



water & sanitation

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**Attention:** Manager Assessments: NORM

Dear Madam,

**DWS EASTERN BASIN WATER TREATMENT PLANT AND SLUDGE MANAGEMENT OPERATIONS: APPLICATION FOR EXEMPTION FROM REGULATORY CONTROLS**

Your letters dated 2 February 2024 and 19 November 2024 respectively, refer.

Please find attached herewith the following Reports for your review and consideration;

- AqSiSim Report for DWS Eastern Basin Water Treatment Plant and Sludge Management Operations: Radiological Safety Assessment;
- Artesium Report for East Rand Basin Numerical Groundwater Model for the Waste Disposal Flow and Advective Transport Evaluation.

Should further information be required, please direct correspondence to Ms RN Mazwi, tel. 012 336 7554 or email [mazwir@dws.gov.za](mailto:mazwir@dws.gov.za).

Yours sincerely,



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**MS R N MAZWI**

**DIRECTOR: Mining & Industrial Water Quality Regulation**

**Date:** 27 March 2025

**CC: Ms. Sophia Tlale – TCTA**

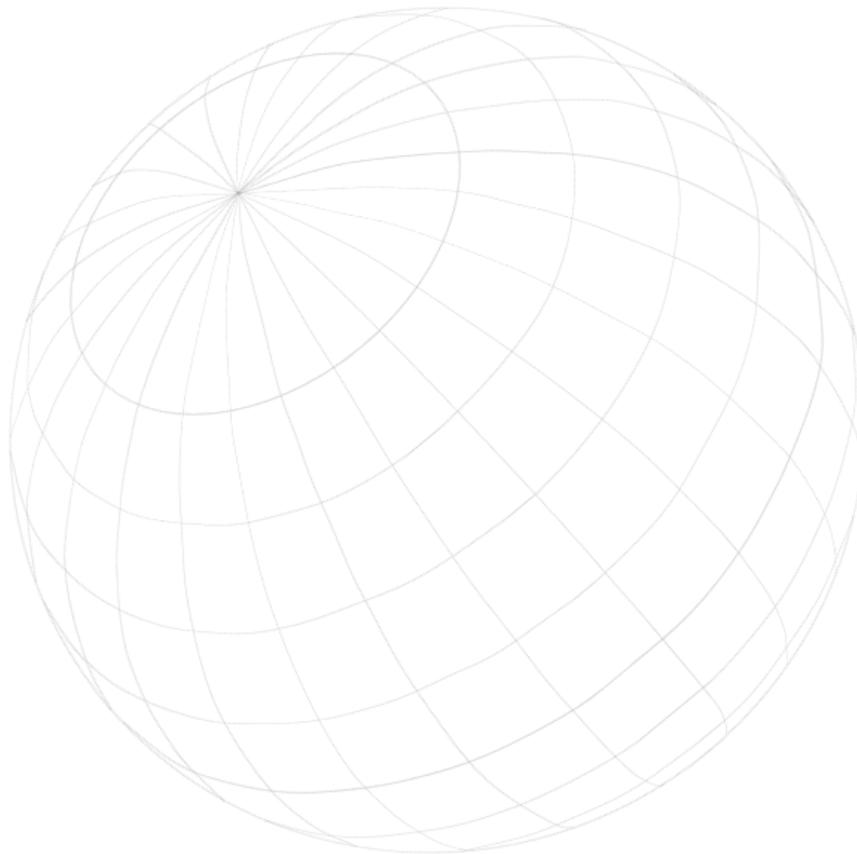
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# DWS Eastern Basin Water Treatment Plant and Sludge Management Operations: Radiological Safety Assessment



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# Technical Report



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## List of Acronyms

ALARA	As Low As Reasonably Achievable
AMD	Acid Mine Drainage
Bq	Becquerel
CoE	<i>Certificate of Exemption</i>
CoR	Certificate of Registration
DFFE	Department of Forestry, Fisheries and Environment
DMRE	Department of Mineral Resources and Energy
DoE	Department of Energy
DWS	Department of Water and Sanitation
ECL	Environmental Critical Level
GSR	IAEA General Safety Requirement
HDS	High-Density Sludge
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
Mamsl	Metres above mean sea level
mSv	millisievert
NEA	Nuclear Energy Act (Act No. 46 of 1999)
NEM:WA	National Environmental Management:Waste Act (Act 59 of 2008)
NEMA	National Environmental Management Act (Act 107 of 1998)
NGOs	Non-Governmental Organisations
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act (Act 47 of 1999)
NORM	Naturally Occurring Radioactive Materials
NRWMP	National Radioactive Waste Management Policy and Strategy
OEPs	Occupationally Exposed Persons
RG	Regulatory Guide
TCTA	Trans-Caledon Tunnel Authority
TSFs	Tailings Storage Facilities
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

## Credentials: Dr JJ van Blerk



Before joining AquiSim Consulting (Pty) Ltd (AquiSim) as Director 24 years ago, Dr Japie van Blerk worked at the South African Nuclear Energy Corporation (Necsa) for 11 years, with the post-closure safety assessment of the Vaalputs National Radioactive Waste Disposal Facility in South Africa as his main responsibility. During this period, he obtained a PhD in geohydrology from the University of the Free State in South Africa. He is registered as a Professional Natural Scientist (Pr.Sci.Nat.) in the field of Radiation Science and Earth Science (Reg. no 400239/05) through the South African Council for Natural Scientific Professions (SACNASP).

Through his responsibility for the post-closure safety assessment of Vaalputs, he obtained in-depth knowledge of the performance of near-surface radioactive waste disposal systems, especially under arid conditions. After joining AquiSim in 2000, he continued to provide consultancy services to Necsa in the field and radioactive waste management and post-closure safety assessment. The current Vaalputs post-closure safety assessment was prepared by him in collaboration with Dr Matt Kozak (Interra, USA), while the 2024 Vaalputs PCRSA is currently being performed by Dr van Blerk. This assessment included an in-depth review of the national inventory of radioactive waste earmarked for disposal at Vaalputs.

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

For the past 27 years, Dr. van Blerk has provided extensive consultancy and technical training services to the IAEA in the fields of post-closure safety assessment, safety case development, radioactive waste management (including NORM), development of disposal concepts for Disused Sealed Radioactive Sources (DSRS), as well as the cradle-to-grave management of DSRS.

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

He has extensive experience in performing and managing radiological public safety assessment projects for mining and mineral processing facilities and operations involving NORM, both locally and abroad (e.g., uranium, gold, rare earth, copper, mineral sands, phosphate, etc.), for regulatory and ESIA purposes under operational and post-operational conditions. For the past 24 years, he has performed and managed more than 70 radiological public safety assessment-related projects for the NORM and nuclear industry. Many of these projects were in South Africa, but also include countries such as Namibia, Mozambique, Madagascar, Ukraine, Kazakhstan, Mali, Sierra Leone, and Malawi.

His knowledge and experience in the nuclear industry are complemented by a very good working knowledge of a diversity of environmental processes and disciplines related to geology, geohydrology, geochemistry, hydrology, and meteorology. His understanding of these disciplines and knowledge of

groundwater modelling principles for saturated and unsaturated conditions are well suited for reviewing waste disposal programmes and the impact and safety of these programmes on human health and the environment during the period following closure.

### **Certification**

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



Jacobus Josia van Blerk (PhD)

**Director: AqSiSim Consulting (Pty) Ltd**



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# 1 Introduction

## 1.1 Background

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After more than 120 years of deep-level gold mining in the Witwatersrand, mining and dewatering have stopped due to the exhaustion of economic gold resources. The cessation of dewatering has resulted in progressive flooding of the mine voids since 1997. In the case of gold mining on the Witwatersrand, numerous large old mining areas have become connected thus allowing water to migrate from one mine to another (Digby Wells Environmental, 2015).

The Witwatersrand gold mining area is broadly divided into three basins spatially illustrated in Figure 1.1, namely the Western Basin, the Central Basin and the Eastern Basin. The Far Western Basin, which forms part of the Witwatersrand gold mining area, is considered to fall within the Western Basin. The Eastern Basin, which is the focus of this report, covers mine lease areas that extend over an area of 768 km<sup>2</sup> and includes towns such as Boksburg, Benoni, Brakpan, Springs and Nigel (see Figure 1.1).

The voids filled with water during flooding and the reaction between this water and the rock surface, in the presence of oxygen, resulted in heavy metals dissolving and becoming suspended in the water and generation of Acid Mine Drainage (AMD). To prevent decanting to surface water bodies and the environment in general, engineered and environmental solutions have either been implemented or proposed to treat AMD emanating from the three basins.

To prevent an impact on infrastructure and aquifers, an Environmental Critical Level (ECL) has been defined for each basin. The ECL is defined as the maximum height to which the underground water level will be allowed to rise before it results in a significant impact on the environment. The ECL is governed by geology and the mining voids in the basins. In the Central Basin, there is no sensitive geology. However, due to the presence of dolomite in the Western Basin and Eastern Basin, the ECLs in these basins were selected to protect the geological formations that contain large and important aquifers. By maintaining the water level below the chosen ECL, groundwater users would be protected against contamination of water. The predefined ECL in the three basins is 1,550 metres above mean sea level (mamsl) for the Western Basin, 1,467 mamsl for the Central Basin, and 1,280 mamsl for the Eastern Basin (Digby Wells Environmental, 2015).

The AMD management measures for the Eastern Basin include a water treatment process that results in the generation of a High-Density Sludge (HDS) (characterised as Type 3 waste in terms of the NEM:WA) that needs to be managed appropriately. The water treatment plant neutralises the acidic water to levels suitable for human consumption or discharge to the environment.

In January 2013, the Department of Environmental Affairs (DEA) granted an exemption for the abstraction of AMD from the Grootvlei No. 3 Shaft located in the Eastern Basin, the construction and operation of the High-Density Sludge (HDS) plant and neutralised water pipeline for the discharge of treated water into the Blesbok Spruit. The Blesbok Spruit is classified as a wetland of international importance for the conservation of waterfowl in terms of the Ramsar Convention (Digby Wells Environmental, 2015).

Naturally occurring radionuclides associated with the uranium, thorium and actinium decay series are associated with the gold-bearing reefs of the Witwatersrand Basin. These naturally occurring radionuclides are also present in the AMD and consequently will be carried through to the HDS residue. Low levels of naturally occurring radionuclides may also be associated with the treated water. Materials and residues that contain naturally occurring radionuclides are generally referred to as Naturally Occurring Radioactive Materials (NORM) (IAEA, 2007).

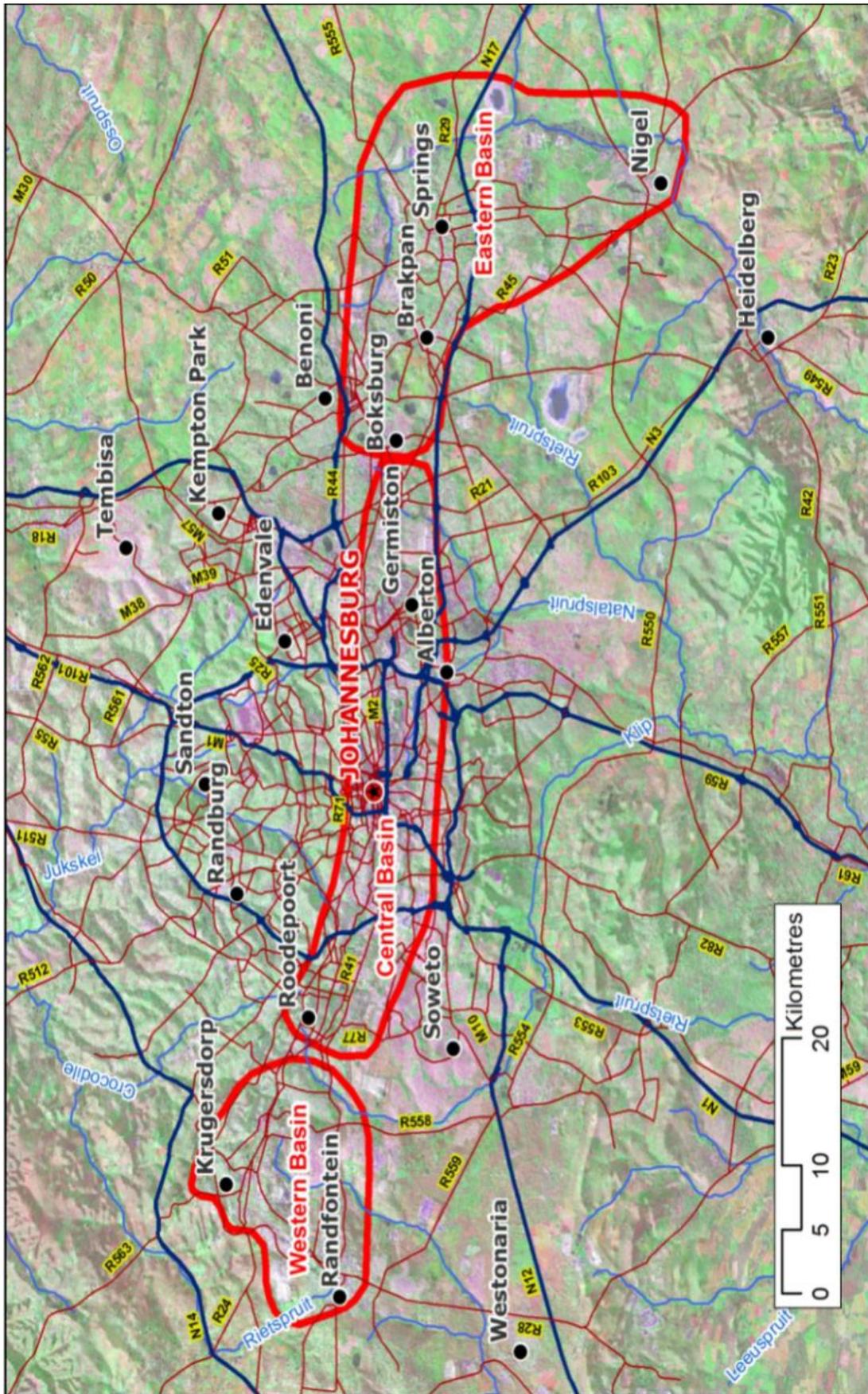


Figure 1.1 Spatial distribution of the Western Basin, Eastern Basin and Central Basin associated with the Witwatersrand gold mining area (Digby Wells Environmental, 2015).

The Trans-Caledon Tunnel Authority (TCTA) was instructed by the National Government, through the Department of Water and Sanitation (DWS), to manage AMD generated from the Western Basin, Eastern Basin and Central Basin of the Witwatersrand gold fields in the Gauteng Province. TCTA appointed AECOM South Africa (Pty) Ltd (AECOM) as the Principal Consultant concerning the implementation of the AMD and sludge management measures.

AquiSim Consulting (Pty) Ltd (AquiSim) was appointed to assess the radiological safety of workers (occupational exposure) and members of the public for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, to apply for exemption from nuclear regulatory controls if possible.

## 1.2 Natural Background Radiation

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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)<sup>1</sup> 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, 2006). In undisturbed environmental conditions, these naturally occurring radionuclides form part of the natural background radiation to which all humans are exposed daily through the air they breathe, the water they drink, the soil they live and work on, as well as the food they eat (Kathren, 1998).

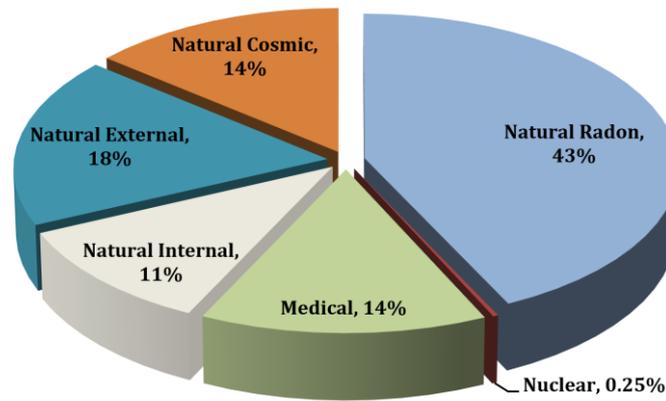
The annual dose averaged over the population of the world, is about 2.8 mSv in total. As indicated in Figure 1.2, over 85% of this total is from natural sources, with about half coming from radon decay products in the home (2.4 mSv). Medical exposure of patients accounts for 14% of the total (0.4 mSv),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

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, therefore, have the potential to alter the natural background radiation and potentially increase radiation exposure on members of the public 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.

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<sup>1</sup> 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.



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

### 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  $0.5 \text{ Bq}\cdot\text{g}^{-1}$  or  $500 \text{ Bq}\cdot\text{kg}^{-1}$  (radionuclide specific).

Section 22 (1) of the NNRA states:

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

In addition, Section 22 (3) of the NNRA states:

*“The chief executive officer may, with the approval of the board – (a) refuse to grant an application for a CoE or CoR made in terms of subsection (1) and must provide the applicant in writing with reasons for the refusal; or (b) issue -*

*(i) a CoR subject to such conditions as may be determined in terms of Section 23; or (ii) a CoE if satisfied that the action in question complies with the exemption criteria specified in the safety standards contemplating in Section 36”.*

### 1.4 Purpose of the Report

Although constructed in 2014 and operational since 2016, the DWS has not been granted a CoR or CoE from the NNR under Section 22 of the NNRA for the Eastern Basin Water Treatment Plant and Sludge Management Operations. Disposal of the sludge residue produced by the water treatment plant into the Eastern Basin mine void began in August 2016.

This report outlines the radiological safety assessments for both the public and workers at the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations. If the results support it, they will form the basis for an application to the NNR requesting exemption from nuclear regulatory controls for these operations.

## 1.5 Scope and Structure of the Document

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This report focuses solely on the radiological impacts and safety considerations related to the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, and it does not cover any non-radiological health and safety issues that may be associated with these operations.

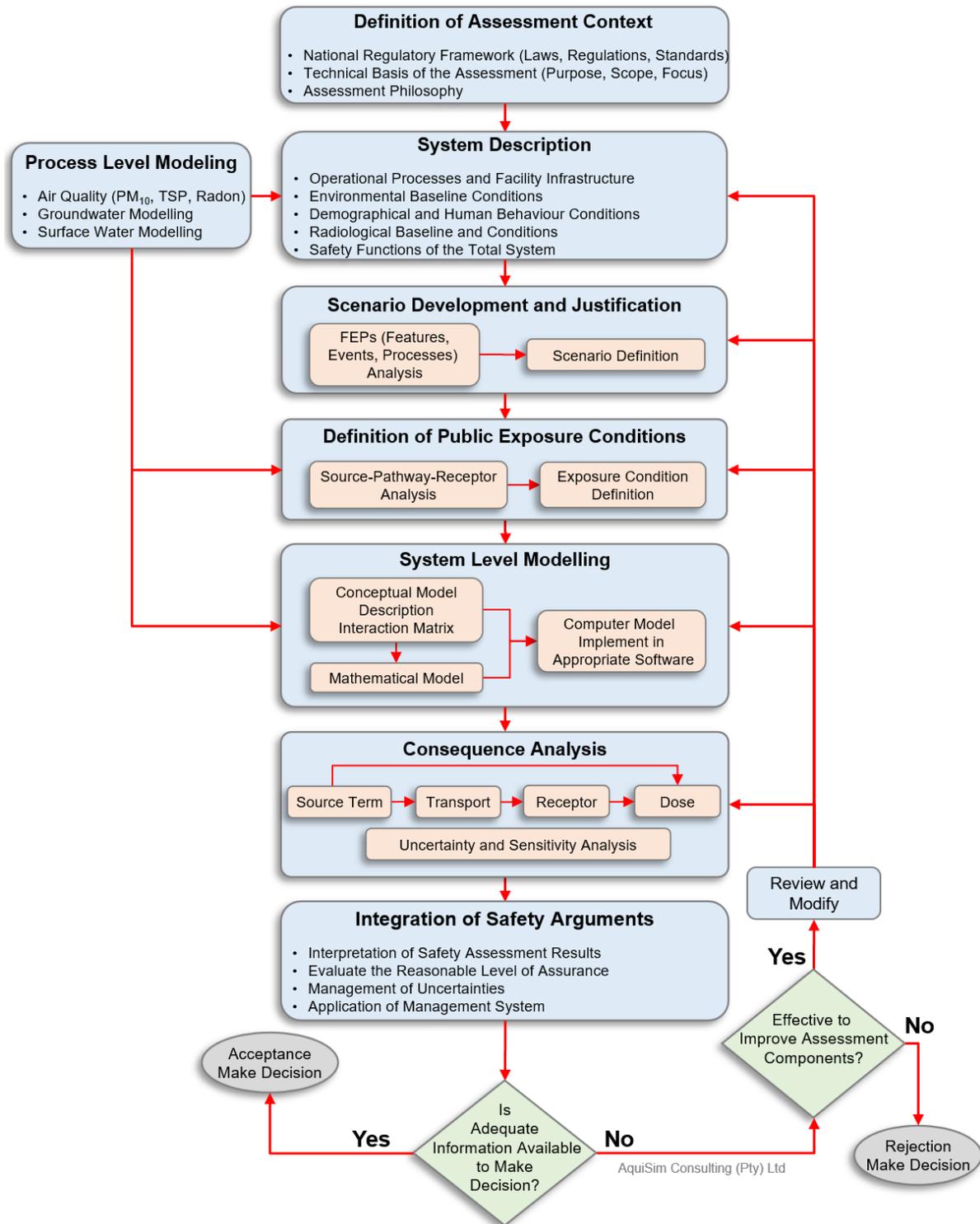
The scope of this report is limited to the requirements of the NNRA and does not address the requirements of the National Environmental Management Act, 1998 (Act 107 of 1998) (NEMA) or the National Environmental Management: Waste Act, 2008 (Act 59 of 2008) (NEM:WA). Although the radiological impact on members of the public and a lesser extent workers could provide input into the NEMA and NEM:WA processes, these are addressed through separate processes.

The report assumes that readers have a basic understanding of ionising 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).

Multiple methodologies exist for conducting radiological safety assessments for the public and workers, and no single method is universally accepted as the definitive approach. What is important is selecting an approach that is fit for purpose, instils confidence in the results, and follows the principles of a graded safety assessment (IAEA, 2009a).

The methodological safety assessment framework broadly followed for this assessment is schematically illustrated in Figure 1.3. It resembles the IAEA ISAM methodology developed for the safety assessment of near-surface radioactive waste disposal facilities (IAEA, 2004b). To comply with the inherently systematic and structured nature of the safety assessment framework, the report is structured as follows:

- Section 2 defines the assessment context that includes the regulatory framework as well as the technical basis of the assessment (e.g., purpose, scope and focus of the radiological safety assessment).
- Section 3 presents a summary description of the overall system and associated subcomponents that include the DWS Eastern Basin Water Treatment Plant, the Sludge Management Operations, and the release of treated water to the environment.
- Section 4 presents the radiological public safety assessment for the overall system, with the information presented in the assessment context and system description as a basis for the safety assessment.
- Section 5 presents the radiological worker safety assessment for the overall system, with the information presented in the assessment context and system description as a basis for the safety assessment.
- The report is concluded in Section 6 with overall conclusions and recommendations for the management of radiation exposure to members of the public and workers.



**Figure 1.3** Schematic illustration of the framework that is broadly followed for the radiological safety assessment of the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations.

## 2 Assessment Context

### 2.1 General

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Within the conceptual framework presented in Figure 1.3 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 safety 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. Once developed, it serves as a communication tool to inform interested parties of what is included or excluded from the assessment, and justification for the choices made clearly and consistently.

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 Regulatory Framework

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#### 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, 2013a). RG-002 is intended to provide guidelines to holders and prospective holders of NNR authorisations on how to conduct prior and operational public safety assessments for activities and operations involving NORM.

LG-1029 (NNR, 1997) serves as a guideline for worker safety assessments from surface operations at mining and minerals processing facilities, while RD-006 states the requirements for the control of radiation hazards at these facilities (NNR, 2013b).

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 ionising 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 publications and reports that contribute to the overall framework for the protection of human health and the environment from exposure to ionising radiation.

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

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

## 2.2.3 The ICRP System of Radiological Protection

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.

The ICRP's revised System of Protection recognises three types of exposure situations which are intended to cover the entire range of possible exposures (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.

Planned exposure situations are normally within the scope of regulatory requirements for radiation protection. The concepts of exclusion, exemption and clearance may thus be used to justify and optimise regulatory control by avoiding the application of unamendable and unwarranted regulatory measures (ICRP, 2007). The implementation of a water treatment plant and the sludge management operations falls within the category of a *Planned Exposure Situation*.

## 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 Exemption Principles and Criteria

### 2.2.5.1 Principles

The general principles for the issue of a CoE as contemplated in Section 22 (3) (b) (ii) of the NNRA are as follows:

- The radiation risk to individuals caused by the action concerned must be sufficiently low not to be of regulatory concern;
- The collective radiological impact of the action concerned must be sufficiently low not to warrant regulatory control in the prevailing circumstances; and
- The action concerned must be inherently safe, with no appreciable likelihood of scenarios that could lead to a failure to meet the criteria in Section 2.2.1.1 and Section 2.2.1.2 of Regulation 388.

### 2.2.5.2 Exemption without Further Consideration

Actions involving radioactive material will qualify for the exemption by the Regulator without further consideration where the following criteria are fulfilled in all feasible situations:

- The effective dose expected to be incurred by any member of the public due to the exempted action is 10  $\mu$ Sv per annum or less, and the collective effective dose committed by performing the action for one year is no more than 1 person-Sv; or
- An assessment for the optimisation of protection shows that exemption is the optimum option; or
- Either the radioactivity concentration or the total radioactivity content of each radioactive nuclide in the radioactive material is below the levels specified in Annexure 1 (of Regulation 388) and the quantity possessed or processed in a period of one year is less than one tonne; or

- The radioactivity in the material is associated with naturally occurring radioactive nuclides that are not processed for their radioactive, fissile or fertile properties, and the effective dose expected to be incurred by any members of the public due to the exempted action is less than 0.25 mSv per annum.

### 2.2.5.3 Exemption with Further Consideration

Actions that involve radioactive material which does not qualify for exemption without further consideration as envisaged in Section 2.2.2 of Regulation 388 can be given further consideration subject to a case-by-case evaluation by the Regulator based on the specific radioactivity, the total radioactivity or discrete radioactive nuclides or exposure scenarios.

## 2.2.6 Compliance Criteria for Workers

Annexure 2 of Regulation No. 388 provides dose limits for occupational exposure, exposure of visitors and non-occupationally exposed workers at nuclear sites, as well as public exposure. The latter states the following:

*.... occupational exposure of workers shall be so controlled that the following limits are not exceeded:*

- An (average) effective dose of 20 mSv per year averaged over five consecutive years, with a (maximum) effective dose of 50 mSv in a single year;
- An equivalent dose to the lens of the eye of 150 mSv in a year; and
- An equivalent dose to the extremities (hand and feet) or the skin of 500 mSv in a year.

The annual effective dose limit for women of reproductive capacity is the same as that which is generally specified for occupational exposure. Following the declaration of pregnancy, a limit on the equivalent dose to the abdomen of 2 mSv for the remainder of the pregnancy applies<sup>2</sup>.

## 2.2.7 Area Classification Criteria for Worker Exposure Conditions

The area classification scheme for radiological areas at mining and mineral processing facilities as summarised in Table 2.1, is based on average dose rates and air activity concentrations for a 2,000-hour per annum occupancy. If justified, alternative occupancy factors can be motivated and used. Control measures recommended by the NNR for the different area classifications are summarized in Table 2.2.

**Table 2.1 Classification of designated areas based on measured average conditions and taking occupancy factors into account (NNR, 1997).**

Designated Area	Total Annual Effective Dose (All Pathways) (mSv.year <sup>-1</sup> )
Non-controlled	May exceed 0.25 mSv but will not exceed 1 mSv above background.
Supervised	May exceed 1 mSv but will not exceed 5 mSv above background.
Controlled	May exceed 5 mSv but will not exceed 20 mSv above background.

In addition, LG-1029 (Section 6.3) makes the following stipulations regarding surface contamination levels (NNR, 1997):

*“Where surface contamination above 0.4 Bq.cm<sup>-2</sup> (beta-gamma), and 0.04 Bq.cm<sup>-2</sup> (alpha) is measured, or where it is identified that there is a potential for surface contamination (e.g., due to an open process), accepted radiation protection practice is for such areas to be classified as controlled areas. This is due to the large uncertainties associated with the quantification of internal doses and the difficulties of controlling the spread of contamination”.*

<sup>2</sup> Note that the limit in Regulation No. 388 is different from RD-10 Section 1.5 (5 m Sv in 2 months and 5 mSv for duration of pregnancy).

**Table 2.2 Control measures recommended by the NNR for the different area classifications.**

Area	Control Measure
Non-Controlled Area	No controls or limited confirmatory monitoring is required for the possibility of an effective dose of 0.25 mSv.year <sup>-1</sup> to 1 mSv. year <sup>-1</sup>
Supervised Area	No possibility of an effective dose exceeding 5 mSv. year <sup>-1</sup>
	Occupationally Exposed Person (OEP) status
	No controls are needed to limit exposures below 5 mSv. year <sup>-1</sup>
	Continual confirmatory monitoring: <ul style="list-style-type: none"> <li>○ persons, activities, environment</li> <li>○ extent dependent on proximity to limit, the potential for variability and ease of measurement</li> </ul>
	Dose recording, training and medical
Controlled Area	Possibility of an effective dose exceeding 5 mSv. year <sup>-1</sup>
	Active controls are needed to maintain worker exposures at acceptable levels within the annual limits.
	Confirmatory monitoring of the working environment
	Full radiation worker status
	Individual dosimetry / Dose Assignment, training and medical

### 2.2.8 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 (1994) (unless deviations therefrom can be justified).

Table 2.3 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, 1994). The IAEA classification scheme has subsequently been revised and is presented in IAEA (2009b).

**Table 2.3 Summary of the National Radioactive Waste Classification Scheme (DME, 2005).**

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

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

<sup>(1)</sup> 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, 1994). The IAEA classification scheme has subsequently been revised (IAEA, 2009b).

