



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.

Yours sincerely,



MS R N MAZWI

DIRECTOR: Mining & Industrial Water Quality Regulation

Date: 27 March 2025

CC: Ms. Sophia Tlale – TCTA

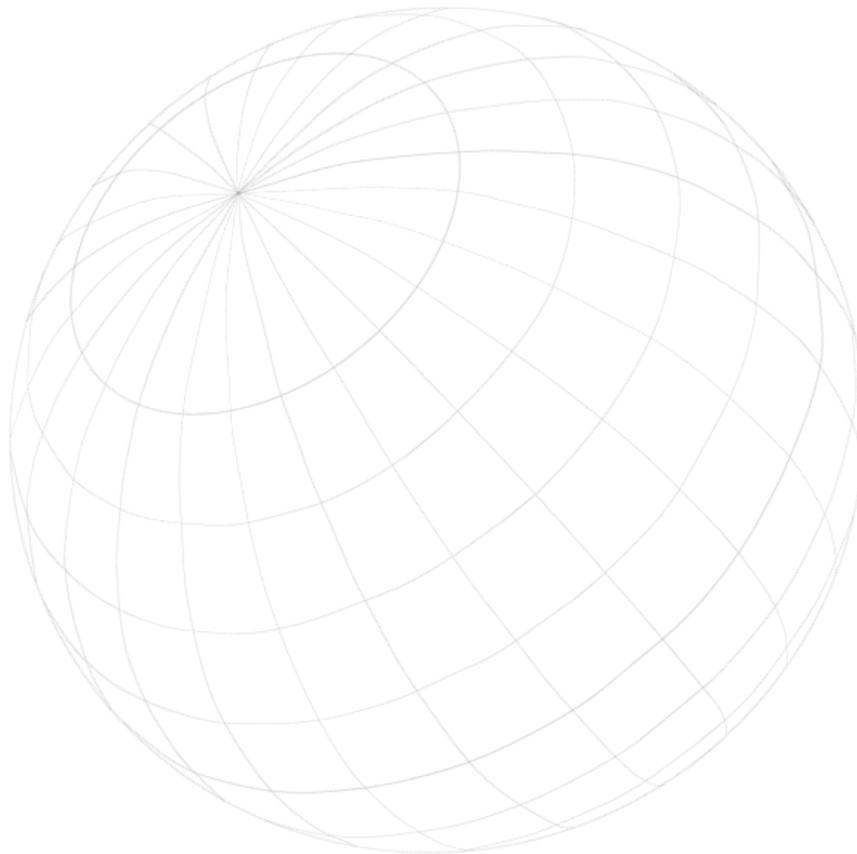
CC: Mr. Goitseone Kgwele - TCTA

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



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Technical Report



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

Document Reference Number: ASC-1035K
Document Version Number: Reversion 2
Date: March 2025

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

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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

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 km² 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).

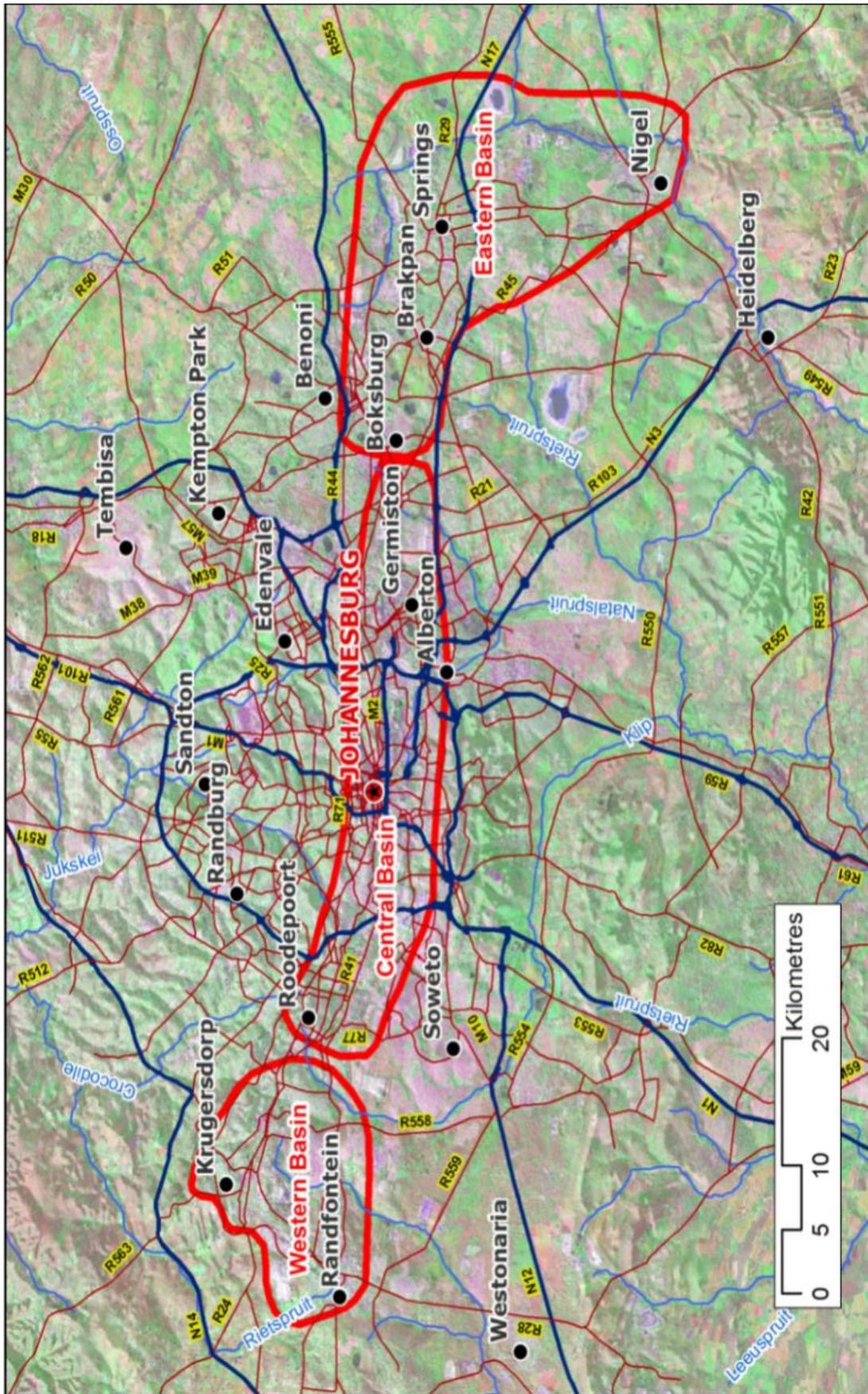


Figure 1.1 Spatial distribution of the Western Basin, Eastern Basin and Central Basin associated with the Witwatersrand gold mining area (Digby Wells Environmental, 2015).

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

Many radioactive isotopes (or radionuclides) occur naturally throughout the Earth's crust and are present in most rocks, soils, river water, as well as in seawater. Most of these naturally occurring radionuclides are members of four radioactive series identified as the uranium (U-238), actinium (U-235), thorium (Th-232), and neptunium (Np-237)¹ series, named according to the radionuclides that serve as progenitor (or parent) to the series products. Naturally occurring radionuclides that are of particular interest to radiation protection, which are not members of any of the four-decay series, include isotopes of potassium (K-40) and rubidium (Rb-87). These isotopes are of interest because of their presence in environmental media and their contribution to human exposure (Martin, 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.

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

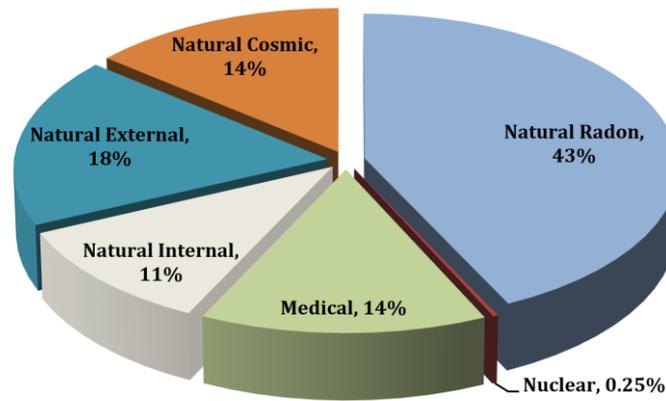


Figure 1.2 Distribution of the background radiation contribution as a percentage of the annual dose, average over the population of the world [Reproduced from IAEA (2004a)].

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

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.

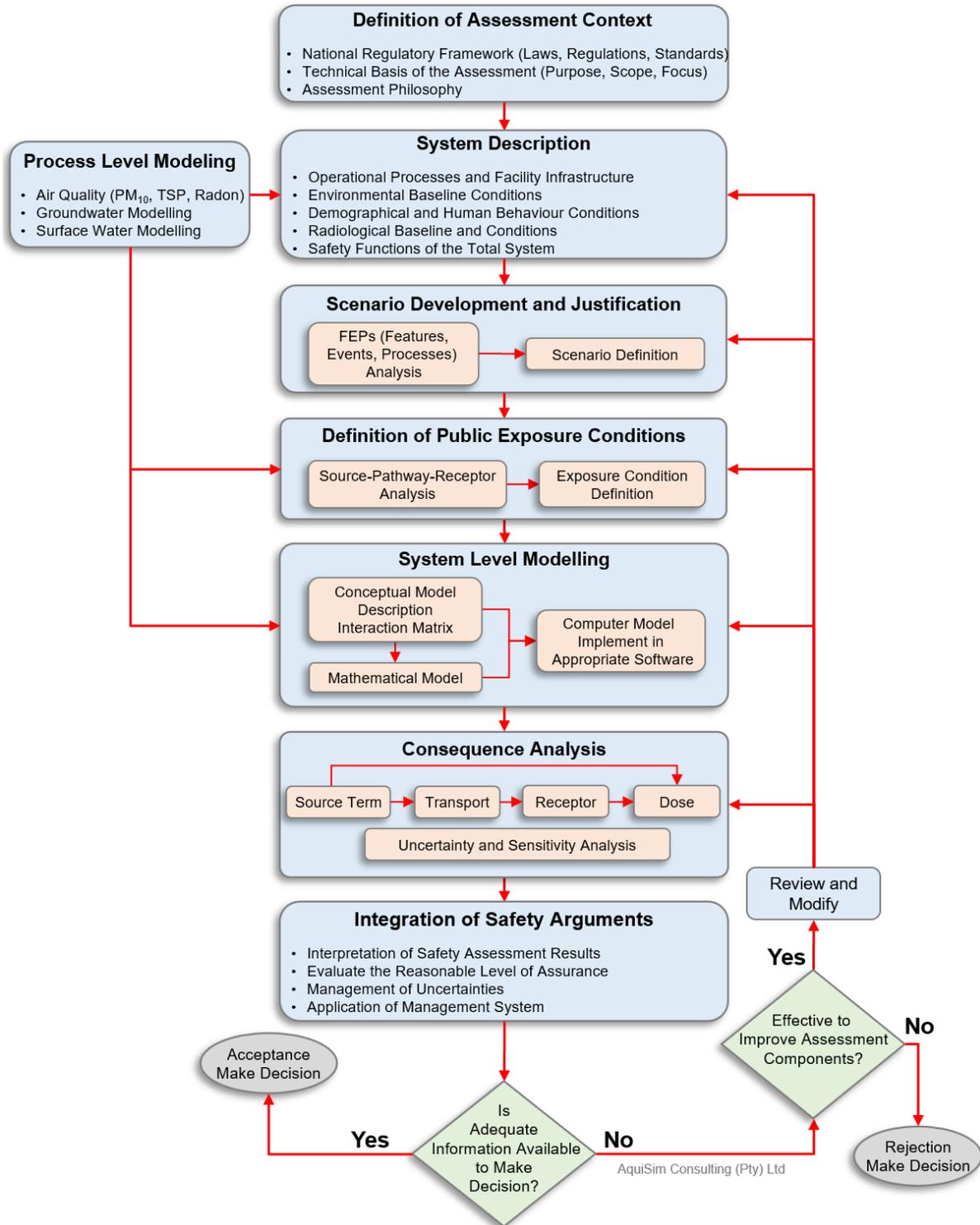


Figure 1.3 Schematic illustration of the framework that is broadly followed for the radiological safety assessment of the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations.

2 Assessment Context

2.1 General

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

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 μ 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 applies².

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 ⁻¹)
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⁻² (beta-gamma), and 0.04 Bq.cm⁻² (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”.

² 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 ⁻¹ to 1 mSv. year ⁻¹
Supervised Area	No possibility of an effective dose exceeding 5 mSv. year ⁻¹
	Occupationally Exposed Person (OEP) status
	No controls are needed to limit exposures below 5 mSv. year ⁻¹
	Continual confirmatory monitoring: <ul style="list-style-type: none"> ○ persons, activities, environment ○ extent dependent on proximity to limit, the potential for variability and ease of measurement
	Dose recording, training and medical
Controlled Area	Possibility of an effective dose exceeding 5 mSv. year ⁻¹
	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 ⁽¹⁾	Disposal / Management Options
1 HLW	Heat generating radioactive waste with high long and short-lived radionuclide concentrations.	1 Used fuel declared as waste or used fuel recycling products 2 Sealed sources	1 Thermal power > 2 kW/m ² . OR 2 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels > levels specified for LILW-LL OR 3 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) above 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 100 years). The waste form shall be solid with additional characteristics as prescribed for a specific repository.	1 (a) Regulated deep disposal (100's of metres). (b) Reprocessing, Conditioning and Recycling (c) Long Term Above Ground Storage
2 LILW-LL	Radioactive waste with low or intermediate short-lived radionuclide and intermediate long-lived radionuclide concentrations.	1 Irradiated uranium (isotope production). 2 Un-irradiated uranium (nuclear fuel production). 3 Fission and activation products (nuclear power generation and isotope production) 4 Sealed sources.	1 Thermal power (mainly due to short-lived radio nuclides (T _{1/2} < 31 y) < 2 kW/m ²) AND 2 Long-lived radio nuclides (T _{1/2} > 31 y) concentrations. ❖ Alpha: < 4000 Bq/g ❖ Beta and gamma: < 40000 Bq/g (Maximum per waste package up to 10x the concentration levels specified above). OR 3 Long-lived alpha, beta and gamma emitting radionuclides at activity concentration levels that could result in inherent intrusion dose (the intrusion dose assuming the radioactive waste is spread on the surface) between 10 and 100 mSv per annum	Waste package suitable for handling, transport and storage (storage period in the order of 50 years). The waste form shall be solid with additional characteristics as for a specific repository.	1 Regulated medium depth disposal (10's of metres). 2 Managed as NORM-E waste (un-irradiated uranium)

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

Waste Class	Waste Description	Waste type / Origin	Waste Criteria	Generic waste treatment / conditioning requirements ⁽¹⁾	Disposal / Management Options
					impoundment 3 Authorised disposal 4 Clearance
6 NORM-E (enhanced activity)	Radioactive waste containing enhanced concentrations of NORM.	1 Scales 2 Soils contaminated with scales	1 Long-lived radio nuclide concentration: > 100 Bq/g.	Packaged or unpackaged waste in a miscible or solid form with additional characteristics for a specific repository.	1 Dilute and re-use as underground backfill material in an identified underground area. 2 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.

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

Note that at the time (in 2005) when the Policy and Strategy were drafted, the waste classification scheme was in line with the IAEA waste classification scheme (IAEA, 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⁻¹) or enhanced activity (long-lived radionuclide concentration > 100 Bq.g⁻¹). 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 ⁻¹)	Enhanced Activity NORM (more than 100 Bq.g ⁻¹)
Reuse NORM as underground backfill material in an underground area.	
Extraction of any economically recoverable minerals from the NORM, followed by disposal in any mine tailings dam or another sufficiently confined surface impoundment	
Authorised disposal	Regulated deep or medium-depth disposal
Clearance	

2.3 Technical Basis of the Assessment

2.3.1 General

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 α and β emitting radionuclides explicitly considered in the Flat Mines Project radiological public safety and impact assessment.

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

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

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

2.3.4.4 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

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

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

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.

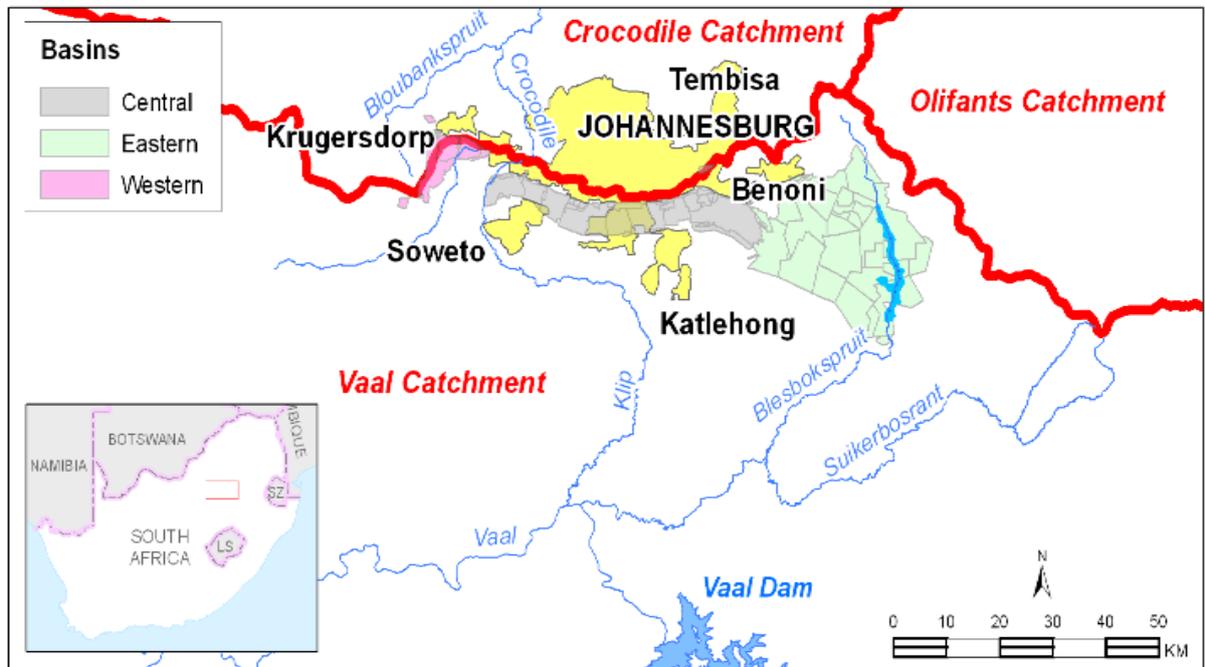


Figure 3.2 Map showing the 3 main basins, with the Blesbok Spruit draining the Eastern Basin flowing into the Suikerbosrand as part of the Vaal River catchment area (<https://www.dws.gov.za/iwrp/amdfs/lts/default.aspx>).



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 m³ 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.

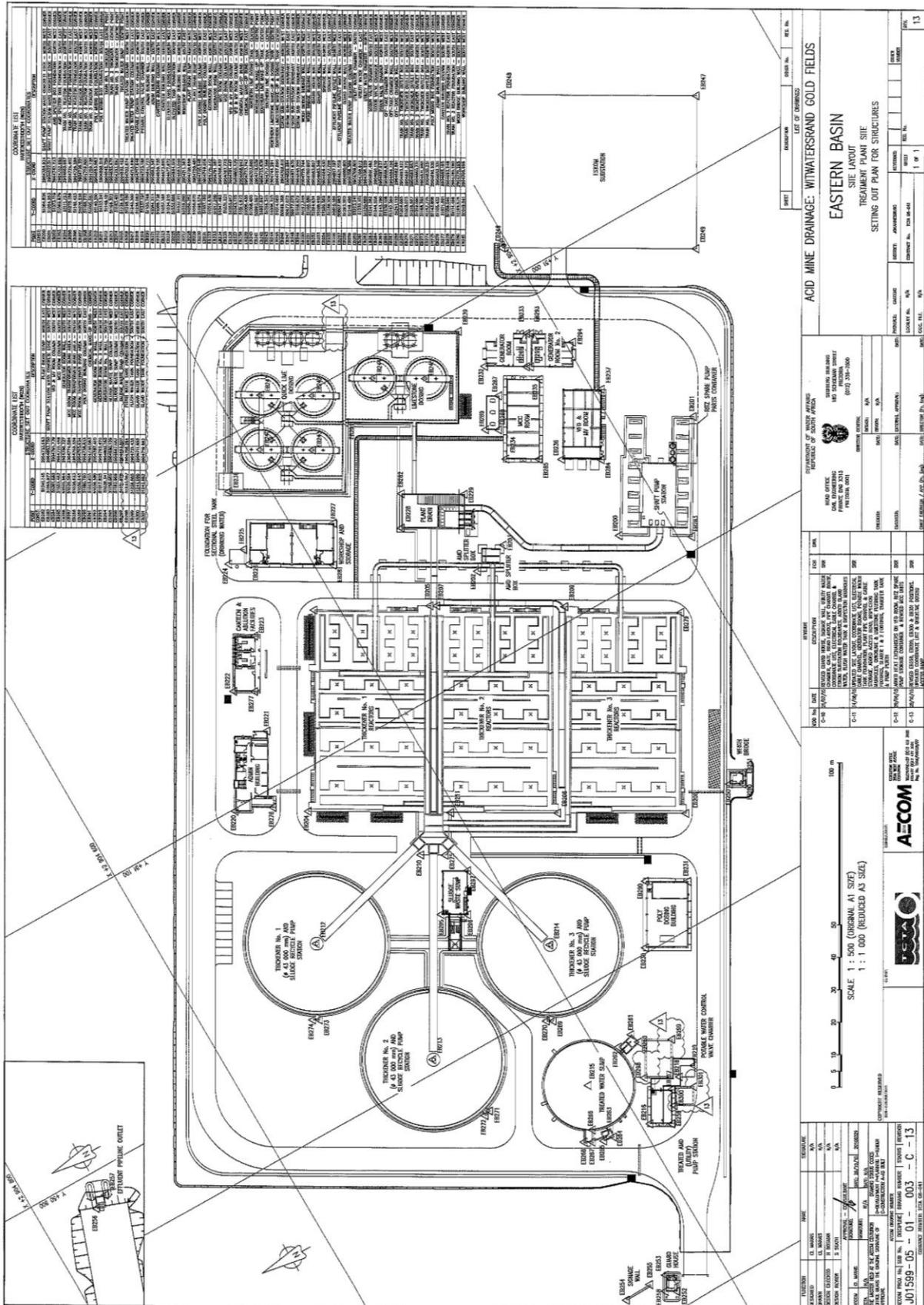


Figure 3.4 Engineering drawing of the site layout of the DWS Eastern Basin Water Treatment Plant.

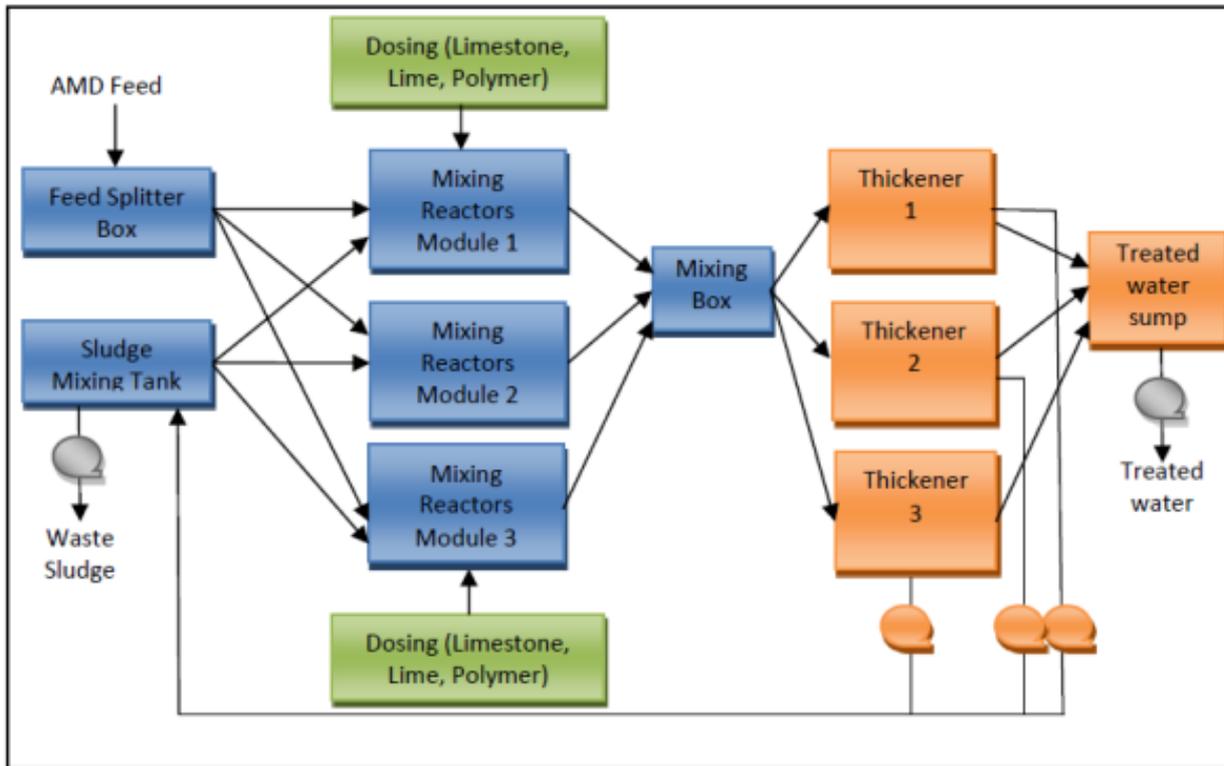


Figure 3.5 Simplified process flow diagram of the DWS Eastern Basin Water Treatment Plant.

