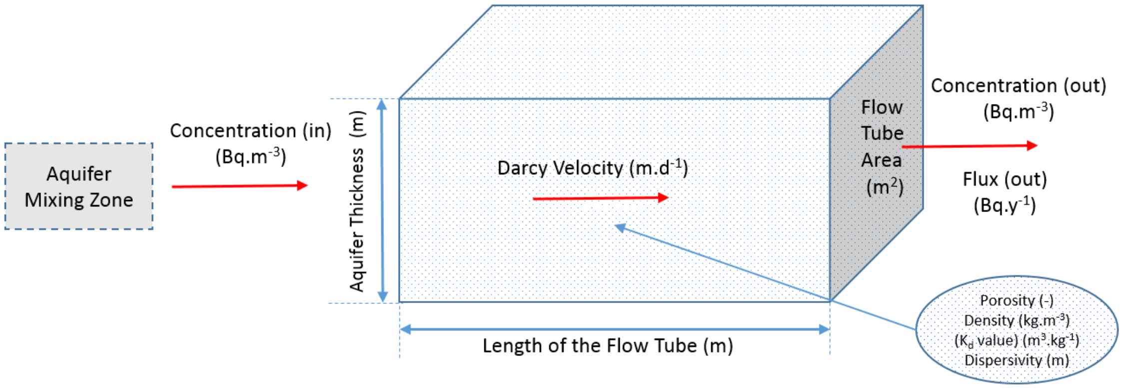

Figure D 7 Conceptual representation and associated parameter values for the aquifer (saturated zone) model.

The concentration of the water abstracted from the borehole is simplistically taken as the sum of the flow tube concentration (Bq.m^{-3}) multiplied by the fraction of the borehole intersecting the plume, and the background concentration (Bq.m^{-3}) multiplied by the fraction intersecting the uncontaminated water. As a conservative assumption, it is assumed that the whole screen intersection the contaminant plume. Figure D 8 is a simplified representation of the borehole abstraction module and the most important parameters.

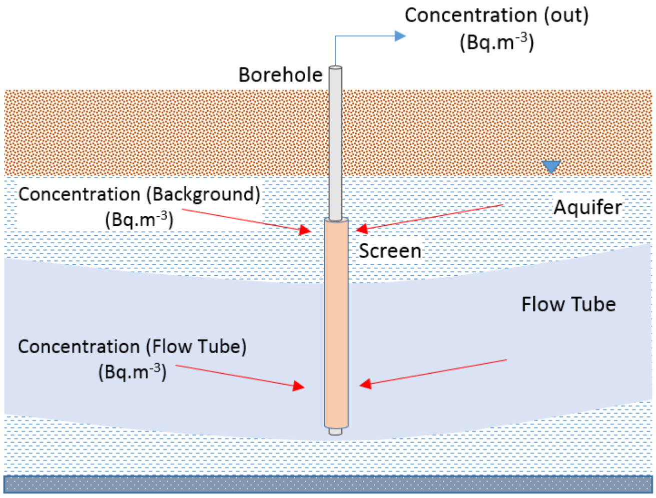

Figure D 8 Conceptual representation and associated parameter values for the borehole abstraction model.

Appendix E:
Necsa Radioanalysis Laboratory Results

RadioAnalysis and Calibration Laboratory
P. O. Box 582
PRETORIA
Gauteng
South Africa
0001

Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
North West Province 0240
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Web www:necsa.co.za

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RADIOACTIVITY ANALYSIS TEST REPORT

Quotation number	Contract(C4607KS01)	Purchase order number	4513221612
Report number	RS2024-0909-01	Report date	2024/06/20

1 Particulars of the customer

Customer name	Tronox KZN Sands (Pty) Ltd	Contact person	Mr Kiran Dhanraj
Address	Private Bag X 20010 Toliara Sands Projects 3880	Tel: Email:	071 862 0220 Kiran.dhanraj@tronox.com

2 Sample Information

Sample descriptions	Solid Samples		
Sample receipt date	2024/04/10	Number of samples	18

3 Laboratory Environmental Conditions

Temperature	12 °C – 30 °C	Relative Humidity	0 – 80%

4 Test Results

Sample Number: RS2024-0909X001 Customer ID: Zircon Prime

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	4480	60
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	4520	60
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	3360	40
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	957	162
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	206	3
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	527	16
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	401	33
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	424	12
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 340	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	33800	3000
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	4480	60

Job Card Number: RS2024-0909
Purchase Order Number: 4513221612

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P. O. Box 582
PRETORIA
Gauteng
South Africa
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Building P1600
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Madibeng Municipality
North West Province 0240
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Sample Number: RS2024-0909X002 Customer ID: Zircon Standard