The NRWMP provides several options for NORM management. The options available depend on the classification of the NORM as either low activity (long-lived radionuclide concentration < 100 Bq.g<sup>-1</sup>) or enhanced activity (long-lived radionuclide concentration > 100 Bq.g<sup>-1</sup>). Table 2.4 summarises the management options available to each of these classes of NORM waste.

**Table 2.4 Management options for Low Activity NORM and Enhanced Activity NORM as defined in DME (2005).**

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

## 2.3 Technical Basis of the Assessment

### 2.3.1 General

A radiological 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, as well as the Department of Energy (DoE), the Department of Forestry, Fisheries and Environment (DFFE), and the Department of Water and Sanitation (DWS);
- TCTA and the Operator in their managing and implementation capacity of the water treatment and sludge management project, as well as all workers involved in the different elements of the overall project;
- Members of the public living near the water treatment plant, as well as those downstream of any release point to the environment that may potentially be affected by the facilities and activities (e.g., ward councillors, labour unions, agriculture, and landowners);
- Mining and industry, in particular, those mining companies and industries that are active in the Eastern Basin; and
- Technical, scientific, semi-Government entities (parastatals), and Non-Governmental Organisations (NGOs) (e.g., environmental organisations, community-based organisations) that might have an interest in the approach being followed and the outcome of the assessment results.

### 2.3.3 Purpose and Objectives of the Assessment

Companies planning to develop mining or mineral processing operations must undergo a thorough permitting process to assure regulators and stakeholders that their facilities can be safely constructed, operated, decommissioned, and closed without posing risks to workers and public health, nearby communities, or the environment (Chambers *et al.*, 2012). A critical component of this process is the radiological public safety assessment, which evaluates the system's performance—such as the mining or processing operation—and its impact. The assessment measures radiological safety based on the total effective dose received by workers and the public (IAEA, 2007). This definition is consistent with Regulation No. 388.

The nuclear regulatory framework (see Section 2.2) clearly outlines the overarching safety objective (IAEA, 2006) and the necessity of safeguarding human health and the environment over relevant timescales 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 perspective, the purpose of the radiological safety assessment can be defined as follows:

*To assess the radiological safety of workers and members of the public induced by the DWS Eastern Basin Water Treatment Plant and associated Sludge Management Operations in a comprehensive, systematic, and transparent manner that is consistent with the NNRA and NEA, as well as with NNR requirements and regulations in general.*

The primary objective of the radiological safety assessment is to demonstrate to the NNR and other stakeholders that workers and members of the public are not exposed to levels of ionising radiation induced by the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations that exceed the regulatory compliance criteria established for radiation exposure as defined in Section 2.2. The secondary objective of the radiological safety assessment is to show that the potential levels of ionising radiation from the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations adhere to the criteria for exemption from regulatory control as defined in Section 2.2.

## 2.3.4 Scope and Focus of the Assessment

### 2.3.4.1 Natural Background Radiation

The contribution of naturally occurring radionuclides to background radiation was introduced in Section 1.2. Nationally and internationally, the contribution of natural background radiation is not amenable to regulatory control. The focus of this assessment is thus on the radiation exposure contribution induced by DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, *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.

### 2.3.4.1 Site-Specific Assessment

The radiological 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. All assumptions and conditions used in the assessment are documented and justified accordingly.

### 2.3.4.2 Assessment of Exposure to Radiation

NORM 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 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.

### 2.3.4.3 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, a high-density metallic element, is naturally found in the earth's crust at an average concentration of 3 ppm and includes the isotopes U-238, U-235, and U-234. U-238 and U-235 are the parent isotopes in two separate decay series, while U-234 is a decay product of U-238. Thorium (Th-232)

also has a decay series often included in assessments of naturally occurring radionuclides. Thorium is more abundant than uranium and occurs as black thorium oxide.

Exposure to uranium, thorium, and their decay products can have harmful health effects, especially due to their emission of ionizing radiation. Epidemiological studies have shown a link between these exposures and health issues (Klaassen, 2001), although not all radionuclides in these decay chains contribute equally to the total radiation dose. Only those radionuclides significantly contributing to the effective dose are considered in the assessment, with specific dose conversion factors and half-lives taken into account.

The radioactive decay and in-growth of daughter products are factored into the assessment to prevent overly conservative results and to account for the long-term impacts of radioactive decay. Some radioisotopes in these decay chains remain a concern for thousands of years. Table 2.5 lists the radionuclides explicitly considered in the radiological safety assessment.

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 radioisotopes will remain a concern for periods of thousands of years.

**Table 2.5 List of  $\alpha$  and  $\beta$  emitting radionuclides explicitly considered in the Flat Mines Project radiological public safety and impact assessment.**

Long-lived Alpha ( $\alpha$ ) Radiation Emitters	Beta ( $\beta$ ) 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.

#### 2.3.4.4 Assessment of Non-Human Biota

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

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

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

### 2.3.5 Spatial Domain of Concern

The spatial domain for the radiological public safety assessment is primarily determined by understanding the processes that govern the movement of radionuclides and potential exposure pathways for at-risk groups. While physical boundaries cannot be strictly applied to all these processes, a 3 to 5 km radius around the environmental release points is generally used to define the area for evaluating environmental pathways. If necessary, a broader study area may be established to account for processes that affect radionuclide movement beyond this range. Since the focus of the analysis is on critical groups, the exposure locations to be considered are expected to be close to the sources, meaning the spatial scale of the assessment will be constrained by the selected public exposure conditions.

### 2.3.6 Assessment Timescales

The life cycle of operations, facilities and activities can be considered as three distinct periods, namely a pre-operational period (i.e., design, construction, and commissioning period), an operational period, and a post-operational period. A period of active or passive institutional control may apply to the post-operational period. A national regulation concerned with nuclear authorization does not provide specific guidance on the period or conditions to assume for institutional control.

The AMD is known to contain trace amounts of naturally occurring radionuclides. It is reasonable to assume that the mineral processing activities may lead to the release and accumulation of these radionuclides in environmental media such as soil, water, sediment or the uptake in plants and animals living in the area. These radionuclides can stay active in the environment for thousands of years and can remain in the environment long after the cessation of the mineral processing activities.

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

Note that an assessment of the potential radiological impact during the operational phase can be performed with a greater level of certainty since the conditions at present or in the near future are known or can be more reliably predicted than conditions during the post-operational period. Conditions during the post-operational period are more uncertain, in which case provision has to be made to address these uncertainties in the assessment.

### 2.3.7 Assessment Endpoint

Assessment (or calculation) endpoints for a radiological public safety assessment are guided by the regulatory framework, as well as the purpose, scope, and focus of the assessment. Additional endpoints may also be determined by the interested parties. While quantitative endpoints are typically used in safety assessments, qualitative endpoints may also be necessary in certain cases.

In line with the ICRP System of Protection defined in Section 2.2.4, the primary assessment endpoint is the annual individual effective dose rate. Unless otherwise specified, the term "dose" refers to the annual individual effective radiation dose to members of the public, as calculated using the method outlined in ICRP (1991). This aligns with NNR requirements for radiological protection of the public, as reflected in Safety Standards and Regulatory Practices outlined in Regulation No. 388.



## 3 System Description

### 3.1 General

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The purpose of this section is to provide a summary description of the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations and its associated subcomponents. The information serves as a basis for the radiological safety assessment and can be divided into three categories: the DWS Eastern Basin Water Treatment Plant (Water Treatment Plant) and associated sludge disposal facilities and operations, the potentially affected environment, and the radiological conditions of the source and residue materials that are of relevance to the assessment.

The section is structured as follows. Section 3.2 describes the geographical setting of the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, followed by more detailed descriptions of the water treatment plant itself in Section 3.3 and the sludge management process in Section 3.4. Section 3.5 summarises the outcome of the monitoring programme that was implemented in June 2016 for the Grootvlei No. 3 Shaft, while Section 3.6 provides a brief overview of the potentially affected environment. A summary of the radiological conditions in the form of laboratory analysis results and a radiation survey is presented in Section 3.8. The section concludes with a description of the anticipated maintenance activities in Section 3.9.

### 3.2 Geographical Setting

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The DWS Eastern Basin Water Treatment Plant and Sludge Management Operations cover an area of about 6 ha and are located in the Eastern Basin mine lease area near the town of Springs on the East Rand, approximately 70 km east of Johannesburg, in the Gauteng Province of South Africa.

Figure 3.1 shows the site that hosts both the Water Treatment Plant and the Grootvlei No. 3 Shaft is located adjacent to the Strubenvale residential area. Figure 3.2 shows that the Blesbok Spruit that is used as a discharge point of treated water is flowing on the eastern side of the site in a southerly direction into the Suikerbosrand as part of the greater Vaal River catchment area.

### 3.3 Eastern Basin Water Treatment Plant

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#### 3.3.1 General

The main purpose of the Water Treatment Plant is neutralisation and metal removal from the AMD water in the Eastern Basin. Based on the water qualities in the basin, this includes the following as a minimum (AECOM, 2015b):

- Iron oxidation, neutralisation and metals removal;
- Sulphate precipitation/removal to the gypsum solubility limit in water (in the order of  $3,000 \text{ mg.L}^{-1}$ ); and
- Final clarification and removal of precipitated products (sludge) before discharge to the environment.

Figure 3.3 is an aerial view of the Water Treatment Plant with the three thickeners and treated water sump in the foreground and the Grootvlei No. 3 Shaft in the top right-hand corner. Figure 3.4 presents an engineering drawing of the site layout of the water treatment plant.



Figure 3.1 Google image showing the location of the DWS Eastern Basin Water Treatment Plant and associated Grootvlei No. 3 Shaft.

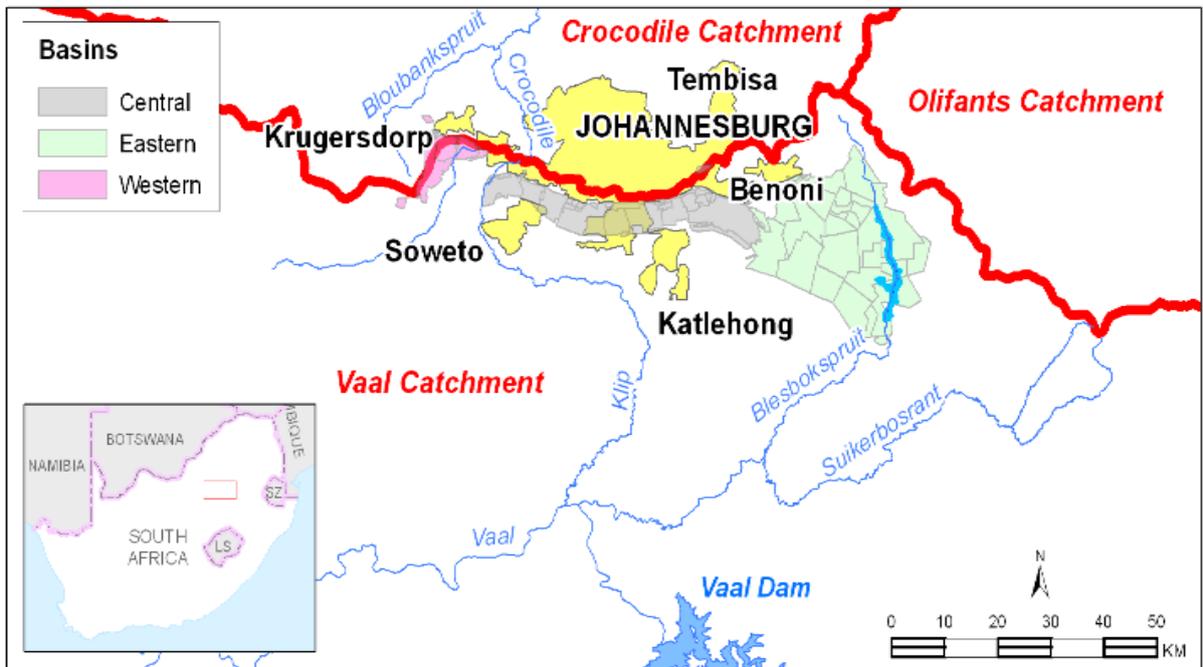


Figure 3.2 Map showing the 3 main basins, with the Blesbok Spruit draining the Eastern Basin flowing into the Suikerbosrand as part of the Vaal River catchment area (<https://www.dws.gov.za/iwrp/amdfs/lts/default.aspx>).



**Figure 3.3** Aerial view of the DWS Eastern Basin Water Treatment Plant near Springs.

### 3.3.2 Process Description

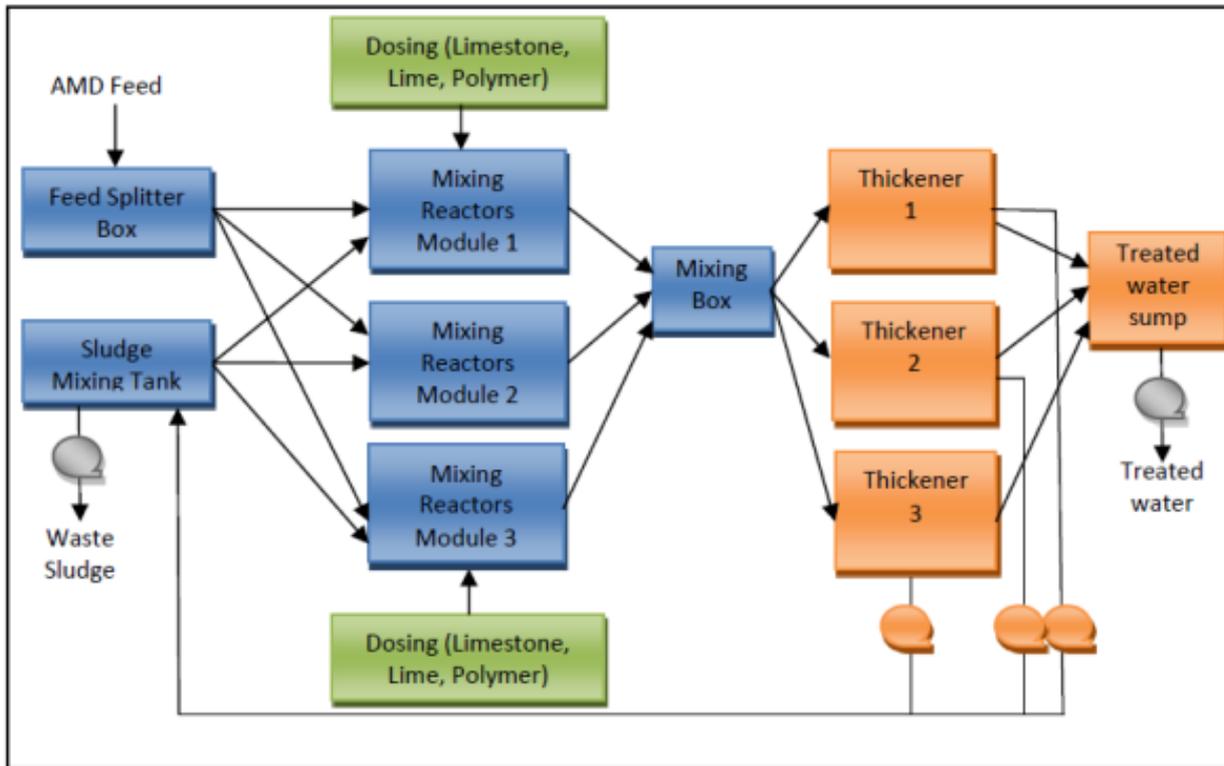
A detailed description of the control- and operational philosophy of the Water Treatment Plant is presented in AECOM (2015a). Figure 3.5 presents a simplified process flow diagram. A detailed process flow diagram, together with the Process Functional Description Report, is attached as Appendix C to AECOM (2015a).

The Water Treatment Plant is designed to treat a maximum of 110 ML of AMD water per day continuously for 24 hours, seven days a week. Under these conditions, all three treatment modules will be in operation. The number of treatment modules in operation can be reduced based on the AMD water feed flow requirement. The average flow is expected to be in the order of 82 ML per day. Three heavy-duty Ritz dewatering pumps are situated 160 m below the surface. Each pump transfers 1,500 m<sup>3</sup> of AMD water to the surface every hour. Each pump requires 24,00 kW of power to operate.

The AMD feed is transferred to an AMD splitter box, from where it is separated across three reactor circuits for pre-neutralisation, neutralisation and gypsum crystallization. The water treatment plant consumes on average 55 tons of lime daily to deliver the required water quality, which is clarified in three 43 m diameter thickeners before being discharged as treated water to the Blesbok Spruit. The entire water treatment process is monitored *via* a control room and a sophisticated software system. Each thickener is equipped with a Tecrover proprietary mechanical drive head capable of delivering 1.2 million newton metres of torque.

The treated water overflows from the three thickeners to the treated water sump, which provides the necessary water for utility water pumps, chemical makeup water pumps, flushing of the sludge waste pipeline and future connections for treatment of the treated water to potable water quality. The treated water overflows from the treated water sump over a weir and is then discharged by gravity to the Blesbok Spruit. If the treated water is not within the discharge specification, the operator will activate the “Recycle Mode” until the quality of the water is acceptable.





**Figure 3.5 Simplified process flow diagram of the DWS Eastern Basin Water Treatment Plant.**

The settled sludge in the thickeners is pumped from the centre well of the thickeners to the sludge-mixing tank. The sludge flow from each thickener is measured, and the readings are recorded and displayed in the control room. The sludge disposal is done from the mixing tank (see Section 3.4).

Engineered control measures were installed to ensure that no water or sludge spillages were released from the site. For this purpose, the Plant Operator installed sump pits in specific areas on the site close to sludge-carrying pipelines. When a spillage does occur, a pump is placed in the sump, and the spilt sludge is transferred to the channels leading to the plant drain. From the drain, the sludge is preferably pumped back into the process. However, in extreme situations, the sludge and water will flow to the shaft *via* the emergency overflow channel.

### 3.3.3 Waste Management

The biggest volume of waste that is generated at the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations is the HDS that is disposed of in the mine void (see Section 3.4). However, a small volume of other waste types will inevitably be generated, especially at the Water Treatment Plant.

Most notable is the generation of scrap steel or redundant equipment, which is removed by either the original supplier or by the new supplier who is replacing the equipment that is deemed redundant. The situation will be evaluated on a case-by-case specific scenario and the disposal certification is part of the contract to replace the equipment. Currently, all waste is removed by certified contractors with safe disposal certificates for all waste-related activities.

## 3.4 Sludge Disposal

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### 3.4.1 General

Different options have been considered to manage the HDS generated during the water treatment process (AECOM, 2015b). These include co-disposal of the sludge with tailings material onto the DRD Gold Brakpan Tailings Storage Facility (TSF) (initially in 2011), a pipeline to the proposed Withok TSF *via* the Ergo Processing Plant, disposal on the Grootvlei TSF or underground disposal of the HDS in the Eastern Basin mined-out (void) areas.

AECOM (2015b) provides a detailed conceptual review of these alternatives to sludge management, including an overview of the advantages and disadvantages of underground disposal of sludge in the mining void based on a literature review of national and international best practices. All these options are consistent with the waste management options outlined in the NRWMP (see Section 2.2.6 as well as Table 2.3 and Table 2.4).

In June 2016, the DWS granted TCTA approval to proceed with a field study to determine the feasibility of underground sludge disposal as the preferred management option. Sludge from the Water Treatment Plant was to be disposed of into the Grootvlei No.3 Shaft and/or suitably constructed deep boreholes intersecting the Eastern Basin mine void (notably the Kimberley and/or Main Reefs) for 12 months, which was extended for a further 18 months in 2018 and again for a further 24 months in 2020. The disposal of HDS down the Grootvlei No. 3 Shaft into a dewatered pump station area at a depth of 760 m commenced in August 2016.

Conceptually, the method of sludge disposal into mining voids has several advantages, including cost efficiency and the reduction of surface waste facilities. This is a temporary field-based investigation aimed at evaluating the viability of long-term sustainable sludge disposal into mining voids that are permanently flooded with AMD (Exigo Sustainability, 2017a).

### 3.4.2 Sludge Composition

It follows from Section 3.3 that the aim of the Water Treatment Plant is neutralisation and metal removal. The chemical reagents considered for the AMD treatment are oxidation with air (in the pre-neutralization and neutralization reactors), neutralisation with limestone (in the AMD Splitter box when the AMD feed water pH is less than 5) and quicklime (neutralisation and sludge conditioning reactors). According to (AECOM, 2015b), the resulting sludge composition from these processes consists of the following major components: 24% Calcite ( $\text{CaCO}_3$ ), 47% Gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ), 15% Iron hydroxides and 11% other inerts.

AECOM (2015b) further noted that the sludge is classified as a Type 3 waste in terms of the National Environmental Management: Waste Act, 2008 (ACT No. 59 of 2008) (NEM:WA) due to elevated concentrations of Arsenic (As), Cadmium (Cd), Manganese (Mn), Nickel (Ni) and Antimony (Sb). These chemical constituents of the sludge are all present in the water in the mine void. The exception is the addition of lime and limestone (with small amounts of polyelectrolyte to improve the settling characteristics of the sludge). The sludge consists of 85% water and only a maximum of 15% solids.

### 3.4.3 DWS Directives

Following the conceptual design of the underground sludge disposal operation provided in (AECOM, 2015b), a Directive was issued by DWS (Ref: 16/2/7/C231/C068) that requires the following (Exigo Sustainability, 2017a):

- Disposal of sludge into the Grootvlei No. 3 Shaft and/or suitably constructed deep boreholes intersecting the East Rand Basin (ERB) mine void (Kimberley and/or Main Reefs) for 12 months;
- Sludge to be disposed of at a depth of at least 350m below the collar height of the Grootvlei No. 3 Shaft, at an estimated depth of 200m below the Environmental Critical Level (ECL);
- Appoint an independent specialist to develop and implement a comprehensive geohydrological and geochemical monitoring programme to evaluate any potential impact of the disposal on the regional groundwater resource;
- Water quality variables to be assessed daily: pH, EC, TSS, sulphate, iron & manganese. In consultation with the DWS, the monitoring frequency may be reduced subject to the monitoring trend confirming no severe fluctuations;
- Water quality variables to be assessed weekly: uranium, sodium, calcium & aluminium. In consultation with the Department, the monitoring frequency may be reduced subject to the monitoring trend confirming no severe fluctuations;
- Progress reports are to be submitted to the Department monthly and on an ad hoc basis for any urgent matter requiring the Department's immediate intervention;
- An interim evaluation report is to be submitted to the Department six months after the commencement of the activity;
- The interim report must outline a clear position on the viability of long-term disposal of sludge into mine voids that are considerate of *inter alia*, engineering, geotechnical and hydrological aspects; and
- Sludge disposal should be terminated immediately with any inclination that sludge disposal is adversely impacting mine void water (raw AMD) and/ or compromising any element of the ERB plant performance and efficiency.

A further directive, with the same reference, was issued on 20 December 2018 and approved the same disposal of sludge for 18 months and again on 17 January 2020 for a further 24 months. The following was also required in terms of the latest DWS Directive (Ref: 16/2/7/C231/C068) dated 17 January 2020:

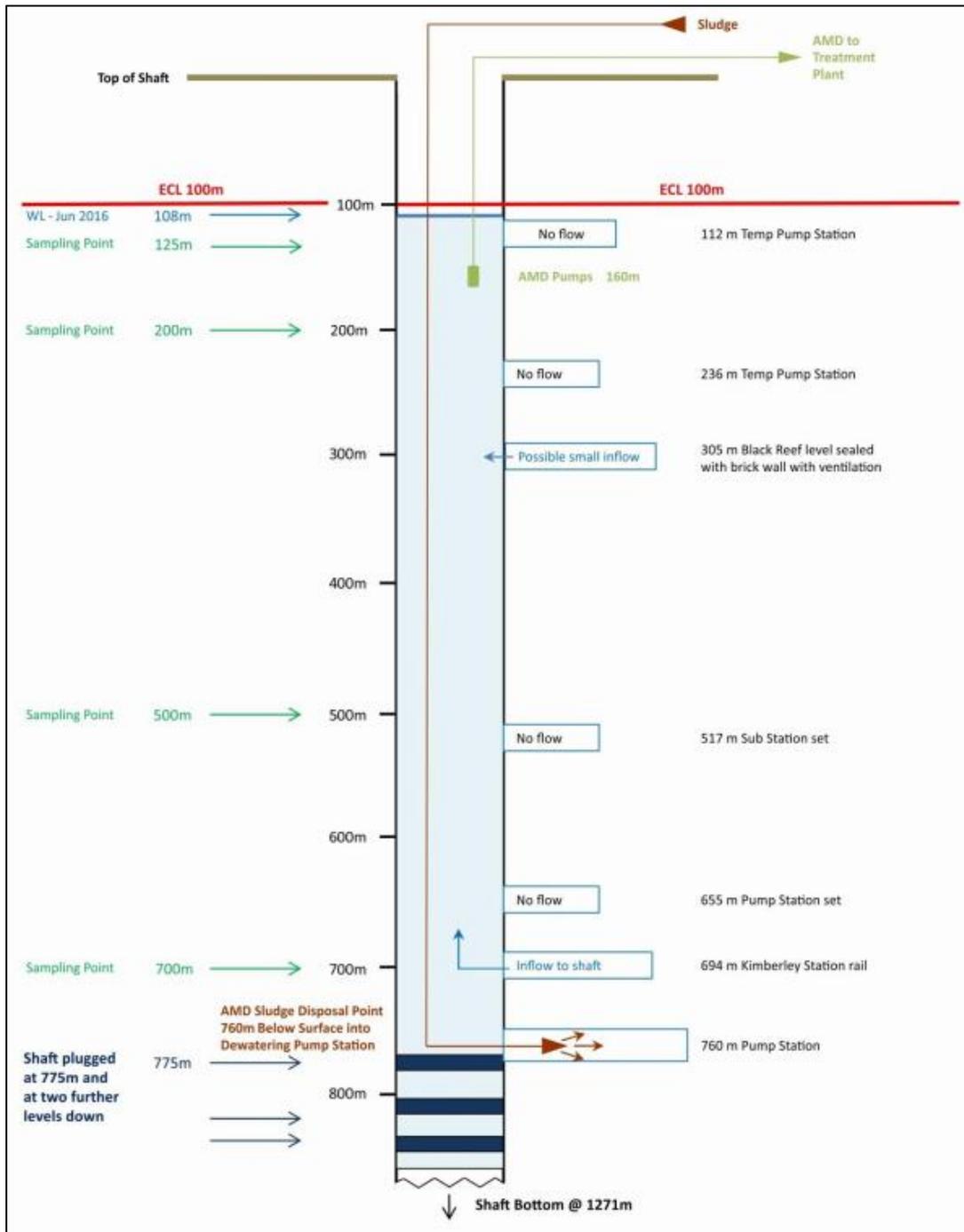
- The representative surface and groundwater resources that may be impacted by the sludge disposal into the deep compartments and/or the existing Grootvlei No. 3 Shaft and/or No. 4 Shaft of the abandoned Eastern Basin mine void must be assessed monthly for the parameters pH, conductivity, total suspended solids, sulphate, iron, manganese and uranium;
- Progress/monitoring reports must be submitted to the Department quarterly from the commencement of activity;
- Sludge disposal should be terminated immediately if there is any indication that sludge disposal is adversely impacting mine void water (raw AMD) and/or compromising any element of the ERB plant performance and efficiency;
- During this period, the TCTA must establish an alternative solution(s) for sludge disposal, should the deposition into the Eastern Basin mine compartments and/or Grootvlei No. 3 Shaft and/or No. 4 Shaft prove to be unsustainable and/or create environmental risks; and
- Before the expiry of this approval, the TCTA must provide the Department with the most pragmatic and sustainable solution for sludge disposal and initiate the necessary regulatory processes to ensure a long-term sustainable solution is implemented for sludge disposal in the Eastern Basin.

### 3.4.4 Conceptual Design

The conceptual design for the sludge disposal operations presented in AECOM (2015b) suggests the use of the Grootvlei No. 3 Shaft and/or suitably constructed deep boreholes intersecting the Eastern Basin mine void (Kimberley and/or Main Reefs) as the disposal zone. The initial indication presented in AECOM (2015b) suggests that considering the daily volume of sludge disposal ( $1,368 \text{ m}^3 \cdot \text{day}^{-1}$  average at 15% solids), the total mining void would provide 400,000 years of storage. This is based on a simplistic calculation, taking the total daily sludge volume as “sludge”. The reality is that the sludge volume consists of 85% water and only a maximum of 15% solids. While it would be naive to assume that the total underground void can be effectively filled with sludge, it can be stated without any doubt that more than enough voids are available to receive the sludge for many years until alternative disposal options become more attractive. Figure 3.6 is a photo of the Grootvlei No. 3 Shaft entrance, showing the main shaft superstructure and overhead superstructure crane, while Figure 3.7 is a schematic diagram of the shaft itself.



**Figure 3.6** Photo of the Grootvlei No. 3 Shaft, showing the main shaft superstructure (Exigo Sustainability, 2017a).



**Figure 3.7 Schematic diagram of the Grootvlei No. 3 Shaft, showing the current sludge disposal point at 760 m below the surface into a submerged dewatering pump station (Exigo Sustainability, 2017a).**

The Grootvlei No. 3 Shaft measures 3.3 x 13 m and is completely covered with a concrete cap. The Shaft comprises 6 compartments and is accessible from the top of the cap. Compartments 1 and 6 are closed off with circular steel plates. Compartments 2 (Pump A), 3 (Pump B) and 4 (Pump C) are equipped with AMD abstraction pumps hanging at a depth of 160 m below the concrete cap collar. Compartment 5 is equipped with a steel cap with the option of lifting and moving the top plate utilizing an overhead superstructure crane (see Figure 3.8). Figure 3.9 shows the high-density polyethylene (HDPE) sludge disposal pipe that is installed in Compartment 5 and that feeds into an existing pipe on the southern side of the compartment, all the way down to a depth of 760 m (Exigo Sustainability, 2017a).



**Figure 3.8** Compartment 5 (left) covered with Top Plate. Compartment 6 (right) is closed off with a Circular Steel Plate(Exigo Sustainability, 2017a).



**Figure 3.9** View into Compartment 5 showing the sludge disposal pipe (Exigo Sustainability, 2017a).

Figure 3.7 shows that the Shaft was developed to a depth of 1,271 m below the surface but was plugged at 775 m and at two levels below that. Figure 3.7 also shows that AMD water flowing into the Shaft is expected to occur at the Kimberley Station Rail level at 694 m, approximately 80 m above the Shaft plug at 775m.