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

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 (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).

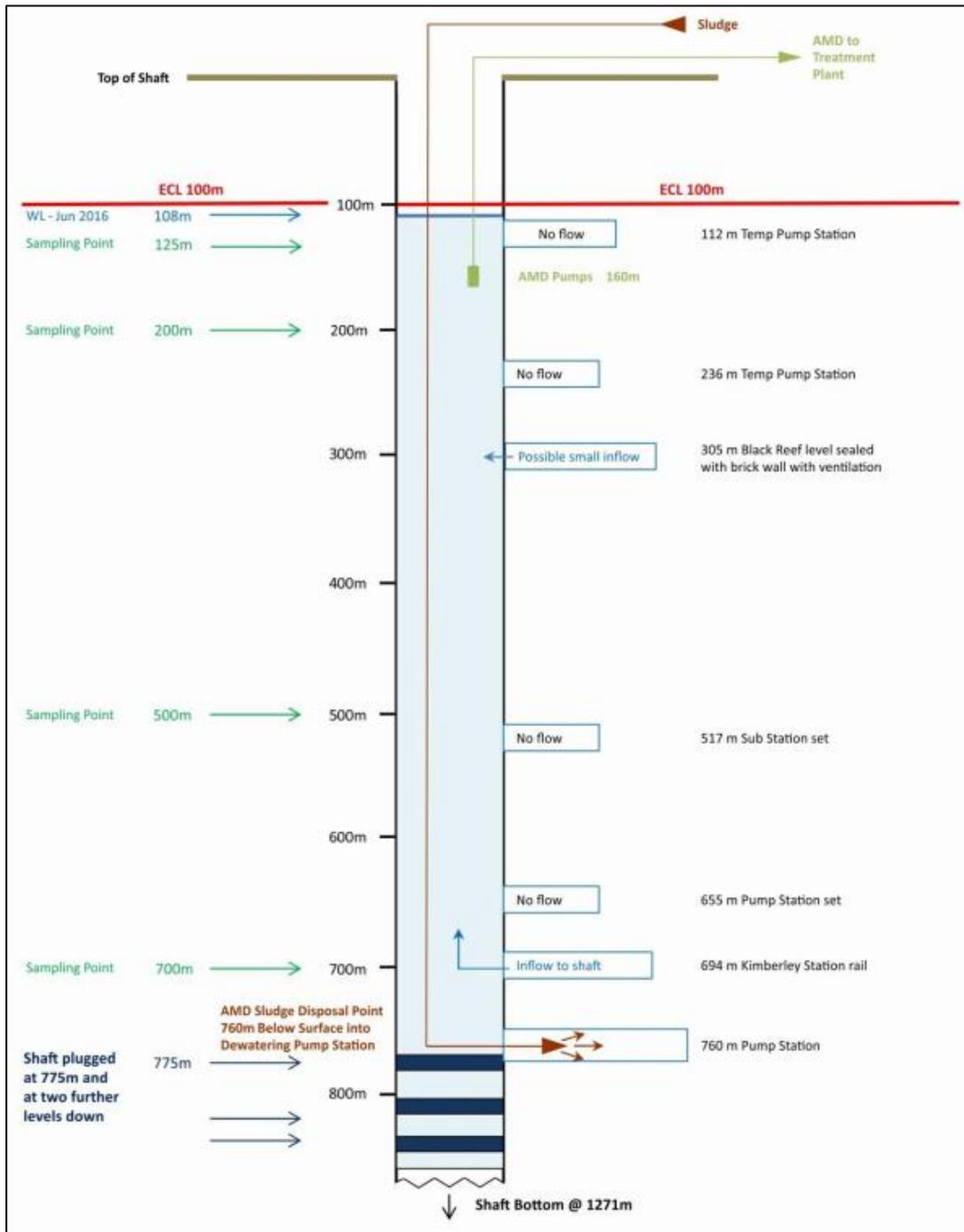


Figure 3.7 Schematic diagram of the Grootvlei No. 3 Shaft, showing the current sludge disposal point at 760 m below the surface into a submerged dewatering pump station (Exigo Sustainability, 2017a).

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 ± 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 ± 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.

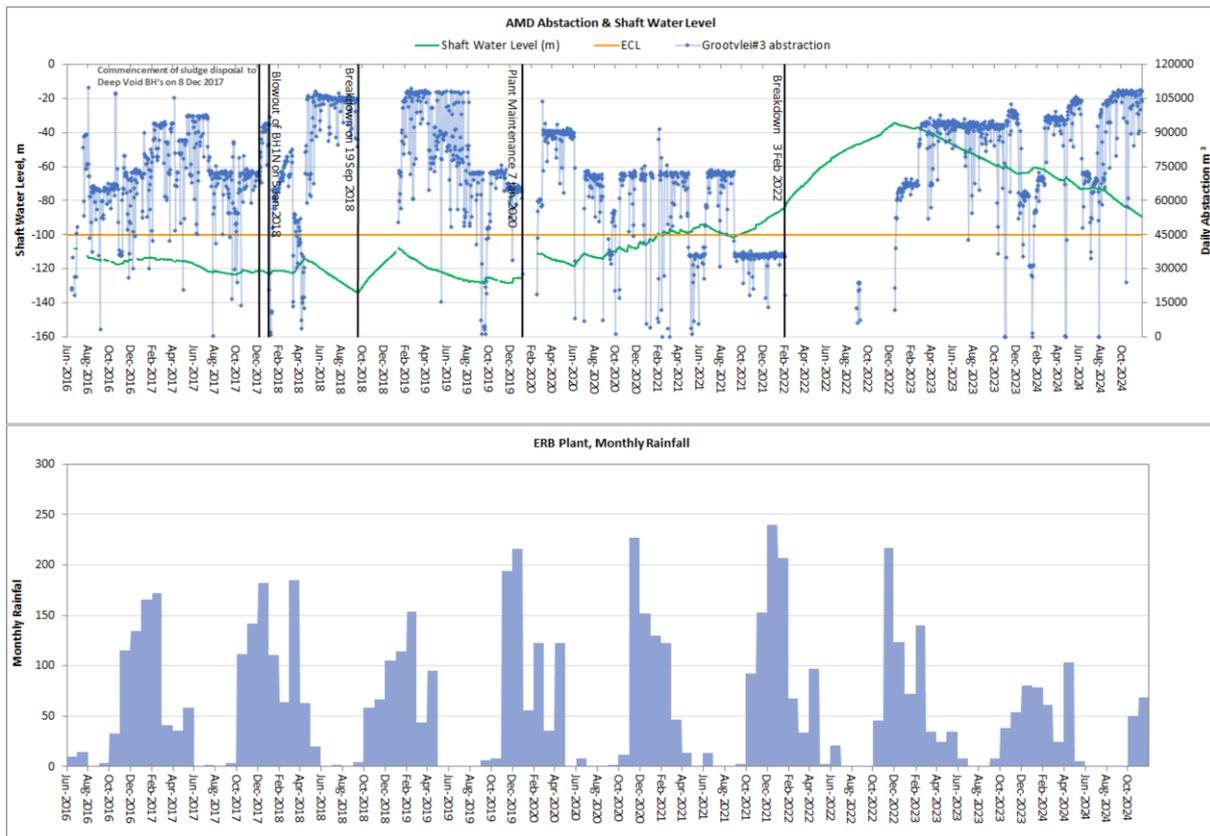


Figure 3.12 The sludge disposal locations, sludge disposal volumes, and the AMD water abstracted volume observed between December 2017 and December 2024 (Artesium, 2024a).

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.

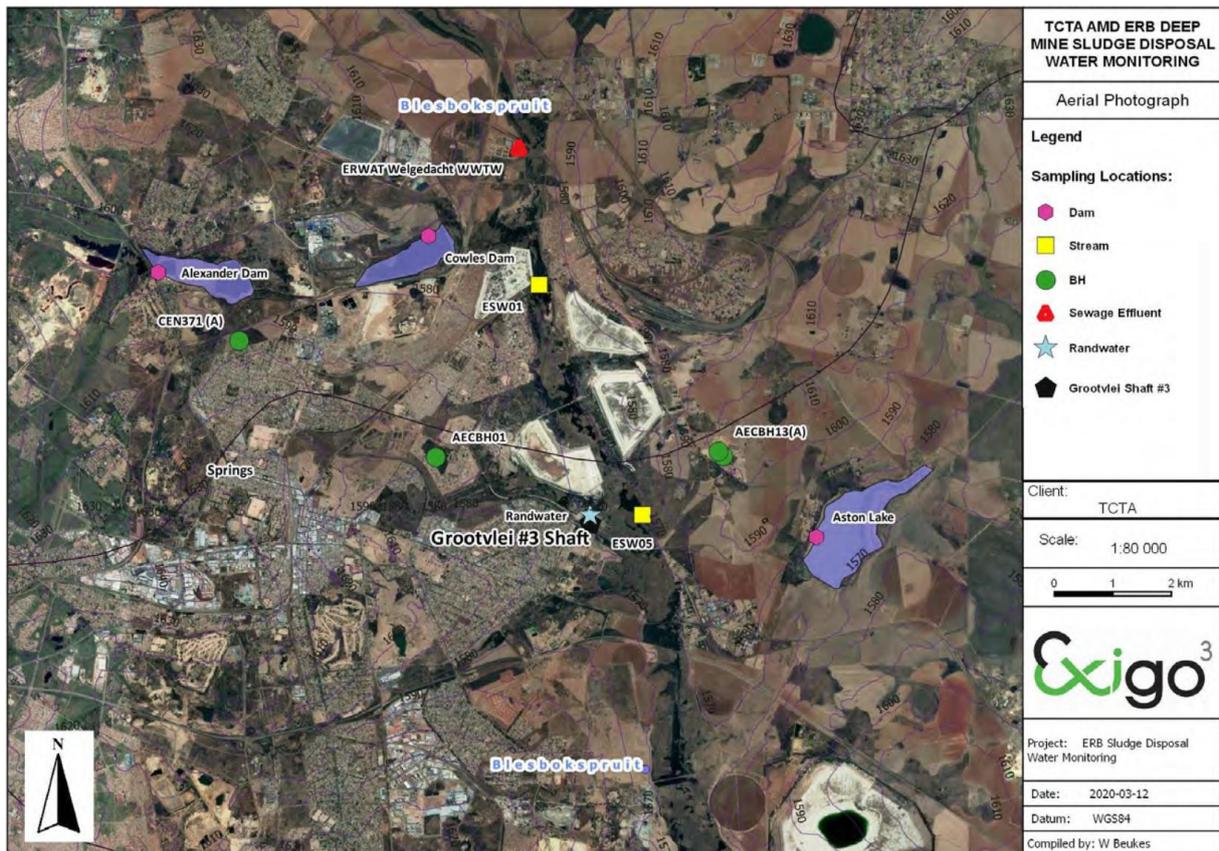


Figure 3.13 Locality map showing the water monitoring locations for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations (Exigo Sustainability, 2020).

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.

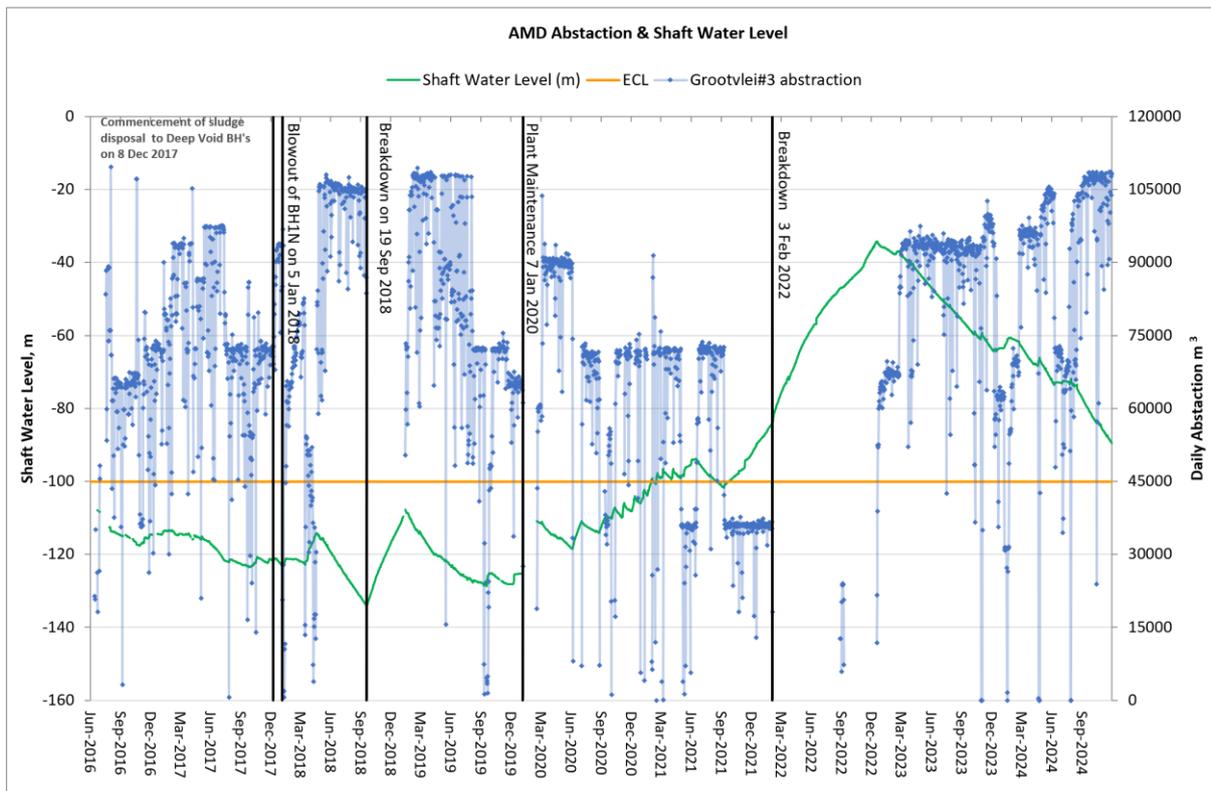


Figure 3.14 the ERB mine void water level relative to the Environmental Critical Level (ECL) and shallow borehole water levels (Artesium, 2024a).

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):

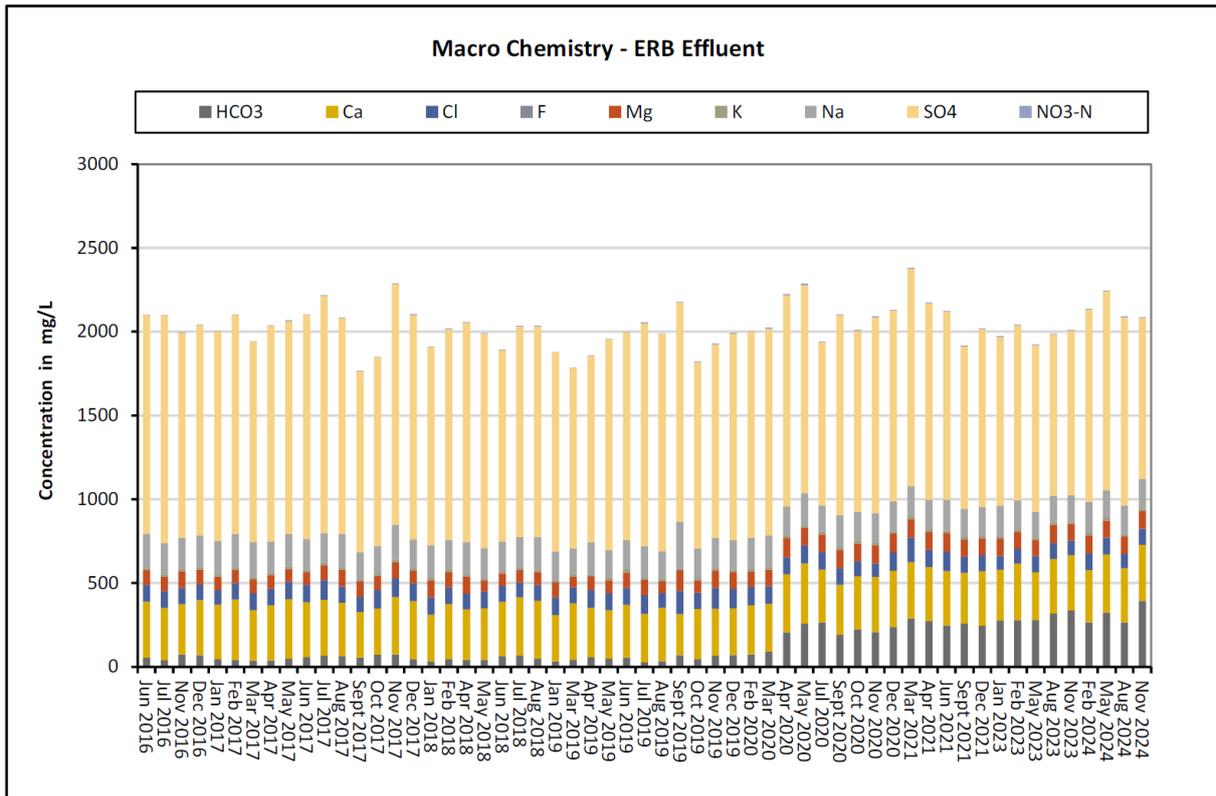


Figure 3.15 Macro chemistry results for the ERB Effluent water for the period 2016 to 2024 (Artesium, 2024a).

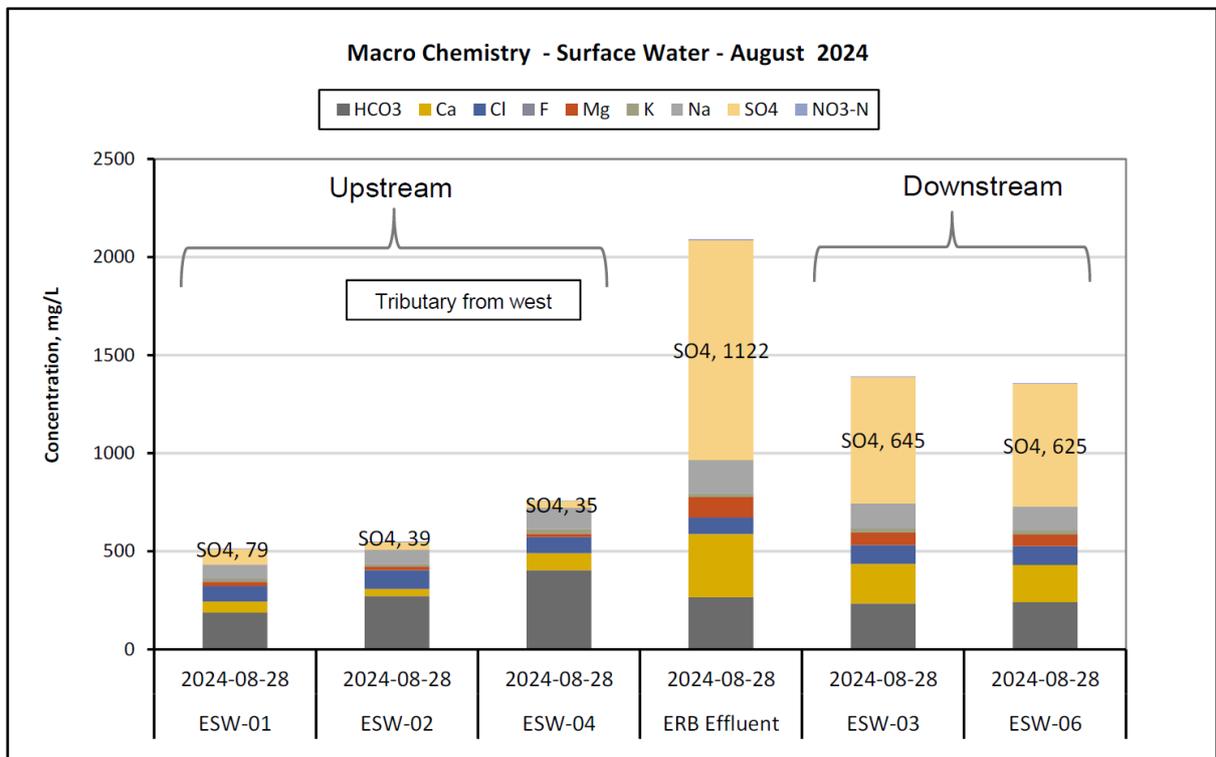


Figure 3.16 Macro chemistry results for the surface water monitoring points in August 2024 (Artesium, 2024a).

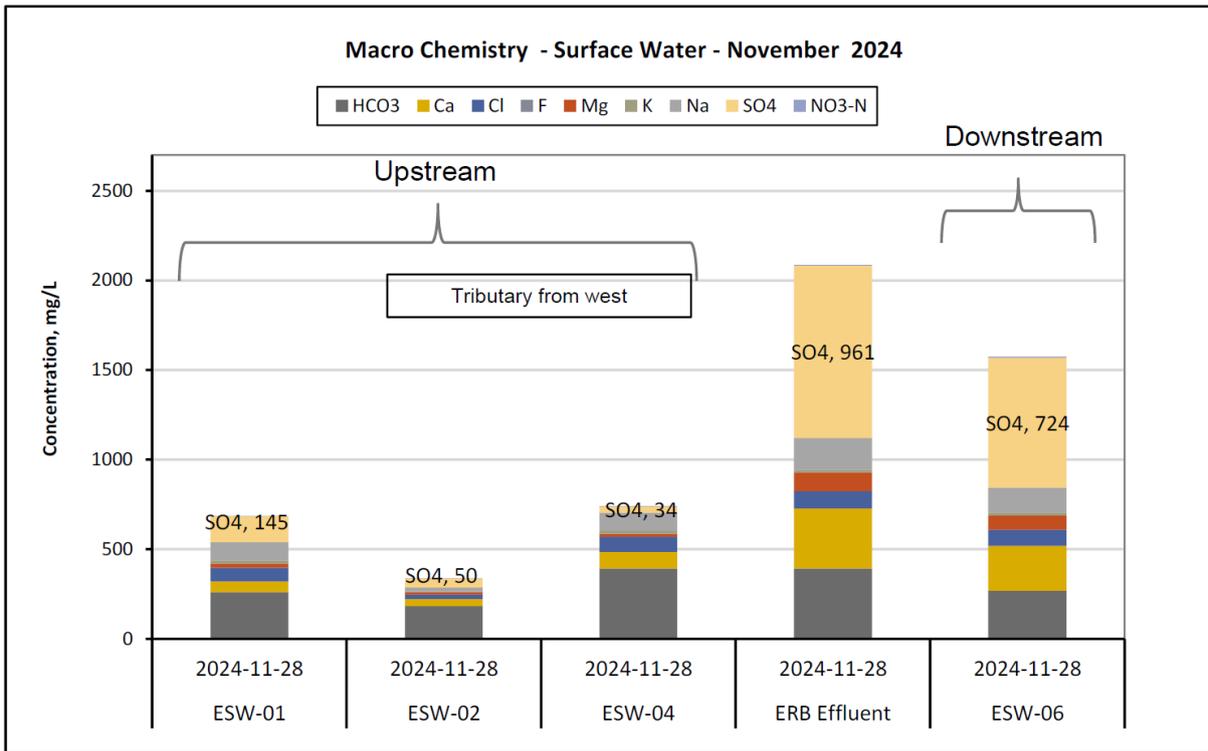


Figure 3.17 Macro chemistry results for the surface water monitoring points in November 2024 (Artesium, 2024a).