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	5110	70
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	5150	70
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	3980	50
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	3920	390
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	235	3
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	653	20
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	517	37
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	510	14
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 370	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	42400	3400
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	17800	400

Sample Number: RS2024-0909X003 Customer ID: Zirkwa

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	5800	90
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	5850	90
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	400	11
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	5180	420
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	267	4
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	1010	30
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	159	17
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	148	6
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< MDA	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	51900	3900
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	21400	500

Sample Number: RS2024-0909X004 Customer ID: Rutile Prime

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	751	14
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	757	14
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	710	17
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	547	57
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	34.6	0.6
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	175	5
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	235	26
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	240	9
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 310	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	5400	1040
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	2610	140

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P. O. Box 582
PRETORIA
Gauteng
South Africa
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Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
North West Province 0240
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Sample Number: RS2024-0909X005					Customer ID: Rutile Standard	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	906	16
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	914	16
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	708	17
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	785	63
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	41.7	0.7
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	245	7
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	260	25
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	215	9
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 270	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	9910	1380
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	3210	160

Sample Number: RS2024-0909X006					Customer ID: Zircon Magnetic Concentrate	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	7740	110
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	7810	110
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	7180	90
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	6030	650
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	356	5
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	18500	500
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	22300	300
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	22000	300
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 860	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	330000	16000
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	73300	1700

Sample Number: RS2024-0909X007					Customer ID: Zircon Magnetic Rejects (MZR)	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	12100	200
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	12200	200
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	12000	100
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	10300	1100
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	557	8
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	35800	1000
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	43900	600
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	42500	600
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 1100	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	707000	33000
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	136000	3000

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RadioAnalysis and Calibration Laboratory
P. O. Box 582
PRETORIA
Gauteng
South Africa
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Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
North West Province 0240
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Sample Number: RS2024-0909X008					Customer ID: Zircon Rutile Concentrate (ZRC)	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	728	14
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	735	14
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	571	14
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	637	64
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	33.5	0.6
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	310	9
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	285	24
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	299	10
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 240	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	5110	1030
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	2930	140

Sample Number: RS2024-0909X009					Customer ID: Ilmenite Zircon Concentrate (IZC)	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	801	15
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	808	15
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	772	20
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	777	124
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	36.9	0.7
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	1520	40
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	1870	60
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	1860	40
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	309	79
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	15800	1800
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	6700	230

Sample Number: RS2024-0909X010					Customer ID: Final Ilmenite Zircon Concentrate (FIZC)	
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	1370	20
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	1380	20
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	925	21
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	957	162
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	63.1	1.1
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	3330	90
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	2710	70
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	2700	50
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 240	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	41400	3200
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	13300	400

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RadioAnalysis and Calibration Laboratory
P. O. Box 582
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South Africa
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Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
North West Province 0240
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Sample Number: RS2024-0909X011				Customer ID: MSP Sand Tails		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	130	4
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	131	4
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	112	10
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	< 96	
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	5.97	0.17
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	71.8	2.4
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	89.7	20.4
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	117	8
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 350	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	1080	230
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	670	29

Sample Number: RS2024-0909X012				Customer ID: MSP Slimes		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	236	6
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	238	6
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	229	15
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	226	40
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	10.9	0.3
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	446	12
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	513	40
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	516	18
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 440	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	5380	440
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	1900	50

Sample Number: RS2024-0909X013				Customer ID: MSP Gypsum		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	347	7
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	350	7
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	176	21
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	453	58
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	16.0	0.3
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	605	16
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	551	62
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	487	23
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 820	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	16700	2000
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	11500	300

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P. O. Box 582
PRETORIA
Gauteng
South Africa
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Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
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Sample Number: RS2024-0909X014				Customer ID: Crude Ilmenite (Tronox KZN)		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	123	4
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	124	4
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	103	7
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	< 180	
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	5.66	0.17
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	224	7
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	224	18
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	275	8
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 200	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	16300	1700
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	2450	160

Sample Number: RS2024-0909X015				Customer ID: Crude Ilmenite (Australia)		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	64.8	2.8
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	65.4	2.9
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	61.6	6.2
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	< 130	
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	2.98	0.13
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	118	4
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	116	15
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	139	6
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 210	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	2910	750
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	971	88

Sample Number: RS2024-0909X016				Customer ID: PWP Heavy Mineral Concentrate (HMC)		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	RA-QMS-WIN-0226	NO	U-238	Bq/kg	621	11
RGI-03007	RA-QMS-WIN-0226	NO	U-234	Bq/kg	626	11
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	499	14
RGI-03009	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	726	85
RGI-03007	RA-QMS-WIN-0226	NO	U-235	Bq/kg	28.6	0.5
RGI-03007	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	552	16
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	595	33
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	558	14
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 260	
RAB-02009	RA-QMS-WIN-0241	NO	Gross Alpha	Bq/kg	2430	680
RAB-02009	RA-QMS-WIN-0241	NO	Gross Beta	Bq/kg	550	71