Also shown in Figure 3.7 is that sludge disposal in the Shaft occurs at a depth of 760 meters into a submerged dewatering pump station (Exigo Sustainability, 2017a). The pump station has approximate dimensions of 90 m long, 10 m wide and 7 m high. This old pump station and adjacent areas connected to the larger Eastern Basin void are the target disposal volumes (AECOM, 2015b). The pump station is already about 450 m underwater and, therefore, can no longer be accessed. Figure 3.10 shows an example of a typical underground dewatering pump station that may include retainer walls to define underground dams.



**Figure 3.10** Example of an underground pump station with container dams behind the pump station (<https://www.wilshaw.com.au/projects/134-pump-station-underground/>).

According to Exigo Sustainability (2020), the disposal of sludge into the Grootvlei No. 3 Shaft was considered a short-term solution (1 year to 18 months). The associated increased suspended solids in the AMD feed to the plant during the fourth quarter of 2017 and later during September 2019 resulted in operational issues.

Three deep boreholes have consequently been drilled for the sludge disposal operations. Table 3.1 summarises the borehole location used for the deep mining void sludge disposal, while Figure 3.11 presents their relative locations to the Grootvlei No. 3 Shaft and the Water Treatment Plant. Detailed borehole (drilling) logs of these boreholes are not available, but it is believed that the boreholes intersect the Kimberley Reef at  $\pm 680$  m and the main Reef at  $\pm 1,148$  m. Collapsed mine voids at these reefs provide the necessary disposal volume. However, the exact volume of mine void that is available around these collapsed mine void areas is unknown.

**Table 3.1 Summary of the borehole location used for the deep mining void disposal of high-density sludge (Exigo Sustainability, 2020)**

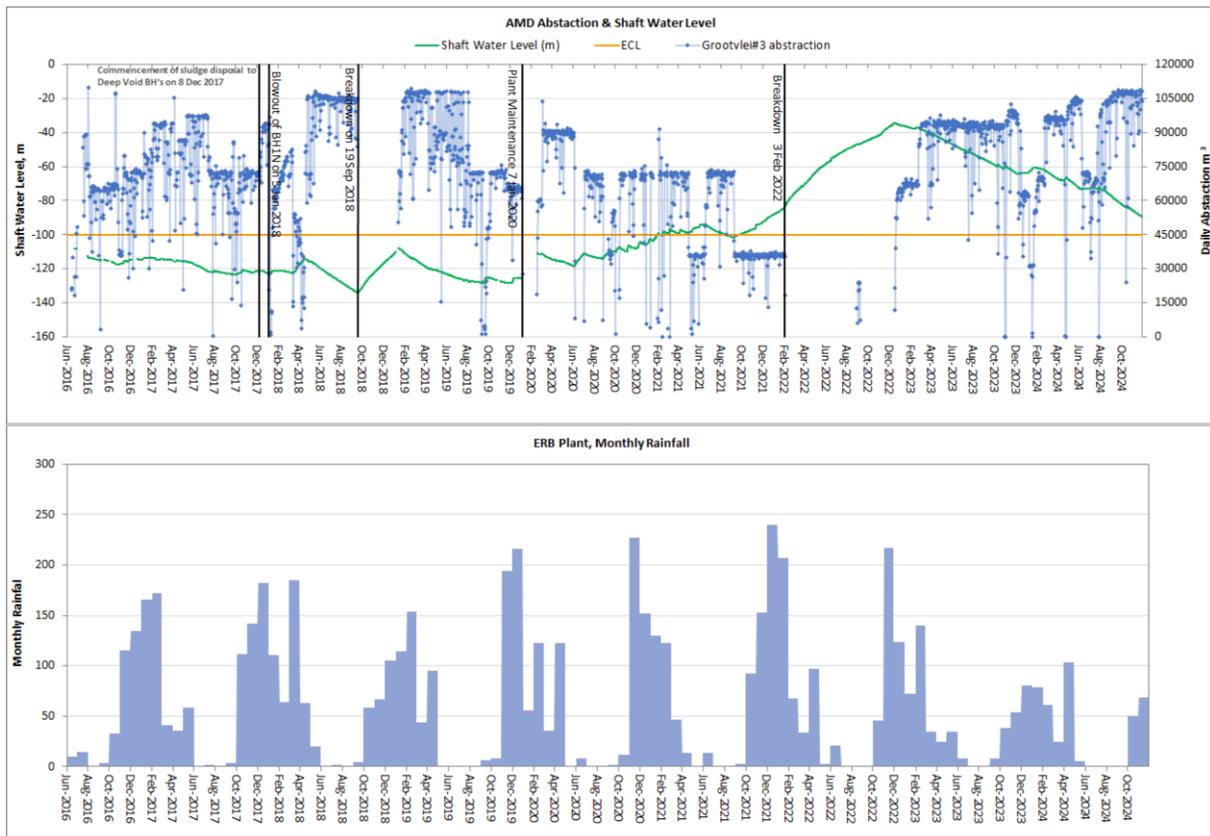
Location	Latitude	Longitude	Description
BH6N	-26.253	28.491	Sludge disposal BH located approx. 220 m southeast of AMD ERB Plant perimeter. Intersected Main Reef Void at 1 148 m on 24 Jul 2018. The sampling run on 27 Oct 2017 failed as the bailer could not be lowered past 460 m.
BH1N	-26.250	28.490	Sludge disposal BH is located on the northeast perimeter of the AMD ERB Plant area. Intersected "Ghost" Kimberley Reef Void at 669 m on 30 Aug 2017. A pressure blowout occurred on 5 Jan 2018. No sludge disposal at the borehole has been done since.
BH8	-26.250	28.487	Sludge disposal BH is located on the northwest perimeter of the AMD ERB Plant area. Intersected Kimberley Reef Void at 684 m on 7 Nov 2017.



**Figure 3.11 Locality map showing the three deep boreholes for sludge disposal in the Eastern Basin mine void, relative to the Grootvlei No. 3 Shaft and the DWS Eastern Basin Water Treatment Plant (Exigo Sustainability, 2020).**

According to Exigo Sustainability (2020), the disposal of boreholes targeting mining voids at a depth of  $\pm 680$  m and  $\pm 1,148$  m commenced in December 2018. From 20 January 2018 to 19 September 2018, sludge was solely disposed of at borehole BH8, except for 3 days. From January 2019 to February 2020, disposal was to BH8, except for 29 days to BH1 and limited disposal to the shaft during September 2019. The sludge disposal locations, sludge disposal volumes, as well as AMD water volume abstracted to date, are presented in Figure 3.12.

The sludge disposal rate in the boreholes is the same as in the Grootvlei No. 3 Shaft (about  $1,400 \text{ m}^3 \cdot \text{day}^{-1}$  average at 15% solids and 85% water). According to Exigo Sustainability (2020), the total Eastern Basin mine void volume was calculated at  $\pm 250 \text{ mil m}^3$ , which would be able to sustain sludge disposal for 860 years (compaction excluded) or at least 400 years if  $\pm 50\%$  filling is assumed. The initial mass balance modelling and risk assessment indicated that sludge disposal is a long-term option that is expected to improve the basin water quality over time.



**Figure 3.12 The sludge disposal locations, sludge disposal volumes, and the AMD water abstracted volume observed between December 2017 and December 2024 (Artesium, 2024a).**

Note that consistent with the Directive by DWS (Ref: 16/2/7/C231/C068) of 17 January 2020, Shaft No. 4 is used at present for the disposal of sludge in the Eastern Basin mine void. The shaft is located approximately 2.5 km from the Grootvlei No. 3 Shaft and extends over the same lithological units of the Eastern Basin (see Figure 3.21).

### 3.5 Monitoring

#### 3.5.1 General

One of the DWS Directive requirements is the implementation of a water quality monitoring programme following the disposal of the sludge in the underground mining void. Exigo Sustainability (Pty) Ltd (Exigo) was initially appointed by AECOM on behalf of the TCTA to implement a monitoring programme to determine the feasibility of underground sludge disposal at the Grootvlei No. 3 Shaft.

Exigo Sustainability (2020) presents an evaluation report of a comprehensive monitoring programme that commenced in June 2016. This includes baseline water monitoring results before sludge disposal commenced, followed by continuous monitoring (daily, weekly or monthly) of various chemical and geochemical parameters at various depths in the Grootvlei No. 3 Shaft (125 m, 200 m, 400 m, 500 m and 700 m) (see Figure 3.7).

Monitoring results are also available and reported in Exigo Sustainability (2020) for the three deep Eastern Basin mining void disposal boreholes (BH6N, BH1N and BH8 – see Figure 3.11), surface water in the Blesbok Spruit, surface water bodies in the area (Alexander Dam, Cowles Dam and Aston lake), shallow groundwater boreholes, Municipal water (Rand Water) and sewage effluent from the ERWAT Treatment Plant. Figure 3.13 is a locality map showing the various water monitoring locations.



**Figure 3.13** Locality map showing the water monitoring locations for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations (Exigo Sustainability, 2020).

The coordinates and a description of the three shallow groundwater monitoring boreholes shown in Figure 3.13 are presented in Table 3.2. These boreholes are used to monitor the impact of the Water Treatment Plant on the shallow aquifer.

**Table 3.2** The coordinates and a description of the three shallow groundwater monitoring boreholes shown in Figure 3.13 (Exigo Sustainability, 2020).

Location	Latitude	Longitude	Description
AECBH01	-26.241	28.462	The borehole is located approximately 2.8 km northwest of the Water Treatment Plant.
AECBH13 (A)	-26.240	28.511	Replacement borehole for AECBH13 since April 2017. Located 2.3 km northeast of Water Treatment Plant
CEN371 (A)	-26.223	28.429	Samples at the tap at the Water Treatment Plant

In June 2022, the monitoring responsibility was transferred to Artesium SA (Pty) Ltd (Artesium), with the following objectives (Artesium, 2024a):

- To provide reliable data on the quality and chemical composition of the surface and groundwater;
- To detect and quantify the presence and significance of any polluting substances in the groundwater and/or surface water as soon as possible;
- To detect the possible release or impending release of contaminants from the facility to the groundwater and/ or surface water environment; and
- To provide an ongoing performance record for effectively controlling pollution.

Table 3.3 summarises the current monitoring programme for the ERB AMD Water Treatment Plant as reported in the latest quarterly monitoring report (Artesium, 2024a).

**Table 3.3 Summary of the ERB AMD Water Treatment Plant monitoring locations (Artesium, 2024a).**

Identification	Type	Sampling Frequency	Lat.	Long.	Description
ESW-01	Surface water	Monthly	-26.2145	28.4799	Located approximately 4 km upstream from the plant, in the Blesbok Spruit
ESW-02			-26.2457	28.4716	Located approximately 1.6 km upstream from the plant, in a tributary of the Blesbok Spruit, flowing from the west
ESW-03 (discontinued after September 2024)			-26.2556	28.4983	Located approximately 700 m downstream from the plant, in the Blesbok Spruit
ESW-04			-26.2473	28.4823	Located approximately 500 m upstream from the plant, in a tributary of the Blesbok Spruit, flowing from the west
ESW-05 (discontinued after April 2021)			-26.2502	28.4976	Located on the eastern bank of a vlei in the Blesbok Spruit and approximately opposite the effluent discharge point and downstream from the old Tailings Storage Facility (TSF)
ESW-06			-26.2668	28.5032	Located at the R29 (Ermelo) road bridge over the Blesbok Spruit, approximately 1.7 km downstream from ESW03
Discharge Effluent	Process Water	Monthly	-26.2517	28.4914	Discharge point of treated AMD water.
EBH-01	Groundwater (Boreholes)	Quarterly	-26.2493	28.4876	The borehole is located just outside the northern corner of the plant area.
EBH-02			-26.2499	28.4887	The borehole is located halfway along the northern perimeter of the plant area.
EBH-03			-26.2506	28.4900	The borehole is located just inside the eastern corner of the plant area.
EBH-04			-26.2515	28.4895	The borehole is located along the eastern perimeter of the plant area.
AMD water	Process Water	Monthly	-26.2516	28.4888	AMD water in Grootvlei #3 shaft, either bailed or from the abstraction stream.

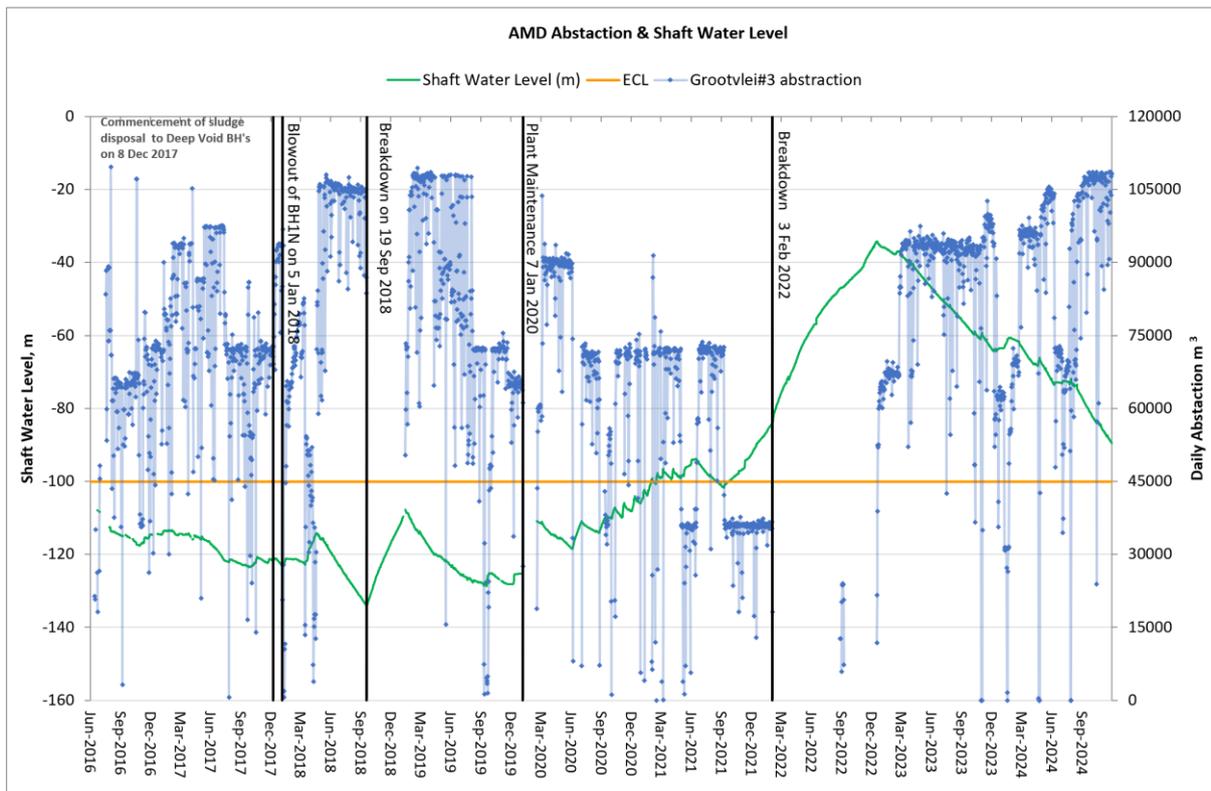
### 3.5.2 Water Level Monitoring

The ECL was previously determined to protect the dolomitic aquifer, which is considered a regional groundwater resource and a potential long-term water supply source (see Section 1.1 and Section 3.4.3). This means that if the water level is kept below the ECL, then the AMD water will have no impact on the shallow aquifer system (80 to 100 m below surface) and thus, the local groundwater users that abstract groundwater from the dolomitic aquifer (AECOM, 2015b).

Since 2016, the Grootvlei No. 3 Shaft water level and thus the Eastern Basin mine void water level remained below the ECL of 100m for most of the time, as illustrated in Figure 3.14. As the mine void water (i.e., raw AMD) was not in contact with the dolomitic aquifer situated above the ECL (up to February 2020), it is inferred that the dolomitic aquifer was not negatively impacted as a result of sludge disposal within the Grootvlei No. 3 Shaft or deep mining voids *via* deep boreholes (Exigo Sustainability, 2020).

However, between September 2020 and January 2023, a steady increase in the water level was observed, mainly due to a breakdown that occurred in February 2022, resulting in a breach of the ECL. Thereafter, the water level started to drop again and was just above the ELC in November 2024, as illustrated in Figure 3.14.

*Note that there are no specific measures in place to ensure that the ECL is not breached other than to monitor the water level continuously and maintain a constant pumping rate of AMD water sufficient to ensure that the water level remains below the ECL. It has been reported by TCTA that the ECL was indeed breached at the time of writing the report.*



**Figure 3.14 the ERB mine void water level relative to the Environmental Critical Level (ECL) and shallow borehole water levels (Artesium, 2024a).**

### 3.5.3 Summary of 2017 Monitoring Results

Following the first 6 months of monitoring, Exigo Sustainability (2017a) reported the following findings (amongst others):

- The disposal of sludge into the Grootvlei No. 3 Shaft is considered a viable short-term solution (6 months to 1 year), which should be confirmed with future monitoring. However, disposal into the Grootvlei No. 3 Shaft should be substituted with disposal into the mining voids (deep boreholes) as soon as possible. Disposal of sludge into mining voids should still be confirmed as a medium to long-term solution utilizing future monitoring.
- AMD water flowing into the Grootvlei No. 3 Shaft is expected to mainly occur at the Kimberley Station Rail level at 694 m. The increase in sludge level with time above the main AMD inflow level will result in an increase in sludge uptake to the AMD abstraction pumps situated at a depth of 160m. The suspended sludge volume returned to the Water Treatment Plant will increase with time, which at some point will begin to compromise the performance and efficiency of the plant.
- From the latest profiling results of the Grootvlei No. 3 Shaft water column, it was inferred that the estimated level of sludge build-up within the Shaft is currently at around 655 m below the surface. No adverse impact on the water quality at the AMD abstraction pump level was observed. The performance and efficiency of the Water Treatment Plant were thus not compromised.

### 3.5.4 Summary of 2020 Monitoring Results

Following the first 4 years of monitoring, Exigo Sustainability (2020) reported the following findings (amongst others):

- The regional shallow (<100 m depth) groundwater resource represented by the near-surface dolomite aquifer was not negatively impacted as the ECL of the mine void water at 100 m depth was not breached. Furthermore, regional shallow groundwater monitoring conducted within the greater Eastern Basin and shallow groundwater monitoring conducted at the Water Treatment Plant-specific monitoring boreholes did not show any negative impacts as a result of the sludge disposal into the Grootvlei No. 3 Shaft.
- No significant adverse impact on the Grootvlei No. 3 Shaft water (raw AMD) was observed as a result of sludge disposal within the deep void borehole. The sludge disposal was also not observed to be compromising any element of the performance and efficiency of the Water Treatment Plant. This was confirmed by the Grootvlei No. 3 Shaft profiling results and hydrochemical data, as well as the operational data from the Water Treatment Plant operations.
- Based on the total suspended solids sampled up to February 2020, sludge disposal in the deep void borehole BH8 at a depth of 684 m did not have a noticeable effect on Grootvlei No. 3 Shaft water quality.
- The isotope results indicated that the component of water in the Grootvlei No. 3 Shaft that originates from surface water varies from  $\pm 40\%$  during the dry season to  $\pm 80\%$  during the wet season. The results were similar to a simulated ingress study that indicated that  $\pm 50 \text{ ML}\cdot\text{day}^{-1}$  (65%) ingress originates from the Blesbok Spruit and  $\pm 25 \text{ ML}\cdot\text{day}^{-1}$  (35%) from the Dolomite Aquifer. The surface water flow in the Blesbok Spruit is sustained by the sewage works discharges of  $<100 \text{ ML}\cdot\text{day}^{-1}$  on the Eastern Basin catchment area. If these discharges could be downstream from the basin, it could potentially significantly reduce the ingress/treatment problem.

### 3.5.5 Summary of the 2024 Monitoring Results

Since 2022, the monitoring focus shifted toward monitoring the potential impact of the Water Treatment Plant on surface water and groundwater quality (see Section 3.5.1 and Table 3.3). In addition to reporting the water levels of selected boreholes, the hydrochemistry of selected boreholes, process water (treated AMD water), untreated AMD water and surface water is reported.

Figure 3.15 presents the macro chemistry results for the ERB Effluent water for the period 2016 to 2024, which shows that the water quality was relatively unchanged to date. A slight increase can be observed since 2020, which correlates well with the increase in the mine void water level in Figure 3.14.

Figure 3.16 and Figure 3.17 present the macro chemistry results for the surface water monitoring points in August 2024 and November 2024, respectively. Relative to the ERB effluent water, it shows that the downstream values are lower, but significantly higher than the upstream values. The longer-term monitoring results for ESW-03, the sampling of which was terminated in August 2024, is presented in Figure 3.18.

### 3.5.6 Uranium Monitoring Results

The information received from the Water Treatment Plant operations includes the weekly monitoring of Uranium (in  $\text{mg}\cdot\text{L}^{-1}$ ) at various depths in the Grootvlei No. 3 Shaft. A baseline average uranium concentration in solution of  $0.094 \text{ mg}\cdot\text{L}^{-1}$  was measured during 2004 and 2005 and is representative of the Eastern Basin before flooding conditions. During June 2016, an average baseline concentration of  $0.010 \text{ mg}\cdot\text{L}^{-1}$  was measured for all Grootvlei No. 3 Shaft samples, representing the Eastern Basin after flooding conditions but before AMD abstraction and sludge disposal (Exigo Sustainability, 2020).

The results are presented in Figure 3.19. The following was concluded for the first 4 years of Uranium monitoring in the Grootvlei No. 3 Shaft (amongst others) (Exigo Sustainability, 2020):

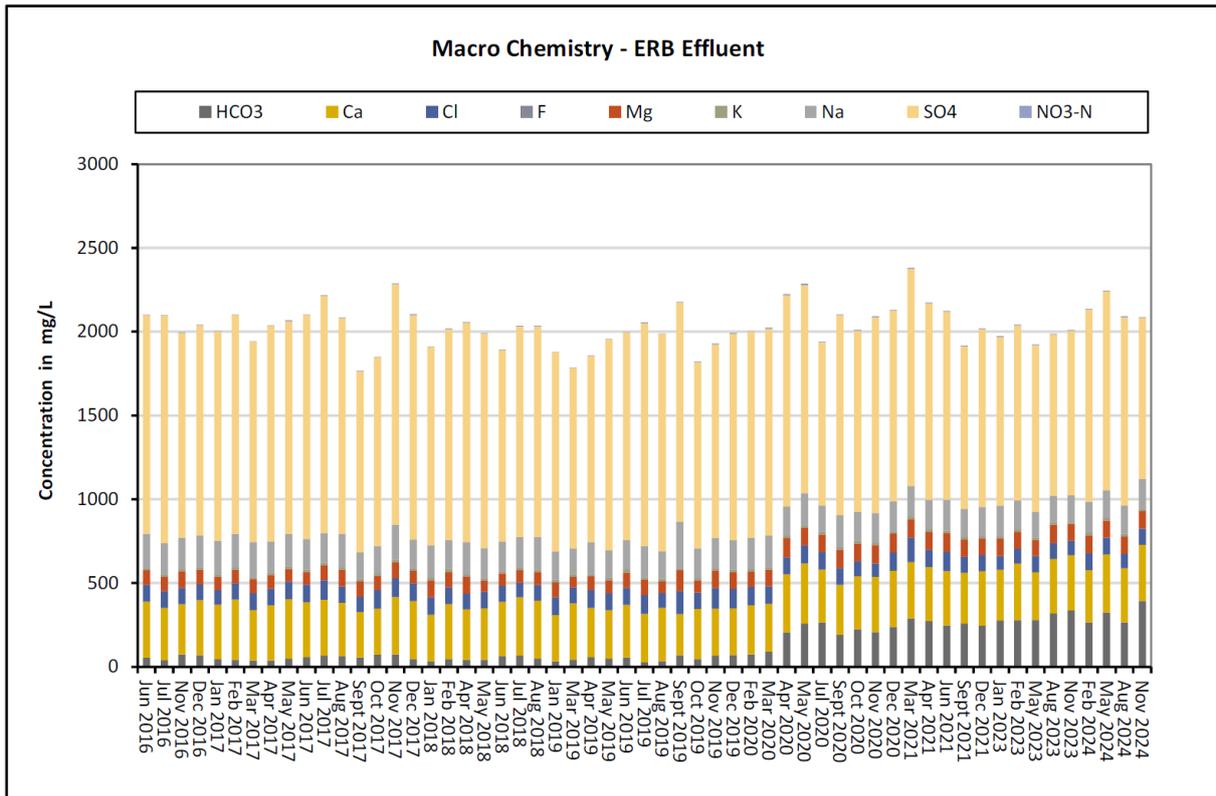


Figure 3.15 Macro chemistry results for the ERB Effluent water for the period 2016 to 2024 (Artesium, 2024a).

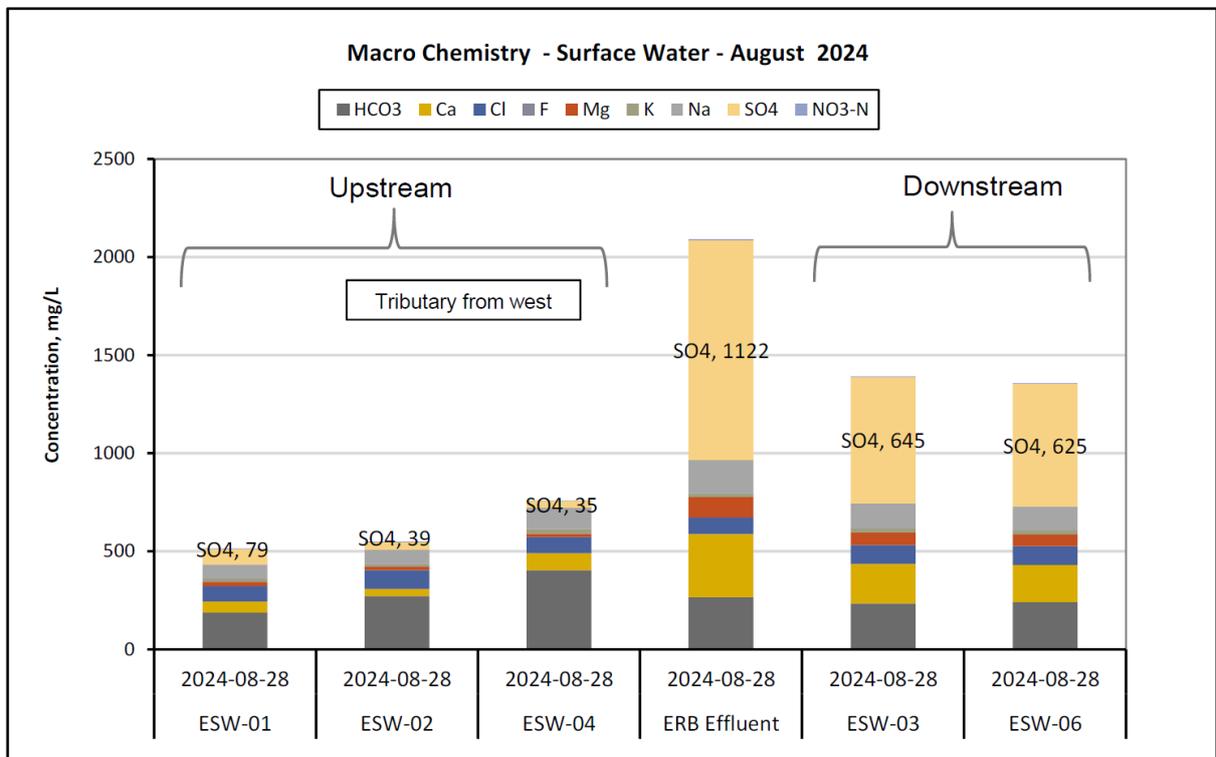
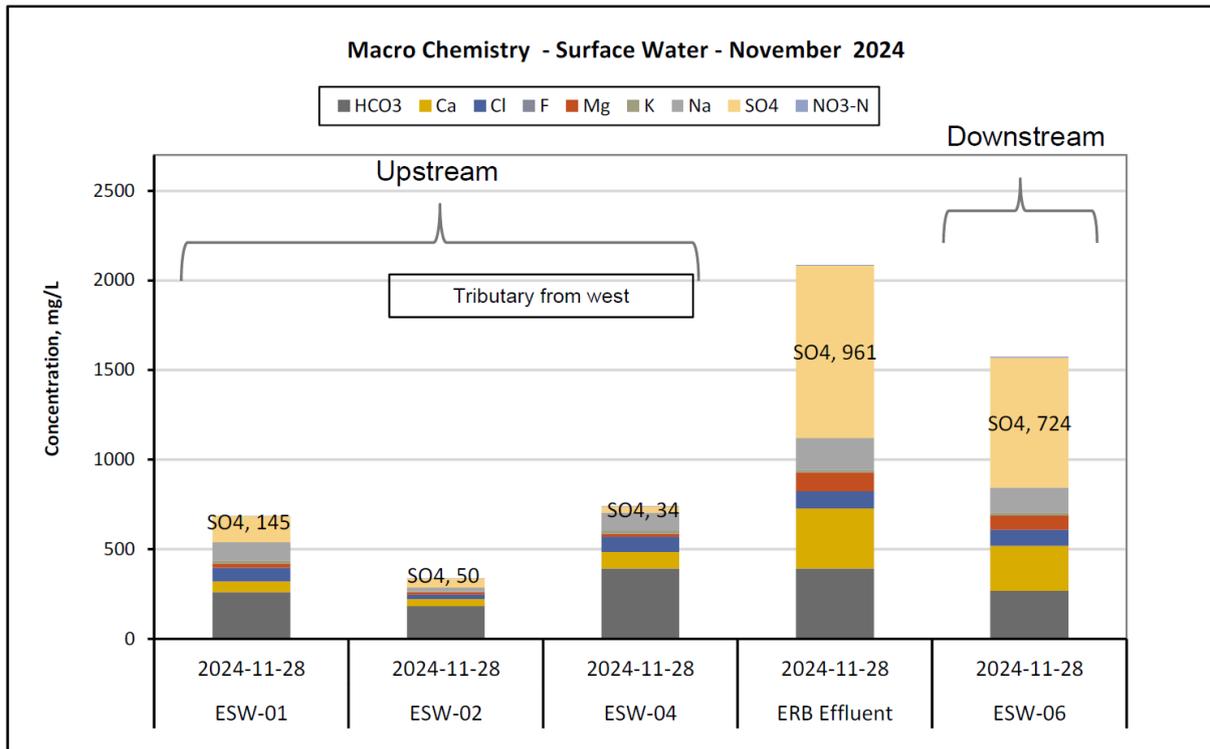
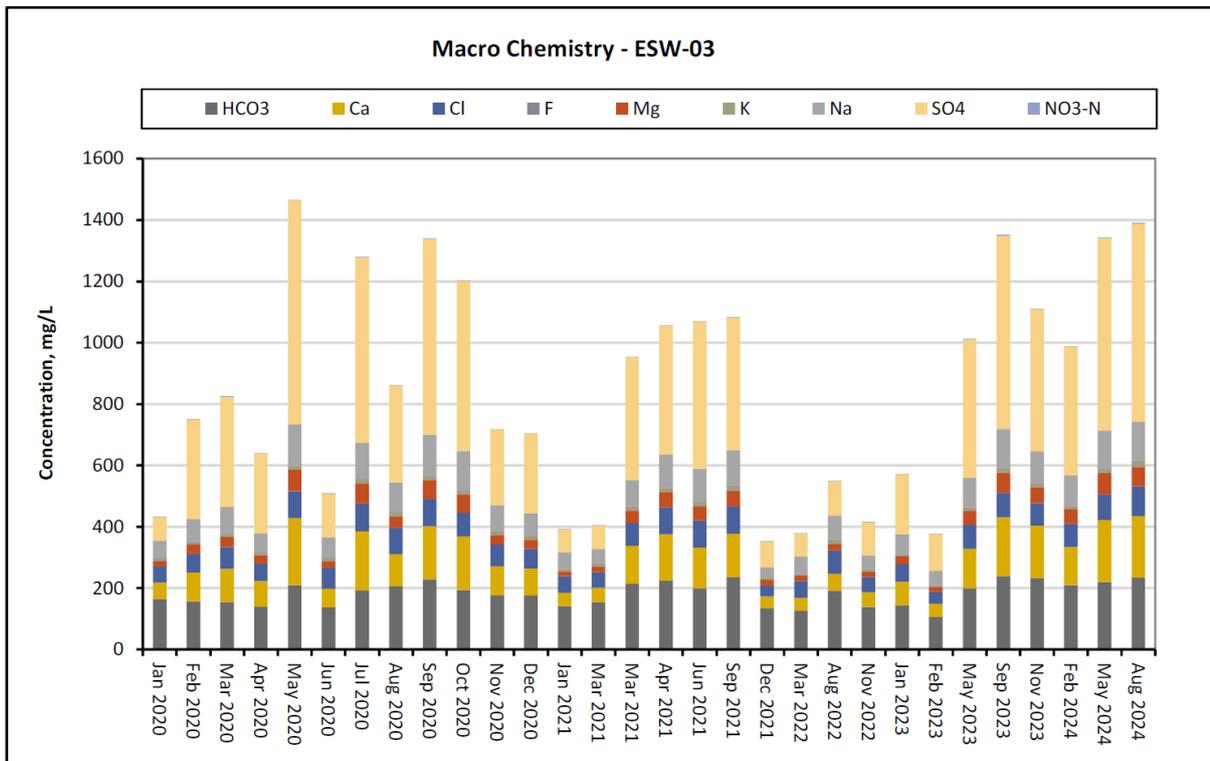