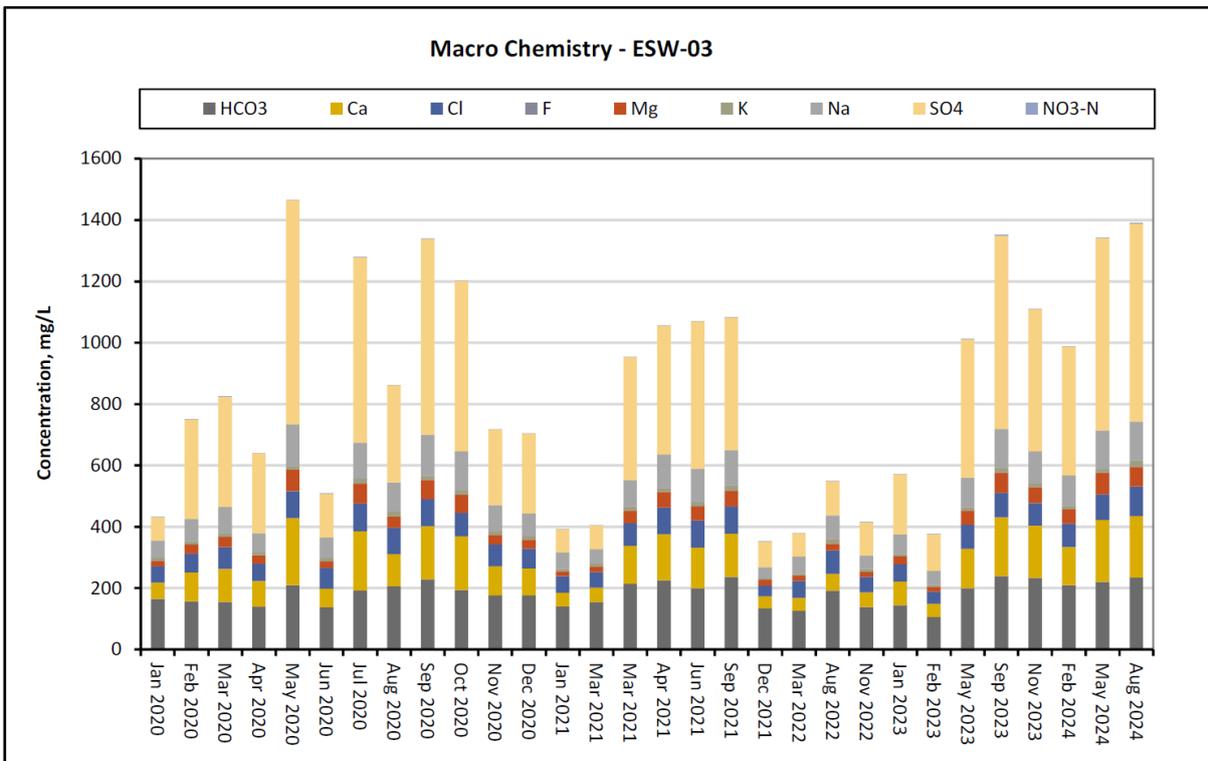


Figure 3.18 Macro chemistry results for ESW-03 for the monitoring period 2020 to 2024 (Artesium, 2024a).

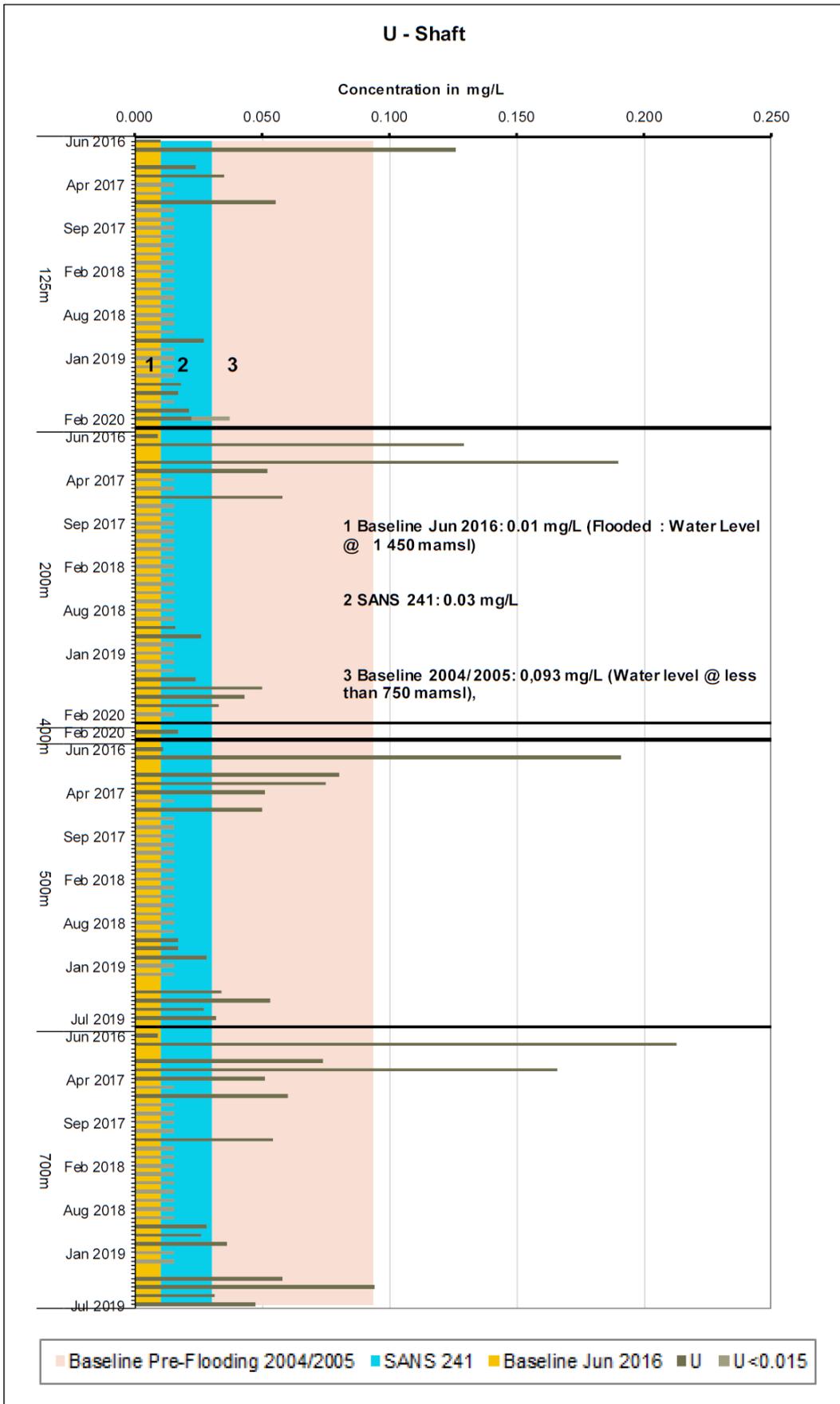


Figure 3.19 The Uranium concentration (in mg.L⁻¹) as observed between June 2016 and February 2020 at 4 depths in the Grootvlei No. 3 Shaft (Exigo Sustainability, 2020).

- After an average uranium concentration of 0.056 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 mg.L^{-1} exceeded the SANS 241 drinking water limit of 0.03 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 mg.L^{-1} to 0.036 mg.L^{-1} . The concentration of one sample (0.036 mg.L^{-1} taken at 700 m during December 2018) exceeded the SANS 241 (2015) limit of 0.03 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 mg.L^{-1} at 125 m to 0.094 mg.L^{-1} at 700 m during May 2019. A Uranium concentration of 0.047 mg.L^{-1} and 0.031 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 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 (mg.L^{-1}), but except for 2 AMD feed samples in March 2017 (0.049 mg.L^{-1}) and April 2017 (0.47 mg.L^{-1}) all available Uranium results are below 0.015 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 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 mg.L^{-1} .

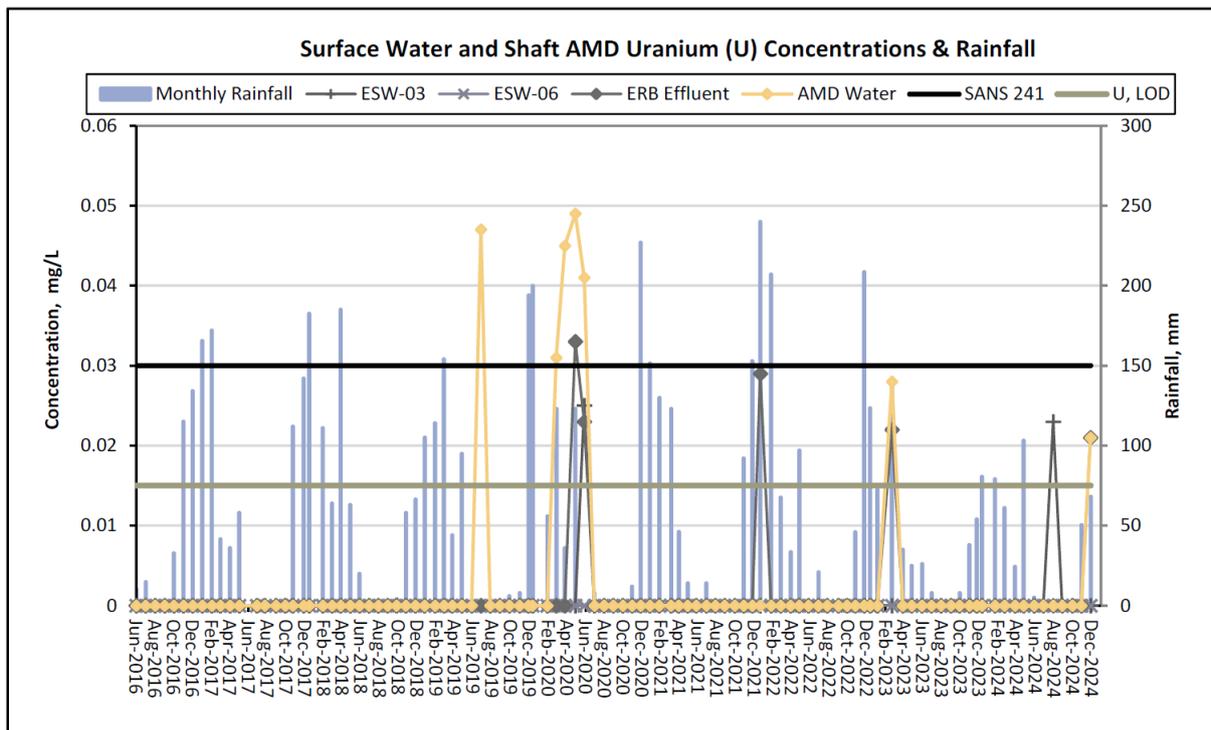


Figure 3.20 The surface water and AMD water Uranium (U) concentrations for the monitoring period 2016 to 2024 (Artesium, 2024a).

3.5.8 Shallow Aquifer and Surface Water Monitoring

Monitoring results indicated that no uranium was measured above the detection limit of 0.015 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 ± 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 km^3 (207 billion 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 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.

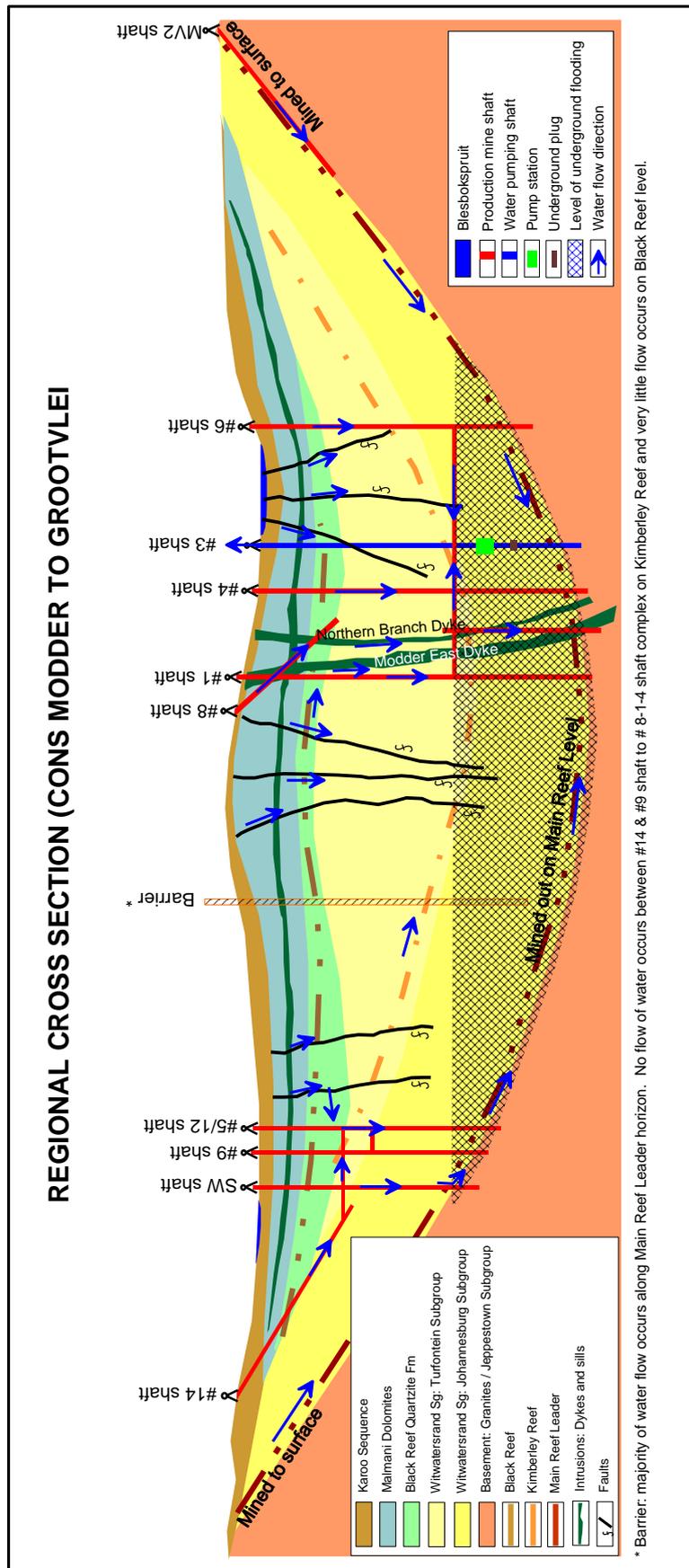


Figure 3.21 Schematic geological cross-section of the Eastern Basin indicating ingress of water into the mining basin.



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



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

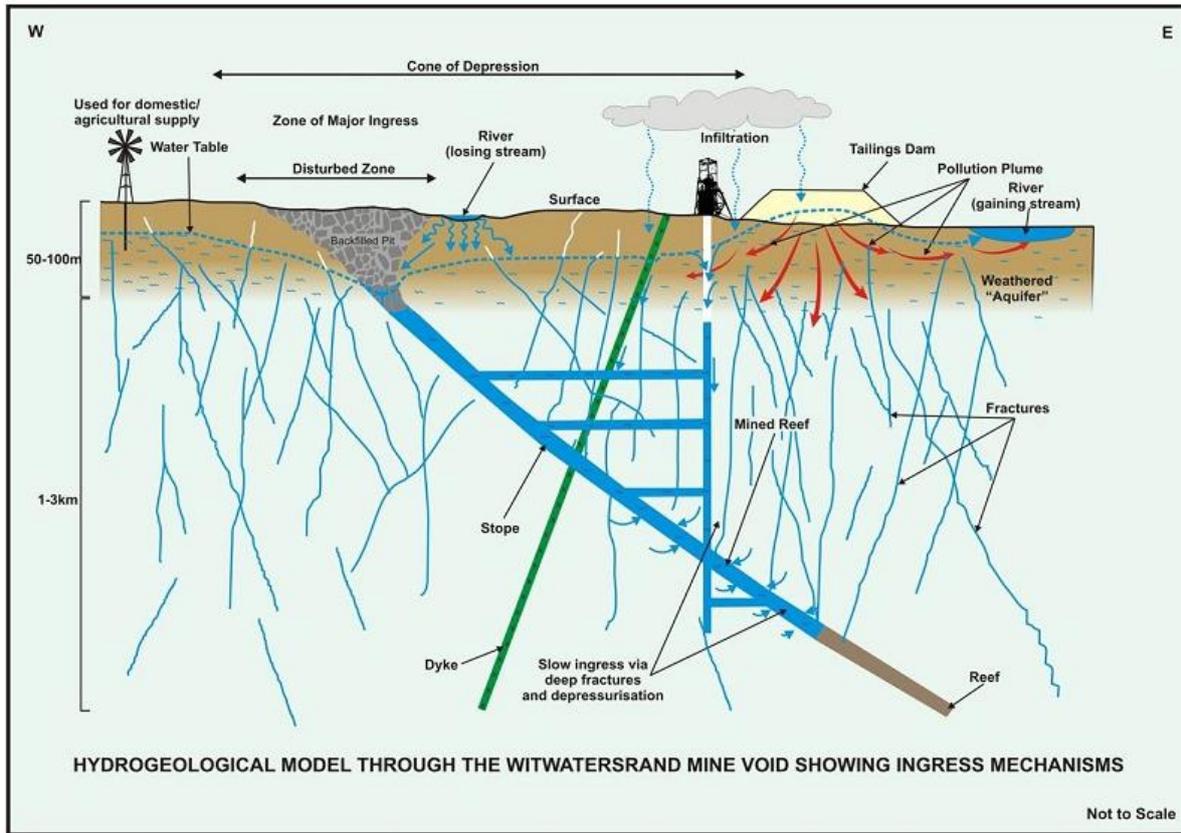


Figure 3.24 Graphical representation of a mine void and underground connectivity (DWS Website: <https://www.dwaf.gov.za/Projects/AMDFSLTS/default.aspx>).

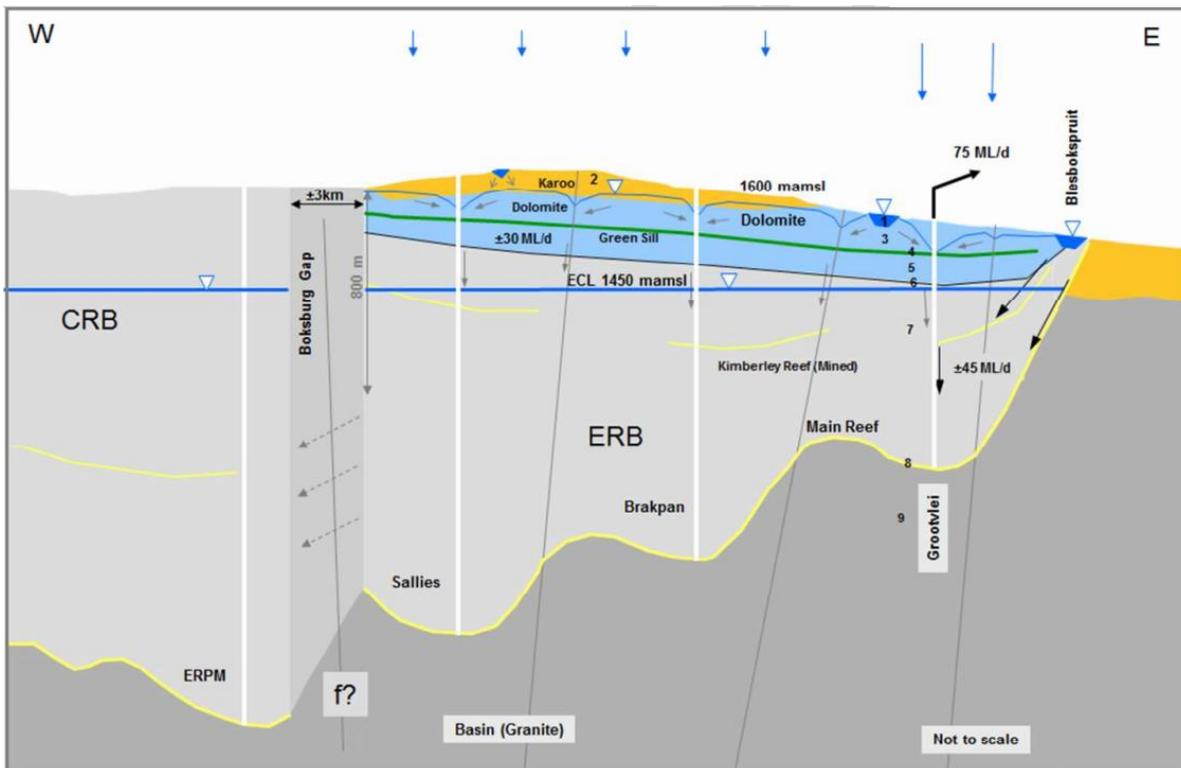


Figure 3.25 The conceptual model for the Eastern Basin used as the basis for the initial risk assessment performed by Exigo Sustainability (2017b).

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).

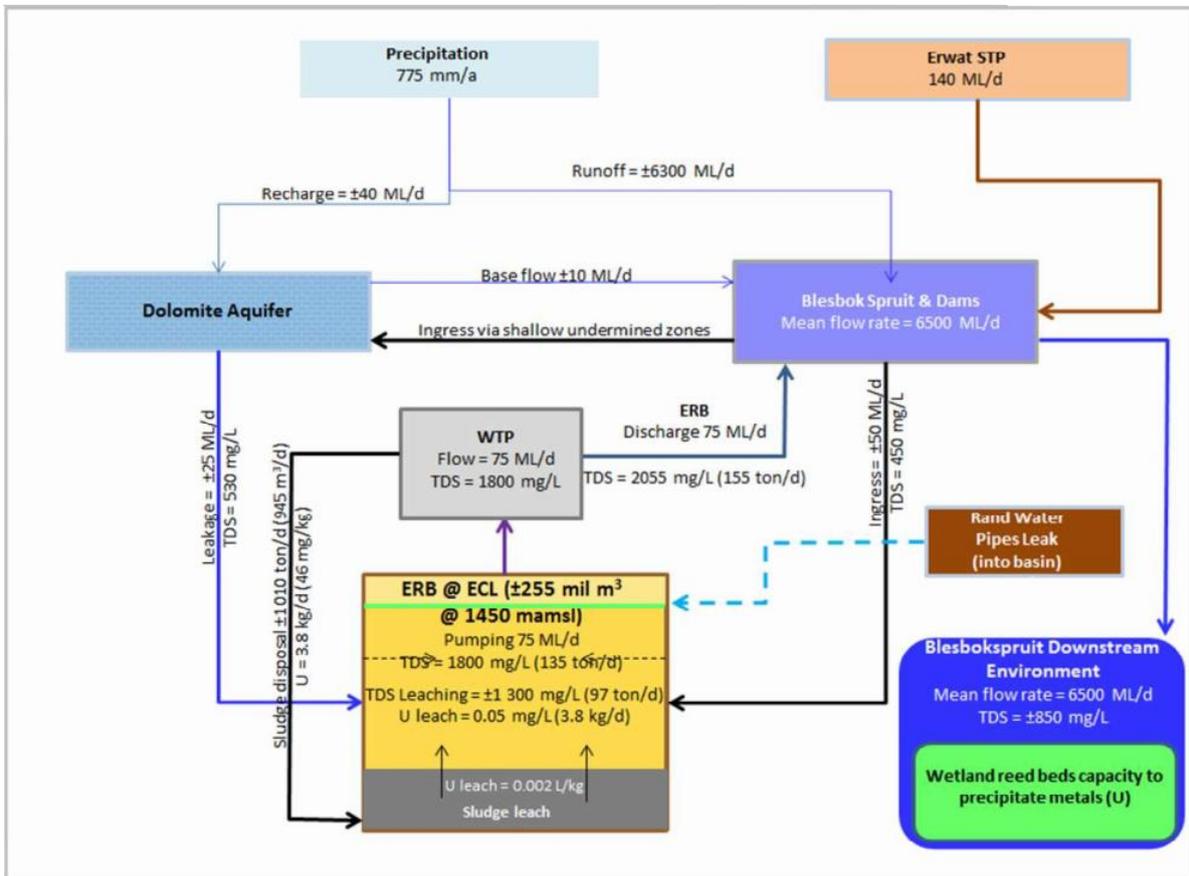


Figure 3.26 The resulting conceptual flow and mass flux system model developed for the Eastern Basin (Exigo Sustainability, 2017b).

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.