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Building P1600
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Sample Number: RS2024-0909X017				Customer ID: PWP Sand Tails		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-238**	**Bq/kg**	**15.4**	**1.2**
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-234**	**Bq/kg**	**15.6**	**1.2**
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	19	8.0
RGI-03009	**RA-QMS-WIN-0158**	**NO**	**Pb-210**	**Bq/kg**	**< 71**	
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-235**	**Bq/kg**	**0.711**	**0.057**
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**Th-232**	**Bq/kg**	**13.3**	**0.9**
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	< 67	
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	< 31	
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 320	
RAB-02009	**RA-QMS-WIN-0241**	**NO**	**Gross Alpha**	**Bq/kg**	**7930**	**1260**
RAB-02009	**RA-QMS-WIN-0241**	**NO**	**Gross Beta**	**Bq/kg**	**3640**	**160**

Sample Number: RS2024-0909X018				Customer ID: PWP Slimes		
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-238**	**Bq/kg**	**41.2**	**2.2**
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-234**	**Bq/kg**	**41.6**	**2.2**
RGI-03005	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	29	9.0
RGI-03009	**RA-QMS-WIN-0158**	**NO**	**Pb-210**	**Bq/kg**	**< 110**	
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**U-235**	**Bq/kg**	**1.90**	**0.10**
RGI-03007	**RA-QMS-WIN-0226**	**NO**	**Th-232**	**Bq/kg**	**49.1**	**2.4**
RGI-03005	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	117	21
RGI-03005	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	75.5	12.1
RGI-03005	RA-QMS-WIN-0101	YES	K-40	Bq/kg	< 470	
RAB-02009	**RA-QMS-WIN-0241**	**NO**	**Gross Alpha**	**Bq/kg**	**979**	**216**
RAB-02009	**RA-QMS-WIN-0241**	**NO**	**Gross Beta**	**Bq/kg**	**400**	**25**

4.1 Explanatory notes

(a) A result with its associated uncertainty is reported only if it is greater than the minimum detectable activity (MDA) of the relevant test measurement, else the minimum detectable activity value will be reported with a less than symbol ("<") in front of the value.
(b) Minimum detectable activity is reported with a confidence level of 95%. Measurement of uncertainty is reported with a coverage factor of k=1
(c) The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements.
(d) The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities.
(e) Results indicated in bold were obtained from methods that are not included in the SANAS schedule of Accreditation for this laboratory.

Job Card Number: RS2024-0909
Purchase Order Number: 4513221612

RadioAnalysis and Calibration Laboratory
P. O. Box 582
PRETORIA
Gauteng
South Africa
0001

Building P1600
R104 Pelindaba
Elias Motsoaledi Street
Extension
Madibeng Municipality
North West Province 0240
Email Labservices@necsa.co.za
Web www.necsa.co.za

necsa
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5 Date(s) of performance of laboratory activities

Method / Activity		Date completed	Analyst
RA-QMS-WIN-0114	Method for the preparation of geological type material for analytical purpose	2024-04-17	ME Motlhabane
RA-QMS-WIN-0241	Meurement of the gross alpha/beta-activity of powder samples using oxford lb instrument	2024-04-23	NQ Daniels
RA-QMS-WIN-0226	Neutron irradiation and counting of solid samples	2024-06-19	MA Sathekge
RA-QMS-WIN-0101	Measurement of the gamma-activiy of a sample using high energy gamma detector	2024-06-03	MA Sathekge
RA-QMS-WIN-0158	Method for the determination of the gamma-activity of a sample using a low-energy detector	2024-06-14	MM Rapetsoa
Report compilation		2024-06-20	MA Sathekge

5.1 Explanatory notes

(a) The date of completion is the date on which the total number of samples have been completed by an activity or method.

6 OPINIONS AND INTERPRETATIONS

(a) None

7 Disclaimers

Results relate only to samples tested as received from client. Necsa are not liable for errors that are due to sampling and transport of samples by external parties. The results, opinions and/or interpretations expressed are based only on thesamples received and tests performed. Opinions and interpretations are outside of the scope of SANAS accreditation. Results indicated in bold were obtained from methods that are not included in the SANAS schedule of Accreditation for this laboratory.Reports issued by NECSA shall not be reproduced, except in full, without the written approval of NECSA. Only the original version of this report, as kept by NECSA, shall be used in case of a dispute.

Compiler	Technical Signatory	Authoriser
MA Sathekge - Technician	MMF Seaga – Section Head	EN Moalosi – Manager

END OF REPORT

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