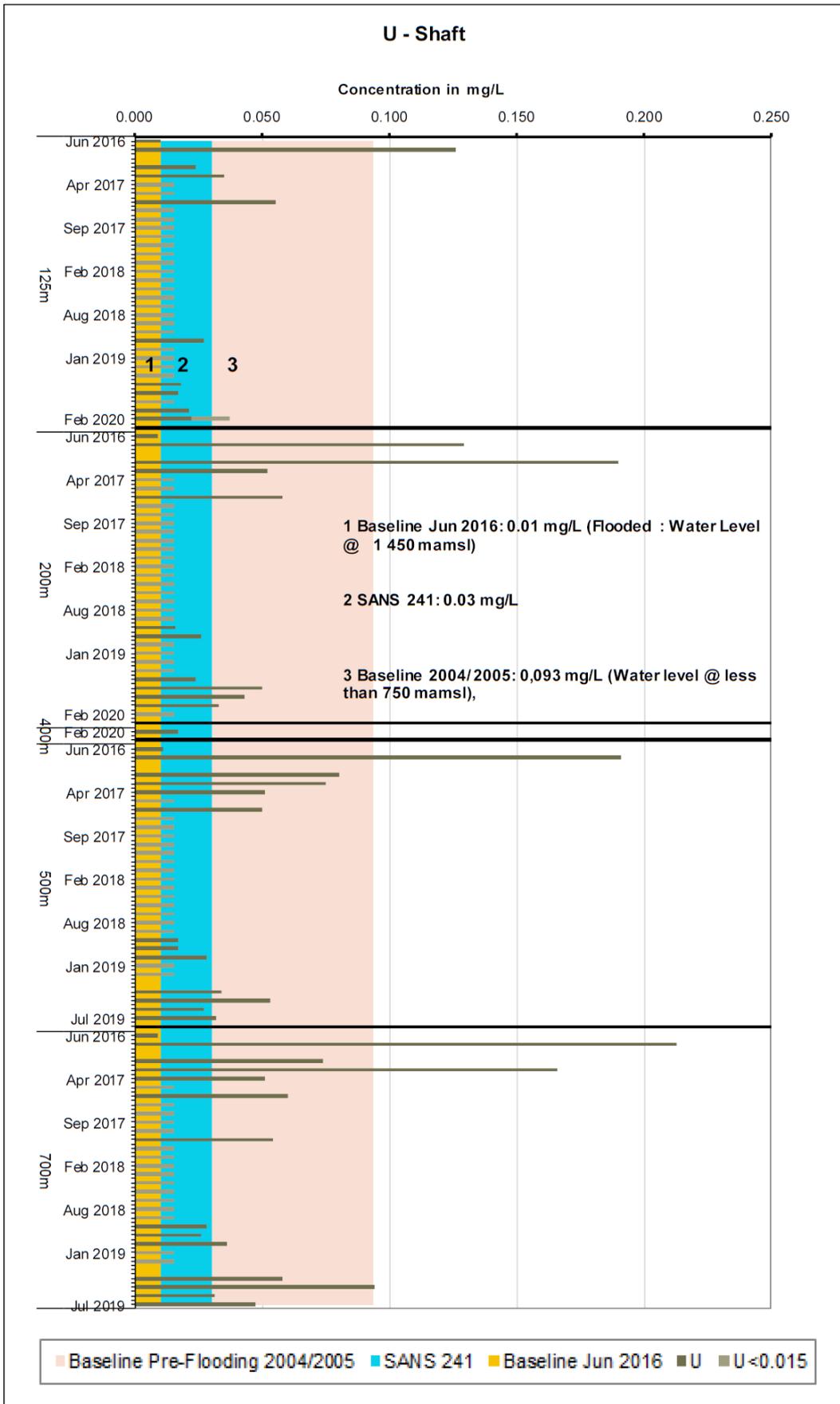
Figure 3.16 Macro chemistry results for the surface water monitoring points in August 2024 (Artesium, 2024a).



**Figure 3.17 Macro chemistry results for the surface water monitoring points in November 2024 (Artesium, 2024a).**



**Figure 3.18 Macro chemistry results for ESW-03 for the monitoring period 2020 to 2024 (Artesium, 2024a).**



**Figure 3.19 The Uranium concentration (in mg.L<sup>-1</sup>) as observed between June 2016 and February 2020 at 4 depths in the Grootvlei No. 3 Shaft (Exigo Sustainability, 2020).**

- After an average uranium concentration of  $0.056 \text{ mg.L}^{-1}$  was observed for all Grootvlei No. 3 Shaft samples during June 2017, uranium was only detected again in November 2017 in the sample from 700 m. The value of  $0.054 \text{ mg.L}^{-1}$  exceeded the SANS 241 drinking water limit of  $0.03 \text{ mg.L}^{-1}$ .
- Uranium was again detected after AMD abstraction and sludge disposal were terminated on 19 September 2018. It was detected in nine of the twelve samples taken and at concentrations from  $0.016 \text{ mg.L}^{-1}$  to  $0.036 \text{ mg.L}^{-1}$ . The concentration of one sample ( $0.036 \text{ mg.L}^{-1}$  taken at 700 m during December 2018) exceeded the SANS 241 (2015) limit of  $0.03 \text{ mg.L}^{-1}$ . It is known that uranium as found naturally in ore can be oxidized by atmospheric oxygen to more water-soluble species containing U(VI). It is therefore inferred that the exposure of the Grootvlei No. 3 Shaft void to atmospheric oxygen to the deepest depth of 134 m during September 2018 facilitated the formation of soluble species of Uranium. Rising water levels after 19 September 2018 took the newly formed species into solution. Uranium was detected at all three locations below 125 m after a rise in water level of 10.6 m by 31 October 2018. It was detected at all four depths in November 2018 and 500 m and 700 m in December 2018.
- From January 2019 to March 2019 no Uranium was detected in any of the twelve samples taken from the Grootvlei No. 3 Shaft. From April 2019 to February 2020, Uranium was detected in fifteen of the seventeen samples taken. Concentrations varied from  $0.017 \text{ mg.L}^{-1}$  at 125 m to  $0.094 \text{ mg.L}^{-1}$  at 700 m during May 2019. A Uranium concentration of  $0.047 \text{ mg.L}^{-1}$  and  $0.031 \text{ mg.L}^{-1}$  were determined in the samples taken from the AMD feed to the Water Treatment Plant during June 2019 and February 2020, respectively.
- Uranium was not measured in concentrations above the detection limit of  $0.015 \text{ mg.L}^{-1}$  in surface water and shallow surface groundwater in the vicinity of the Water Treatment Plant or treated effluent discharged into the Blesbok Spruit.

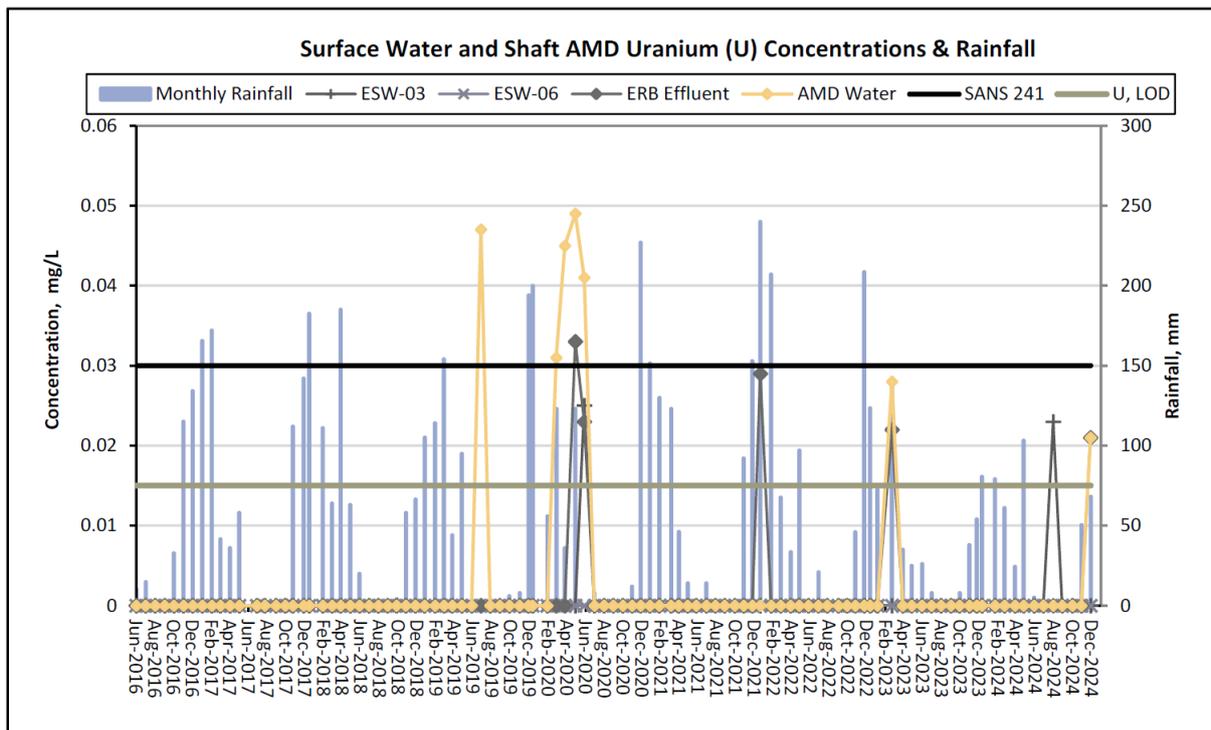
Note that since January 2017 the Water Treatment Plant operator has performed weekly and bi-weekly monitoring of a wide spectrum of chemical analyses of AMD water feed and treated water, using the West Bio-Chemical Water Analytical Laboratory. The analysis includes Uranium ( $\text{mg.L}^{-1}$ ), but except for 2 AMD feed samples in March 2017 ( $0.049 \text{ mg.L}^{-1}$ ) and April 2017 ( $0.47 \text{ mg.L}^{-1}$ ) all available Uranium results are below  $0.015 \text{ mg.L}^{-1}$ .

Figure 3.20 presents the surface water and AMD water uranium concentrations for the monitoring period 2016 to 2024 (Artesium, 2024a). It shows a few spikes in the ERB Effluent water uranium concentration (e.g., 2020 and 2022). These spikes correlate well with some of the uranium concentration spikes in the AMD water.

Although uranium was detected in the ERB Effluent water during November 2024, it was not detected downstream at ESW-06 at the same time. The most recent downstream detection of uranium was at ESW-03 on 30 July 2024 ( $0.023 \text{ mg.L}^{-1}$ ) following two days when the Water Treatment Plant was offline and not abstracting or discharging water. Before July 2024, the detection of uranium at ESW-03 was during May 2020 (Artesium, 2024a).

### 3.5.7 Deep Mine Void Borehole Monitoring

The locations of the three deep void sludge disposal boreholes are shown in Figure 3.11, with location descriptions in Table 3.1. Boreholes BH6N, BH1N and BH8 were respectively sampled during July 2018, September 2018 and November 2018. The boreholes were sampled after being drilled to gain baseline data. Borehole BH6N was drilled to a depth of 1,148 m into Main Reef, whereas BH1N (669 m) and BH8 (684 m) were only drilled up to the Kimberley Reef. The Uranium concentrations at all three boreholes were below the detection limit of  $0.015 \text{ mg.L}^{-1}$ .



**Figure 3.20 The surface water and AMD water Uranium (U) concentrations for the monitoring period 2016 to 2024 (Artesium, 2024a).**

### 3.5.8 Shallow Aquifer and Surface Water Monitoring

Monitoring results indicated that no uranium was measured above the detection limit of  $0.015 \text{ mg.L}^{-1}$  in surface water and shallow surface groundwater monitoring locations (see Figure 3.13) or treated effluent discharged into the Blesbok Spruit from June 2016 to December 2019 (Exigo Sustainability, 2020).

## 3.6 Potentially Affected Environment

### 3.6.1 General

The potentially affected environment is mainly defined by the area surrounding the Water Treatment Plant, the surface area affected by the discharge of treated water to the environment, and the subsurface area where sludge residue is disposed of. Given the nature of the water treatment and sludge management operations, the ability of the various activities to serve as potential sources of radiation exposure to the environment will differ.

### 3.6.2 Water Treatment Plant

The physical location of the Water Treatment Plant, which covers an area of about 6 ha was presented in Section 3.2. The area is located close to residential areas but the nature of the plant is such that the environment will not be affected by potential releases of naturally occurring radionuclides outside the plant boundaries (see Section 3.3). Engineered systems are in place that will contain any solid or liquid during normal and upset conditions (see Section 3.3.2). In addition, it employs a wet process to treat the AMD water, which means that dust release into the atmosphere is not possible. As such the Water Treatment Plant follows a zero-release management principle.

### 3.6.3 Release of Treated Water

The treated water is released to the Blesbok Spruit. The Spruit originates to the north of Benoni and Daveyton and flows southwards through Springs and Nigel towards the Vaal River (see Figure 3.2). It is a perennial second-order stream that is a tributary of the Suikerbosrand, which then flows into the Vaal River. According to Exigo Sustainability (2017a), the surface water in the Blesbok Spruit is driven by sewage work discharges of  $\pm 120$  ML per day onto the Eastern Basin catchment area.

The Blesbok Spruit is classified as a wetland of international importance for the conservation of waterfowl in terms of the Ramsar Convention. Several fauna and flora species are associated with the Blesbok Spruit and associated wetland areas (Digby Wells Environmental, 2015), including the Marievale Nature Reserve. It is expected that parts are highly modified by agriculture and human settlement. Key industries, such as mines (mine dumps and slime dams), waste disposal sites, intensive agriculture and sewage works impact negatively on water quality.

### 3.6.4 Underground Disposal

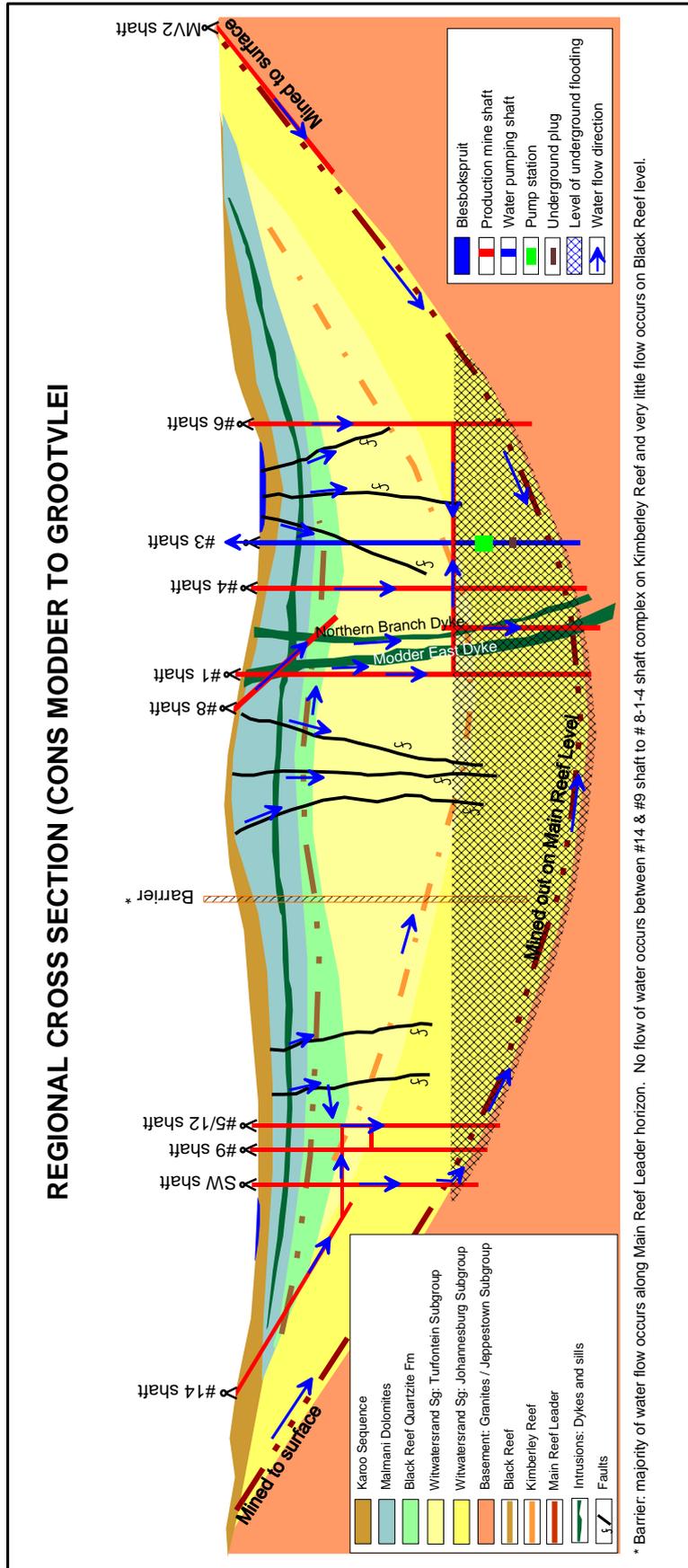
The affected environment for the underground disposal of residue sludge is mainly defined by the underlying geology and the associated aquifer system fed by the ingress of surface water, which has been greatly disturbed by historical mining (see Figure 3.21). This resulted in a significantly complex underground environmental system of mining voids made up of various tunnel structures and caverns that were required to access and extract the gold-bearing ore from underground. Figure 3.22, Figure 3.23 and Figure 3.24 give some perspective regarding the structure and connectivity of the underground void.

Figure 3.24 also provides a conceptual model of how water enters the mine void (ingress), resulting in AMD that is rising towards the surface. It is estimated that at least  $207 \text{ km}^3$  (207 billion  $\text{m}^3$ ) of rock was mined out of the Eastern Basin over the years that could be used as the potential sludge disposal volume (AECOM, 2015b).

Exigo Sustainability (2017b) performed an initial risk assessment of the impact of the underground disposal of sludge residue on the groundwater environment that included the development of a water flow volume and mass balance model. Figure 3.25 is the conceptual model for the Eastern Basin used as a basis for the initial risk assessment that shows, amongst others, the water ingress points, the distribution of the Kimberley Reef and Main Reef relative to the solid Granite, the depth of the ECL, and the abstraction rate of water from the Grootvlei No. 3 Shaft. An updated assessment of the Eastern Basin sludge disposal operations was recently performed and presented in detail in Artesium (2024b) (see Section 4.3.2).

According to Exigo Sustainability (2017b), the average pumping rate since abstraction started in June 2016, was  $75.8 \text{ ML}\cdot\text{day}^{-1}$  and ranged between a minimum of  $30 \text{ ML}\cdot\text{day}^{-1}$  and a maximum of  $109.8 \text{ ML}\cdot\text{day}^{-1}$ . They also noted that the flooding of the basin reduced the oxygen levels available to oxidise pyrite and acid formation, which resulted in an increase in the pH and a reduction in the TDS and sulphate levels.

Using the rise in water level when pumping ceased, the re-watering data and fit between reef porosity with depth, and the subsequent abstraction rate of  $75.8 \text{ ML}\cdot\text{day}^{-1}$ , the best estimated minimum basin volume was calculated as  $255 \text{ Mil m}^3$  at the ECL (1,450 mamsl) (Exigo Sustainability, 2017b). They concluded that the actual volume may be higher but unknown due to the selective and unknown collapse of the mine stopes when mining stopped.



**Figure 3.21 Schematic geological cross-section of the Eastern Basin indicating ingress of water into the mining basin.**



Figure 3.22 An example of historical underground mining operations (AECOM, 2015b).



Figure 3.23 An example of modern underground mining operations (AECOM, 2015b).

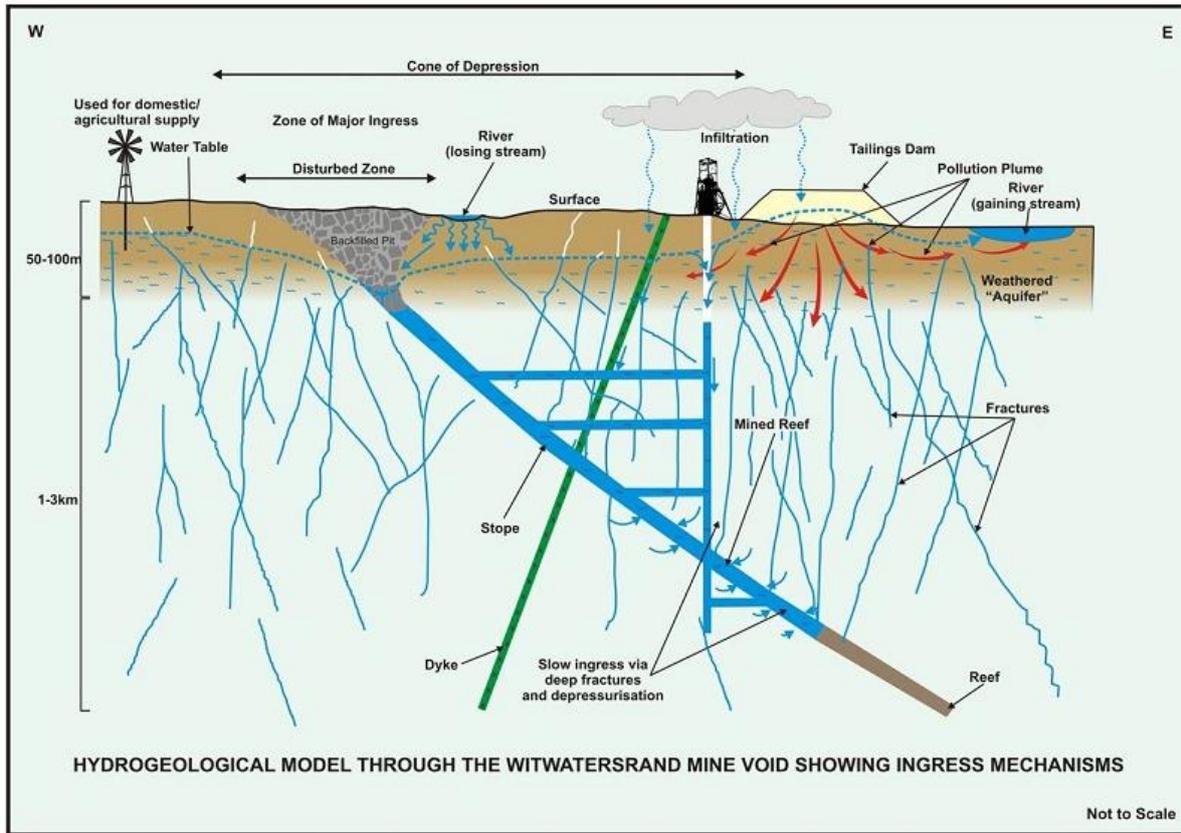


Figure 3.24 Graphical representation of a mine void and underground connectivity (DWS Website: <https://www.dwaf.gov.za/Projects/AMDFSLTS/default.aspx>).

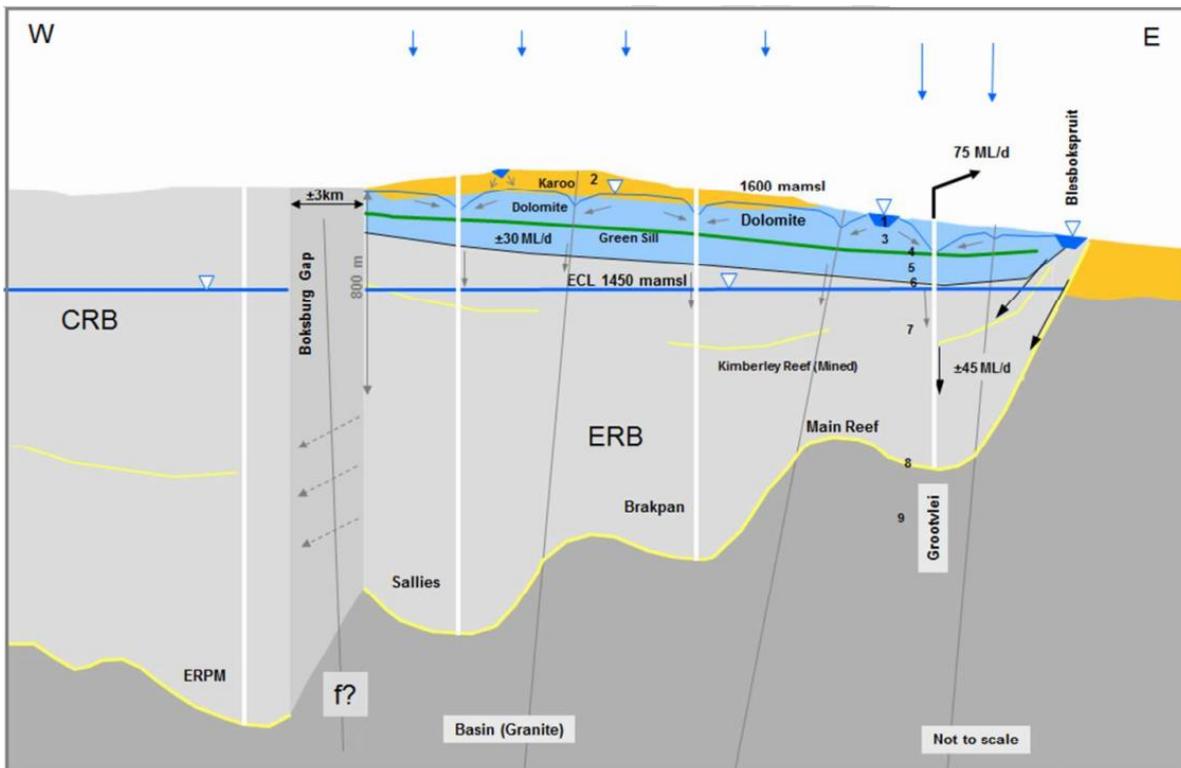
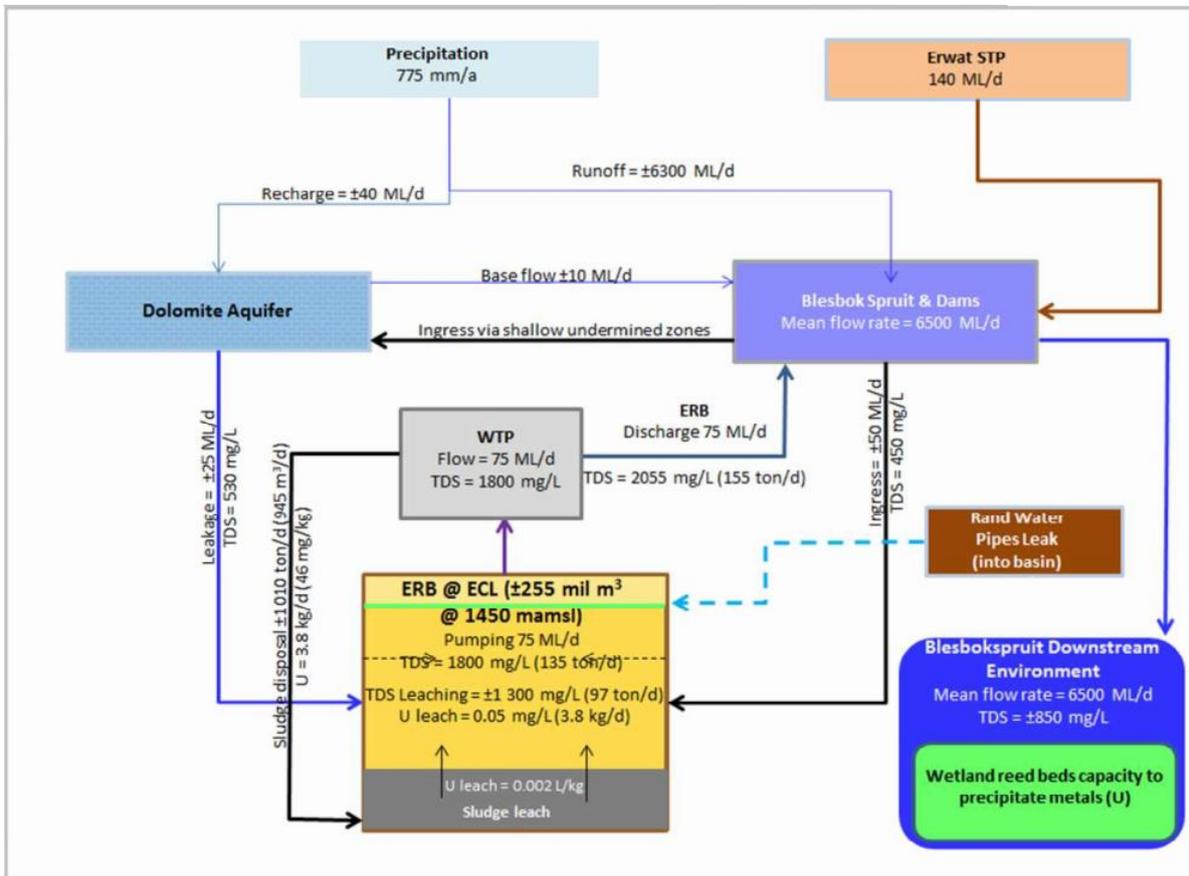


Figure 3.25 The conceptual model for the Eastern Basin used as the basis for the initial risk assessment performed by Exigo Sustainability (2017b).