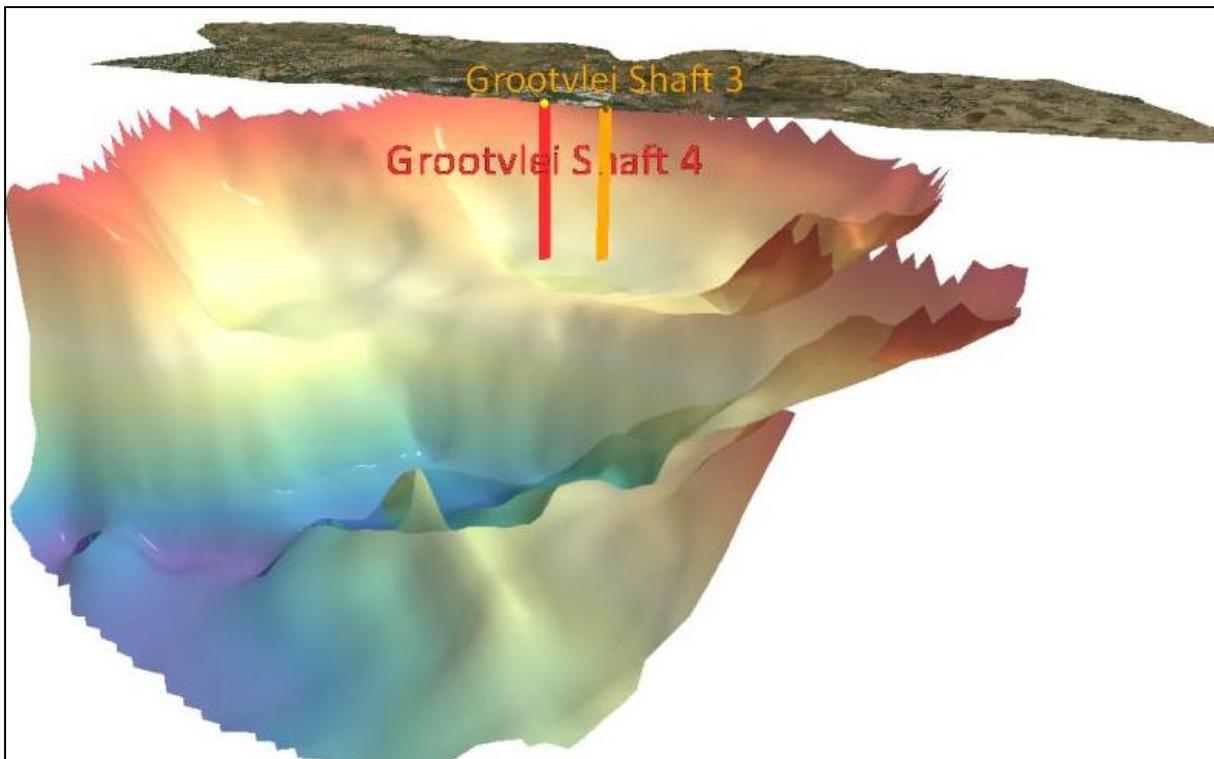


Figure 3.27 Three-dimensional view of the East Rand Basin with the Grootvlei Basin where water is abstracted (Grootvlei No. 3 Shaft) and where the disposal will take place (Grootvlei No. 4 Shaft) (Artesium, 2024b).

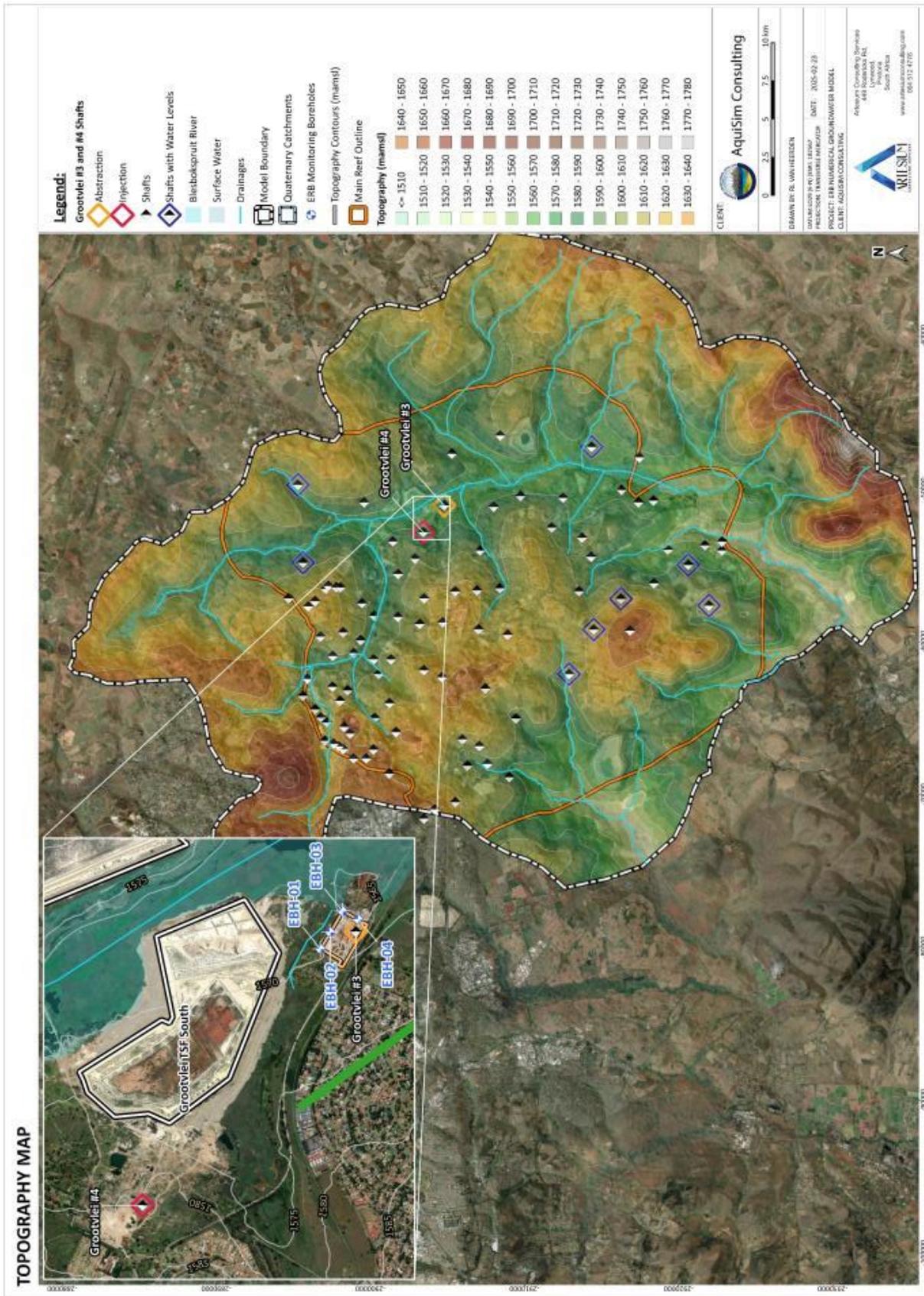


Figure 3.28 The regional extent of the numerical model developed for the ERB sludge disposal operation, overlaid on the topography of the area (Artesium, 2024b).

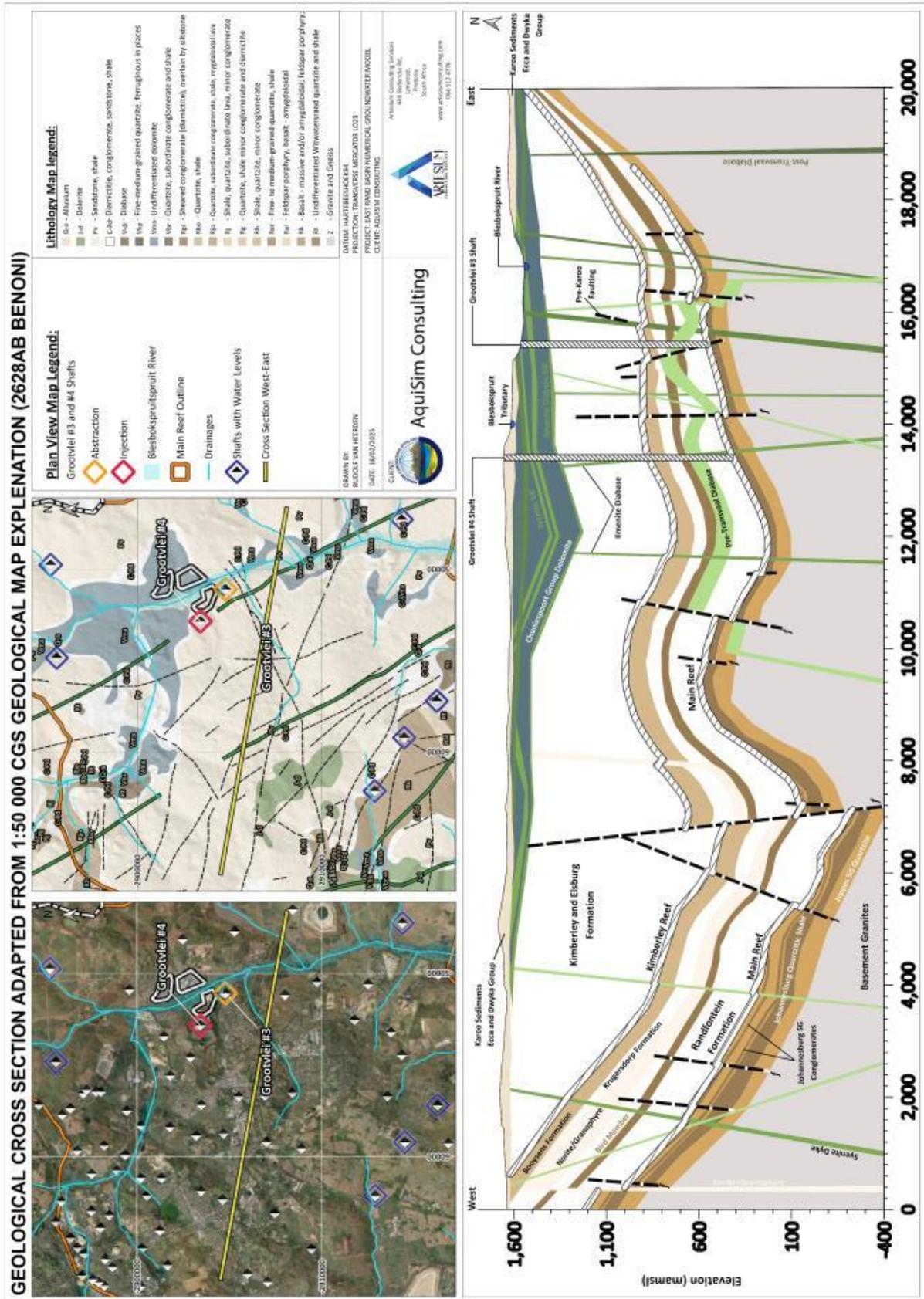


Figure 3.29 The geological cross-section through the modelling domain, indicating the location of the Grootvlei No. 3 Shaft and Grootvlei No. 4 Shaft relative to the different underlying formations, reefs and geological structures (Artesium, 2024b).

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.

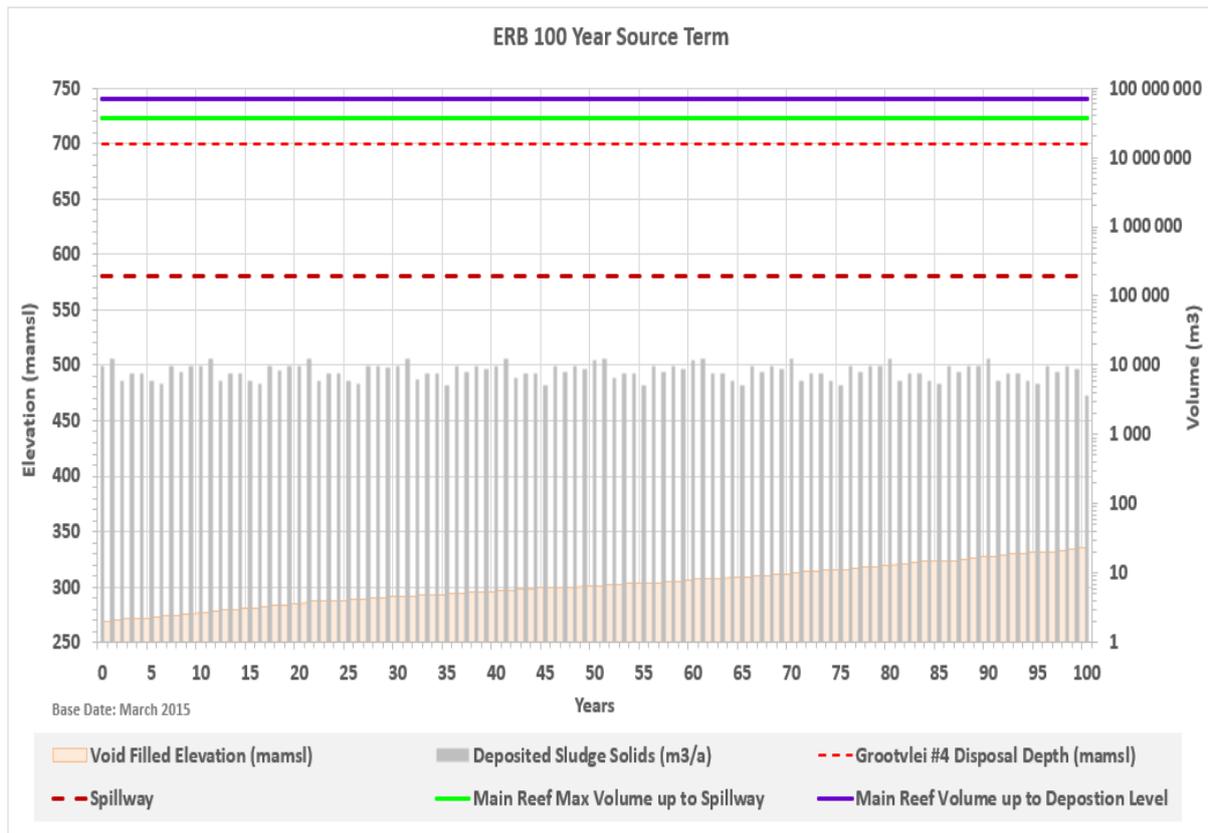


Figure 3.30 Graphical representation of the ERB sludge disposal source term for 100 years (Artesium, 2024b).

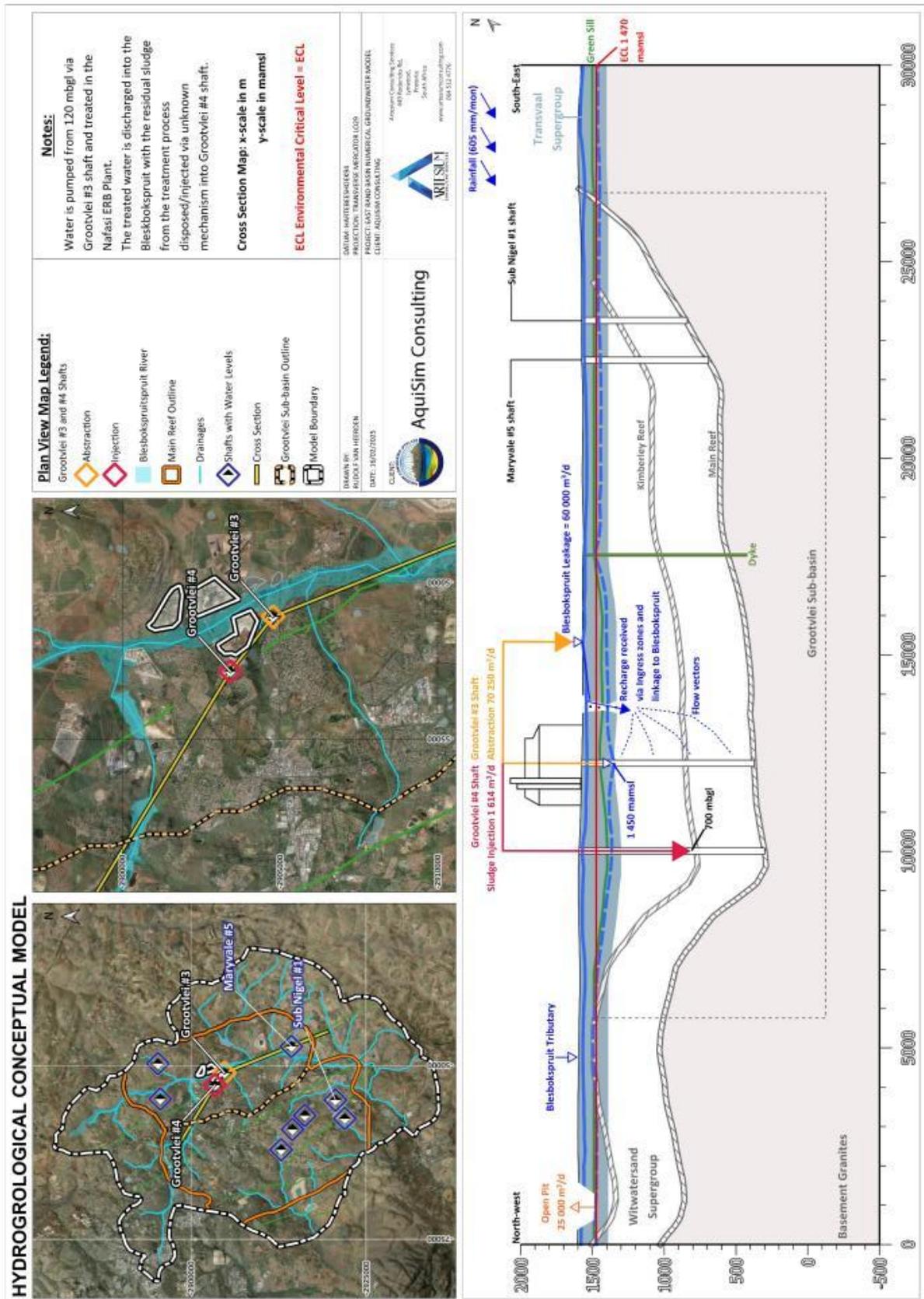


Figure 3.31 The hydrogeological conceptual model, which shows the different components relevant to evaluating the ERB Water Treatment Plant and Sludge Disposal Operations (Artesium, 2024b).

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 m³ for the Main Reef, with a 70% void volume (i.e., 181,956,655 m³);
- The Main Reef filled to a level of 276 mamsl (sludge solids deposited = 616 440 m³); 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.

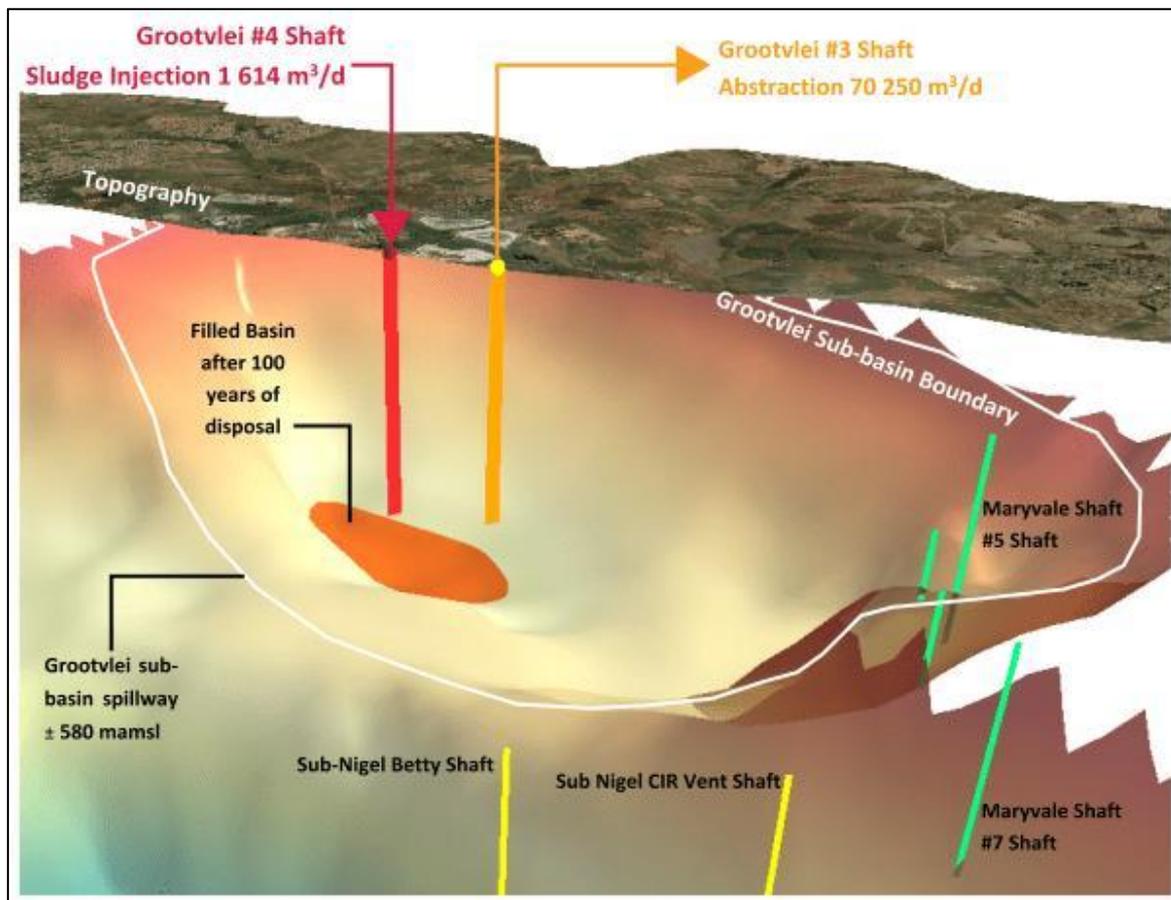


Figure 3.32 A three-dimensional representation of the total volume of sludge relative to the Grootvlei Sub-basin, after 100 years of sludge deposition into the Grootvlei No. 4 Shaft (Artesium, 2024b).

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).

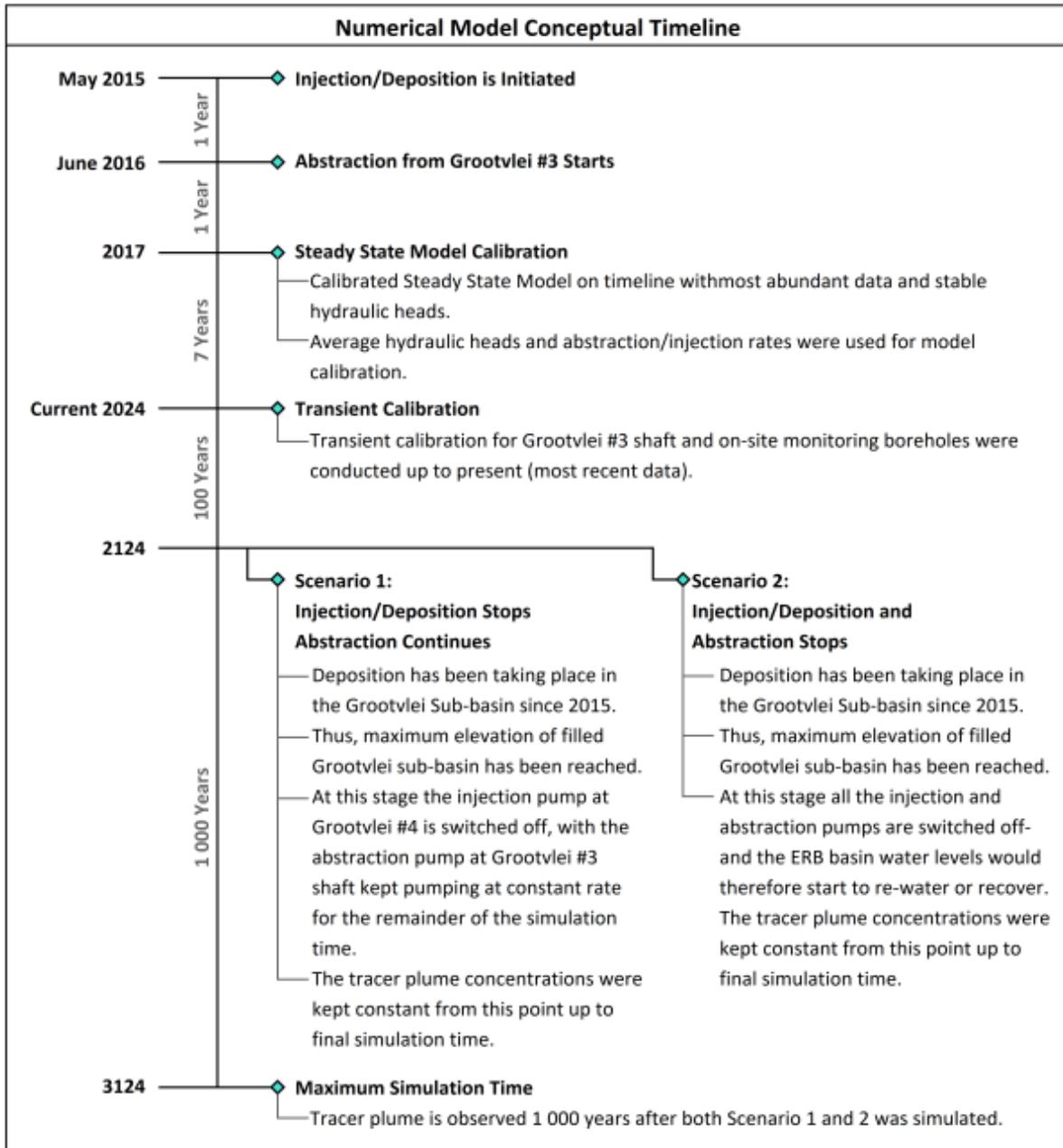


Figure 3.33 The timeline and scenarios that were considered to evaluate the ERB sludge disposal operations (Artesium, 2024b).