Figure 3.26 presents the resulting conceptual flow and mass flux system model developed for the Eastern Basin. Sludge is produced at a rate of  $13.16 \text{ kg}\cdot\text{m}^{-3}$ , which corresponds to a volume of  $945 \text{ m}^3\cdot\text{day}^{-1}$  ( $1,010 \text{ tons}\cdot\text{day}^{-1}$ ). This means the total void volume will take about 730 years to be filled. If a 50% filling space is assumed, there would be sufficient volume for sludge disposal for at least 360 years (Exigo Sustainability, 2017b). According to Exigo Sustainability (2017b), this represents a more realistic estimate of the total void volume available for sludge disposal than the initial estimate presented in AECOM (2015b) (see Section 3.4.4).



**Figure 3.26 The resulting conceptual flow and mass flux system model developed for the Eastern Basin (Exigo Sustainability, 2017b).**

AECOM (2015b) noted that the velocity of water in the mine voids is typically extremely low, which ensures the settling of the sludge (solids). However, during deposition, there is sufficient velocity to allow for some spreading (distribution) of the sludge within the void before it settles. Furthermore, deposition of the sludge may improve the pH of the mine water with time, as observed in the Western Basin.

It could, therefore, be concluded that a significant volume of water abstracted from the Eastern Basin as AMD originates as ingress from surface water bodies over the basin. This water is abstracted from a depth of 160 m, well below the ECL of 100 m for the Eastern Basin to ensure that the Dolomitic Aquifer is protected. The ECL can be protected by monitoring the water level in the Eastern Basin and maintaining a sufficient pumping rate as the ingress fluctuates. The AMD water abstracted at this depth could potentially originate from anywhere in the Eastern Basin.

Furthermore, the sludge is disposed of at depths ranging from 670 m to 1,150 m in the Grootvlei No. 3 Shaft (in submersed dewatering pumping station) or one of the deep mining boreholes (in the collapsed mining void). The exact void of these areas is unknown, but it can be assumed that following disposal and the initial turbulence, the sludge will disperse before settling. However, due to the very slow groundwater flow

velocities at these depths, the spreading will be limited. It is also very unlikely that the abstraction of AMD water at 160 m would create a sufficient hydraulic gradient to cause the upward movement of the deposited sludge to the surface.

## 3.7 Hydrogeological Evaluation of the Sludge Disposal Operation

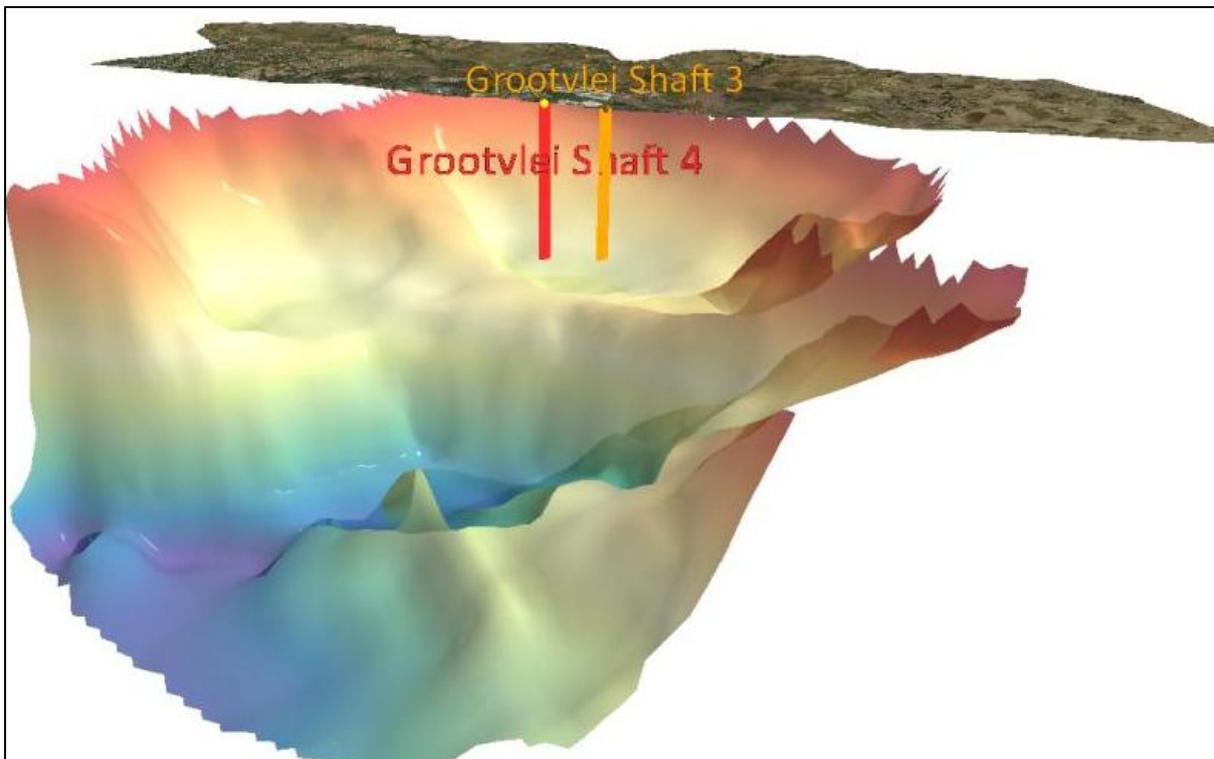
### 3.7.1 General

Artesium was commissioned to develop a numerical groundwater flow and advective mass transport model for the ERB sludge disposal operation (Artesium, 2024b). Presented here is an overview of the model development process and results. The report is attached as Appendix E to this report and consequently, the detail will not be repeated here.

### 3.7.2 Model Extent

Figure 3.28 presents the regional extent and numerical model boundaries used for the ERB sludge disposal operation, overlaid on the topography of the area. Figure 3.29 presents the geological cross-section through the modelling domain, indicating the location of the Grootvlei No. 3 Shaft and Grootvlei No. 4 Shaft relative to the different underlying formations, reefs and geological structures.

Figure 3.27 is a three-dimensional view of the East Rand Basin with the Grootvlei Sub-basin where water is abstracted (Grootvlei No. 3 Shaft) and where the disposal will take place (Grootvlei No. 4 Shaft), and the deeper Main Reef towards the from.



**Figure 3.27** Three-dimensional view of the East Rand Basin with the Grootvlei Basin where water is abstracted (Grootvlei No. 3 Shaft) and where the disposal will take place (Grootvlei No. 4 Shaft) (Artesium, 2024b).

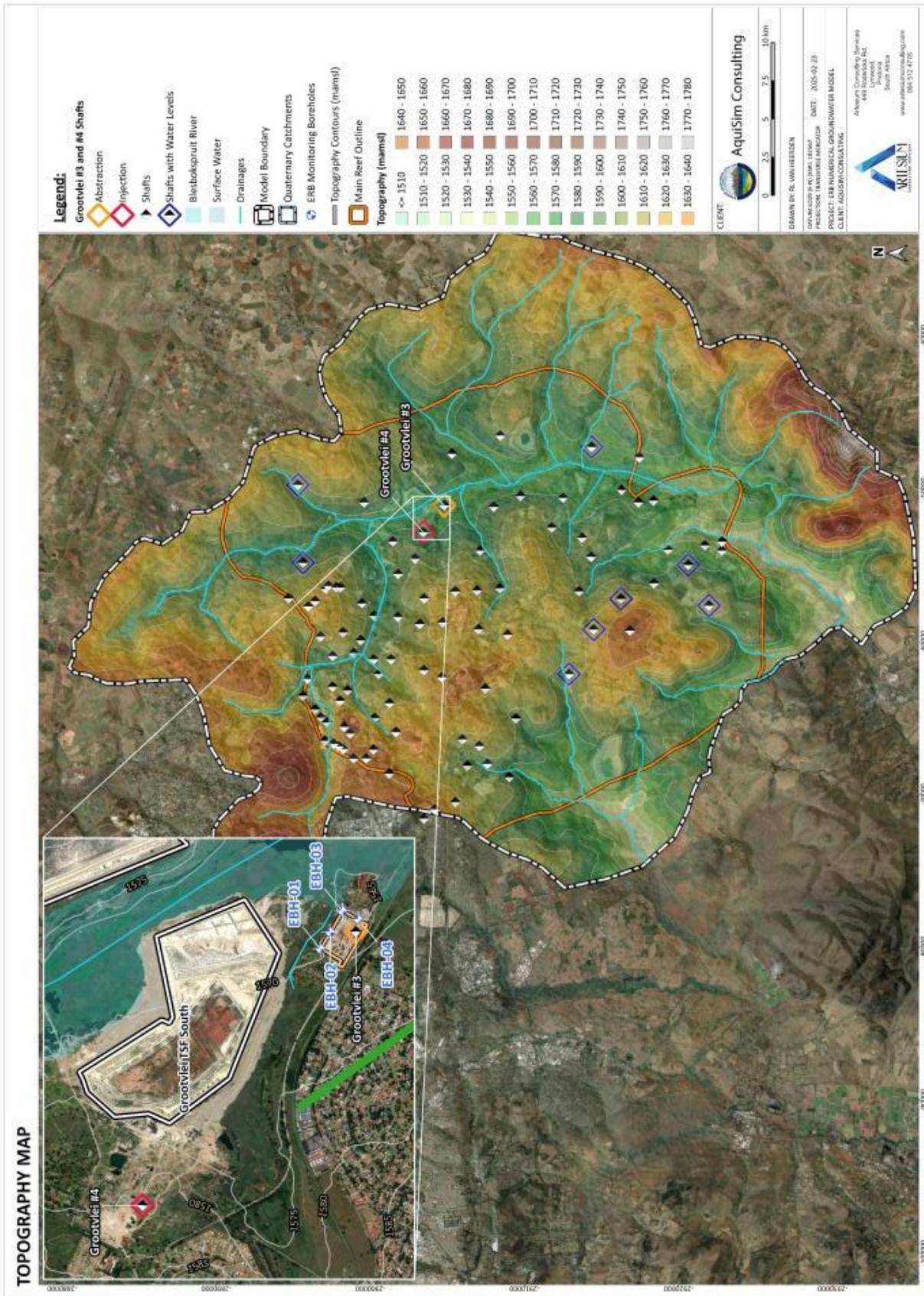


Figure 3.28 The regional extent of the numerical model developed for the ERB sludge disposal operation, overlaid on the topography of the area (Artesium, 2024b).



### 3.7.3 Hydrogeological Conceptual Model

Figure 3.31 presents the hydrogeological conceptual model, which shows the different components relevant to evaluating the ERB Water Treatment Plant and Sludge Disposal Operations. It shows the extent of the Grootvlei Sub-basin, the point of water abstraction (160 mbgl) and the point of sludge discharge onto the Kimberley Reef at a depth of 700 mbgl (see Figure 3.7). It also shows that a large portion of the water abstracted from Grootvlei No. 3 Shaft is from ingress water from the Blesbok Spruit.

The shape of the ERB was derived using ACS archives in conjunction with the geometry of the Green Sill, which was assumed to be impermeable. In the model, the Main Reef is assigned a thickness of 1 m, while the Kimberley Reef is placed 500 m above the Main Reef and modelled with the same thickness and hydraulic conductivity. The dykes in the model domain are characterized by an impermeable matrix, with their contact zones serving as preferential flow pathways. Other flow pathways incorporated into the model include the shaft annulus, the Main Reef outcrop, and sinkholes underlain by the Weathering After Dolomite (WAD) (Artesium, 2024b).

### 3.7.4 Mass Source Term

Figure 3.30 presents the ERB sludge disposal source term for 100 years. It shows the increase in the void-filled elevation as a function of the annual sludge deposition rate and total volume of the Main Reef and Main Reef up to the spillway.

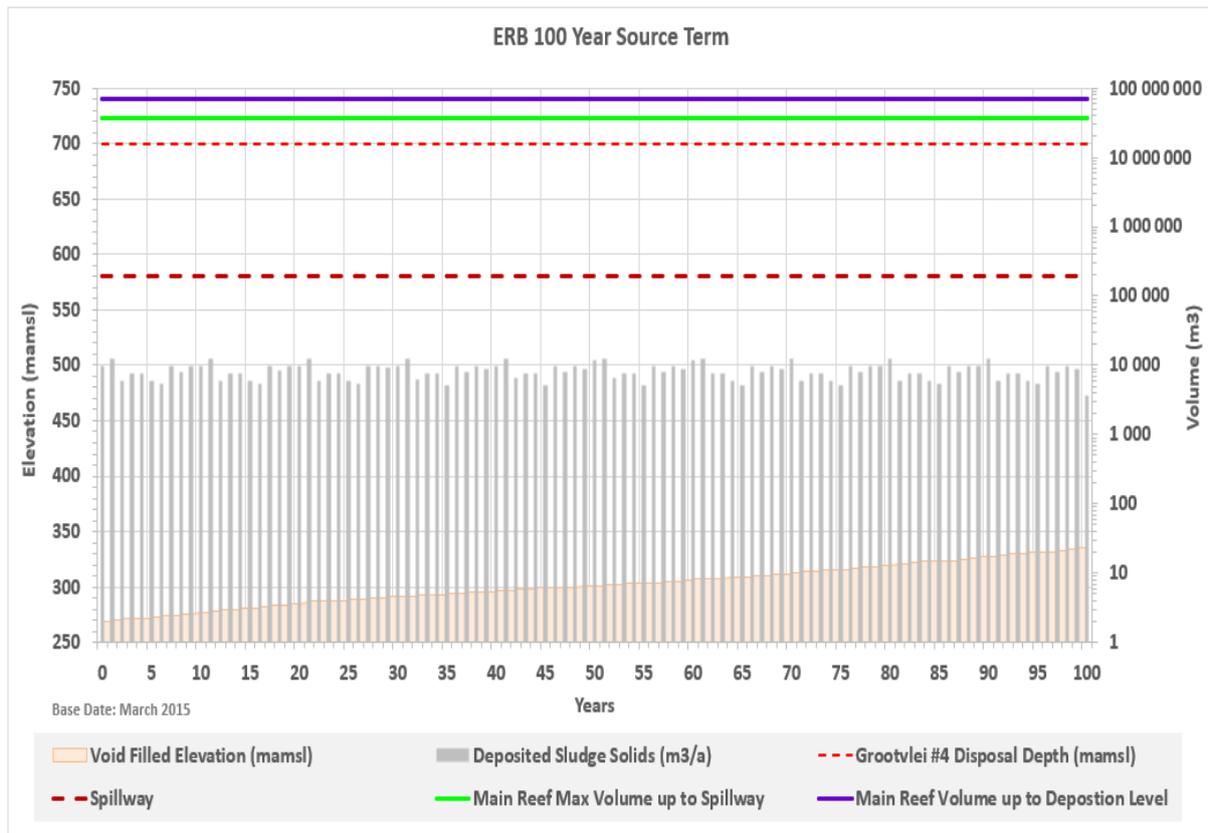


Figure 3.30 Graphical representation of the ERB sludge disposal source term for 100 years (Artesium, 2024b).

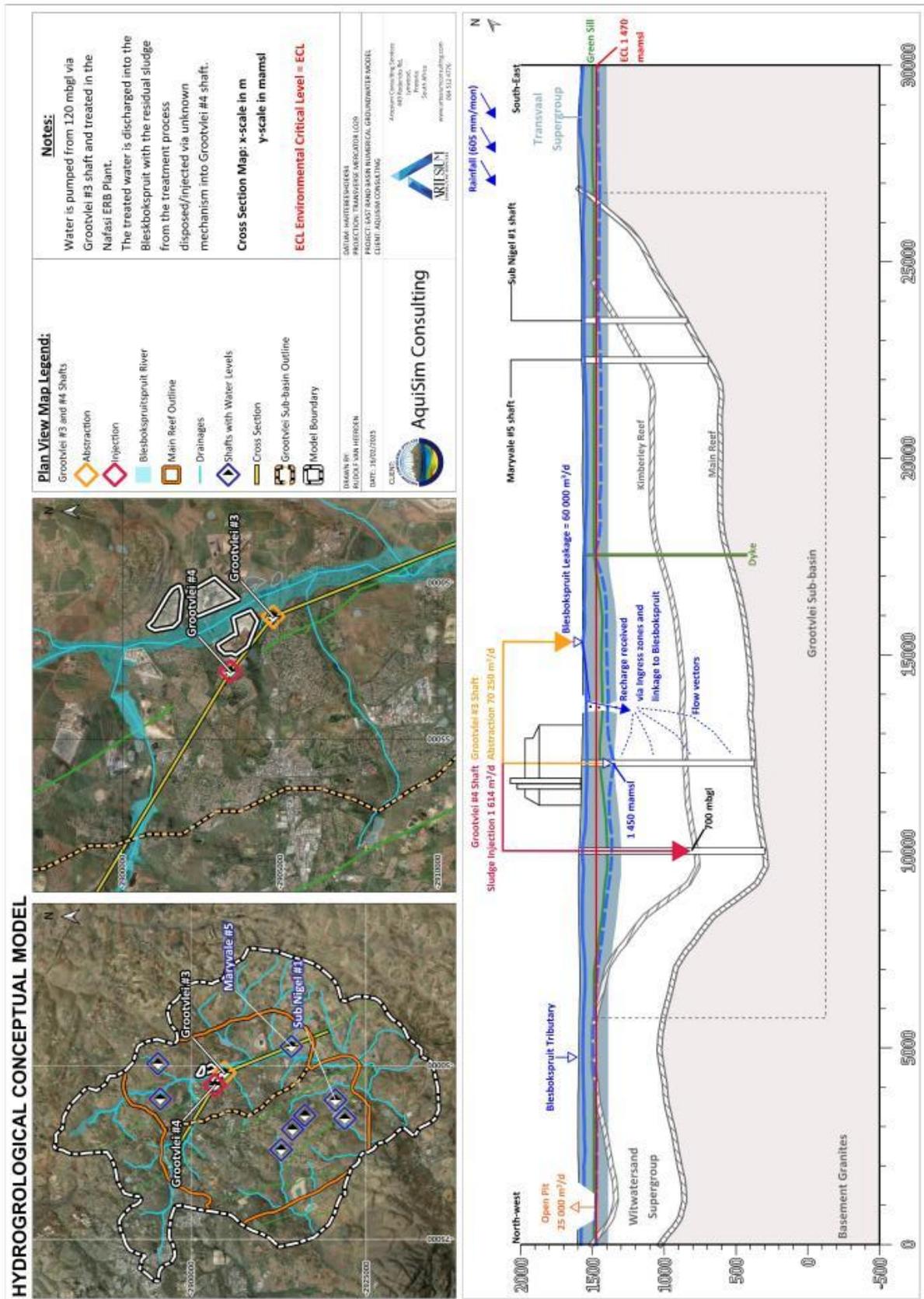
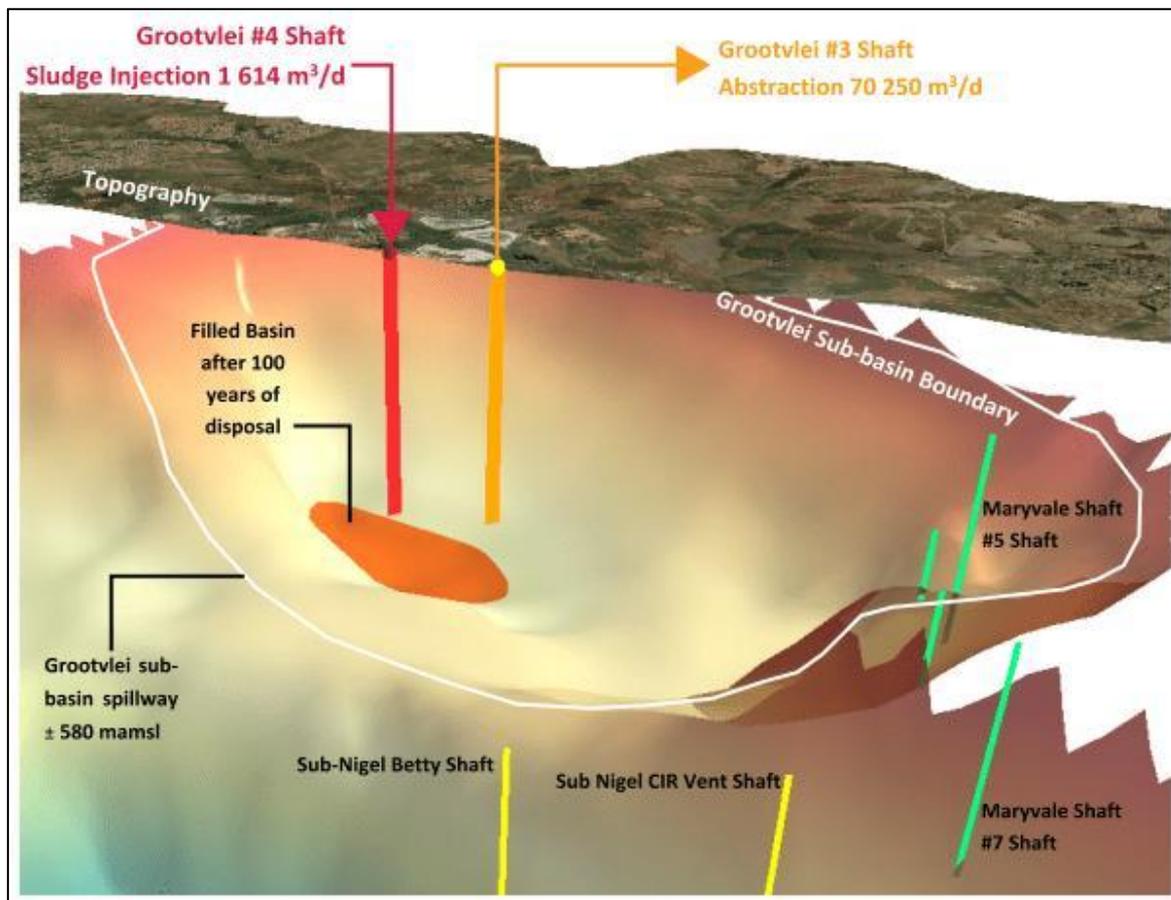


Figure 3.31 The hydrogeological conceptual model, which shows the different components relevant to evaluating the ERB Water Treatment Plant and Sludge Disposal Operations (Artesium, 2024b).

Artesium (2024b) used the following assumption to calculate the source term:

- Liquid Solid Ratio of 1:10 (i.e. 10% is solids). This volumetric ratio was estimated from a sludge sample collected from the ERB Water Treatment Plant;
- A total volume of 259,938,078 m<sup>3</sup> for the Main Reef, with a 70% void volume (i.e., 181,956,655 m<sup>3</sup>);
- The Main Reef filled to a level of 276 mamsl (sludge solids deposited = 616 440 m<sup>3</sup>); and
- The current surface area for the source was calculated at 192 ha in the Reef, with the source growing up to 1,001 ha (after 100 years of deposition).

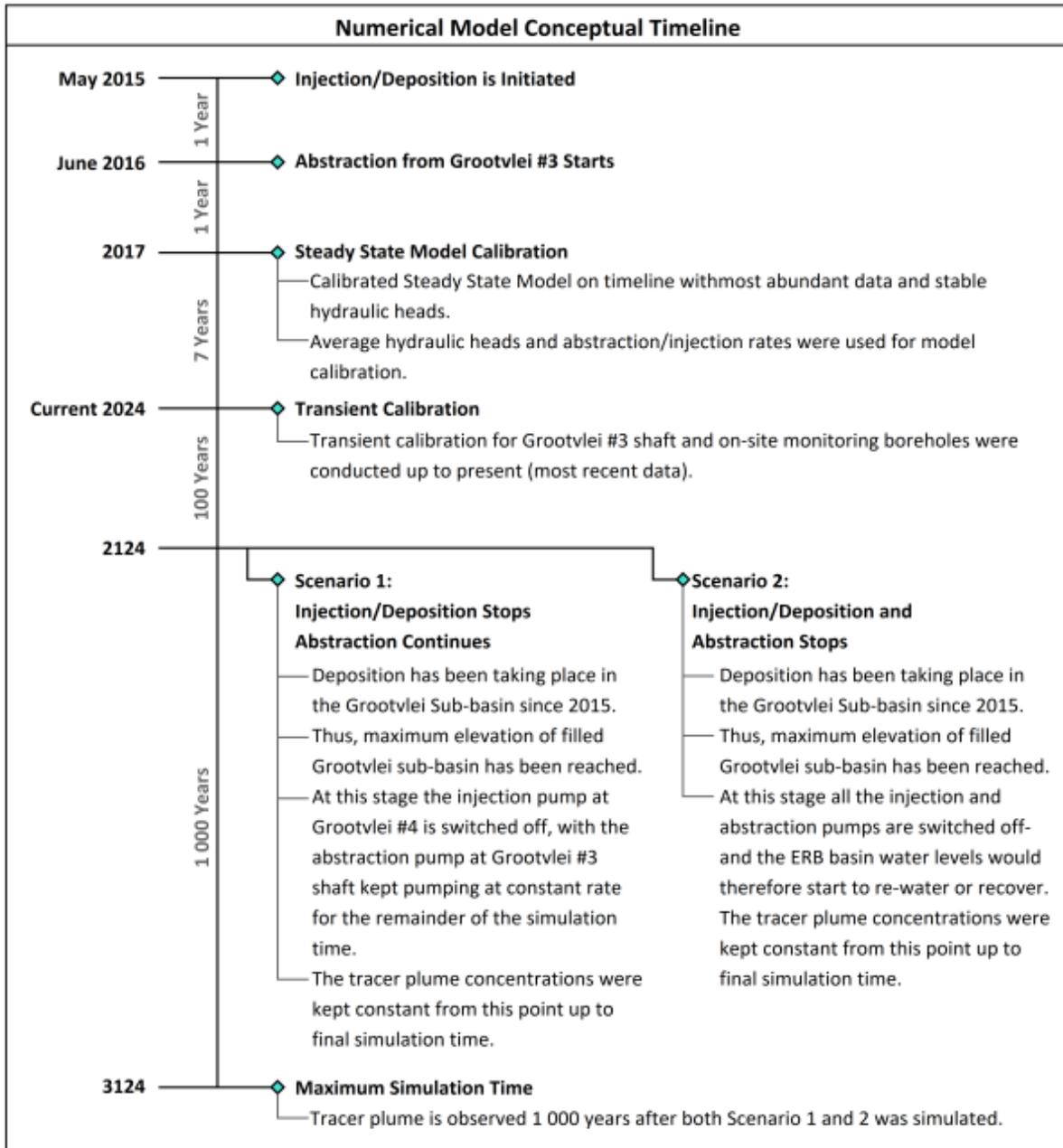
Figure 3.32 is a three-dimensional representation of the total volume of sludge relative to the Grootvlei Sub-basin, after 100 years of sludge deposition into the Grootvlei No. 4 Shaft.



**Figure 3.32** A three-dimensional representation of the total volume of sludge relative to the Grootvlei Sub-basin, after 100 years of sludge deposition into the Grootvlei No. 4 Shaft (Artesium, 2024b).

### 3.7.5 Mass Transport Results

Figure 3.33 presents the timeline and scenarios that were considered to evaluate the ERB sludge disposal operations. It assumes that the injection of the sludge commenced in 2015 and the abstraction of AMD water from the Grootvlei No. 3 Shaft in 2016. A steady-state calibration was first performed for conditions observed in 2017, followed by a transient calibration for conditions observed at present (2024). The transient simulation was performed for a further 100 years (2124). Thereafter, two scenarios were evaluated for a further 1,000 years (3124) assuming either that injection stops and abstraction continues (Scenario 1) or that both injection and abstraction stop (Scenario 2).



**Figure 3.33 The timeline and scenarios that were considered to evaluate the ERB sludge disposal operations (Artesium, 2024b).**

Figure 3.34 presents the spatial and cross-sectional distribution of a non-reactive mass tracer plume after 100 years, assuming an initial concentration of 1,000 mg.L<sup>-1</sup>. It shows vertical migration upwards and downwards along the annulus of the Grootvlei No. 4 Shaft (considered as a pathway). Once it reaches the Main Reef, migration is lateral along the Main Reef and then laterally along the more permeable Main Reef.

Figure 3.35 presents the spatial and cross-sectional distribution of a non-reactive mass tracer plume for Scenario 2 after 1,000 years, assuming an initial concentration of 1,000 mg.L<sup>-1</sup>. It shows that further migration along the Main Reef and, to a lesser extent, the Kimberley Reef. Migration in the Main Reef towards the southeast is more dominant and eventually decants at the Main Reef surface outcrop about 17 km from the injection point but with at least a 1:10 dilution in the initial source concentration. Figure 3.36 presents the three potential surface decant points for Scenario 2 after 1,000 years for tracer plume concentrations of at least 10 mg.L<sup>-1</sup>.



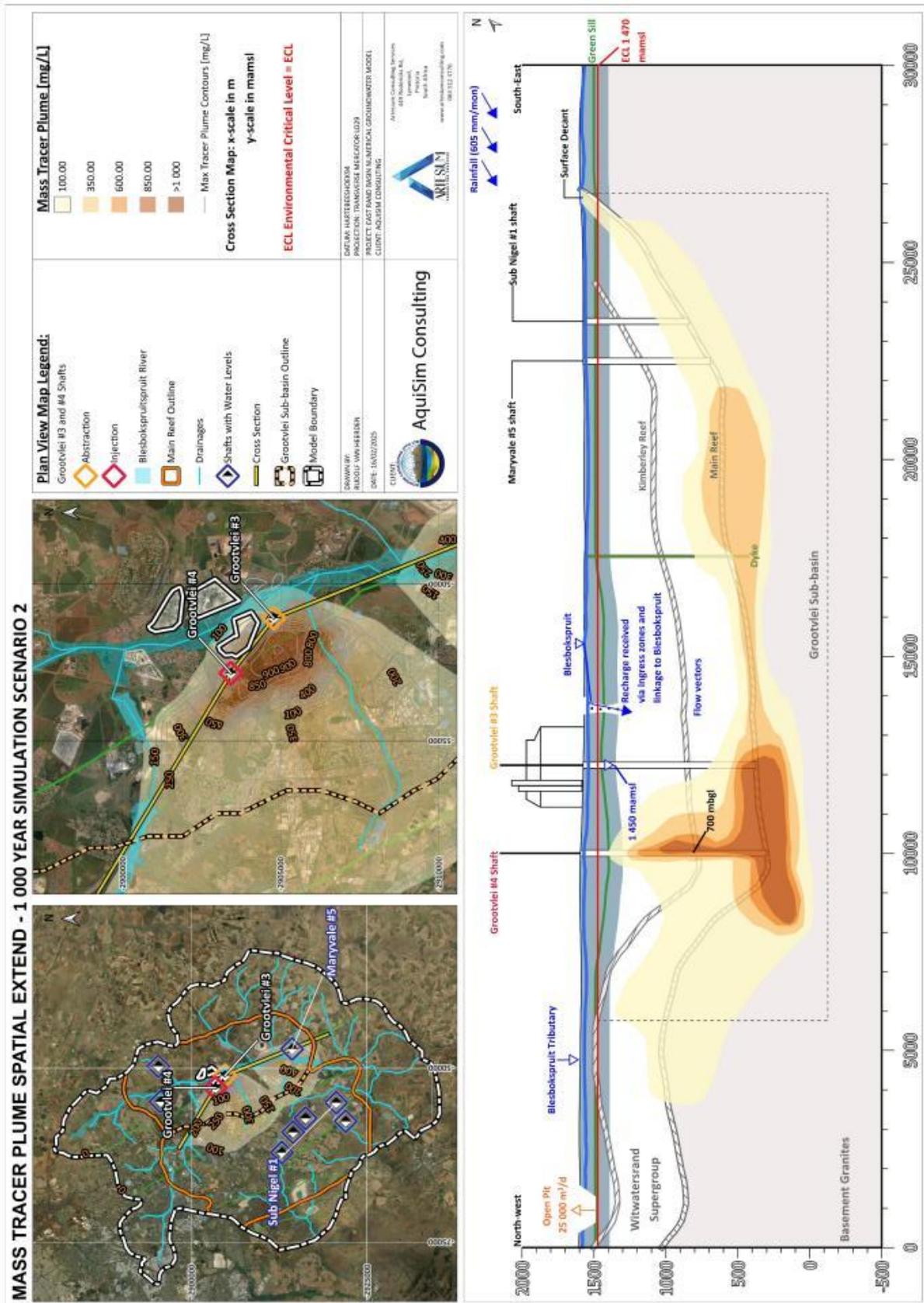


Figure 3.35 The spatial distribution of a non-reactive mass tracer plume for Scenario 2 after 1,000 years assuming an initial concentration of 1,000 mg.L<sup>-1</sup> (Artesium, 2024b).

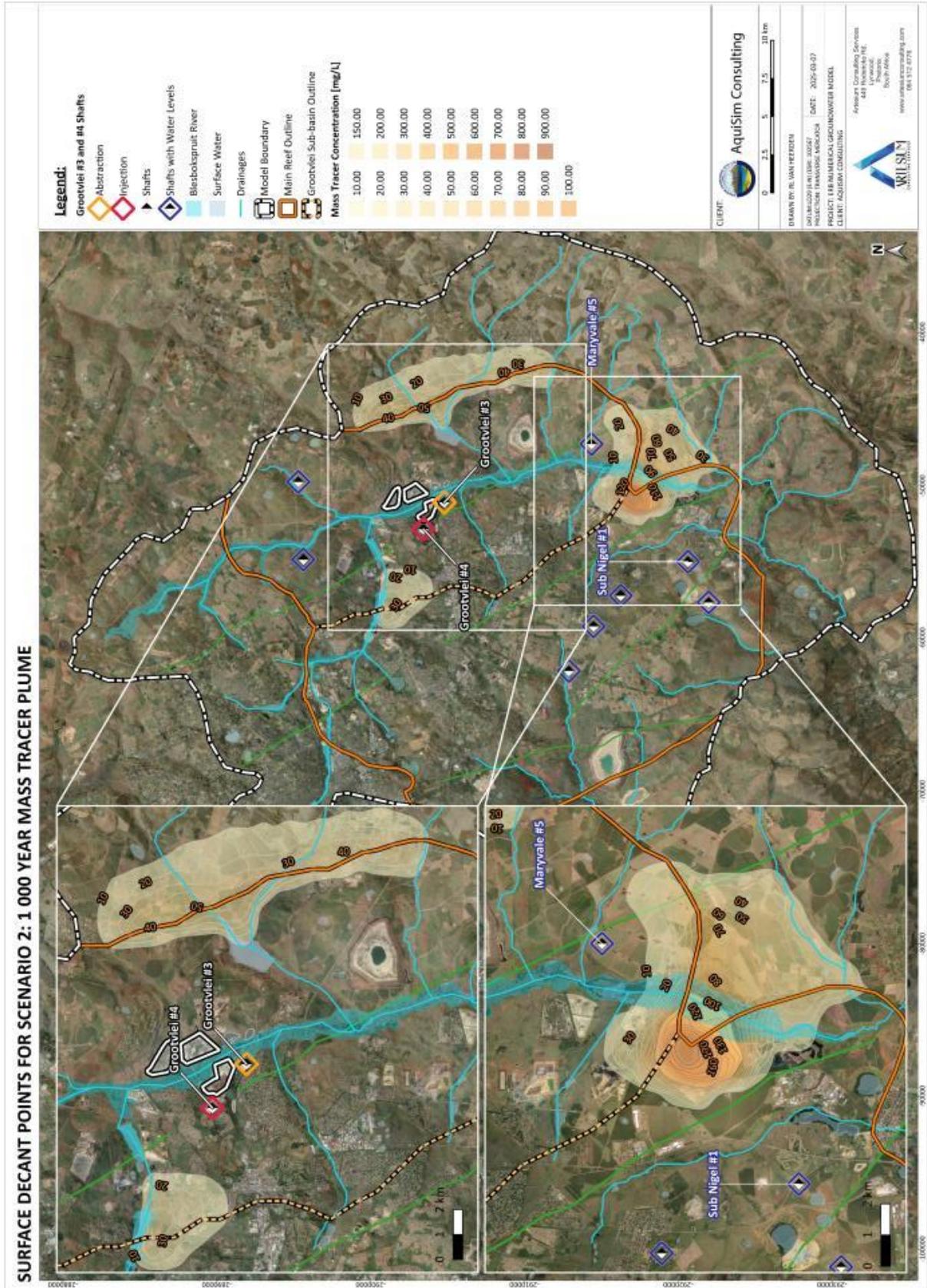


Figure 3.36 Surface decant points for Scenario 2 after 1,000 years, for tracer plume concentrations of at least 10 mg.L<sup>-1</sup> (Artesium, 2024b).

### 3.7.6 Discussion of Results

The current volume of solid sludge deposited is 75,944 m<sup>3</sup> (999 tons), assuming a density of 1,316 kg.m<sup>-3</sup>, with the main reef void volume calculated at 181 mil m<sup>3</sup>. If referred to the spillway (±580 mamsl) for the Grootvlei Sub-basin, the reef is currently filled up to 0.2% of its capacity, and after 100 years of disposal at current injection rates, the reef will be filled up to approximately 17% capacity. This is without the volume of the Kimberley Reef and associated mined-out voids included.

The simulations revealed that should abstraction from Grootvlei No. 3 Shaft continues, the sludge mass plume would remain relatively stagnant with a footprint of 1,000ha at 335 mamsl. The most conservative estimate for a mass tracer plume given 100 years of sludge deposition, after which the pumping from Grootvlei No. 3 Shaft was ceased, had a maximum plume extend of 23 km x 10 km when observed in the disposal zone and decants at 3 main zones at the surface along the main reef basin outcrops.

The main pathway for the tracer source to reach possible surface receptors such as groundwater users, surface water features (dam, rivers wetlands), is the shafts, Main Reef and Kimberley Reef voids, other shallow mined-out areas, and the open pit located to the north-west of the ERB Water Treatment Plant this would only occur if all pumping from Grootvlei No. 3 Shaft is stopped and the water levels within the basin recover completely.

## 3.8 Radiological Conditions and Data

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### 3.8.1 General

The radiological conditions and data available for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations include a contamination and dose radiation survey, as well as full-spectrum radioanalysis results of residue material (sludge), untreated water, treated water and water samples from the discharge points in the Blesbok Spruit. Samples of the selected water and sludge were submitted to the Necsa Radioanalytical Laboratory for full-spectrum radioanalysis (see Appendix B for the Necsa Laboratory reports).

### 3.8.2 Residue Material (Sludge)

One can assume that the technology used to treat the AMD water will result in the concentration of naturally occurring radionuclides in the sludge residue. Table 3.4 summarises the full spectrum analysis results of sludge samples collected in 2016 and 2024. The results presented in Table 3.4 show that, except for Ra-226, all radionuclides in the 2024 sample are below 500 Bq.kg<sup>-1</sup> (or 0.5 Bq.g<sup>-1</sup>), with a significant reduction in the U activity concentrations. The 2024 Ra-226 activity concentration, on the other hand, is significantly higher than in 2016.

The Ra-226 activity concentration that is above the exemption level means that the material does not automatically comply with the exemption in terms of Regulation 388 (see Section 2.2). Samples should be collected more regularly for full-spectrum radioanalysis to develop a record of the radiological characteristics of the sludge material(see Section 6.3).

### 3.8.3 Water Analysis Results

#### 3.8.3.1 General

The 2016 radioanalysis results were limited to a treated water sample. The 2014 samples were extended to include an untreated and a treated water sample. Furthermore, two water samples were also taken near the discharge point in the Blesbok Spruit.

**Table 3.4 Summary of the Necsa laboratory full spectrum analysis for sludge residue samples collected in 2016 and 2024.**

Sampling Date	10/11/2016	14/11/2024
Necsa Report No.	RS2016-4005	JOB00002321-01
Sampling Point	Sludge Residue	ERB Sludge
Radionuclide	Activity Concentration (Bq.kg <sup>-1</sup> )	
U-238	503	178
U-234	507	179
Ra-226	538	985
Pb-210	< MDA	< MDA (240)
U-235	23.1	8.19
Th-232	< MDA	3.4
Ra-228	76	118
Th-228	< MDA	< MDA (78)
K-40	300	447
Gross α	2870	-
Gross β	958	-

**3.8.3.2 Untreated (AMD) Water**

Due to the nature of the underlying geology, one can assume that naturally occurring radionuclides will be associated with the AMD water that is abstracted from Grootvlei No. 3 Shaft for treatment. This AMD water present in the Eastern Basin represents an existing exposure situation, as opposed to a planned exposure situation (see Section 2.2.3).

In line with radiological baseline characterisation, full-spectrum radioanalysis results are needed for the untreated water since this will represent the source term for all on-surface operational activities and, therefore, must be quantified, especially for input into the worker safety assessment. Table 3.5 lists the full-spectrum analysis results for an untreated water sample collected in 2024. A photo of the sample taken in 2024 is shown in Figure 3.37.

**Table 3.5 Summary of the Necsa laboratory full spectrum analysis for an untreated water sample collected in 2024.**

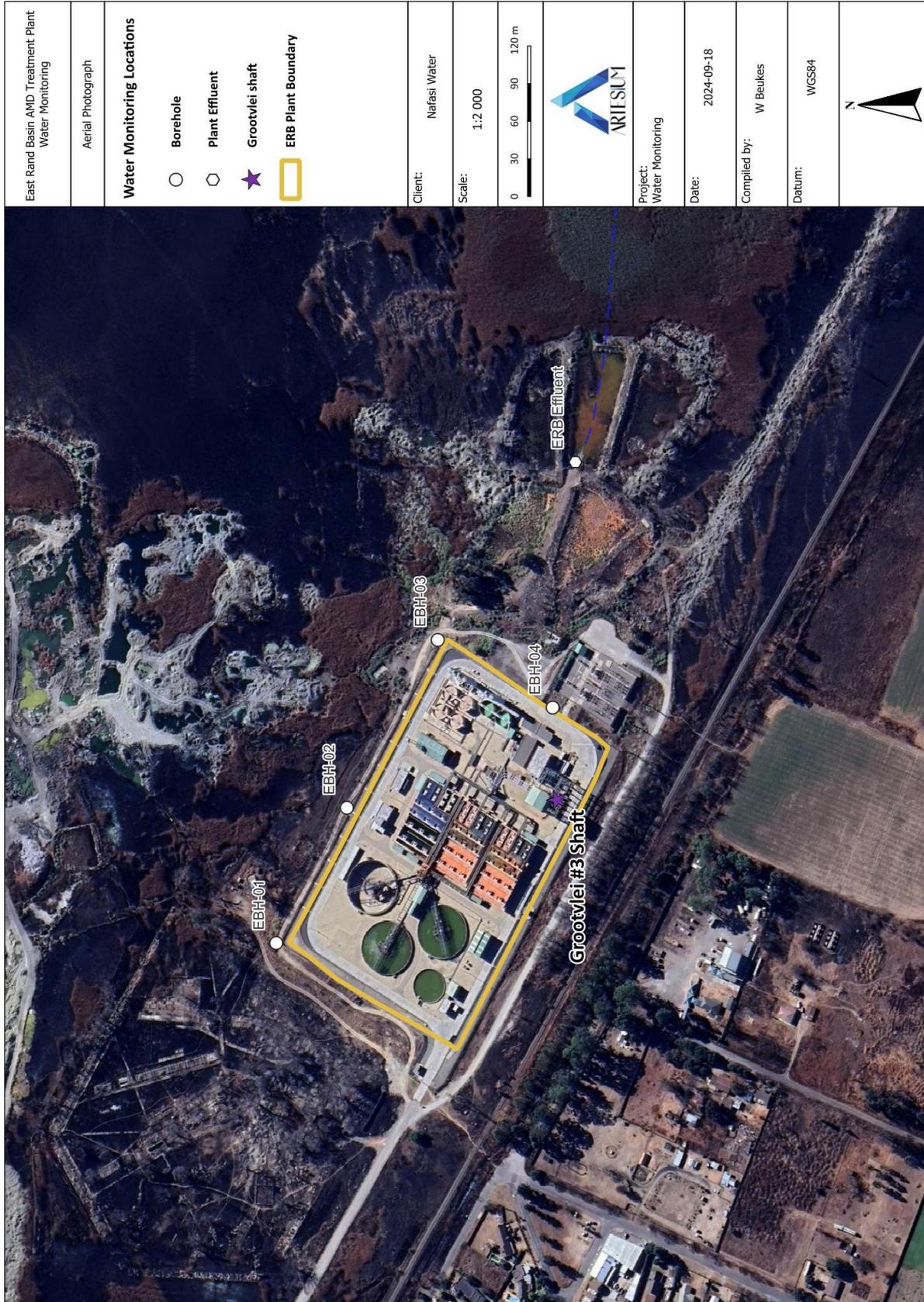
Sampling Date	12/11/2024
Necsa Report No.	SOQ0000337
Sampling Point	AMD Water
Radionuclide	Activity Concentration (mBq.L <sup>-1</sup> )
U-238	563
U-234	596
Th-230	30.1
Ra-226	353
Pb-210	<MDA (12)
Po-210	<MDA (12)
U-235	25.9
Th-227	< MDA (9)
Ra-223	< MDA (11)
Th-232	< MDA (6.5)
Th-228	< MDA (9.9)
Ra-224	< MDA (7.9)
Gross α	891
Gross β	< MDA (85)



**Figure 3.37** Photos of the water sampling points at ESW-01 and ESW-03 (top) and the AMD water and ERB effluent discharge point at the Water Treatment Plant (bottom).

### 3.8.3.3 Treated Water

The purpose of the Water Treatment Plant is to remove heavy metals to levels that treated water can be released back into the environment without a human health risk. During this process, naturally occurring radionuclides are also removed from the AMD water and concentrated in the sludge residue. The treated AMD water is released into the environment just outside the Water Treatment Plant, to the east. Figure 3.38 and Figure 3.39 are two locality maps showing the ERB effluent discharge point relative to the Water Treatment Plant, before being discharged into the Blesbok Spruit. A photo of the sample taken in 2014 is shown in Figure 3.37. Table 3.6 summarises the full spectrum Necs analysis results of samples of treated water from 2016 and 2024.



**Figure 3.38** Local locality map showing the ERB effluent discharge point relative to the Water Treatment Plant.



**Figure 3.39** Regional locality map showing the ERB effluent discharge point relative to the Water Treatment Plant, as well as the location of ESW-01 and ESW-03.

**Table 3.6 Summary of the Necsa laboratory full spectrum analysis for the treated water samples collected in 2016 and 2024.**

Sampling Date	13/10/2016	12/11/2024
Necsa Report No.	RS2016-4006	SOQ0000337
Sampling Point	Treated Water	ERB Effluent Water
Radionuclide	Activity Concentration (mBq.L <sup>-1</sup> )	
U-238	34.8	472
U-234	60.1	516
Th-230	29	50.4
Ra-226	25.4	184
Pb-210	-	< MDA (14)
Po-210	9.06	< MDA (14)
U-235	1.6	21.7
Th-227	5.42	<MDA 14)
Ra-223	-0.65	< MDA (11)
Th-232	3.98	9.07
Th-228	9.98	< MDA (12)
Ra-224	< MDA	< MDA (25)
Gross α	340	1010
Gross β	1320	1440

#### 3.8.3.4 Blesbok Spruit Samples

The two sampling points in the Blesbok Spruit represent an upstream and downstream scenario. The location of the two points presented in Figure 3.39 shows that ESW-01 is located upstream from the ERB Effluent discharge points, whereas ESW-03 is located downstream. Photos of the sample taken in 2014 are shown in Figure 3.37. ESW-03 is about 300 m downstream of the discharge point. Table 3.7 lists the full-spectrum analysis results for ESW-01 and ESW-03 collected in 2024.

#### 3.8.3.5 Discussion of the Results

No samples of the untreated (AMD) water were sampled and analysed in 2016. Table 3.5 shows that most of the radionuclides are below the MDA. The U-238 and U-234 activity concentrations are between 550 and 600 mBq.L<sup>-1</sup>, while the Ra-226 is about 350 mBq.L<sup>-1</sup>.

The treated water analysis results in Table 3.6 show a significant difference between the 2016 and 2024 results. All the 2024 results that are not below the detection limit are higher than the sample from 2016. These are the only two analysis results available for treated water and, consequently, any reason as to why it is higher would be speculative. One could argue that the water treatment process is not as effective as it was in 2016 since the U isotopes in Table 3.4 for 2024 are lower than the 2016 values. However, the same argument does not hold for the Ra isotopes (Ra-226 and Ra-228). As with the sludge, water samples should be collected more regularly for full-spectrum radioanalysis to develop a record of the radiological characteristics of the treated and untreated water (see Section 6.3).

The water analysis results in Table 3.7 suggest that the activity concentration of the water in the Blesbok Spruit is higher after the discharge point than upstream before the discharge point. This suggests that the discharge of the ERB effluent (i.e., the treated water) negatively influences the quality of the water in the Blesbok Spruit, especially in terms of the U isotopes. However, it is important to again emphasise that this is based on one set of results and is not necessarily conclusive even though it is consistent with the treated water results in Table 3.6.

### 3.8.4 Radiation Survey

#### 3.8.4.1 General

Two surface contamination and dose rate surveys were performed at the Water Treatment Plant to date. The first was in 2016 when the plant was only operational for a very short time, while the most recent survey was conducted in 2024. It can be assumed that the 2024 survey would be more representative of the actual radiation exposure conditions associated with the Water Treatment Plant at present. For completeness and to maintain records of the available data, the results of both surveys are presented here.

**Table 3.7 Summary of the Necsa laboratory full spectrum analysis results for ESW-01 and ESW-03 collected in 2024.**

Sampling Date	12/11/2024	12/11/2024
Necsa Report No.	SOQ0000337	SOQ0000337
Sampling Point	ESW-01	ESW-03
Radionuclide	Activity Concentration (mBq.L <sup>-1</sup> )	
U-238	30.2	289
U-234	67.8	321
Th-230	67.2	34.7
Ra-226	< MDA (6)	< MDA (9)
Pb-210	<MDA (12)	<MDA (11)
Po-210	<MDA (12)	<MDA (11)
U-235	1.39	13.3
Th-227	10.9	< MDA (7.6)
Ra-223	< MDA (12)	< MDA (10)
Th-232	12.3	10.3
Th-228	< MDA (11)	< MDA (9.1)
Ra-224	< MDA (18)	< MDA (8.2)
Gross α	243	501
Gross β	956	1400

#### 3.8.4.2 September 2016

A radiation survey was performed in September 2016 to assess the surface contamination and dose rate level at the Water Treatment Plant. An Electra-GM with serial No. 468 was used for this purpose. The calibration certificates are attached as Appendix D to this report. In addition to a background reading (Claire's office), a total of 80 measurements were taken. The locations of the readings are shown in Figure 3.40, while Table 3.8 lists the values recorded for surface contamination and dose rate (contact and at a height of 1 m). Table 3.9 summarises the minimum, maximum, average and 90<sup>th</sup> percentile values, which shows that the expected dose rates are relatively low.

#### 3.8.4.3 January 2025

A radiation survey was again performed in January 2025 to assess the surface contamination and dose rate level at the Water Treatment Plant. A Rad eye SX with serial No. Sn.51475/11332 and a Rad eye G10 with serial No Sn.057 were used for this purpose. The calibration certificates are attached as Appendix D to this report. In addition to a background reading (Christopher's office), a total of 163 measurements were taken. The locations of the readings are shown in Figure 3.41, while Table 3.10 lists the values recorded for surface contamination and dose rate (contact and at a height of 1 m). Table 3.11 summarises the minimum, maximum, average and 90<sup>th</sup> percentile values, which shows that the expected dose rates are relatively low.



Figure 3.40 Google image showing the locations where surface contamination and dose rate measurements were taken in September 2016 at the Water Treatment Plant (see Table 3.8 for results).

**Table 3.8 Radiation survey results performed at the Water Treatment Plant during September 2016.**

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/Y	Y	β	Contact	1 Meter
<b>Claire Office</b>	<b>Background</b>	<b>0.01</b>	<b>0.32</b>	<b>0.24</b>	<b>0.08</b>	<b>0.23</b>	<b>0.25</b>
Guard House	AMD 1	0.00	0.54	0.39	0.15	0.23	0.11
Treated Water Pump Station	AMD 2	0.00	0.59	0.43	0.16	0.34	0.11
Treated Water Sump	AMD 3	0.00	0.42	0.28	0.14	0.28	0.17
Thickener No.2	AMD 4	0.02	0.57	0.52	0.05	0.17	0.34
Valve	AMD 5	0.03	0.46	0.43	0.03	0.23	0.23
Thickener No.2	AMD 6	0.02	0.53	0.41	0.12	0.06	0.32
Utility Water Reticulation	AMD 7	0.00	0.22	0.25	0.00	0.11	0.34
Thickener No.3	AMD 8	0.02	0.66	0.38	0.28	0.17	0.11
Poly Dosing Building	AMD 9	0.03	0.37	0.39	0.00	0.17	0.40
Thickener No.3	AMD 10	0.00	0.54	0.48	0.06	0.40	0.34
Thickener No.1	AMD 11	0.00	0.66	0.62	0.04	0.34	0.28
Thickener No.1	AMD 12	0.00	0.63	0.77	0.00	0.06	0.23
Thickener No.2	AMD 13	0.00	0.46	0.35	0.11	0.17	0.17
Thickener No.1	AMD 14	0.00	0.21	0.34	0.00	0.11	0.11
Thickener No.3	AMD 15	0.02	0.46	0.36	0.10	0.11	0.17
Thickener No.3	AMD 16	0.00	0.29	0.26	0.03	0.06	0.23
Eastern Corner	AMD 17	0.00	0.32	0.29	0.03	0.34	0.11
Inspection Manhole	AMD 18	0.03	0.36	0.45	0.00	0.17	0.17
Generator Room 2	AMD 19	0.00	0.45	0.50	0.00	0.28	0.17
South Corner	AMD 20	0.00	0.37	0.25	0.12	0.06	0.17
Shaft Pump Station	AMD 21	0.00	0.44	0.32	0.12	0.51	0.23
VFD & MV Room	AMD 22	0.01	0.66	0.48	0.18	0.28	0.29
MCC Room	AMD 23	0.02	0.52	0.53	0.00	0.17	0.23
Limestone Dosing	AMD 24	0.01	0.46	0.44	0.02	0.19	0.23
Limestone Dosing	AMD 25	0.00	0.39	0.31	0.08	0.26	0.21
Quick Lime Dosing	AMD 26	0.02	0.56	0.42	0.14	0.31	0.26
Quick Lime Dosing	AMD 27	0.02	0.23	0.35	0.00	0.40	0.21
Quick Lime Dosing	AMD 28	0.02	0.42	0.36	0.06	0.16	0.31
Quick Lime Dosing	AMD 29	0.01	0.39	0.33	0.06	0.28	0.21
Lime Dosing Pipe	AMD 30	0.02	0.43	0.29	0.14	0.29	0.23
Generator Room 1	AMD 31	0.03	0.31	0.63	0.00	0.19	0.26
Generator Room 2	AMD 32	0.03	0.69	0.39	0.30	0.09	0.17
Between Generator rooms 1 & 2	AMD 33	0.00	0.29	0.26	0.03	0.19	0.28
Limestone Dosing Pipe	AMD 34	0.00	0.31	0.38	0.00	0.11	0.31
Plant Drain	AMD 35	0.04	0.37	0.33	0.04	0.23	0.09
Steps at Plant Drain	AMD 36	0.01	0.27	0.23	0.04	0.07	0.32
Pipes from the Shaft Pump Station	AMD 37	0.00	0.32	0.17	0.15	0.28	0.34
Pipes from the Shaft Pump Station	AMD 38	0.00	0.29	0.26	0.03	0.21	0.26
Steps to Thickening Reactors	AMD 39	0.02	0.46	0.38	0.08	0.31	0.21
Inspection Manhole	AMD 40	0.00	0.42	0.41	0.01	0.16	0.17
Corner of Thickening Reactors	AMD 41	0.01	0.33	0.31	0.02	0.11	0.51
Thickening Reactors	AMD 42	0.02	0.38	0.27	0.11	0.26	0.23
Thickening Reactors	AMD 43	0.01	0.63	0.41	0.22	0.40	0.34
Thickening Reactors	AMD 44	0.00	0.52	0.47	0.05	0.19	0.31
Thickening Reactors	AMD 45	0.01	0.48	0.40	0.08	0.31	0.39
Thickening Reactors	AMD 46	0.00	0.56	0.51	0.05	0.11	0.41
Thickening Reactors	AMD 47	0.00	0.36	0.29	0.07	0.18	0.44

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/Y	Y	β	Contact	1 Meter
Thickening Reactors	AMD 48	0.00	0.39	0.30	0.09	0.17	0.23
Thickening Reactors	AMD 49	0.01	0.32	0.23	0.09	0.26	0.20
Thickening Reactors	AMD 50	0.00	0.27	0.34	0.00	0.17	0.26
Thickening Reactors	AMD 51	0.00	0.39	0.31	0.08	0.21	0.28
Thickening Reactors	AMD 52	0.01	0.31	0.26	0.05	0.29	0.41
Thickening Reactors	AMD 53	0.01	0.39	0.44	0.00	0.17	0.28
Thickening Reactors	AMD 54	0.00	0.39	0.33	0.06	0.23	0.24
Thickening Reactors	AMD 55	0.01	0.29	0.21	0.08	0.31	0.36
Thickening Reactors	AMD 56	0.00	0.27	0.23	0.04	0.19	0.39
Thickening Reactors	AMD 57	0.00	0.41	0.33	0.08	0.18	0.40
Thickening Reactors	AMD 58	0.02	0.43	0.33	0.10	0.23	0.17
Thickening Reactors	AMD 59	0.00	0.29	0.30	0.00	0.06	0.23
Thickening Reactors	AMD 60	0.00	0.22	0.25	0.00	0.19	0.17
Thickening Reactors	AMD 61	0.00	0.31	0.29	0.02	0.17	0.28
Thickening Reactors	AMD 62	0.00	0.27	0.21	0.06	0.19	0.31
Thickening Reactors	AMD 63	0.03	0.41	0.20	0.21	0.06	0.26
Thickening Reactors	AMD 64	0.01	0.42	0.39	0.03	0.29	0.41
Thickening Reactors	AMD 65	0.00	0.36	0.31	0.05	0.23	0.36
Thickening Reactors	AMD 66	0.03	0.31	0.26	0.05	0.29	0.39
Thickening Reactors	AMD 67	0.01	0.32	0.26	0.06	0.22	0.38
Canteen	AMD 68	0.00	0.19	0.11	0.08	0.19	0.31
Workshops	AMD 69	0.00	0.76	0.63	0.13	0.33	0.31
Workshops	AMD 70	0.00	0.61	0.58	0.03	0.48	0.43
Workshops	AMD 71	0.00	0.52	0.48	0.04	0.37	0.41
Workshops	AMD 72	0.00	0.54	0.44	0.10	0.33	0.40
Workshops	AMD 73	0.00	0.51	0.47	0.04	0.39	0.36
Offices Reception	AMD 74	0.00	0.58	0.52	0.06	0.46	0.41
Offices	AMD 75	0.00	0.49	0.34	0.15	0.42	0.33
Offices	AMD 76	0.03	0.73	0.59	0.14	0.19	0.23
Offices	AMD 77	0.02	0.76	0.68	0.08	0.28	0.19
Offices	AMD 78	0.02	0.42	0.39	0.03	0.29	0.37
Offices Control Room	AMD 79	0.01	0.39	0.33	0.06	0.23	0.27
Offices Control Room	AMD 80	0.00	0.71	0.55	0.16	0.17	0.28

**Table 3.9 Summary of surface contamination and dose rate values measured at the Water Treatment Plant during the September 2016 survey.**

Parameter	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
	α	β/Y	Y	β	Contact	1 Meter
<b>Background</b>	<b>0.01</b>	<b>0.32</b>	<b>0.24</b>	<b>0.08</b>	<b>0.23</b>	<b>0.25</b>
Minimum	0.00	0.19	0.11	0.00	0.06	0.09
Maximum	0.04	0.76	0.77	0.30	0.51	0.51
Average	0.01	0.43	0.37	0.07	0.23	0.28
90 <sup>th</sup> Percentile	0.03	0.63	0.53	0.15	0.37	0.40



**Figure 3.41** Google image showing the locations where surface contamination and dose rate measurements were taken in January 2025 at the Water Treatment Plant (see Table 3.8 for results).