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⁻¹. 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⁻¹. 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⁻¹.

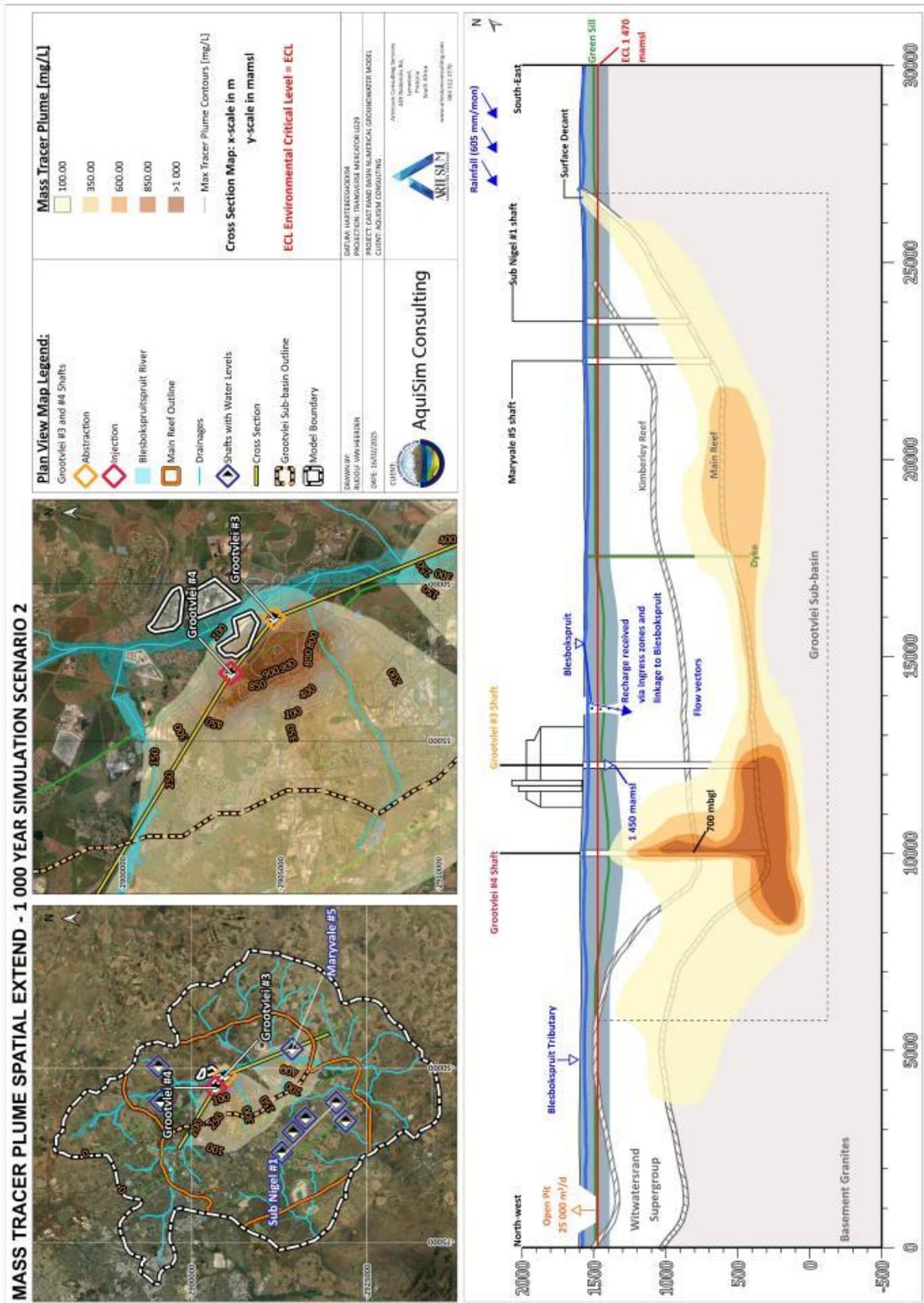


Figure 3.35 The spatial distribution of a non-reactive mass tracer plume for Scenario 2 after 1,000 years assuming an initial concentration of 1,000 mg.L⁻¹ (Artesium, 2024b).

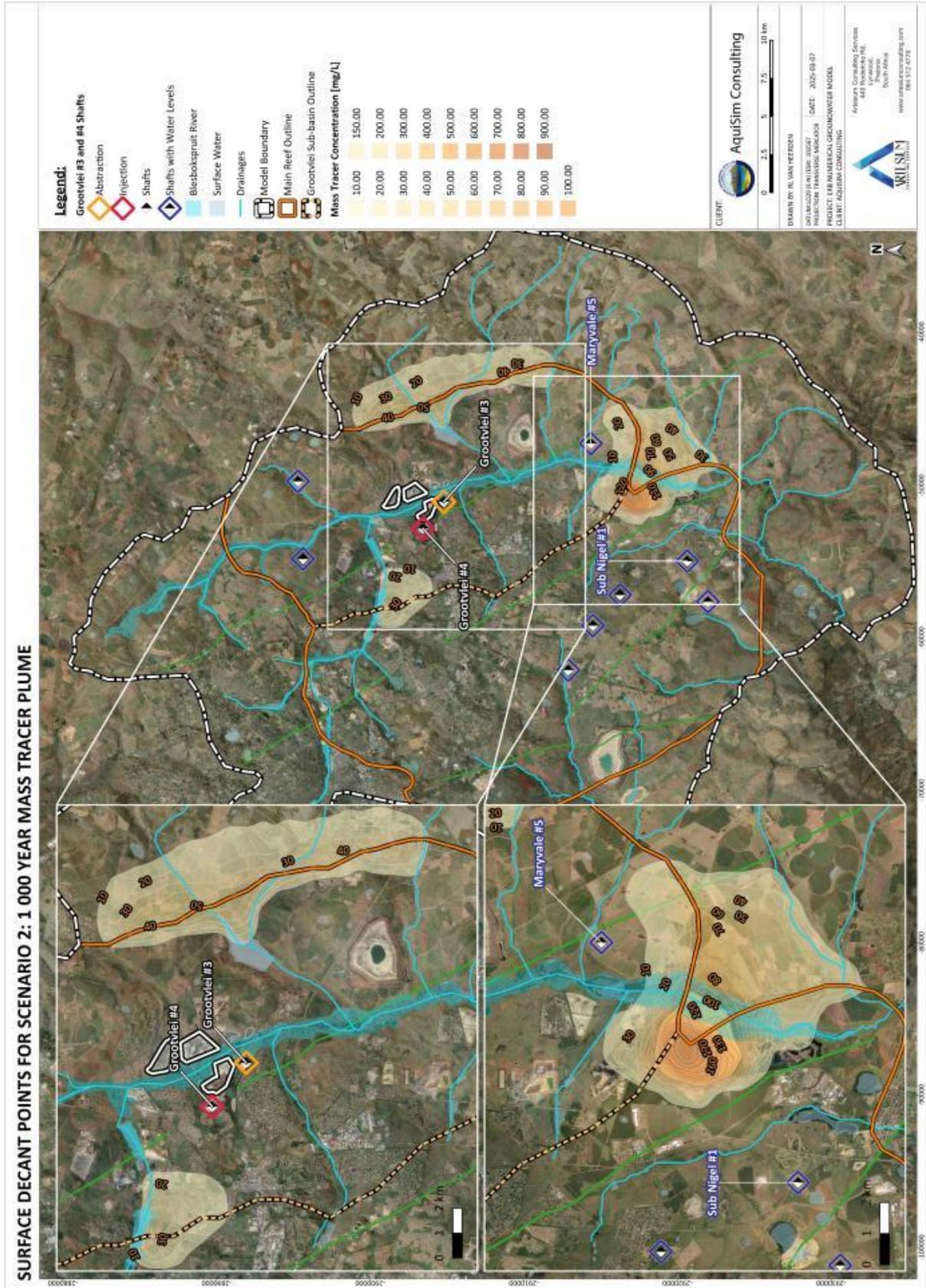


Figure 3.36 Surface decant points for Scenario 2 after 1,000 years, for tracer plume concentrations of at least 10 mg.L⁻¹ (Artesium, 2024b).

3.7.6 Discussion of Results

The current volume of solid sludge deposited is 75,944 m³ (999 tons), assuming a density of 1,316 kg.m⁻³, with the main reef void volume calculated at 181 mil m³. 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

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⁻¹ (or 0.5 Bq.g⁻¹), 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 ⁻¹)	
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 ⁻¹)
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 ⁻¹)	
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⁻¹, while the Ra-226 is about 350 mBq.L⁻¹.

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 ⁻¹)	
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 90th 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 90th 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 ⁻²				Dose Rate μSv.h ⁻¹	
		α	β/Y	Y	β	Contact	1 Meter
Claire Office	Background	0.01	0.32	0.24	0.08	0.23	0.25
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 ⁻²				Dose Rate μSv.h ⁻¹	
		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 ⁻²				Dose Rate μSv.h ⁻¹	
	α	β/Y	Y	β	Contact	1 Meter
Background	0.01	0.32	0.24	0.08	0.23	0.25
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 th 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 ⁻²				Dose Rate μSv.h ⁻¹	
		α	β/Y	Y	β	1 Meter	Contact
Background	Christopher Office (Background)	0.00	0.56	0.49	0.07	0.10	0.12
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 ⁻²				Dose Rate μSv.h ⁻¹	
		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 ⁻²				Dose Rate μSv.h ⁻¹	
		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 ⁻²				Dose Rate μSv.h ⁻¹	
		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 ⁻²				Dose Rate μSv.h ⁻¹	
	α	β/γ	γ	β	Contact	1 Meter
Background	0.00	0.56	0.49	0.07	0.10	0.12
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 th 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.

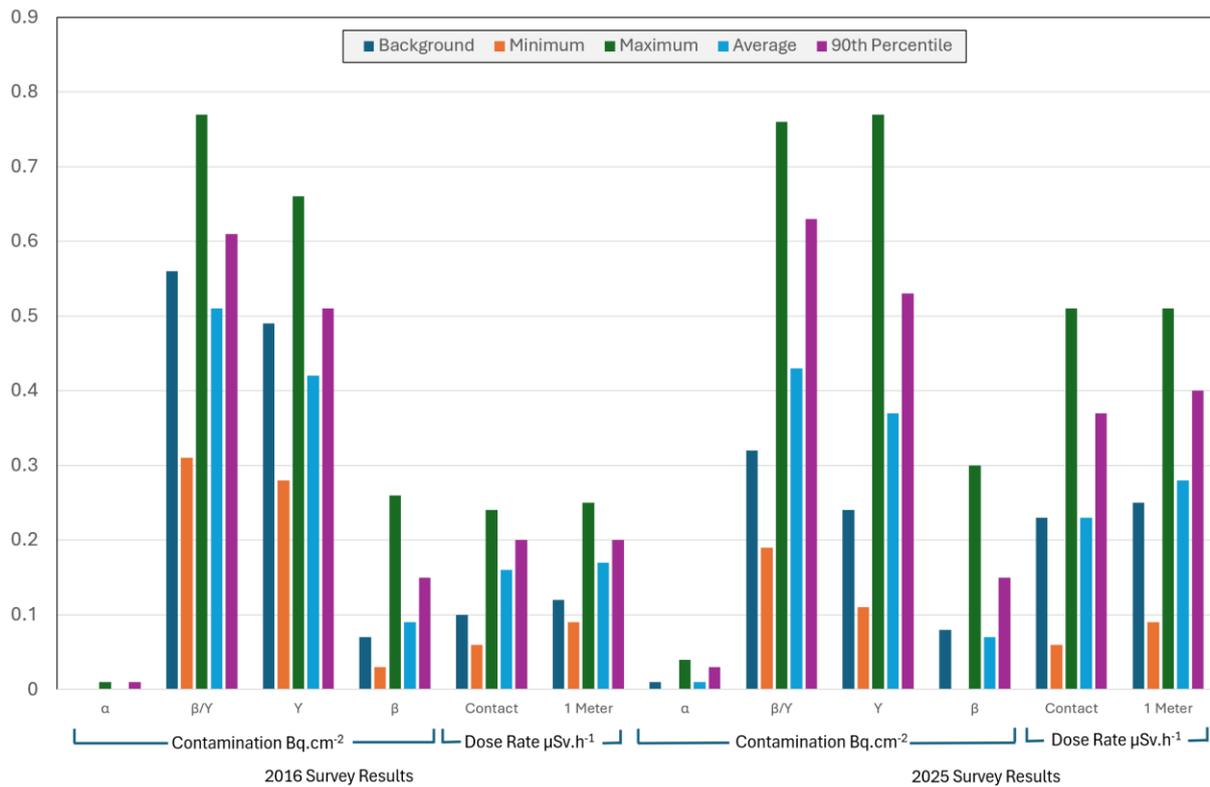


Figure 3.42 A graphical comparison between the summary of the results presented in Table 3.9 and Table 3.11.

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⁻¹) 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

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

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 ⁻¹)					
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

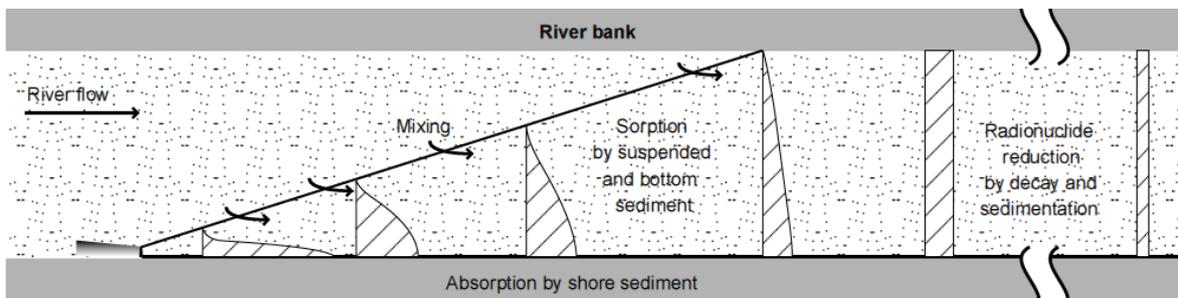


Figure 4.1 Processes affecting the movement of radionuclides from the point of discharge into a surface water body (IAEA, 2001).

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.

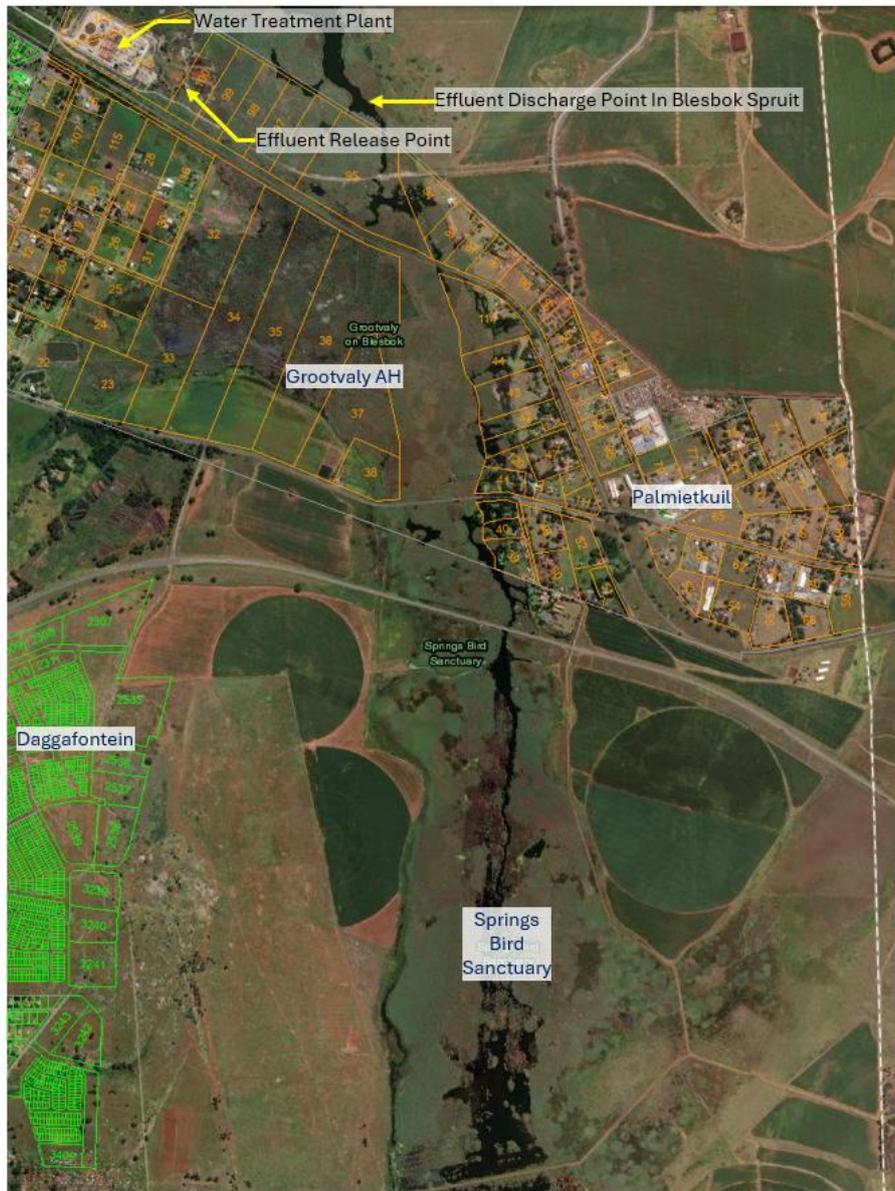


Figure 4.2 Locality map of the areas downstream of the Water Treatment Plant, showing the current land use conditions along the Blesbok Spruit.

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 ⁻¹				
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 ⁻¹	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 $\mu\text{Sv}\cdot\text{year}^{-1}$.

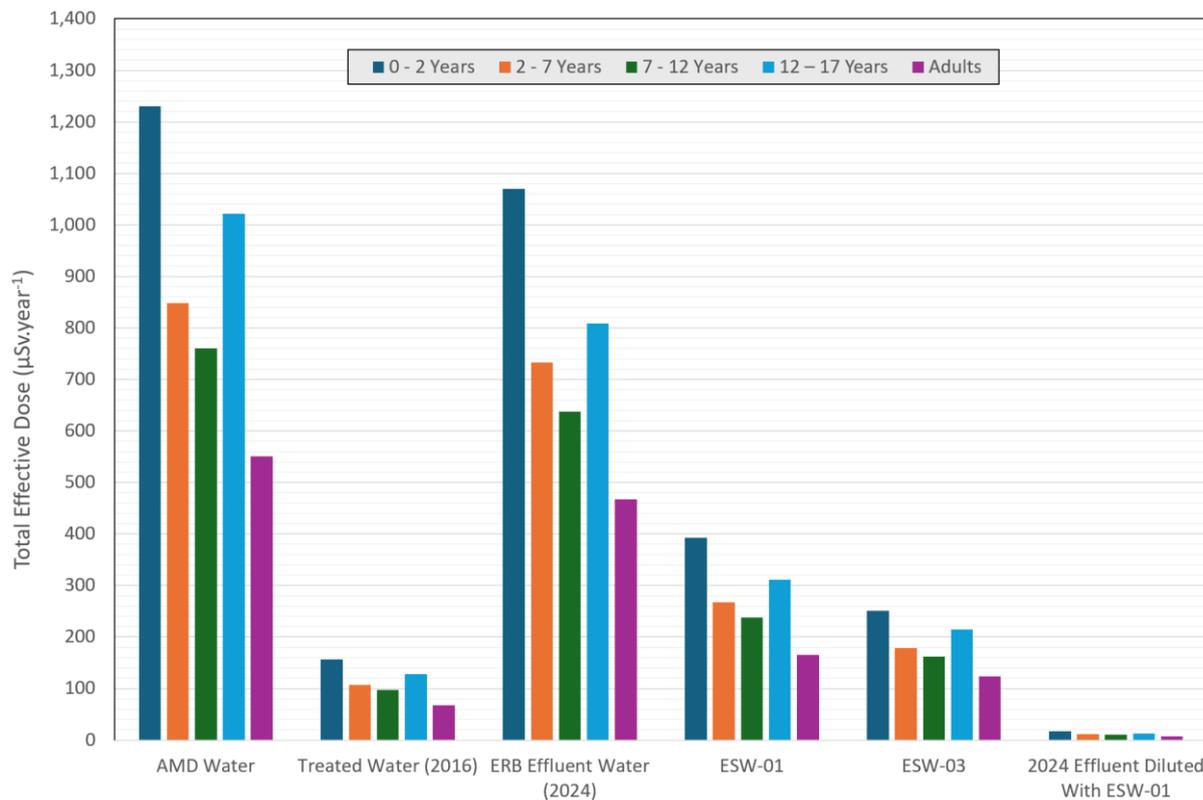


Figure 4.3 The total effective dose, assuming an agricultural exposure condition with all relevant exposure routes identified in NNR (2013a) included.

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

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⁻¹). Transfer and loss rates are represented by λ . λ_N is the decay constant for radionuclide N (year⁻¹) and λ_{ji} and λ_{ij} are transfer coefficients (year⁻¹) 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 tool³ (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.

³ 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.

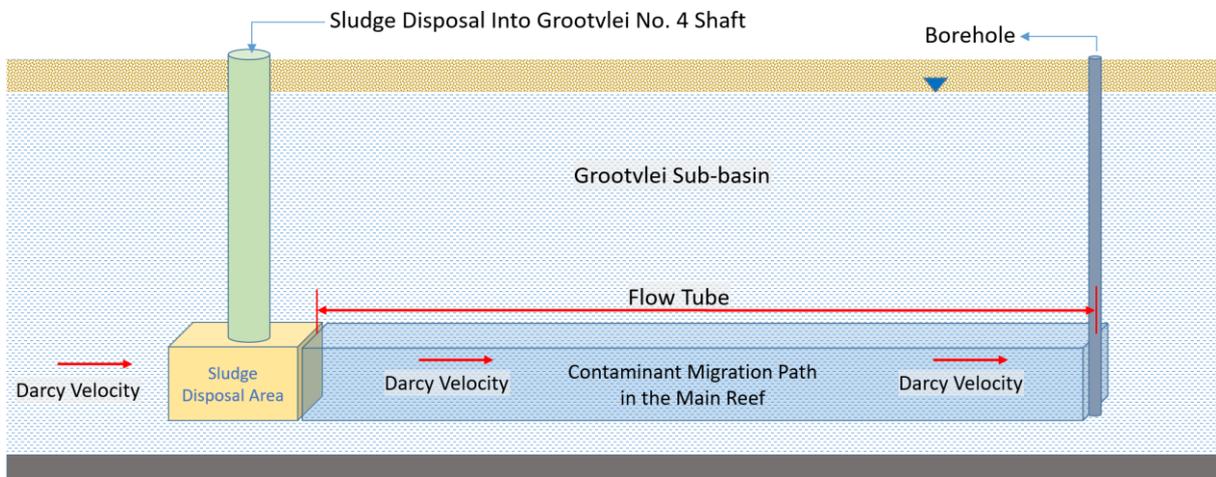


Figure 4.4 Schematic diagram that illustrates the conceptual model adopted for the System Level model.

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 ($\text{Bq}\cdot\text{m}^{-3}$).

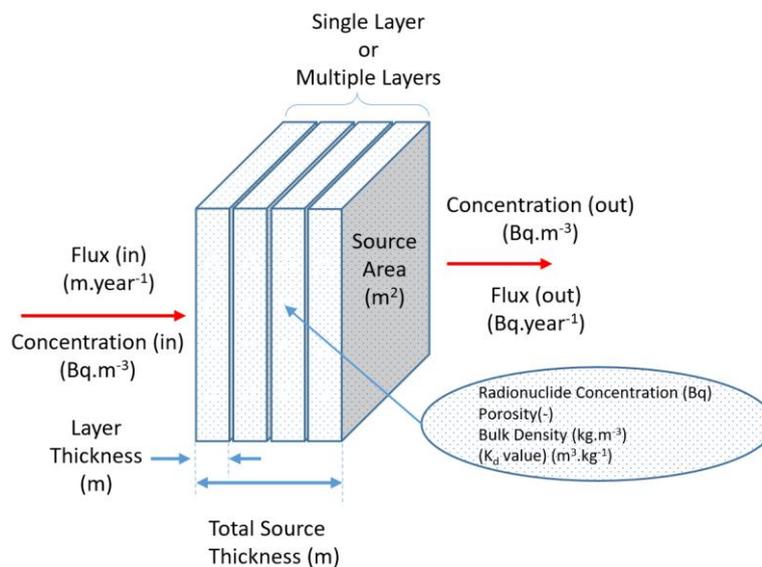


Figure 4.5 Conceptual representation and associated parameter values for the source term model.

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 (λ_{Adv} , in 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 ($\text{m}\cdot\text{year}^{-1}$), ϵ_{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

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

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 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

in the flow tube originating from the source, while the other part of the borehole intersects uncontaminated "background" groundwater. Figure 4.7 is a simplified representation of the borehole abstraction module and the most important parameters.

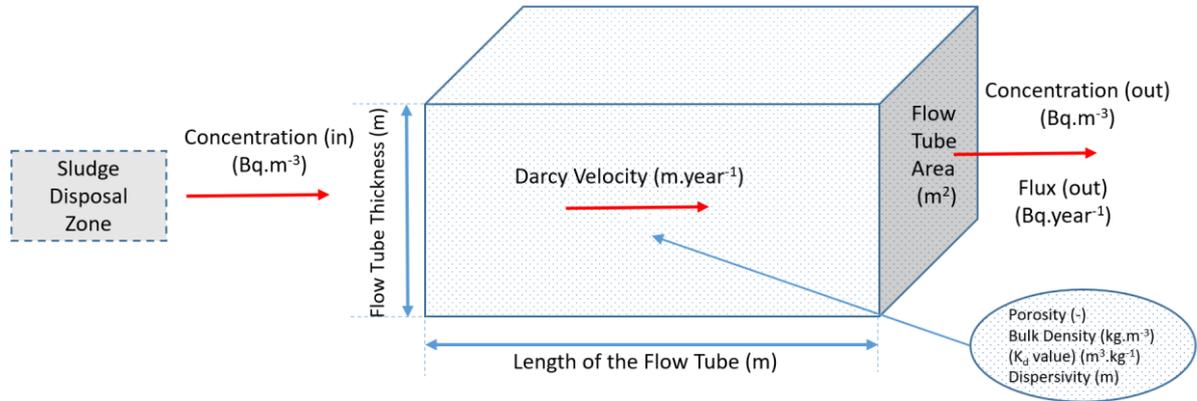


Figure 4.6 Conceptual representation and associated parameter values for the aquifer (saturated zone) model.

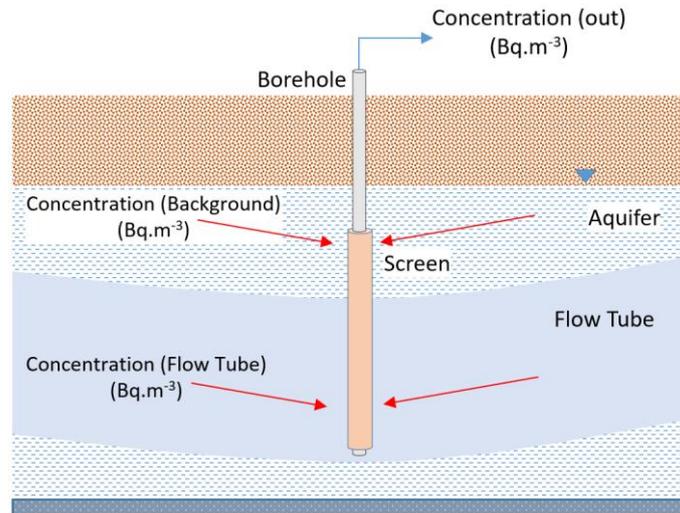


Figure 4.7 Conceptual representation and associated parameter values for the borehole abstraction model.

The concentration of the water abstracted from the borehole is simplistically taken as the sum of the flow tube concentration (Bq.m^{-3}) multiplied by the fraction of the borehole intersecting the plume, and the background concentration (Bq.m^{-3}) multiplied by the fraction intersecting the uncontaminated water. The resulting radionuclide concentration in groundwater extracted from the borehole ($C_{\text{Water}, \text{Bh}, \text{out}}$, in Bq.m^{-3}) is defined as follows:

Equation 6

$$C_{\text{Water}, \text{Bh}, \text{out}} = f_{\text{Bh}} \cdot C_{\text{Water}, \text{FT}, \text{in}} + (1 - f_{\text{Bh}}) \cdot C_{\text{Water}, \text{Bg}, \text{in}}$$

where f_{Bh} is the borehole fraction intersecting contaminated groundwater originating from the contaminated site, $C_{\text{Water}, \text{FT}, \text{in}}$ is the radionuclide concentration flowing in from the flow tube into the borehole (Bq.m^{-3}) and $C_{\text{Water}, \text{Bg}, \text{in}}$ is the radionuclide concentration in background groundwater in the area flowing into the borehole (Bq.m^{-3}). As a conservative assumption, it can be assumed that the whole screen intersects the contaminant plume (i.e., f_{Bh} equals 1). Note that the conceptual representation presented above is conservative. Under site-specific conditions, abstracted groundwater from a borehole will draw water from uncontaminated areas, and the contaminated water will consequently be diluted further.

4.3.6 Parameter Values

Table 3.4 lists the available full spectrum analysis results of two ERB sludge samples, one from 2016 and one more recent sample from 2024. Table 4.4 lists the radionuclide specific activity concentrations derived for the analysis. The secular equilibrium assumptions introduced in Section 2.3.4.3 were applied to those radionuclides for which analysis results were not available in Table 3.4.

Table 4.4 The radionuclide specific activity concentrations for ERB sludge samples and their average, used for the System Level model to evaluate the radiological impact on members of the public.

Radionuclide	2016 Sample	2024 Sample	Average
	Activity Concentration (Bq.kg ⁻¹)		
U-238	503.0	178.0	340.5
U-234	507.0	179.0	343.0
Th-230	507.0	179.0	343.0
Ra-226	538.0	985.0	761.5
Pb-210	538.0	985.0	761.5
Po-210	538.0	985.0	761.5
U-235	23.1	8.2	15.6
Pa-231	23.1	8.2	15.6
Ac-227	23.1	8.2	15.6
Th-232	76.0	3.4	39.7
Ra-228	76.0	118.0	97.0

Note: Values in red were assumed to be in secular equilibrium with the parent radionuclide. Values in blue were taken to be in equilibrium with the daughter radionuclide.

Section 3.7.4 presents the mass source term after 100 years of sludge disposal. It was estimated that after 100 years of sludge deposition, the total volume of solids is in the order of 6,254,345 m³, covering an area of 1001 ha. For the radiological impact evaluation, a total thickness of 1 m was assumed over an area of 1000 ha, with a length of about 1,000 m in the direction of flow and a width of 10,000 m perpendicular to the direction of flow. The distance of the flow path from the disposal zone to a water abstraction borehole was taken to be 17 km (17,000 m), with a 1 m thickness. For transport in the Wits Quartzite (Deep Confinement Zone), a thickness of 1 m was also assumed.

Table 4.5 lists parameter values for the key geological units abstracted from the Process Level model for the ERB sludge disposal operations. Parameter values for the Main Reef in the sludge disposal zone were reduced to account for the change in properties due to the presence of the sludge that will reduce the porosity and the Darcy flux.

Table 4.5 Summary of parameter values abstracted from the Process Level model for the ERB sludge disposal operations (Artesium, 2024b).

Parameter	Unit	Main Reef (Sludge Disposal Zone)	Main Reef (Grootvlei Sub-basin)	Wits Quartzite (Deep Confinement Zone)	
Porosity	-	1.00E-01	7.00E-01	1.00E-02	
Hydraulic Conductivity	Horizontal	m.day ⁻¹	1.00E+01	1.00E+02	3.45E-01
	Vertical		1.00E+01	1.00E+02	3.45E-01
Hydraulic Head	Horizontal	-	2.65E-04	2.65E-04	2.65E-04
	Vertical		2.65E-08	2.65E-08	3.21E-07
Darcy Velocity	Horizontal	m.day ⁻¹	2.65E-03	2.65E-02	9.37E-05
	Vertical		2.65E-07	2.65E-06	1.14E-07

The most sensitive parameters in the radionuclide leaching equation are the distribution coefficient (or K_d-value) and the solubility limits. Low K_d values were used as distribution coefficients for the disposed sludge.

This is very conservative, assuming little absorption to retard the migration of radionuclides through the system. For this assessment, no solubility limits were applied, which implies that all activity in the tailings is available for dissolution and leaching. *In practice, this is not the case and represents a very conservative approach.*

The approach adopted for the analysis presented here is to use a conservative range of K_d values from the literature for illustrative purposes. Table 4.6 lists soil distribution coefficients for selected radionuclides published in RG-002 (NNR, 2013a), as well as the range of values from the literature for different soil types as published by the Argonne National Laboratory (Yu *et al.*, 1993). The comparison shows that the values of the distribution coefficients found in the literature can vary significantly.

Table 4.6 Distribution coefficients from literature for the elements of concern, as well as the K_d values in the analysis for illustrative purposes (NNR, 2013a; Yu *et al.*, 1993).

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

4.3.7 Potential Radiological Impact

4.3.7.1 General

Due to the inherent complexities of the ERB sludge disposal operations, uncertainties exist within both the conceptual model and parameter values used in the System Level model. Consequently, a series of simulations were conducted to address these uncertainties and to demonstrate the sensitivity of the model to variations in its conceptual framework and parameter inputs.

4.3.7.2 Base Case

The base case analysis assumed the 2024 sample in Table 4.4 as the initial activity concentrations for the sludge disposed of in the Main Reef, with the properties of the Main Reef (Sludge Disposal Zone) and Main Reef (Grootvlei Sub-basin) as indicated in Table 4.5.

Figure 4.8 presents the resulting nuclide-specific activity concentrations in the groundwater abstracted from the borehole, which shows that the initial peak concentration is only visible after 80,000 years (the Th-232 decay chain only becomes visible after 700,000 years). If one assumes the RG-002 (NNR, 2013a) water ingestion rates for the different age groups listed in Table 4.3, then the groundwater activity concentrations in Figure 4.8 translate to water ingestion doses shown in Figure 4.9. It illustrates that for the assumed conditions, the maximum potential water ingestion dose at a borehole located 17 km from the disposal zone is only at 100,000 years, and potentially at doses between 300 and 700 $\mu Sv.year^{-1}$ for the different age groups.

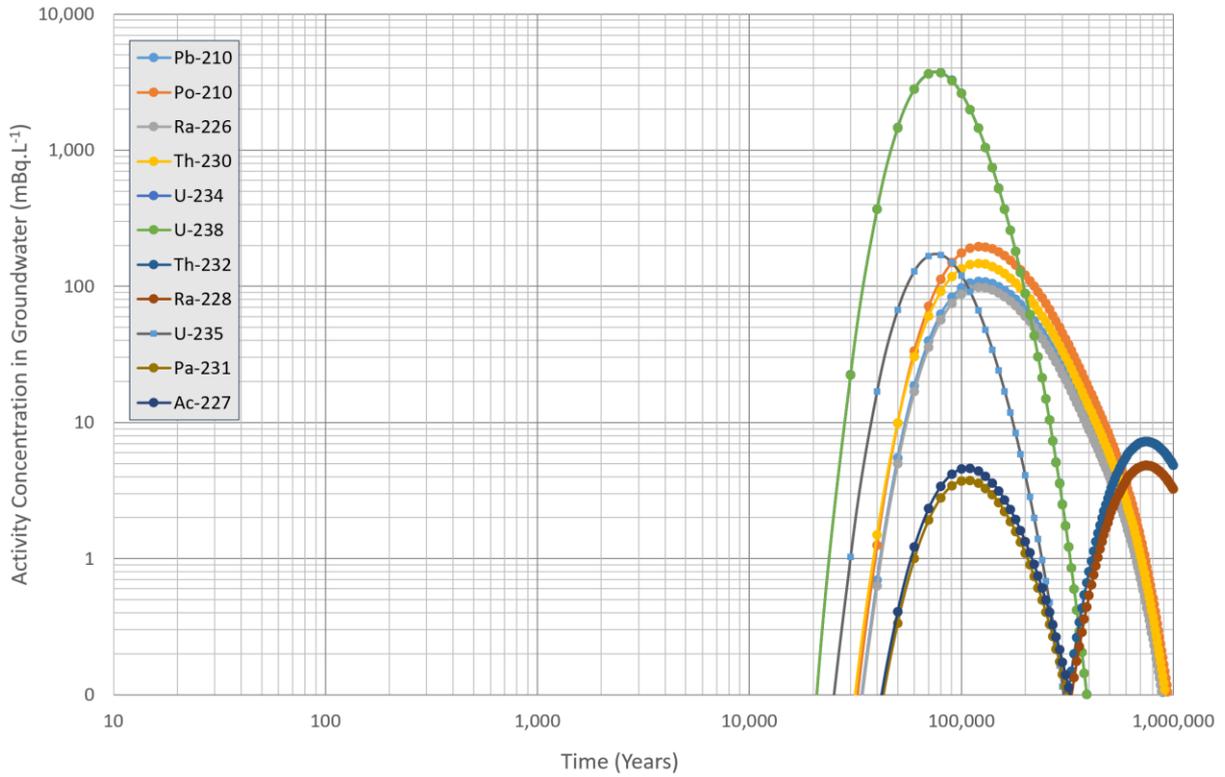


Figure 4.8 The simulated activity concentration in groundwater abstracted from a borehole 17 km from the sludge disposal zone.

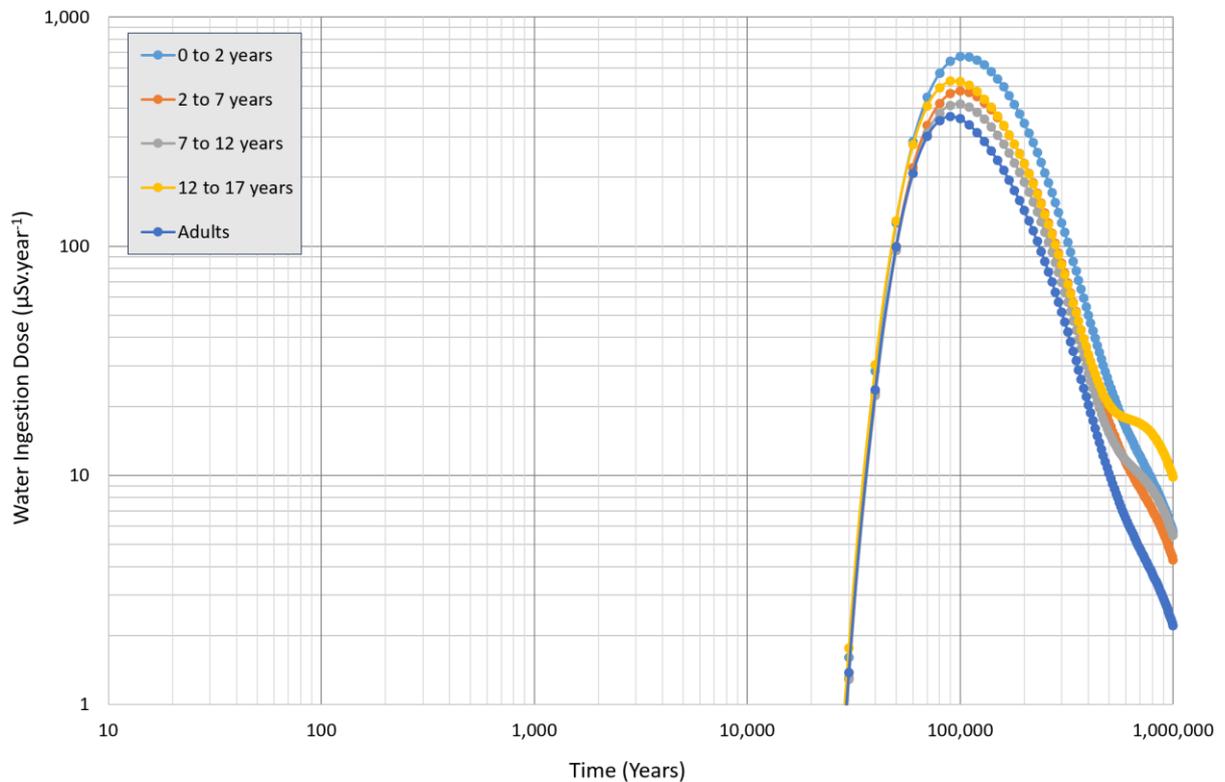


Figure 4.9 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, using the activity concentrations in Figure 4.8.

4.3.7.3 Variation in Activity Concentration

The results presented in Section 4.3.7.2 assumed the 2024 sample in Table 4.4 as the initial activity concentrations for the sludge disposed of in the Main Reef. Figure 4.10 and Figure 4.11 present the potential water ingestion doses using the 2016 and average sludge sample analysis results in Table 4.4 as the initial activity concentrations for the disposal zone. A comparison with Figure 4.9 shows that the time of maximum is the same, as expected, but that the peak doses for the different age groups are noticeably higher. This could be attributed to the higher U and Th isotope activity concentrations associated with the 2016 sample, which also influenced the average values.

4.3.7.4 Variation in K_d -values

The base case analysis assumed a conservative set of K_d -values for the different isotopes, as listed in Table 4.6. Lower K_d -values mean less adsorption, and the radionuclides will migrate faster along the Main Reef. However, it also means that radionuclides will be released faster from the disposal zone (see Equation ??). Figure 4.12 and Figure 4.13 present the potential water ingestion doses using K_d -values that are an order lower than those listed in Table 4.6 for the Base Case, and the RG-002 K_d -values listed in Table 4.6. The sensitivity of the K_d -values is clearly illustrated in comparison with Figure 4.9. The lower K_d -values in Figure 4.12 show that the plume will migrate faster through the Main Reef, reaching the first peak dose after 10,000 years at the borehole 17 km from the disposal zone but at higher water ingestion doses. The higher K_d -values in Figure 4.13 show that the plume will migrate slower through the Main Reef, reaching the first peak dose after 850,000 years at the borehole 17 km from the disposal zone but at significantly lower water ingestion doses.

4.3.7.5 Migration Through the Wits Quartzite (Deep Confinement Zone)

The Base Case assume that the plume migrates through the more permeable Main Reef. However, radionuclides may also migrate through the Wits Quartzite (Deep Confinement Zone), with parameter values as listed in Table 4.5. However, the potential water ingestion doses for migration through the quartzites are insignificant and do not reach the borehole 17 km away from the disposal zone. For illustrative purposes, the potential water ingestion doses at a point 1 km (1,000 m) from the disposal zone are presented in Figure 4.14, which shows doses in the order of $100 \mu\text{Sv}\cdot\text{year}^{-1}$ at about 900,000 years.

4.3.7.6 Variation in Darcy Flux and Porosity in the Disposal Zone

The Base Case assume that the Darcy velocity through the sludge disposal zone is an order lower than in the Main Reef. The porosity was also reduced accordingly. Figure 4.15 and Figure 4.16 present the potential water ingestion doses assuming an order higher and order lower Darcy flux through the disposal zone than those listed in Table 4.5, respectively. The porosity was adjusted to 0.7 and 0.05, respectively. Figure 4.15 shows that higher fluxes through the disposal zone will reduce the source terms release rate significantly, resulting in much lower water ingestion doses. Figure 4.16, on the other hand, shows that lower fluxes through the disposal zone will retain the radionuclides, resulting in much slower source terms release rates. This will result in higher doses at later times.

4.3.7.7 Additional Contribution from the Untreated AMD Water

The Base Case assume that the only contribution to the water ingestion dose is from the water leaching from the disposal zone. However, the untreated AMD water is likely present in the basin and that water abstracted from the basin includes AMD water. Figure 4.17 presents the potential water ingestion doses, assuming an additional contribution from the untreated AMD water sample listed in Table 4.1. It shows a marginal increase in the water ingestion dose in comparison with Figure 4.9 but with a constant contribution after the plume itself dissipated.

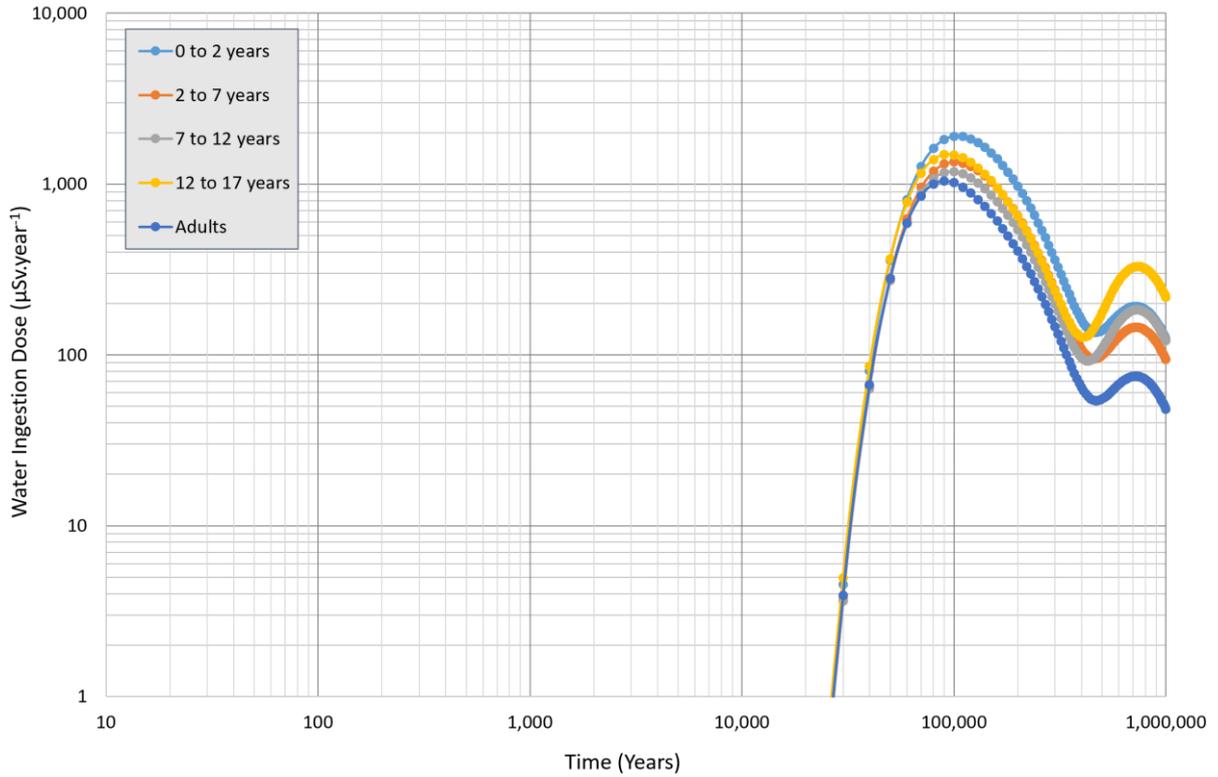


Figure 4.10 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, using the 2016 sludge sample in Table 4.4 as the initial activity concentrations.