**Table 3.10 Radiation survey results performed at the Water Treatment Plant during September 2016.**

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/Y	Y	β	1 Meter	Contact
<b>Background</b>	<b>Christopher Office (Background)</b>	<b>0.00</b>	<b>0.56</b>	<b>0.49</b>	<b>0.07</b>	<b>0.10</b>	<b>0.12</b>
1	Security office main gate	0	0.52	0.46	0.06	0.14	0.18
2	Security office main gate	0	0.49	0.42	0.07	0.16	0.19
3	Security office main gate	0	0.55	0.43	0.12	0.15	0.2
4	Utility water pump station outside	0	0.4	0.36	0.04	0.16	0.2
5	Utility water pump station outside	0.01	0.53	0.47	0.06	0.17	0.19
6	Utility water pump station outside	0	0.49	0.42	0.07	0.17	0.18
7	Polydosing storage area	0	0.44	0.38	0.06	0.2	0.19
8	Polydosing storage area	0	0.54	0.48	0.06	0.16	0.17
9	Polydosing storage area	0	0.57	0.46	0.11	0.17	0.17
10	Polydosing storage area	0	0.59	0.53	0.06	0.21	0.19
11	Weighbridge office	0	0.53	0.46	0.07	0.18	0.19
12	Weighbridge office	0	0.42	0.36	0.06	0.14	0.16
13	Weighbridge office	0.01	0.57	0.49	0.08	0.16	0.17
14	Weighbridge office	0	0.59	0.51	0.08	0.15	0.13
15	Weighbridge office	0.01	0.59	0.48	0.11	0.11	0.14
16	Reactor 3 top	0	0.46	0.4	0.06	0.14	0.16
17	Reactor 3 top	0.01	0.41	0.37	0.04	0.16	0.17
18	Reactor 3 top	0	0.47	0.41	0.06	0.17	0.19
19	Reactor 3 top	0	0.49	0.41	0.08	0.18	0.16
20	Reactor 3 top	0	0.39	0.34	0.05	0.14	0.2
21	Reactor 3 top	0	0.47	0.41	0.06	0.14	0.16
22	Reactor 3 top	0	0.51	0.43	0.08	0.16	0.17
23	Reactor 3 top	0	0.46	0.36	0.1	0.11	0.14
24	Reactor 3 top	0	0.43	0.38	0.05	0.14	0.11
25	Reactor 3 top	0	0.41	0.34	0.07	0.14	0.16
26	Reactor 3 top	0	0.42	0.32	0.1	0.16	0.19
27	Reactor 3 top	0	0.46	0.4	0.06	0.19	0.21
28	Reactor 2 top	0	0.37	0.32	0.05	0.19	0.19
29	Reactor 2 top	0	0.36	0.28	0.08	0.16	0.16
30	Reactor 2 top	0	0.42	0.34	0.08	0.14	0.17
31	Reactor 2 top	0	0.49	0.43	0.06	0.13	0.14
32	Reactor 2 top	0.01	0.42	0.37	0.05	0.14	0.16
33	Reactor 2 top	0	0.44	0.36	0.08	0.16	0.15
34	Reactor 2 top	0	0.41	0.37	0.04	0.14	0.13
35	Reactor 2 top	0	0.49	0.41	0.08	0.13	0.14
36	Reactor 2 top	0	0.59	0.53	0.06	0.1	0.11
37	Reactor 2 top	0	0.51	0.46	0.05	0.09	0.1
38	Reactor 2 top	0	0.46	0.37	0.09	0.11	0.11
39	Reactor 2 top	0	0.43	0.39	0.04	0.11	0.11
40	Reactor 1 top	0	0.41	0.29	0.12	0.14	0.16
41	Reactor 1 top	0	0.39	0.34	0.05	0.11	0.14
42	Reactor 1 top	0	0.37	0.31	0.06	0.1	0.12
43	Reactor 1 top	0	0.42	0.36	0.06	0.14	0.16
44	Reactor 1 top	0.01	0.46	0.41	0.05	0.13	0.14
45	Reactor 1 top	0	0.51	0.43	0.08	0.16	0.17
46	Reactor 1 top	0	0.44	0.4	0.04	0.14	0.13
47	Reactor 1 top	0	0.46	0.36	0.1	0.13	0.12
48	Reactor 1 top	0.01	0.41	0.38	0.03	0.12	0.14

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/γ	γ	β	1 Meter	Contact
49	Reactor 1 top	0	0.43	0.36	0.07	0.11	0.13
50	Reactor 1 top	0	0.4	0.37	0.03	0.09	0.11
51	Reactor 1 top	0	0.47	0.43	0.04	0.1	0.14
52	Shaft pump station	0	0.43	0.36	0.07	0.16	0.17
53	Shaft pump station	0	0.44	0.39	0.05	0.17	0.18
54	Shaft pump station	0	0.47	0.41	0.06	0.14	0.19
55	Shaft pump station	0	0.49	0.43	0.06	0.13	0.14
56	Shaft pump station	0	0.51	0.46	0.05	0.16	0.17
57	VFD building outside	0	0.43	0.37	0.06	0.16	0.17
58	VFD building outside	0	0.56	0.51	0.05	0.17	0.19
59	VFD building outside	0	0.67	0.56	0.11	0.21	0.21
60	VFD building outside	0	0.54	0.48	0.06	0.2	0.19
61	MCC building outside	0	0.43	0.38	0.05	0.19	0.18
62	MCC building outside	0	0.56	0.51	0.05	0.2	0.19
63	MCC building outside	0	0.71	0.66	0.05	0.21	0.22
64	MCC building outside	0	0.74	0.61	0.13	0.2	0.21
65	Generator 1 building outside	0	0.47	0.41	0.06	0.17	0.2
66	Generator 1 building outside	0	0.51	0.46	0.05	0.16	0.17
67	Generator 1 building outside	0	0.54	0.43	0.11	0.15	0.18
68	Generator 2 building outside	0	0.61	0.51	0.1	0.14	0.17
69	Generator 2 building outside	0	0.54	0.44	0.1	0.17	0.16
70	Generator 2 building outside	0	0.48	0.37	0.11	0.19	0.15
71	Limestone and lime dosing area	0	0.36	0.31	0.05	0.17	0.2
72	Limestone and lime dosing area	0	0.41	0.36	0.05	0.16	0.21
73	Limestone and lime dosing area	0	0.37	0.33	0.04	0.15	0.19
74	Limestone and lime dosing area	0	0.44	0.37	0.07	0.16	0.17
75	Limestone and lime dosing area	0	0.51	0.41	0.1	0.17	0.16
76	Limestone and lime dosing area	0	0.47	0.43	0.04	0.14	0.13
77	Limestone and lime dosing area	0	0.41	0.36	0.05	0.15	0.14
78	Limestone and lime dosing area	0	0.43	0.32	0.11	0.16	0.17
79	Limestone and lime dosing area	0	0.54	0.41	0.13	0.17	0.19
80	Limestone and lime dosing area	0	0.49	0.36	0.13	0.18	0.2
81	Mechanical workshop	0	0.48	0.41	0.07	0.16	0.17
82	Mechanical workshop	0	0.49	0.38	0.11	0.17	0.16
83	Mechanical workshop	0.01	0.51	0.42	0.09	0.18	0.15
84	Mechanical workshop	0	0.57	0.49	0.08	0.15	0.14
85	Mechanical workshop	0	0.54	0.44	0.1	0.16	0.15
86	Electrical workshop	0	0.43	0.33	0.1	0.19	0.2
87	Electrical workshop	0.01	0.51	0.41	0.1	0.2	0.18
88	Electrical workshop	0	0.46	0.43	0.03	0.16	0.17
89	Electrical workshop	0	0.44	0.37	0.07	0.17	0.16
90	Electrical workshop	0	0.57	0.43	0.14	0.19	0.17
91	Canteen area	0	0.54	0.47	0.07	0.17	0.18
92	Canteen area	0	0.66	0.53	0.13	0.18	0.19
93	Canteen area	0	0.53	0.42	0.11	0.19	0.17
94	Canteen area	0.01	0.49	0.34	0.15	0.2	0.2
95	Canteen area	0.01	0.56	0.41	0.15	0.21	0.2
96	Outside ablution block bathrooms	0	0.54	0.44	0.1	0.16	0.17
97	Outside ablution block bathrooms	0	0.46	0.41	0.05	0.14	0.16
98	Outside ablution block bathrooms	0	0.61	0.53	0.08	0.15	0.17
99	Outside ablution block bathrooms	0	0.59	0.46	0.13	0.17	0.19
100	Outside ablution block bathrooms	0.01	0.54	0.44	0.1	0.18	0.17

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/γ	γ	β	1 Meter	Contact
101	Thickener dam 1	0	0.56	0.39	0.17	0.19	0.16
102	Thickener dam1	0.01	0.52	0.41	0.11	0.12	0.14
103	Thickener dam 1	0	0.49	0.36	0.13	0.14	0.16
104	Thickener dam 1	0.01	0.6	0.49	0.11	0.19	0.17
105	Thickener dam 1	0	0.54	0.41	0.13	0.13	0.18
106	Thickener dam 2	0	0.54	0.41	0.13	0.16	0.19
107	Thickener dam 2	0	0.56	0.39	0.17	0.17	0.19
108	Thickener dam 2	0	0.59	0.44	0.15	0.19	0.16
109	Thickener dam 2	0	0.45	0.36	0.09	0.18	0.17
110	Thickener dam 2	0	0.49	0.36	0.13	0.14	0.16
111	Thickener dam 3	0.01	0.43	0.31	0.12	0.16	0.17
112	Thickener dam 3	0.01	0.46	0.3	0.16	0.117	0.16
113	Thickener dam 3	0.01	0.47	0.31	0.16	0.16	0.19
114	Thickener dam 3	0	0.52	0.44	0.08	0.14	0.13
115	Thickener dam 3	0.01	0.41	0.33	0.08	0.15	0.14
116	Treated water sump dam	0	0.46	0.36	0.1	0.17	0.18
117	Treated water sump dam	0	0.55	0.41	0.14	0.16	0.17
118	Treated water sump dam	0	0.47	0.4	0.07	0.17	0.16
119	Treated water sump dam	0	0.53	0.43	0.1	0.14	0.14
120	Treated water sump dam	0	0.49	0.38	0.11	0.2	0.19
121	Laboratory	0	0.55	0.43	0.12	0.14	0.16
122	Laboratory	0	0.49	0.36	0.13	0.15	0.17
123	Laboratory	0	0.54	0.47	0.07	0.17	0.18
124	Christopher office	0	0.54	0.41	0.13	0.2	0.18
125	Christopher office	0	0.64	0.5	0.14	0.21	0.2
126	Christopher office	0	0.68	0.59	0.09	0.24	0.21
127	Boardroom	0	0.61	0.49	0.12	0.16	0.19
128	Boardroom	0	0.58	0.47	0.11	0.19	0.2
129	Boardroom	0	0.54	0.43	0.11	0.2	0.21
130	Office 2	0	0.64	0.51	0.13	0.18	0.19
131	Office 2	0	0.57	0.44	0.13	0.17	0.2
132	Office 2	0	0.59	0.46	0.13	0.16	0.21
133	Office 3	0	0.46	0.39	0.07	0.23	0.17
134	Office 3	0	0.54	0.41	0.13	0.2	0.18
135	Office 3	0	0.57	0.44	0.13	0.19	0.17
136	Kitchen	0	0.58	0.42	0.16	0.17	0.15
137	Kitchen	0	0.61	0.46	0.15	0.16	0.14
138	Kitchen	0	0.54	0.39	0.15	0.15	0.16
139	Office 1	0	0.63	0.51	0.12	0.23	0.25
140	Office 1	0	0.58	0.49	0.09	0.2	0.21
141	Office 1	0.01	0.54	0.46	0.08	0.19	0.21
142	Laboratory Office	0	0.64	0.51	0.13	0.19	0.17
143	Laboratory Office	0	0.58	0.43	0.15	0.2	0.18
144	Laboratory Office	0	0.74	0.59	0.15	0.21	0.19
145	Reception	0	0.64	0.51	0.13	0.24	0.19
146	Reception	0	0.57	0.46	0.11	0.21	0.2
147	Reception	0	0.69	0.5	0.19	0.23	0.23
148	Control room	0	0.57	0.44	0.13	0.13	0.16
149	Control room	0	0.63	0.51	0.12	0.14	0.15
150	Control room	0	0.53	0.41	0.12	0.16	0.15
151	Control room	0	0.47	0.41	0.06	0.06	0.09
152	Sludge pump station basement	0	0.51	0.4	0.11	0.07	0.11

Location	Ref. Description	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
		α	β/γ	γ	β	1 Meter	Contact
153	Sludge pump station basement	0	0.47	0.36	0.11	0.11	0.14
154	Sludge pump station basement	0	0.54	0.39	0.15	0.12	0.13
155	Sludge pump station basement	0	0.61	0.46	0.15	0.14	0.13
156	Sludge pump station basement	0	0.41	0.33	0.08	0.16	0.17
157	Sludge pump station basement	0.01	0.56	0.41	0.15	0.17	0.19
158	Sludge pump station basement	0	0.61	0.49	0.12	0.16	0.17
159	Sludge pump station basement	0	0.41	0.33	0.08	0.17	0.19
160	Sludge pump station basement	0	0.31	0.28	0.03	0.18	0.2
161	Sludge pump station basement	0	0.47	0.36	0.11	0.19	0.21
162	Sludge pump station basement	0	0.61	0.51	0.1	0.2	0.19
163	Sludge pump station basement	0	0.77	0.51	0.26	0.23	0.24

**Table 3.11 Summary of surface contamination and dose rate values measured at the Water Treatment Plant during the January 2025 survey.**

Parameter	Contamination Bq.cm <sup>-2</sup>				Dose Rate μSv.h <sup>-1</sup>	
	α	β/γ	γ	β	Contact	1 Meter
<b>Background</b>	<b>0.00</b>	<b>0.56</b>	<b>0.49</b>	<b>0.07</b>	<b>0.10</b>	<b>0.12</b>
Minimum	0.00	0.31	0.28	0.03	0.06	0.09
Maximum	0.01	0.77	0.66	0.26	0.24	0.25
Average	0.00	0.51	0.42	0.09	0.16	0.17
90 <sup>th</sup> Percentile	0.01	0.61	0.51	0.15	0.20	0.20

#### 3.8.4.4 Discussion of Results

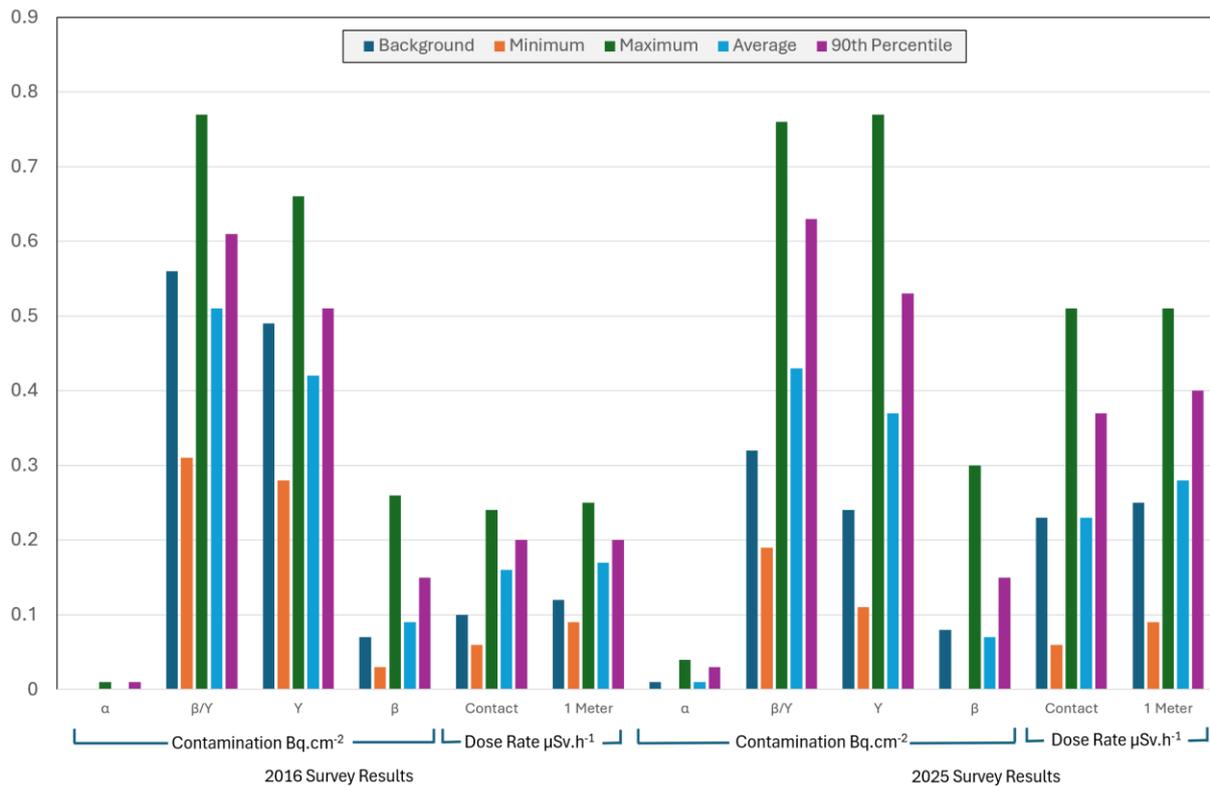
Figure 3.42 presents a comparison between the summary of the results presented in Table 3.9 and Table 3.11. Double the number of readings were taken in 2025 than in 2016. The results show that the readings during the two surveys are very similar, with a possible decrease in the average surface contamination readings from 2016 to 2025 but an increase in the contact and 1 m dose rate reading.

## 3.9 Maintenance Activities

### 3.9.1 General

The Water Treatment Plant operators perform various activities within the main sections of the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations that can be considered normal operating conditions. These conditions are described in detail in AECOM (2015a) and summarised in Section 3.3 and Section 3.4.

Although not in detail, AECOM (2015a) also describe the control and operational philosophy for maintenance mode, recycle mode, start-up mode, shutdown mode and emergency shutdown mode, as applicable for the different sections of the plant. Generally, some maintenance activities have the potential to result in higher dose rates but with much shorter exposure periods than during normal operating conditions.



**Figure 3.42** A graphical comparison between the summary of the results presented in Table 3.9 and Table 3.11.

### 3.9.2 Water Treatment Plant

The operator adheres to a strict Original Equipment Manufacturer & Original Equipment Supplier (OEM & OES) maintenance schedule for the Water Treatment Plant. The equipment that is subject to maintenance is limited to mixers, aerators, pumps and electrical installation. There are a few minor pieces of mechanical equipment like actuated valves and screw conveyors, but the minor pieces of equipment are not in contact with raw AMD water or treated AMD water in the chemical make-up process in the lime and poly areas.

When a treatment module is taken out of operation for maintenance, the Water Treatment Plant is designed to treat 75% (or 82.5 ML.day<sup>-1</sup>) of the maximum design AMD water flow using only two treatment modules. The flow to a reactor can be stopped by manually closing the applicable penstock at the feed splitter box and the applicable penstock at the sludge mixing tank. The flow to a thickener can be stopped by closing the manual penstock in the poly mixing/dosing box.

The pieces of equipment that are possibly contaminated by AMD water that require maintenance are limited to the abstraction pumps and pipework. The process to refurbish or repair the equipment will be handled by the OEM (Ritz). When the situation occurs, Ritz will have to submit their Method Statement and safety files for approval before work can commence.

The other areas in the Water Treatment Plant that are in contact with AMD water are in the first part of the water treatment process. These include:

- Pipework from the shaft cap to the AMD splitter box, consisting of mild steel pipes with HDPE lining and sections of stainless steel 316 pipes;
- The AMD splitter box, which is a concrete box with special acid-resistant coating;
- The AMD splitter box sluice gates that are constructed using stainless steel 316;

- The feed channels to the reactors, consisting of concrete channels with special acid-resistant coating; and
- The pre-neutralization aerators are constructed using stainless steel 316.

The general principle described in AECOM (2015a) for the maintenance mode is that if maintenance or repairs are necessary for a particular line, the affected line will be taken out of operation without affecting the other operating lines in the process. The defective component will be repaired or replaced as required. The specific line will be flushed when in maintenance mode. The OEM & OES should supply a Method Statement and safety files for approvals before work can commence.

Another important maintenance activity in sections of the Water Treatment Plant where sludge is transferred through pipelines (e.g., delivery lines of the sludge recycle pump stations and the sludge waste pump station) is *pigging*. Pigging in the context of pipelines refers to the practice of using devices known as "pigs" to perform various maintenance operations. This is done without stopping the flow of the product in the pipeline. These operations include but are not limited to cleaning and inspecting the pipeline.

### 3.9.3 Sludge Disposal Operations

Under normal operating conditions sludge disposal is done directly from the sludge mixing tank through HDPE pipes down the Grootvlei No. 3 Shaft. Under no condition is a person required to enter below the shaft cap area into the shaft for maintenance purposes. All maintenance activities are performed above ground.

Submersible pumps are used with quick-locking pipes of 12 m lengths. The shaft is equipped with a 130-ton overhead crane that can lift the pipes and the pump, the top pipe is removed while the pipe section below is clamped, the next section of pipes and pump are lifted, the next pipe is clamped, and the top pipe removed, the process continues in this fashion until the pump is the last piece of equipment to leave the shaft.



## 4 Public Safety Assessment Analysis

### 4.1 General

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Consistent with the methodological safety assessment framework presented in Figure 1.3, the purpose of this section is to present the radiological safety assessment analysis results for exposure to members of the public induced by the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations. The basis for the safety assessment analysis is the regulatory framework presented in the assessment context presented in Section 2 and the system description presented in Section 3.

The section is structured as follows. Section 4.2 evaluates and presents the safety assessment analysis for the Water Treatment Plant itself, including the release of treated water from the plant into the environment. Section 4.3 evaluates and presents the safety assessment analysis associated with the sludge disposal operation. A Source-Pathway-Receptor analysis approach is followed for both components of the total system.

### 4.2 Water Treatment Plant

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#### 4.2.1 General

Using a Source-Pathway-Receptor analysis approach, the Water Treatment Plant itself serves as a source of radiation exposure only to workers (occupational exposure). Physical access control is applied at the plant, which means that members of the public do not have free access to the closed-off plant area or the untreated water as a source. The Water Treatment Plant itself will, therefore, not be assessed as a source of radiation exposure to members of the public. However, the treated water released to the Blesbok Spruit may serve as a source of public radiation exposure.

#### 4.2.2 Discharge of Treated Water to the Blesbok Spruit

##### 4.2.2.1 Source-Pathway-Receptor Analysis

Following a Source-Pathway-Receptor analysis approach, the treated water released from the water treatment plant to the Blesbok Spruit may serve as a source of radiation exposure to members of the public. About 75 ML per day are released to the Blesbok Spruit from a point outside the Water Treatment Plant to the east (see Figure 3.37, Figure 3.38 and Figure 3.39).

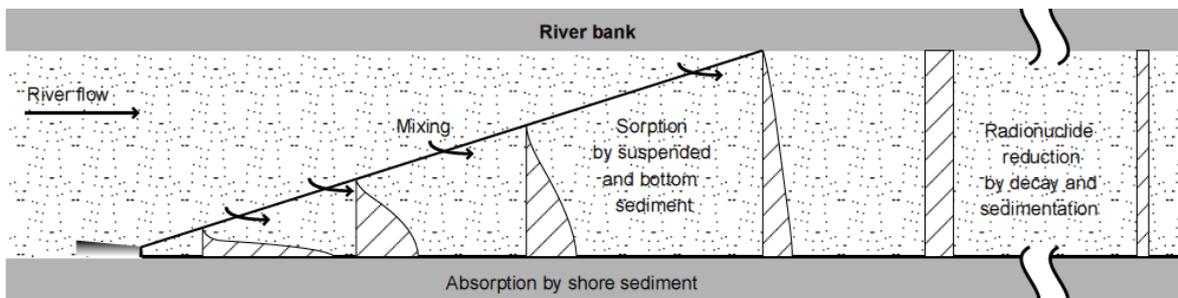
Table 3.5 to Table 3.7 summarises the full spectrum Necs analysis results of the available water samples, while Table 4.1 presents the nuclide-specific activity concentrations for the different samples used in the safety assessment analysis. The most recent analysis results for the treated water (2024) were used for the safety analysis. Other water analysis results included in Table 4.1 were used for reference purposes (e.g., the AMD Water). Also included in Table 4.1 are the analysis results of samples taken upstream and downstream in the Blesbok Spruit (see Table 3.7). Note that the values in red assume secular equilibrium with the parent radionuclide (see Section 2.3.4.3 for conditions assumed for secular equilibrium).

The pathway of concern is mainly the surface water and associated secondary pathways. The latter depends to a large extent on the potential receptors downstream from the discharge point, which is not well defined. Once discharged into the Blesbok Spruit, radionuclides in the discharged water are subject to a series of physical and chemical processes that affect their transport from the point of discharge. These processes include the following (see Figure 4.1) (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; and
- Other processes, including radionuclide decay and other mechanisms that will reduce concentrations in water, such as radionuclide volatilization (if any).