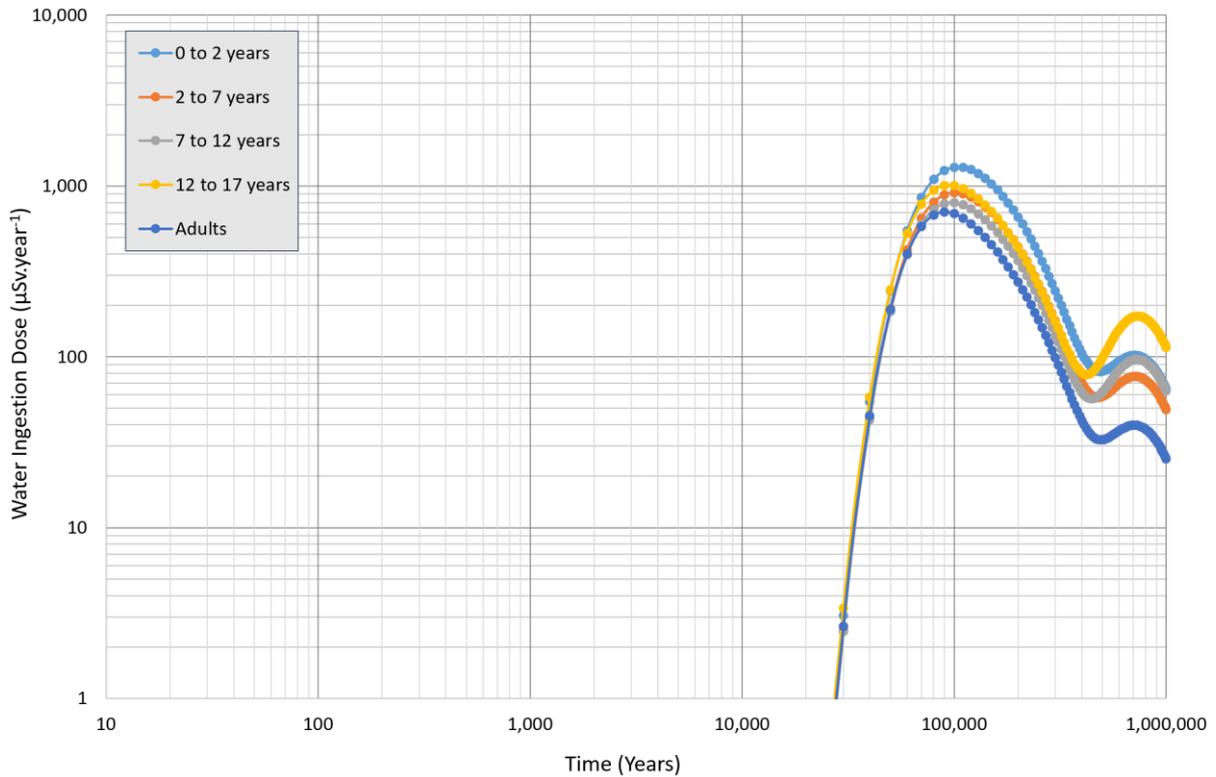


Figure 4.11 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, using the average values in Table 4.4 as the initial activity concentrations.

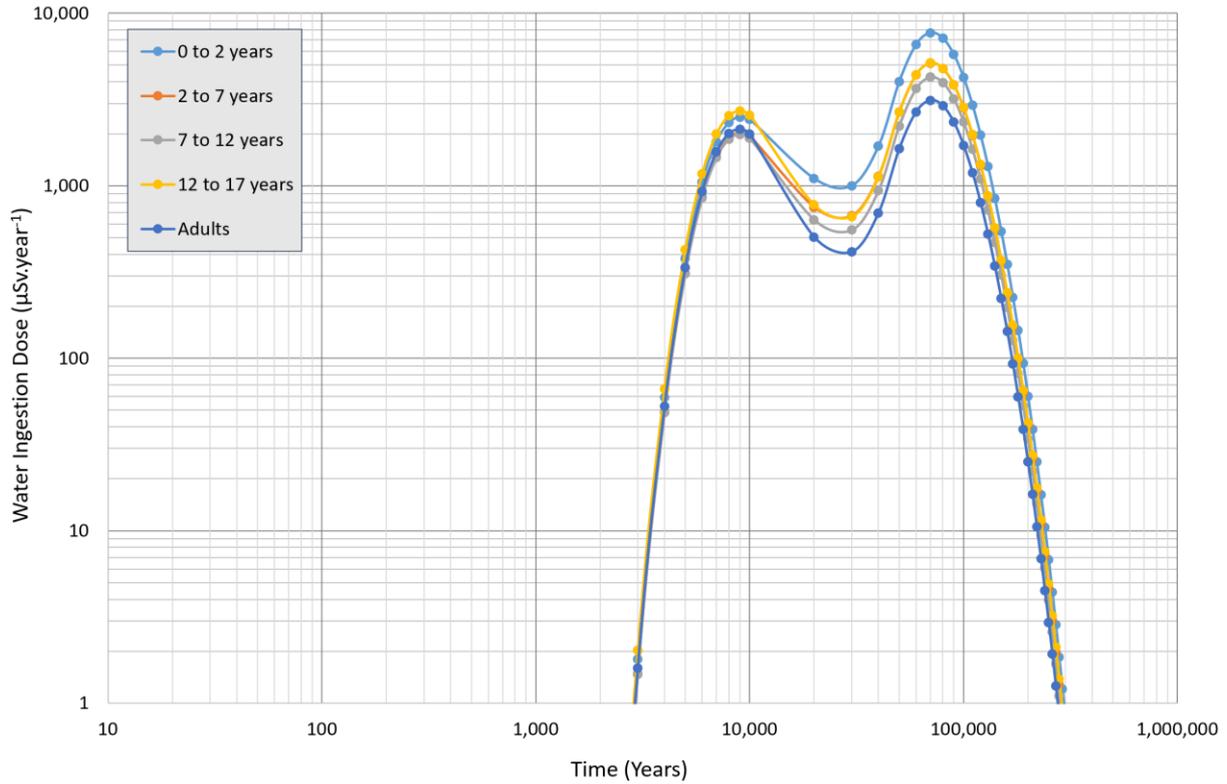


Figure 4.12 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, using K_d -values that are an order lower than listed in Table 4.6 for the Base Case.

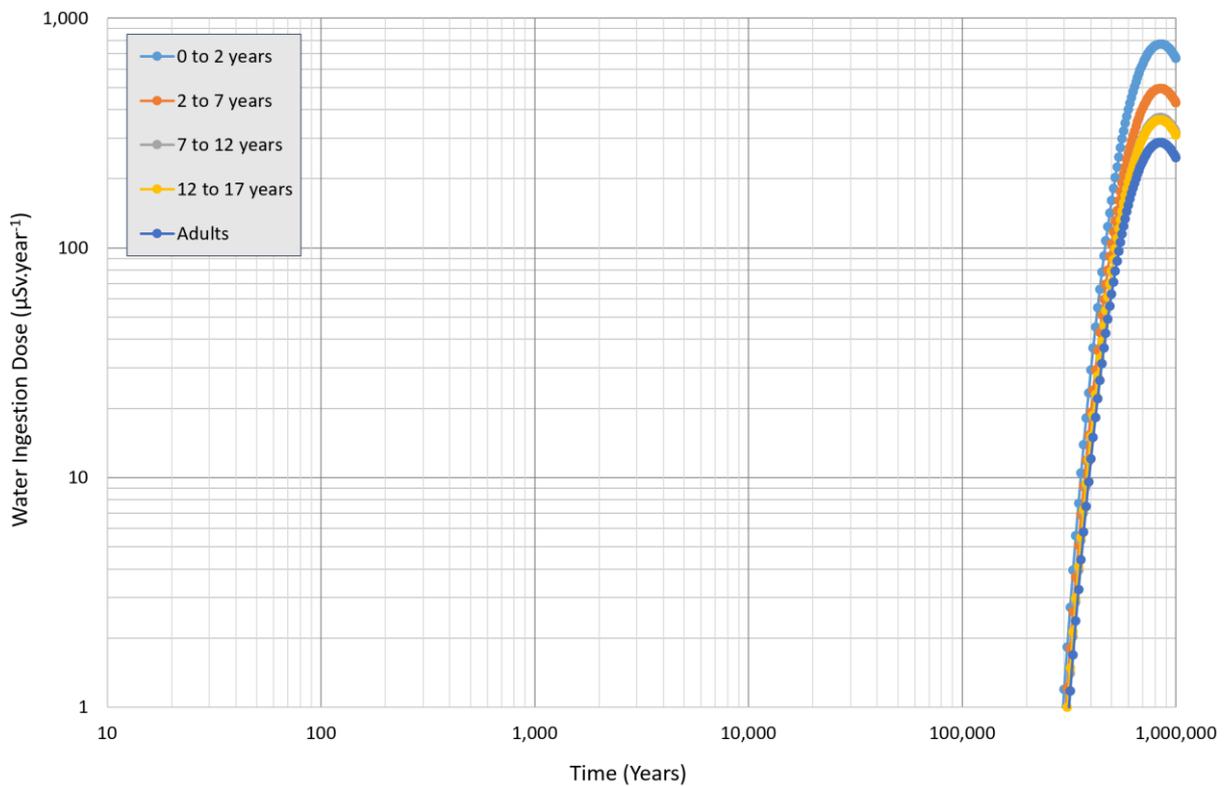


Figure 4.13 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, using the RG-002 K_d -values listed in Table 4.6.

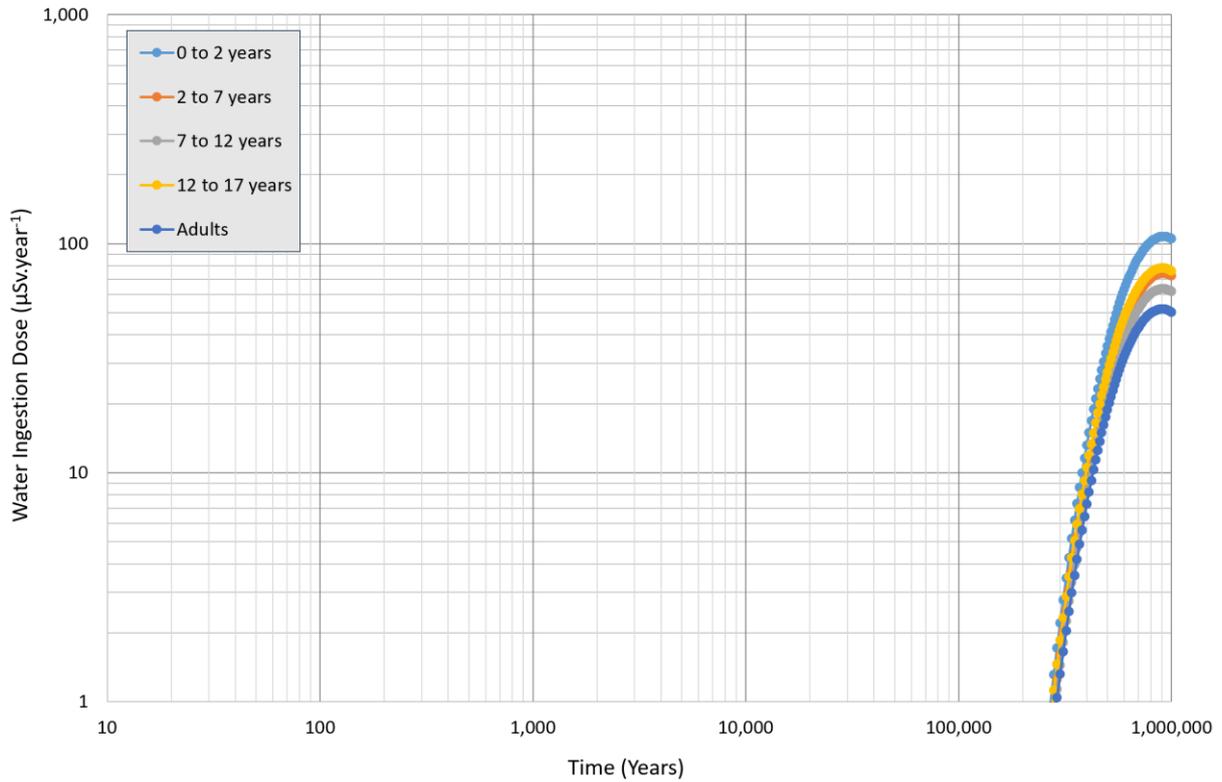


Figure 4.14 The simulated water ingestion dose to the different age groups 1 km from the sludge disposal zone, assuming migration is the Wits Quartzite (Deep Confinement Zone).

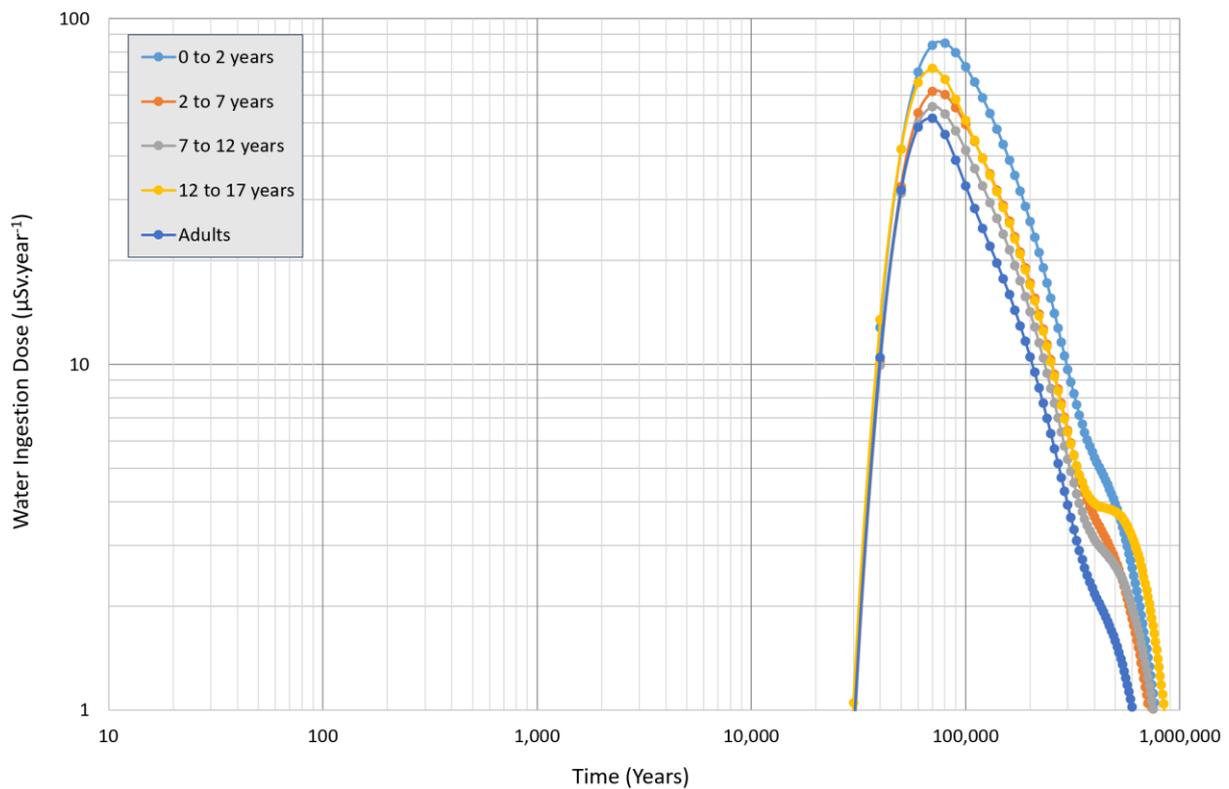


Figure 4.15 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, assuming an order high Darcy flux through the sludge disposal zone.

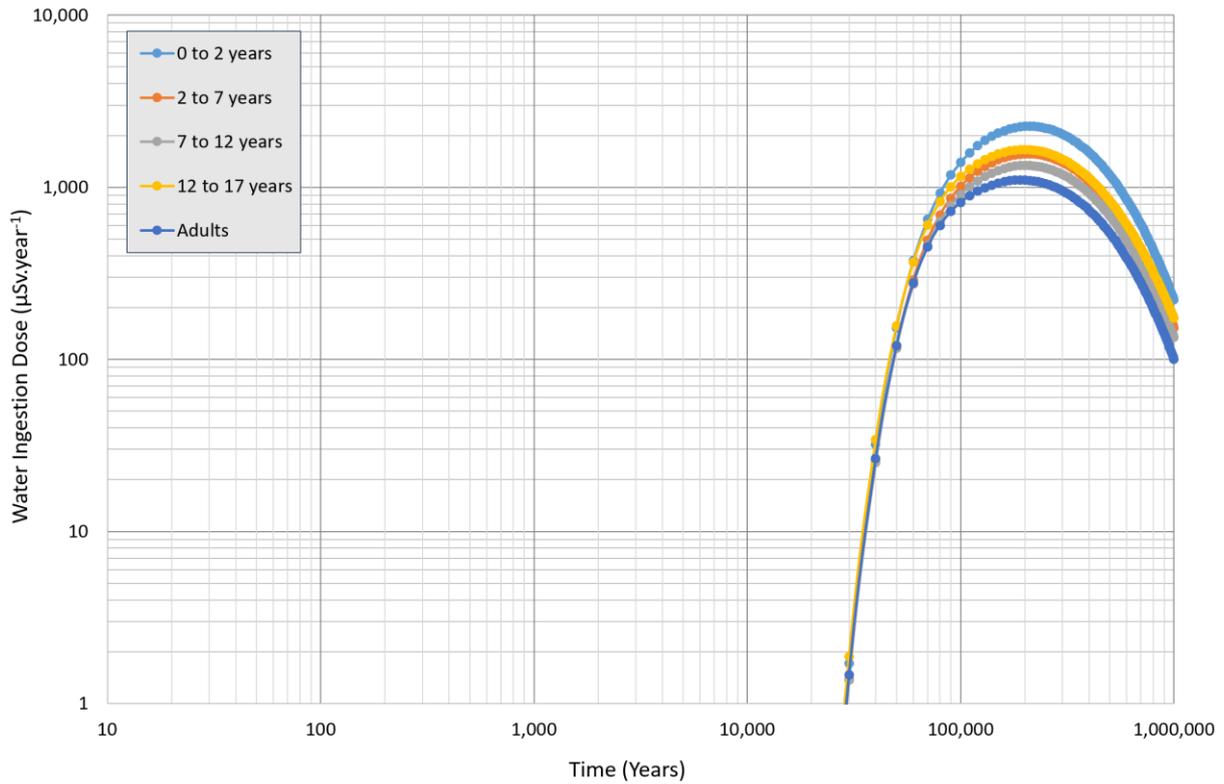


Figure 4.16 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, assuming an order lower Darcy flux through the sludge disposal zone.

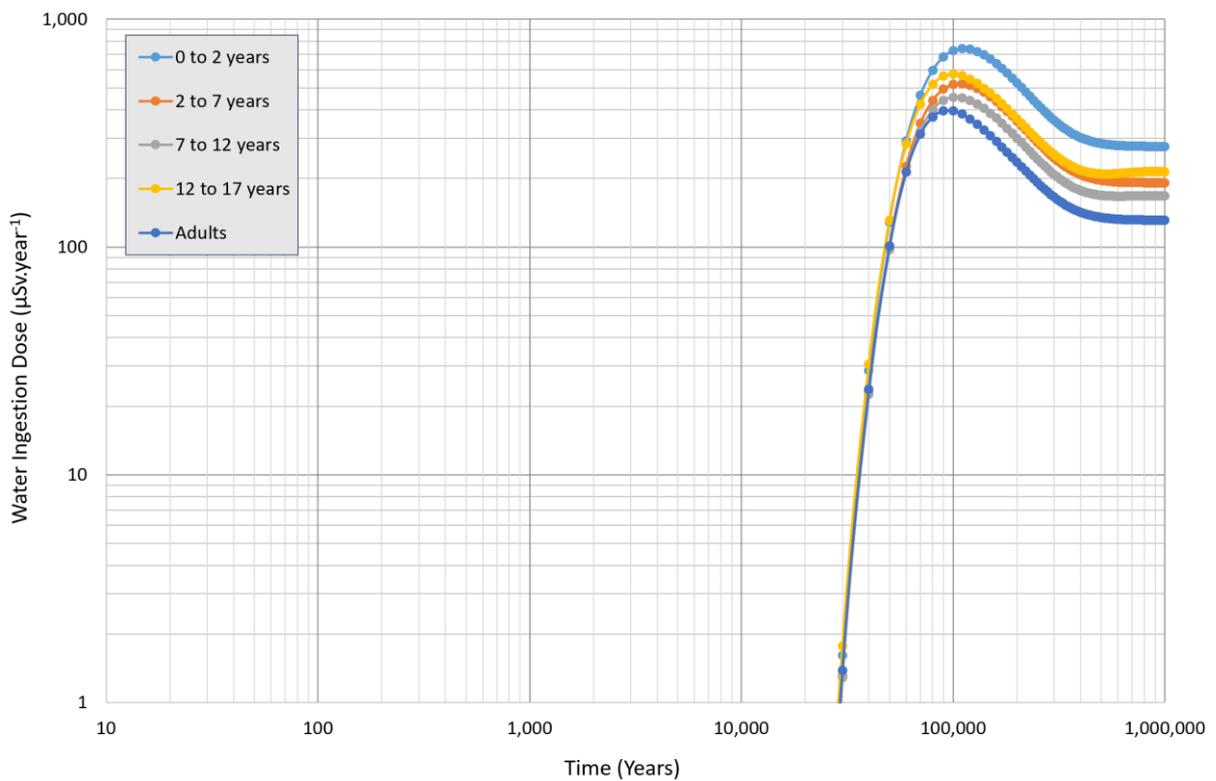


Figure 4.17 The simulated water ingestion dose to the different age groups 17 km from the sludge disposal zone, assuming an additional contribution from the untreated AMD water sample listed in Table 4.1.

4.3.8 Discussion of the Results

The potential radiological impact on the public from the sludge disposal operations was assessed through a series of simulations that explored alternative conceptual models and varied parameter values. This evaluation relied on water ingestion doses, which were compared against the established public dose limit criterion. For this purpose, it was assumed that water is abstracted from the centre of the plume without any dilution from uncontaminated water. Notably, if just 20% of the extracted water were uncontaminated, the calculated doses would be reduced by 20%. In addition, the water ingestion doses were calculated assuming that the abstracted water was the only source of water. For this purpose, the RG-002 suggested ingestion rates were used. Again, if the ingestion rates are reduced by 20%, the calculated doses would be reduced by 20%.

It is important to note that using water ingestion doses as a benchmark is a very conservative approach, given that the quality of untreated water is unsuitable for human consumption—not only from a radiological health perspective but even more so from a macro-chemical standpoint.

The radiological impact assessment assumed that the disposal operations were performed for 100 years, after which the Grootvlei Sub-basin will be filled to only 2% of its disposal capacity. Under these conditions, the total volume of sludge disposed in the basin was estimated at 6,254,345 m³, covering an area of about 1,000 ha (Artesium, 2024b). The Base Case analysis assumed a flow and migration path of about 17 km in the Main Reef.

The following can be noted from the series of simulations for alternative conceptual models and varied parameter values:

- The potential radiological impact on members of the public will manifest itself in only thousands to tens of thousands of years at a point 17 km away from the sludge disposal zone.
- The Base Case simulation using a realistic set of parameter values shows that, in all likelihood, the water ingestion doses will be below the dose limit of 1,000 $\mu\text{Sv}\cdot\text{year}^{-1}$.
- The variation in activity concentration between the 2016 and 2024 samples and the effect on the dose calculations highlight the importance of building a database of sludge radioanalytical results that can be used in subsequent evaluations and for decision-making. The results vary significantly between the two samples and the average between the two samples.
- The most significant variations were observed for different sets of K_d -values, which represent the partitioning of radionuclides between solids and liquids. The low K_d -values that represent little adsorption resulted in a significant radiological impact due to high source term release rates from the disposal zone. In addition, it also resulted in higher migration rates, which means the peak doses were reached at earlier times (10 times earlier). Higher K_d -values, on the other hand, have the opposite effect with peak doses reached at much later times (ten times later).
- The most significant variations were observed when using different sets of K_d -values, which determine how radionuclides partition between solids and liquids. Low K_d -values, which indicate limited adsorption, led to a considerable radiological impact because of the high source term release rates from the disposal zone. Additionally, these values resulted in faster migration, with peak doses occurring up to ten times sooner. Conversely, higher K_d -values had the opposite effect, causing peak doses to be reached much later—about ten times later.
- Any migration through the Wits Quartzite (Deep Confinement Zone) with its much lower permeability is almost none. No activity reaches the compliance point 17 km away from the disposal zone within the simulation period of 1,000,000 years. At a point 1 km away, the water ingestion doses are about 100 $\mu\text{Sv}\cdot\text{year}^{-1}$ after 1,000,000 years.

- Assuming an order of magnitude higher flux through the disposal zone results in a significantly faster source term release rate, which reduces the water ingestion dose to less than $100 \mu\text{Sv}\cdot\text{year}^{-1}$ and at earlier maximum times. Conversely, lower fluxes through the disposal zone resulted in increased doses at much later maximum times.
- The contribution from untreated AMD water to the water ingestion dose is not significant and results in a constant contribution after the plume release from the disposal zone have passed the compliance point.



5 Worker Safety Assessment Analysis

5.1 General

The purpose of this section is to present the safety assessment analysis results for exposure to workers (i.e., occupational exposure) 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 worker safety assessment analysis for the water treatment plant, while Section 4.3 evaluates and presents the safety assessment analysis associated with the sludge disposal operation.