**Table 4.1 The nuclide-specific activity concentrations of the treated water and water sampled from the Blesbok Spruit used in the radiological public safety assessment analysis. The red values assume secular equilibrium with the parent radionuclide (see Section 3.8.1).**

Radionuclide	AMD Water	Treated Water (2016)	ERB Effluent Water (2024)	ESW-01	ESW-03	ERB Effluent Water (Diluted)
	Activity Concentration (mBq.L <sup>-1</sup> )					
U-238	563	34.8	472	30.2	289	5.79
U-234	596	60.1	516	67.8	321	6.74
Th-230	30.1	29	50.4	67.2	34.7	1.36
Ra-226	353	25.4	184	67.2	34.7	2.90
Pb-210	353	25.4	184	67.2	34.7	2.90
Po-210	353	25.4	184	67.2	34.7	2.90
U-235	25.9	1.6	21.7	1.39	13.3	0.27
Pa-231	25.9	1.6	21.7	1.39	13.3	0.27
Ac-227	25.9	1.6	21.7	1.39	13.3	0.27
Ra-223	25.9	1.6	21.7	1.39	13.3	0.27
Th-232	6.5	6.5	9.07	12.3	10.3	0.25
Ra-228	6.5	6.5	9.07	12.3	10.3	0.25
Th-228	6.5	6.5	9.07	12.3	10.3	0.25

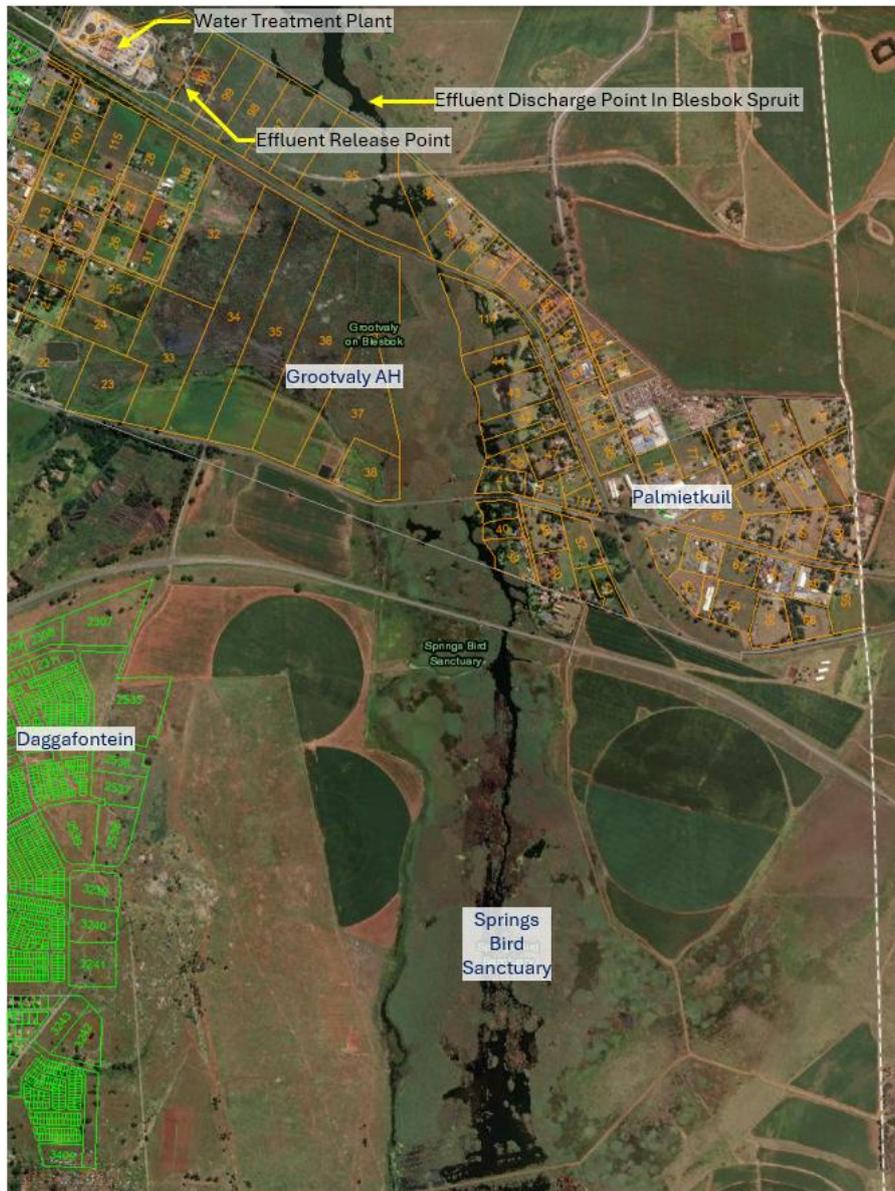


**Figure 4.1 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001).**

Detailed land use and human behavioural studies that define the potentially most exposed receptors downstream of the Blesbok Spruit discharge point are not available at present. Figure 4.2 is a locality map showing the downstream area of the Water Treatment Plant and the associated discharge point into the Blesbok Spruit. It shows agricultural holdings along the Blesbok Spruit, the Springs Bird Sanctuary, with larger agricultural land laterally further away from the Spruit.

However, according to Exigo Sustainability (2017a), the surface water in the Blesbok Spruit is driven by the sewage works discharges of ±120 ML per day in the Eastern Basin catchment area. This means that the Blesbok Spruit water in all likelihood is not suitable for personal, household or even agricultural purposes. Therefore, assuming direct ingestion of the treated water as the only annual source of water to receptors is

very conservative. It is also known that direct ingestion of water is by far the most dominant ingestion exposure route, accounting for more than 60% of a total effective dose.



**Figure 4.2** Locality map of the areas downstream of the Water Treatment Plant, showing the current land use conditions along the Blesbok Spruit.

#### 4.2.2.2 Radiological Impact Assessment Approach

To assess the potential radiological impact, it is assumed conservatively that the treated water is used directly as the only source of drinking water. The effective dose rate from the ingestion of contaminated water ( $ED_{ing,water}$ , in  $\mu\text{Sv}\cdot\text{year}^{-1}$ ) is calculated from the measured radionuclide concentrations of the contaminated water, multiplied with the appropriate ingestion dose coefficients and +water consumption rates, and is given by:

#### Equation 1

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

where  $C_{water}$  is the radionuclide concentration in the water ( $Bq.m^{-3}$ ),  $DC_{ing}$  is the dose coefficient for ingestion ( $\mu Sv.Bq^{-1}$ ), and  $CR_{water}$  is the individual annual water consumption rate ( $m^3.year^{-1}$ ). Table 4.1 presents the radionuclide concentration for the treated water, while Table 4.2 presents the dose conversion factors for ingestion for different age groups. The water ingestion rates as published in NNR (2013a) for the different age groups are listed in Table 4.3.

**Table 4.2 Dose conversion factors ( $Sv.Bq^{-1}$ ) for ingestion exposure to various radionuclides taken from RG-002 (NNR, 2013a). Note that the contribution of the short-lived daughter radionuclides was included in those of the parent radionuclides.**

Radionuclide	0 to 2 years	2 - 7 years	7 to 12 years	12 to 17 years	Adults
	Sv.Bq <sup>-1</sup>				
Th-232	4.50E-07	3.50E-07	2.90E-07	2.50E-07	2.30E-07
Ra-228	6.43E-06	3.79E-06	4.18E-06	5.51E-06	7.62E-07
U-238	1.45E-07	9.30E-08	7.54E-08	7.12E-08	4.84E-08
U-234	1.30E-07	8.80E-08	7.40E-08	7.40E-08	4.90E-08
Th-230	4.10E-07	3.10E-07	2.40E-07	2.20E-07	2.10E-07
Ra-226	9.62E-07	6.21E-07	8.01E-07	1.50E-06	2.80E-07
Pb-210	3.61E-06	2.20E-06	1.90E-06	1.90E-06	6.91E-07
Po-210	8.80E-06	4.40E-06	2.60E-06	1.60E-06	1.20E-06
U-235	1.33E-07	8.62E-08	7.17E-08	7.04E-08	4.73E-08
Pa-231	1.30E-06	1.10E-06	9.20E-07	8.00E-07	7.10E-07
Ac-227	4.27E-06	2.81E-06	1.97E-06	1.59E-06	1.21E-06

#### 4.2.2.3 Results

Table 4.3 presents the resulting water ingestion dose for the different age groups and for the different water samples, which shows that - as expected - the AMD Water resulted in the highest water ingestion dose and is likely not suitable for human consumption continuously. A comparison between the 2016 Treated Water and the 2024 ERB Effluent Water samples shows a noticeable increase in the water ingestion doses for all age groups. This is also expected given the increase in activity concentration discussed in Section 3.8.3. The 2016 results were relatively insignificant (less than  $100 \mu Sv.year^{-1}$ ), whereas the 2024 results indicate significant water ingestion doses (as high as  $500 \mu Sv.year^{-1}$ ).

**Table 4.3 Water ingestion rates as proposed in RG-002 (NNR, 2013a) and associated water ingestion dose for members of the public.**

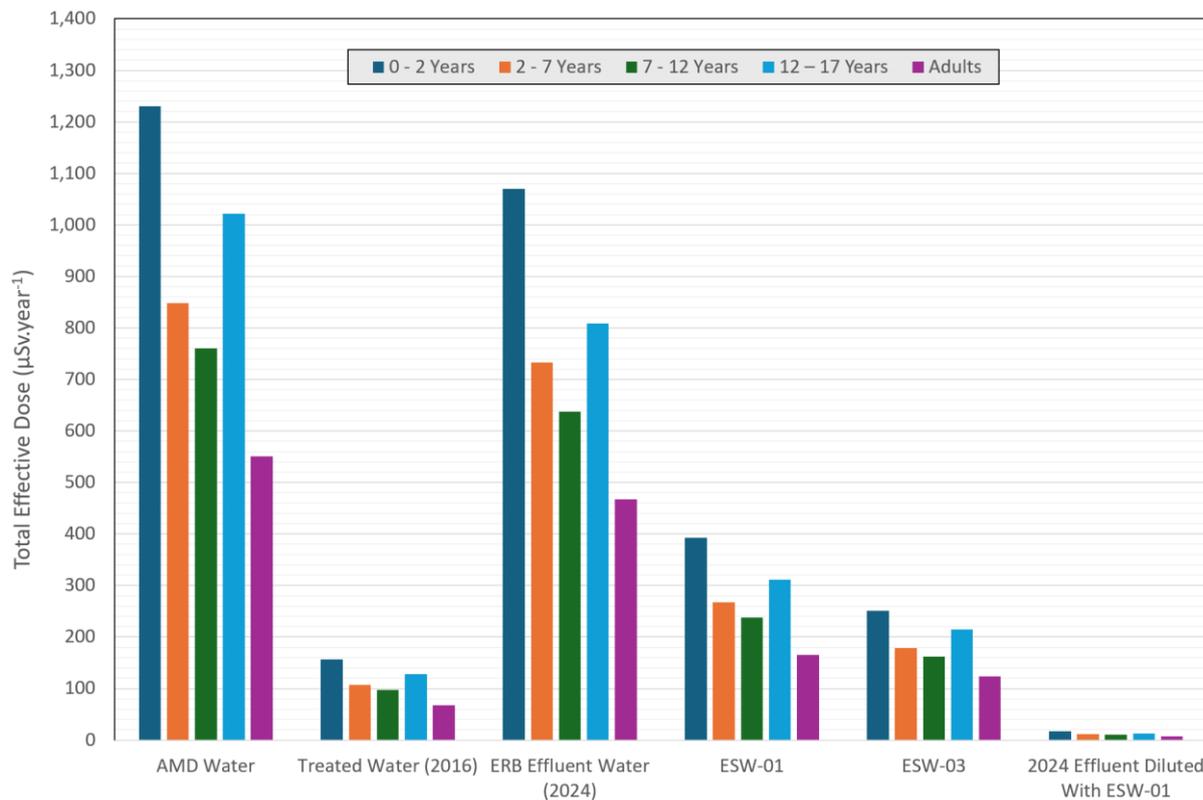
Ingestion Pathway	Unit	Water Ingestion Rates for Different Age Groups				
		0 - 2 Years	2 - 7 Years	7 - 12 Years	12 - 17 Years	Adult
% Of Adult Rate	-	40	50	60	85	100
Water	L.y <sup>-1</sup>	240	300	360	510	600
AMD Water	$\mu Sv.year^{-1}$	915	629	559	749	399
Treated Water		75	53	49	70	34
ERB Effluent Water (Undiluted)		505	351	315	424	229
ESW-01		186	129	119	165	81
ESW-03		128	93	87	121	67
ERB Effluent Water (Diluted)		6.1	4.2	3.8	5.1	2.8

The water ingestion doses were also calculated for the two sampling points in the Blesbok Spruit. What it shows is that the downstream water ingestion doses (ESW-03) are lower than the upstream doses (ESW-01). This is noteworthy since the discussion in Section 3.8.3 suggested that the downstream activity concentrations were higher than the upstream activity concentrations. This is attributed to the lower Ra-

226 activity concentrations (and by implication Pb-210 and Po-210 as well) for ESW-03 (downstream). These lower activity concentrations will result in lower doses despite the much higher activity concentrations for the U isotopes (see Table 4.1).

What is worth noting is that the results for the ERB Effluent Water are conservative, assuming the water is the only source of water on an annual basis. Furthermore, it does not consider any dilution of uncontaminated water flowing in the Blesbok Spruit. It follows from Figure 3.26 that 75 ML of water are released to the Blesbok Spruit daily, while the average daily flow rate in the Blesbok Spruit is in the order of 6,500 ML. This means that the expected dilution factor is in the order of 0.012. Applying this dilution factor between the ESW-01 and ERB Effluent water analysis results in Table 4.1, the results in Table 4.3 suggest that this will reduce the water ingestion doses to less than 10  $\mu\text{Sv}\cdot\text{year}^{-1}$ .

Figure 4.3 presents the total effective dose for all the measured and derived water samples assuming an agricultural exposure condition with all relevant exposure routes identified in NNR (2013a) included. A 100-year deposition period from irrigation was assumed. The results confirm that for the assumed conditions and without any dilution, the AMD Water and ERB Effluent water is not suitable as the only source of water for members of the public. However, with dilution included the total effective dose of the ERB Effluent is reduced to below 20  $\mu\text{Sv}\cdot\text{year}^{-1}$ .



**Figure 4.3** The total effective dose, assuming an agricultural exposure condition with all relevant exposure routes identified in NNR (2013a) included.

#### 4.2.3 Discussion of Results

The physical security measures that are applied at the Water Treatment Plant mean that the plant itself does not serve as a source of radiation exposure to members of the public. It is only the treated water released to the Blesbok Spruit that serves as a source of radiation exposure. However, it was demonstrated that without accounting for dilution, the potential dose to members of the public could still be significant and exceed the public dose constraint of 250  $\mu\text{Sv}\cdot\text{year}^{-1}$ . If water abstracted from the Blesbok Spruit is used

as the sole source of water to sustain a farm system, the doses could even approach the dose limit of 1,000  $\mu\text{Sv}\cdot\text{year}^{-1}$ .

Accounting for dilution in the Blesbok Spruit is probably a more realistic scenario. For this purpose, one can assume the dilution ratio of 0.012 as derived in Section 4.2.2.3 but is strongly dependent on the 75 ML of water released to the Blesbok Spruit daily and the average daily flow rate in the Blesbok Spruit in the order of 6,500 ML. Under these conditions, the total effective dose is less than 20  $\mu\text{Sv}\cdot\text{year}^{-1}$ . Assuming that ESW-03 is representative of the diluted scenario is more defensible but then the total effective doses approach the public dose constraint of 250  $\mu\text{Sv}\cdot\text{year}^{-1}$ .

It can, therefore, be concluded that based on the current radioanalysis results of the treated water, it is inconclusive whether the Water Treatment Plant and associated discharge of treated water to the environment falls within the compliance criteria for exemption as presented in Section 2.2.5.

## 4.3 Sludge Management

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### 4.3.1 General

The conditions and assumptions for the HDS disposal operation were presented in Section 3.4, which suggests that the sludge is directly transferred *via* an HDPE pipeline from the Water Treatment Plant on the surface to the point of disposal in the basin through the Grootvlei No. 4 Shaft into the mine void. The main purpose of this section is thus to assess the potential radiological impact on members of the public induced by the HDS disposal operations.

Viewed conceptually (see Figure 3.21 and Figure 3.25), the Eastern Basin is a closed system stretching over several kilometres with physical boundaries defined by the underlying geology, geological structures and surface topography. Variable ingress rates into the basin still occur, which requires that a minimum volume of water be abstracted from the Grootvlei No. 3 Shaft to maintain the ECL at 1,450 mamsl (or 100 m from the surface). Due to historical mining, the underlying geology and deep aquifer system are significantly disturbed. Figure 3.24 is a graphical illustration of a typical mine void and what one can expect within the Eastern Basin.

### 4.3.2 Process Level Model of the Eastern Basin

Section 3.7 outlines the Process Level hydrogeological model developed by Artesium (2024b) to assess the ERB sludge disposal operations. The results from this model serve as the foundation for the System Level evaluation, which examines both the disposal process and its potential radiological impact on the public. Key information—specifically regarding flow dynamics and mass transport—is extracted from the Process Level model to assess how radionuclides from the disposed sludge might migrate and affect public safety.

Fundamental to this process is the conceptual understanding of the flow dynamics in the Eastern Basin along the Main Reef for 1,000 years, as illustrated in Figure 3.34 and Figure 3.35. Equally important are the groundwater flow velocities derived for the different geological units expressed as the Darcy velocity, as well as the associated porosities of the different units presented in Artesium (2024b), both of which will influence the radionuclide migration. Finally, the Process Level model provides the physical volume of the disposed of sludge after 100 years of disposal in the mine void.

### 4.3.3 System Level Model

The aim of *System Level* modelling within the safety assessment framework is to integrate as many of the system components as possible into an integrated model, with the radiological impact in terms of a total

effective dose as an endpoint. During the process, relevant information and input values are abstracted from the *Process Level* modelling in support of the *System Level* model. A compartment model approach is often used for this purpose to represent the migration and fate of contaminants in the environment. According to Little *et al.* (2003), the use of a compartment model approach places two main constraints on the mathematical representation of a total system.

The first constraint is that the system must be discretised into a series of compartments. Using the compartment modelling approach, a system may be represented by breaking it down into compartments that can correspond to the components identified in the conceptual model. It is assumed that, as soon as a contaminant enters a compartment, instantaneous mixing occurs so that there is a uniform concentration over the whole compartment. Each compartment must be chosen to represent a system component for which this assumption is reasonable.

The second constraint is that processes resulting in the transfer of contaminants from one compartment to another need to be expressed as transfer coefficients that represent the fraction of the activity in a compartment transferred from one compartment to another per unit of time. The mathematical representation of the intercompartmental transfer processes takes the form of a matrix of transfer coefficients that allow the compartmental amounts to be represented as a set of first-order linear differential equations.

For the  $i^{th}$  compartment, the rate at which the inventory of radionuclides in a compartment changes with time is given by (Little *et al.*, 2003):

**Equation 2**

$$\frac{dN_i}{dt} = \left( \sum_{j \neq i} \lambda_{ji} N_j + \lambda_N M_i + S_i(t) \right) - \left( \sum_{j \neq i} \lambda_{ij} N_i + \lambda_N N_i \right)$$

where  $i$  and  $j$  indicate compartments,  $N$  and  $M$  are the amounts (Bq) of radionuclides  $N$  and  $M$  in a compartment ( $M$  is the precursor of  $N$  in a decay chain).  $S(t)$  is a time-dependent external source of radionuclide  $N$  (Bq.year<sup>-1</sup>). Transfer and loss rates are represented by  $\lambda$ .  $\lambda_N$  is the decay constant for radionuclide  $N$  (year<sup>-1</sup>) and  $\lambda_{ji}$  and  $\lambda_{ij}$  are transfer coefficients (year<sup>-1</sup>) representing the gain and loss of radionuclide  $N$  from compartments  $i$  and  $j$ .

The solution of the matrix of equations given above provides the time-dependent inventory of each compartment. Assumptions for compartment sizes then result in estimates of concentrations in the corresponding media, from which doses/intakes can be estimated.

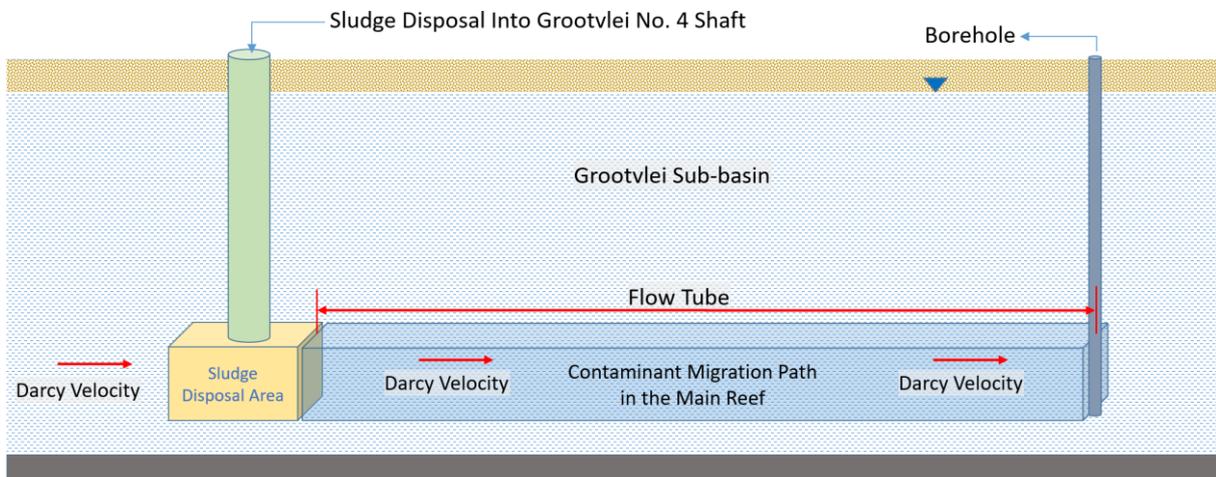
The *System Level* modelling for this assessment is implemented in the AFRY Intelligent Scenario Modelling® software tool<sup>3</sup> (AFRY ISM, see <https://afry.com/en/service/intelligent-scenario-modelling-simulation-software>) Version 8.5, with a clear distinction between the sources, pathways, and receptors. For this purpose, an abstraction of information from the *Process Level* model is needed in terms of pathway-specific parameter values. AFRY ISM® uses a compartment model approach to represent the migration and fate of contaminants in the environment. The system is discretised into a series of compartments and sub-compartments that correspond to the components identified in the conceptual model. It is assumed that as soon as a contaminant enters a compartment, instantaneous mixing occurs so that there is a uniform concentration over the whole compartment. For simplicity, the above Equation 2 assumes a single parent and daughter. However, compartmental modelling software such as AFRY ISM® allows the representation of multiple parents and daughters.

<sup>3</sup> Previously known as Ecolego.

Note that it is not always possible or practical to include all system components into one *System Level* model. The contribution from the atmospheric pathway, for example, is dynamic and the radiological impact on members of the public may be from the first day of operation (i.e., present-day operational conditions). The contribution of the groundwater pathway, on the other hand, is slow, and the potential radiological impact may only occur in the far future (e.g., hundreds of years from now). The timescales of concern, over which the potential radiological impact on members of the public may occur, are thus different. For this reason, separate *System Level* models are often developed to evaluate the contribution of the atmospheric and groundwater pathways.

#### 4.3.4 Conceptual Model

Figure 4.4 is a schematic representation of the conceptual model adopted for the System Level model. It is assumed that the sludge is disposed of in the Grootvlei Sub-basin, resulting in a volume of sludge (after say 100 years) that is termed the sludge disposal area in the Main Reef of the basin. This area can be assumed to have a total volume that can be represented by a rectangular cube. Radionuclides would be released from the disposal zone into the Main Reef that constitutes the contaminant flow and migration path.



**Figure 4.4 Schematic diagram that illustrates the conceptual model adopted for the System Level model.**

The Darcy flux through the disposal zone would be less than in the Main Reef itself due to the properties of the sludge. The radionuclides released from the disposal zone would migrate along the Main Reef with time. The Darcy velocity in the Main Reef is assumed to be constant with time. It is further assumed that at some distance, water is abstracted from a borehole that intersects the Main Reef.

#### 4.3.5 Mathematical Representation

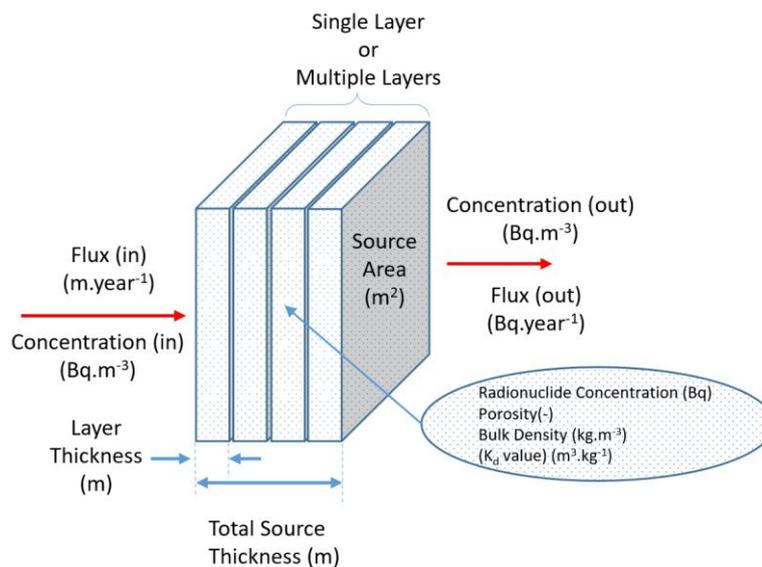
##### 4.3.5.1 Source Term Model

Radionuclides present in the disposal zone will migrate into the adjacent Main Reef compartment under the influence of molecular diffusion and hydrodynamic dispersion caused by passing groundwater. The rate of migration—commonly referred to as the *source term*—is one of the most important quantities to know in an assessment of this nature.

One certain property of the source term is that it must be related to the rate at which the nuclides leach from the source, i.e., the *flux* of dissolved nuclides. Advanced mathematical models based on the hydrodynamic dispersion equation can be used to describe this flux mathematically (Botha, 1996). However, some parameters required for this purpose are difficult to determine in the field, while some of

the functions in the equation are generally unknown. Most of the methods used to compute the source term in radioactive waste disposal assessments, for example, usually represent the source term as a mathematical function with adjustable parameters or even as a constant.

The source term compartment represents the leaching of radionuclides from the disposal zone directly to the saturated zone (Main Reef). Figure 4.5 is a simple representation of the source and the most important parameters. The flux into the disposal zone ( $\text{m}\cdot\text{year}^{-1}$ ) is assumed to be constant and equal to the Darcy velocity. The source term model makes provision for the influx of water to contain radionuclide specific activity concentrations ( $\text{Bq}\cdot\text{m}^{-3}$ ).



**Figure 4.5 Conceptual representation and associated parameter values for the source term model.**

If the source has a relatively thin horizontal extent (thickness), then the source can be represented as a single compartment with homogeneous properties. If the source consists of layers of materials with different properties, then the source term implemented in AFRY ISC may be represented as multiple compartments with different properties. A variation of the latter might be when the first layer does not contain naturally occurring radionuclides but serves as a cover layer.

Figure 4.5 shows that the source term model is a function of the radionuclide specific activity concentration (Bq), the porosity (-), the dry bulk density of the source material ( $\text{kg}\cdot\text{m}^{-3}$ ), and the radioelement-specific distribution coefficient or  $K_d$ -value ( $\text{m}^3\cdot\text{kg}^{-1}$ ).

The advective transfer coefficient in Equation 2 represents the loss of radionuclides from compartment  $i$  to compartment  $j$  ( $\lambda_{Adv}$ , in  $\text{year}^{-1}$ ) and is calculated using the following equation described in IAEA (2004c) and Baes and Sharp (1983):

**Equation 3**

$$\lambda_{Adv,src} = \frac{Influx_{src}}{\epsilon_{src} \cdot Depth_{src} \cdot R_{d,src}}$$

where  $Influx_{src}$  is the influx water rate into the source layer ( $\text{m}\cdot\text{year}^{-1}$ ),  $\epsilon_{src}$  is the porosity in the source layer ( $\text{m}^3\cdot\text{m}^{-3}$ ) and  $Depth_{src}$  is the thickness of the source layer (m).  $R_{d,src}$  is the retardation coefficient for the source layer (unitless) calculated as follows:

**Equation 4**

$$R_{d,Src} = 1 + \frac{\rho_{b,Src} \cdot K_{d,Src}}{\varepsilon_{Src}}$$

where  $\rho_{b,Src}$  is the dry bulk density of the source layer ( $\text{kg}\cdot\text{m}^{-3}$ ) and  $K_{d,Src}$  is the sorption distribution coefficient of the source layer ( $\text{m}^3\cdot\text{kg}^{-1}$ ). For multiple layers with different properties, the transfer coefficient is defined for each layer with the values of its associated parameters. Figure 4.5 shows that the output from the source term model is the radionuclide concentration ( $\text{Bq}\cdot\text{m}^{-3}$ ) or flux ( $\text{Bq}\cdot\text{year}^{-1}$ ) leaving the compartment.

A further variation of the conceptual model presented above is where the source has a significant horizontal extent. Representing the source as a single compartment does not account for the dispersive fluxes within the source, which might be of importance for a source with a large lateral extent. For this configuration, it is proposed that the migration of radionuclides from the source is represented using the Transport Block in AFRY ISC. The Transport Block divides the single compartment into several sub-compartments. The number of compartments **N** is determined automatically considering the accuracy of approximation of the advection-dispersion terms. The transfer coefficient accounting for the effect of dispersion in transport from compartment *i* to compartment *j* ( $\lambda_{Disp,Src}$ , in  $\text{year}^{-1}$ ) is then calculated using the following equation (IAEA, 2004c):

**Equation 5**

$$\lambda_{Disp,Src} = \frac{\alpha_{L,Src}}{Depth_{Src}} \cdot \lambda_{Adv,Src}$$

where  $\alpha_{L,Src}$  is the longitudinal dispersivity of the source layer (m). Note that the transfer coefficient in Equation 5 represents the dispersion of radionuclides between the compartments in both directions. The remaining parameters are listed above.

**4.3.5.2 Aquifer (Saturated Zone)**

The aquifer compartment simulates radionuclide transport in the saturated zone (flow tube), accounting for the advection, dispersion, radioactive decay, and sorption. Figure 4.6 is a simplified representation of the aquifer and the most important parameters. It is assumed that the aquifer is represented as one compartment of known dimensions, which is defined by the aquifer thickness, the area of the flow tube, and the length of the flow tube. The latter is defined by the distance to a receptor point (e.g., borehole or river). The Transport Block in AFRY ISC is used to divide the single compartment into several sub-compartments **N**. The number of compartments **N** is determined automatically considering the accuracy of approximation of the advection-dispersion terms.

The radionuclide concentration ( $\text{Bq}\cdot\text{m}^{-3}$ ) of water entering the aquifer compartment is equal to the outflow concentration from the aquifer mixing zone. The Darcy velocity ( $\text{m}\cdot\text{year}^{-1}$ ) in the aquifer is assumed to be constant with time. The output at the receptor point defines the concentration ( $\text{Bq}\cdot\text{m}^{-3}$ ) and flux ( $\text{Bq}\cdot\text{year}^{-1}$ ) at the borehole (see Section 4.3.5.3).

Figure 4.6 shows that the aquifer model is a function of the Darcy velocity ( $\text{m}\cdot\text{year}^{-1}$ ), the aquifer porosity, the dry bulk density of the aquifer ( $\text{kg}\cdot\text{m}^{-3}$ ), the radioelement specific distribution coefficient or  $K_d$ -value ( $\text{m}^3\cdot\text{kg}^{-1}$ ) for the aquifer, and the dispersivity (m). The advective and dispersive transfer coefficients in Equation 2 that represent the transfer and loss of radionuclides from the aquifer are similar to those presented in Equation 3 to Equation 5, except that it is for the aquifer parameter values.

Note that the implementation of several aquifer models in AFRY ISC can be used to simulate a groundwater flow system with varying hydraulic and/or sorption properties.

**4.3.5.3 Borehole Abstraction**

The borehole abstraction module calculates radionuclide concentration in groundwater pumped from a borehole. It is assumed that some fraction of the borehole intersects the contaminated groundwater plume