5.2 Water Treatment Plant

5.2.1 General

The nature of the Water Treatment Plant is such that it may serve as a source of radiation exposure to workers (occupational exposure). The radiological characteristics of the material that contains naturally occurring radionuclides may differ within the different sections of the Water Treatment Plant, which means that exposure to workers performing activities within the different sections of the plant may potentially vary as well.

5.2.2 Exposure at the Water Treatment Plant

5.2.2.1 General

NRR (1997) provides guidelines for performing worker safety assessments. For this purpose, radiation surveys are conducted to establish the external gamma radiation and surface contamination. The surface contamination contributes to the dust inhalation pathway following resuspension. The results of these surveys serve as input into the worker safety assessment. The outcome of the assessment, in turn, serves as the basis for classifying designated areas according to the criteria presented in Section 2.2.7 into non-controlled, supervised and controlled areas (see Table 2.1). Given the wet nature of the water treatment plant, radon inhalation is not expected to make any contribution as part of the Source-Pathway-Receptor analysis approach.

The results presented here include the September 2016 survey (See Section 3.8.4.2) and the January 2025 survey of the Water Treatment Plant (see Section 3.8.4.3).

5.2.2.2 Methodological Approach

The radiation dose due to dust inhalation following resuspension from surface contamination was conservatively calculated by multiplying the α and β surface contamination values in $\text{Bq}\cdot\text{cm}^{-2}$ converted to $\text{Bq}\cdot\text{m}^{-3}$, with an inhalation rate of $1.2\text{ m}^3\cdot\text{hour}^{-1}$ and using dose conversion factors for particles with an AMAD of $1\mu\text{m}$ (most conservative). The dose conversion factors for $1\mu\text{m}$ particles with a Th/U ratio of 1:7 as provided in the Department of Mines and Petroleum (2010) were used, i.e. 0.0052. A conservative resuspension factor for the dust of $1\text{E-}6$ and an occupancy factor of 2,000 hours were assumed in the calculations.

5.2.2.3 September 2016 Survey Results

Table 3.8 provides the input data used for the assessment. The results are presented in Table 5.1, which show that on average for a 2,000-hour per annum exposure period the total effective dose is 0.27 mSv, with the 90th percentile of 0.46 mSv per annum. The maximum dose rate observed is 0.5 mSv per annum, which means that all areas at the DWS Eastern Basin Water Treatment Plant can be classified as uncontrolled areas as far as worker exposure is concerned (see Table 2.1 and Table 2.2). However, the background value (Claire Office) also results in a total dose of 0.5 mSv per annum, *which suggests very little to no contribution from the Water Treatment Plant in terms of external gamma radiation and inhalation doses to workers.*

5.2.2.4 January 2025 Survey Results

Table 3.10 provides the input data used for the assessment. The results are presented in Table 5.2, which show that on average for a 2,000-hour per annum exposure period the total effective dose is 0.35 mSv, with the 90th percentile of 0.43 mSv per annum. The maximum dose rate observed is 0.51 mSv per annum, which means that all areas at the DWS Eastern Basin Water Treatment Plant can be classified as uncontrolled areas as far as worker exposure is concerned (see Table 2.1 and Table 2.2). However, the background value (Christophor Office) also results in a total dose of 0.22 mSv per annum, *which suggests very little contribution from the Water Treatment Plant in terms of external gamma radiation and inhalation doses to workers.*

5.2.3 Discharge of Treated Water to the Blesbok Spruit

The treated water overflows from the thickeners and flows to the treated water sump. Water overflowing from the sump flows over a weir and is then discharged by gravity to the Blesbok Spruit (see Figure 5.1). Once discharged, the treated serve as a source of radiation exposure to members of the public (see Section 4.2.2), but not to workers.



Figure 5.1 Photo showing the discharge of the treated water from the Water Treatment Plant over the weir into the environment.

Table 5.1 Summary of the worker radiation exposure levels as calculated from the survey results presented in Table 3.8 for the DWS Eastern Basin Water Treatment Plant. Note that the background values (Claire Office) were subtracted from the data.

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Claire Office (Background)	0.01	0.08	0.25	0.09	900	0.0009	0.011232	0.50	0.511
Guard House	0	0.07	0.11	0.07	700	0.0007	0.008736	0.22	0.229
Treated Water Pump Station	0	0.08	0.11	0.08	800	0.0008	0.009984	0.22	0.230
Treated Water Sump	0	0.06	0.17	0.06	600	0.0006	0.007488	0.34	0.347
Thickener No.2	0.01	0.05	0.09	0.06	600	0.0006	0.007488	0.18	0.187
Valve	0.02	0.03	0.23	0.05	500	0.0005	0.00624	0.46	0.466
Thickener No.2	0.01	0.04	0.07	0.05	500	0.0005	0.00624	0.14	0.146
Utility Water Reticulation	0	0	0.09	0	0	0	0	0.18	0.180
Thickener No.3	0.01	0.2	0.11	0.21	2100	0.0021	0.026208	0.22	0.246
Poly Dosing Building	0.02	0	0.15	0.02	200	0.0002	0.002496	0.3	0.302
Thickener No.3	0	0.06	0.09	0.06	600	0.0006	0.007488	0.18	0.187
Thickener No.1	0	0.04	0.03	0.04	400	0.0004	0.004992	0.06	0.065
Thickener No.1	0	0	0.23	0	0	0	0	0.46	0.460
Thickener No.2	0	0.03	0.17	0.03	300	0.0003	0.003744	0.34	0.344
Thickener No.1	0	0	0.11	0	0	0	0	0.22	0.220
Thickener No.3	0.01	0.02	0.17	0.03	300	0.0003	0.003744	0.34	0.344
Thickener No.3	0	0.03	0.23	0.03	300	0.0003	0.003744	0.46	0.464
Eastern Corner	0	0.03	0.11	0.03	300	0.0003	0.003744	0.22	0.224
Inspection Manhole	0.02	0	0.17	0.02	200	0.0002	0.002496	0.34	0.342
Generator Room 2	0	0	0.17	0	0	0	0	0.34	0.340
South Corner	0	0.04	0.17	0.04	400	0.0004	0.004992	0.34	0.345
Shaft Pump Station	0	0.04	0.23	0.04	400	0.0004	0.004992	0.46	0.465
VFD & MV Room	0	0.1	0.04	0.1	1000	0.001	0.01248	0.08	0.092
MCC Room	0.01	0	0.23	0.01	100	0.0001	0.001248	0.46	0.461
Limestone Dosing	0	0.02	0.23	0.02	200	0.0002	0.002496	0.46	0.462
Limestone Dosing	0	0	0.21	0	0	0	0	0.42	0.420
Quick Lime Dosing	0.01	0.06	0.01	0.07	700	0.0007	0.008736	0.02	0.029
Quick Lime Dosing	0.01	0	0.21	0.01	100	0.0001	0.001248	0.42	0.421

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1 µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Quick Lime Dosing	0.01	0.06	0.06	0.07	700	0.0007	0.008736	0.12	0.129
Quick Lime Dosing	0	0.06	0.21	0.06	600	0.0006	0.007488	0.42	0.427
Lime Dosing Pipe	0.01	0.06	0.23	0.07	700	0.0007	0.008736	0.46	0.469
Generator Room 1	0.02	0	0.01	0.02	200	0.0002	0.002496	0.02	0.022
Generator Room 2	0.02	0.22	0.17	0.24	2400	0.0024	0.029952	0.34	0.370
Between Generator rooms 1 & 2	0	0.03	0.03	0.03	300	0.0003	0.003744	0.06	0.064
Limestone Dosing Pipe	0	0	0.06	0	0	0	0	0.12	0.120
Plant Drain	0.03	0.04	0.09	0.07	700	0.0007	0.008736	0.18	0.189
Steps at Plant Drain	0	0.04	0.07	0.04	400	0.0004	0.004992	0.14	0.145
Pipes from the Shaft Pump Station	0	0.07	0.09	0.07	700	0.0007	0.008736	0.18	0.189
Pipes from the Shaft Pump Station	0	0.03	0.01	0.03	300	0.0003	0.003744	0.02	0.024
Steps to Thickening Reactors	0.01	0	0.21	0.01	100	0.0001	0.001248	0.42	0.421
Inspection Manhole	0	0.01	0.17	0.01	100	0.0001	0.001248	0.34	0.341
Corner of Thickening Reactors	0	0.02	0.26	0.02	200	0.0002	0.002496	0.52	0.522
Thickening Reactors	0.01	0.03	0.23	0.04	400	0.0004	0.004992	0.46	0.465
Thickening Reactors	0	0.14	0.09	0.14	1400	0.0014	0.017472	0.18	0.197
Thickening Reactors	0	0.05	0.06	0.05	500	0.0005	0.00624	0.12	0.126
Thickening Reactors	0	0	0.14	0	0	0	0	0.28	0.280
Thickening Reactors	0	0.05	0.16	0.05	500	0.0005	0.00624	0.32	0.326
Thickening Reactors	0	0.07	0.19	0.07	700	0.0007	0.008736	0.38	0.389
Thickening Reactors	0	0.01	0.23	0.01	100	1E-04	0.001248	0.46	0.461
Thickening Reactors	0	0.01	0.2	0.01	100	1E-04	0.001248	0.4	0.401
Thickening Reactors	0	0	0.01	0	0	0	0	0.02	0.020
Thickening Reactors	0	0	0.03	0	0	0	0	0.06	0.060
Thickening Reactors	0	0.05	0.16	0.05	500	0.0005	0.00624	0.32	0.326
Thickening Reactors	0	0	0.03	0	0	0	0	0.06	0.060
Thickening Reactors	0	0.06	0.24	0.06	600	0.0006	0.007488	0.48	0.487
Thickening Reactors	0	0	0.11	0	0	0	0	0.22	0.220
Thickening Reactors	0	0.04	0.14	0.04	400	0.0004	0.004992	0.28	0.285
Thickening Reactors	0	0	0.15	0	0	0	0	0.3	0.300
Thickening Reactors	0.01	0.02	0.17	0.03	300	0.0003	0.003744	0.34	0.344

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1 µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Thickening Reactors	0	0	0.23	0	0	0	0	0.46	0.460
Thickening Reactors	0	0	0.17	0	0	0	0	0.34	0.340
Thickening Reactors	0	0.02	0.03	0.02	200	0.0002	0.002496	0.06	0.062
Thickening Reactors	0	0.06	0.06	0.06	600	0.0006	0.007488	0.12	0.127
Thickening Reactors	0.02	0.13	0.01	0.15	1500	0.0015	0.01872	0.02	0.039
Thickening Reactors	0	0.03	0.16	0.03	300	0.0003	0.003744	0.32	0.324
Thickening Reactors	0	0.05	0.11	0.05	500	0.0005	0.00624	0.22	0.226
Thickening Reactors	0.02	0.05	0.14	0.07	700	0.0007	0.008736	0.28	0.289
Thickening Reactors	0	0.06	0.13	0.06	600	0.0006	0.007488	0.26	0.267
Canteen	0	0	0.06	0	0	0	0	0.12	0.120
Workshops	0	0.05	0.06	0.05	500	0.0005	0.00624	0.12	0.126
Workshops	0	0.03	0.18	0.03	300	0.0003	0.003744	0.36	0.364
Workshops	0	0.04	0.16	0.04	400	0.0004	0.004992	0.32	0.325
Workshops	0	0.02	0.15	0.02	200	0.0002	0.002496	0.3	0.302
Workshops	0	0.04	0.11	0.04	400	0.0004	0.004992	0.22	0.225
Offices Reception	0	0.06	0.16	0.06	600	0.0006	0.007488	0.32	0.327
Offices	0	0.07	0.08	0.07	700	0.0007	0.008736	0.16	0.169
Offices	0.02	0.06	0.23	0.08	800	0.0008	0.009984	0.46	0.470
Offices	0.01	0	0.19	0.01	100	0.0001	0.001248	0.38	0.381
Offices	0.01	0.03	0.12	0.04	400	0.0004	0.004992	0.24	0.245
Offices Control Room	0	0.06	0.02	0.06	600	0.0006	0.007488	0.04	0.047
Offices Control Room	0	0.08	0.03	0.08	800	0.0008	0.009984	0.06	0.070
Average	0.004	0.039	0.132	0.043	430.000	0.000	0.0054	0.264	0.269
Maximum	0.030	0.220	0.260	0.240	2400.000	0.002	0.0300	0.520	0.522
Minimum	0.000	0.000	0.010	0.000	0.000	0.000	0.0000	0.020	0.020
90 th Percentile	0.020	0.070	0.230	0.071	710.000	0.001	0.0089	0.460	0.463

Table 5.2 Summary of the worker radiation exposure levels as calculated from the survey results presented in Table 3.8 for the DWS Eastern Basin Water Treatment Plant. Note that the background values (Christopher's Office) were subtracted from the data.

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Christopher Office (Background)	0.000	0.070	0.100	0.120	1200	0.001	0.015	0.200	0.215
Security office main gate	0.000	0.060	0.140	0.180	1800	0.002	0.022	0.280	0.302
Security office main gate	0.000	0.070	0.160	0.190	1900	0.002	0.024	0.320	0.344
Security office main gate	0.000	0.120	0.150	0.200	2000	0.002	0.025	0.300	0.325
Utility water pump station outside	0.000	0.040	0.160	0.200	2000	0.002	0.025	0.320	0.345
Utility water pump station outside	0.010	0.060	0.170	0.190	1900	0.002	0.024	0.340	0.364
Utility water pump station outside	0.000	0.070	0.170	0.180	1800	0.002	0.022	0.340	0.362
Polydosing storage area	0.000	0.060	0.200	0.190	1900	0.002	0.024	0.400	0.424
Polydosing storage area	0.000	0.060	0.160	0.170	1700	0.002	0.021	0.320	0.341
Polydosing storage area	0.000	0.110	0.170	0.170	1700	0.002	0.021	0.340	0.361
Polydosing storage area	0.000	0.060	0.210	0.190	1900	0.002	0.024	0.420	0.444
Weighbridge office	0.000	0.070	0.180	0.190	1900	0.002	0.024	0.360	0.384
Weighbridge office	0.000	0.060	0.140	0.160	1600	0.002	0.020	0.280	0.300
Weighbridge office	0.010	0.080	0.160	0.170	1700	0.002	0.021	0.320	0.341
Weighbridge office	0.000	0.080	0.150	0.130	1300	0.001	0.016	0.300	0.316
Weighbridge office	0.010	0.110	0.110	0.140	1400	0.001	0.017	0.220	0.237
Reactor 3 top	0.000	0.060	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 3 top	0.010	0.040	0.160	0.170	1700	0.002	0.021	0.320	0.341
Reactor 3 top	0.000	0.060	0.170	0.190	1900	0.002	0.024	0.340	0.364
Reactor 3 top	0.000	0.080	0.180	0.160	1600	0.002	0.020	0.360	0.380
Reactor 3 top	0.000	0.050	0.140	0.200	2000	0.002	0.025	0.280	0.305
Reactor 3 top	0.000	0.060	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 3 top	0.000	0.080	0.160	0.170	1700	0.002	0.021	0.320	0.341
Reactor 3 top	0.000	0.100	0.110	0.140	1400	0.001	0.017	0.220	0.237
Reactor 3 top	0.000	0.050	0.140	0.110	1100	0.001	0.014	0.280	0.294
Reactor 3 top	0.000	0.070	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 3 top	0.000	0.100	0.160	0.190	1900	0.002	0.024	0.320	0.344
Reactor 3 top	0.000	0.060	0.190	0.210	2100	0.002	0.026	0.380	0.406

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Reactor 2 top	0.000	0.050	0.190	0.190	1900	0.002	0.024	0.380	0.404
Reactor 2 top	0.000	0.080	0.160	0.160	1600	0.002	0.020	0.320	0.340
Reactor 2 top	0.000	0.080	0.140	0.170	1700	0.002	0.021	0.280	0.301
Reactor 2 top	0.000	0.060	0.130	0.140	1400	0.001	0.017	0.260	0.277
Reactor 2 top	0.010	0.050	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 2 top	0.000	0.080	0.160	0.150	1500	0.002	0.019	0.320	0.339
Reactor 2 top	0.000	0.040	0.140	0.130	1300	0.001	0.016	0.280	0.296
Reactor 2 top	0.000	0.080	0.130	0.140	1400	0.001	0.017	0.260	0.277
Reactor 2 top	0.000	0.060	0.100	0.110	1100	0.001	0.014	0.200	0.214
Reactor 2 top	0.000	0.050	0.090	0.100	1000	0.001	0.012	0.180	0.192
Reactor 2 top	0.000	0.090	0.110	0.110	1100	0.001	0.014	0.220	0.234
Reactor 2 top	0.000	0.040	0.110	0.110	1100	0.001	0.014	0.220	0.234
Reactor 1 top	0.000	0.120	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 1 top	0.000	0.050	0.110	0.140	1400	0.001	0.017	0.220	0.237
Reactor 1 top	0.000	0.060	0.100	0.120	1200	0.001	0.015	0.200	0.215
Reactor 1 top	0.000	0.060	0.140	0.160	1600	0.002	0.020	0.280	0.300
Reactor 1 top	0.010	0.050	0.130	0.140	1400	0.001	0.017	0.260	0.277
Reactor 1 top	0.000	0.080	0.160	0.170	1700	0.002	0.021	0.320	0.341
Reactor 1 top	0.000	0.040	0.140	0.130	1300	0.001	0.016	0.280	0.296
Reactor 1 top	0.000	0.100	0.130	0.120	1200	0.001	0.015	0.260	0.275
Reactor 1 top	0.010	0.030	0.120	0.140	1400	0.001	0.017	0.240	0.257
Reactor 1 top	0.000	0.070	0.110	0.130	1300	0.001	0.016	0.220	0.236
Reactor 1 top	0.000	0.030	0.090	0.110	1100	0.001	0.014	0.180	0.194
Reactor 1 top	0.000	0.040	0.100	0.140	1400	0.001	0.017	0.200	0.217
Shaft pump station	0.000	0.070	0.160	0.170	1700	0.002	0.021	0.320	0.341
Shaft pump station	0.000	0.050	0.170	0.180	1800	0.002	0.022	0.340	0.362
Shaft pump station	0.000	0.060	0.140	0.190	1900	0.002	0.024	0.280	0.304
Shaft pump station	0.000	0.060	0.130	0.140	1400	0.001	0.017	0.260	0.277
Shaft pump station	0.000	0.050	0.160	0.170	1700	0.002	0.021	0.320	0.341
VFD building outside	0.000	0.060	0.160	0.170	1700	0.002	0.021	0.320	0.341
VFD building outside	0.000	0.050	0.170	0.190	1900	0.002	0.024	0.340	0.364

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
VFD building outside	0.000	0.110	0.210	0.210	2100	0.002	0.026	0.420	0.446
VFD building outside	0.000	0.060	0.200	0.190	1900	0.002	0.024	0.400	0.424
MCC building outside	0.000	0.050	0.190	0.180	1800	0.002	0.022	0.380	0.402
MCC building outside	0.000	0.050	0.200	0.190	1900	0.002	0.024	0.400	0.424
MCC building outside	0.000	0.050	0.210	0.220	2200	0.002	0.027	0.420	0.447
MCC building outside	0.000	0.130	0.200	0.210	2100	0.002	0.026	0.400	0.426
Generator 1 building outside	0.000	0.060	0.170	0.200	2000	0.002	0.025	0.340	0.365
Generator 1 building outside	0.000	0.050	0.160	0.170	1700	0.002	0.021	0.320	0.341
Generator 1 building outside	0.000	0.110	0.150	0.180	1800	0.002	0.022	0.300	0.322
Generator 2 building outside	0.000	0.100	0.140	0.170	1700	0.002	0.021	0.280	0.301
Generator 2 building outside	0.000	0.100	0.170	0.160	1600	0.002	0.020	0.340	0.360
Generator 2 building outside	0.000	0.110	0.190	0.150	1500	0.002	0.019	0.380	0.399
Limestone and lime dosing area	0.000	0.050	0.170	0.200	2000	0.002	0.025	0.340	0.365
Limestone and lime dosing area	0.000	0.050	0.160	0.210	2100	0.002	0.026	0.320	0.346
Limestone and lime dosing area	0.000	0.040	0.150	0.190	1900	0.002	0.024	0.300	0.324
Limestone and lime dosing area	0.000	0.070	0.160	0.170	1700	0.002	0.021	0.320	0.341
Limestone and lime dosing area	0.000	0.100	0.170	0.160	1600	0.002	0.020	0.340	0.360
Limestone and lime dosing area	0.000	0.040	0.140	0.130	1300	0.001	0.016	0.280	0.296
Limestone and lime dosing area	0.000	0.050	0.150	0.140	1400	0.001	0.017	0.300	0.317
Limestone and lime dosing area	0.000	0.110	0.160	0.170	1700	0.002	0.021	0.320	0.341
Limestone and lime dosing area	0.000	0.130	0.170	0.190	1900	0.002	0.024	0.340	0.364
Limestone and lime dosing area	0.000	0.130	0.180	0.200	2000	0.002	0.025	0.360	0.385
Mechanical workshop	0.000	0.070	0.160	0.170	1700	0.002	0.021	0.320	0.341
Mechanical workshop	0.000	0.110	0.170	0.160	1600	0.002	0.020	0.340	0.360
Mechanical workshop	0.010	0.090	0.180	0.150	1500	0.002	0.019	0.360	0.379
Mechanical workshop	0.000	0.080	0.150	0.140	1400	0.001	0.017	0.300	0.317
Mechanical workshop	0.000	0.100	0.160	0.150	1500	0.002	0.019	0.320	0.339
Electrical workshop	0.000	0.100	0.190	0.200	2000	0.002	0.025	0.380	0.405
Electrical workshop	0.010	0.100	0.200	0.180	1800	0.002	0.022	0.400	0.422
Electrical workshop	0.000	0.030	0.160	0.170	1700	0.002	0.021	0.320	0.341
Electrical workshop	0.000	0.070	0.170	0.160	1600	0.002	0.020	0.340	0.360

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Electrical workshop	0.000	0.140	0.190	0.170	1700	0.002	0.021	0.380	0.401
Canteen area	0.000	0.070	0.170	0.180	1800	0.002	0.022	0.340	0.362
Canteen area	0.000	0.130	0.180	0.190	1900	0.002	0.024	0.360	0.384
Canteen area	0.000	0.110	0.190	0.170	1700	0.002	0.021	0.380	0.401
Canteen area	0.010	0.150	0.200	0.200	2000	0.002	0.025	0.400	0.425
Canteen area	0.010	0.150	0.210	0.200	2000	0.002	0.025	0.420	0.445
Outside ablution block bathrooms	0.000	0.100	0.160	0.170	1700	0.002	0.021	0.320	0.341
Outside ablution block bathrooms	0.000	0.050	0.140	0.160	1600	0.002	0.020	0.280	0.300
Outside ablution block bathrooms	0.000	0.080	0.150	0.170	1700	0.002	0.021	0.300	0.321
Outside ablution block bathrooms	0.000	0.130	0.170	0.190	1900	0.002	0.024	0.340	0.364
Outside ablution block bathrooms	0.010	0.100	0.180	0.170	1700	0.002	0.021	0.360	0.381
Thickener dam 1	0.000	0.170	0.190	0.160	1600	0.002	0.020	0.380	0.400
Thickener dam1	0.010	0.110	0.120	0.140	1400	0.001	0.017	0.240	0.257
Thickener dam 1	0.000	0.130	0.140	0.160	1600	0.002	0.020	0.280	0.300
Thickener dam 1	0.010	0.110	0.190	0.170	1700	0.002	0.021	0.380	0.401
Thickener dam 1	0.000	0.130	0.130	0.180	1800	0.002	0.022	0.260	0.282
Thickener dam 2	0.000	0.130	0.160	0.190	1900	0.002	0.024	0.320	0.344
Thickener dam 2	0.000	0.170	0.170	0.190	1900	0.002	0.024	0.340	0.364
Thickener dam 2	0.000	0.150	0.190	0.160	1600	0.002	0.020	0.380	0.400
Thickener dam 2	0.000	0.090	0.180	0.170	1700	0.002	0.021	0.360	0.381
Thickener dam 2	0.000	0.130	0.140	0.160	1600	0.002	0.020	0.280	0.300
Thickener dam 3	0.010	0.120	0.160	0.170	1700	0.002	0.021	0.320	0.341
Thickener dam 3	0.010	0.160	0.117	0.160	1600	0.002	0.020	0.234	0.254
Thickener dam 3	0.010	0.160	0.160	0.190	1900	0.002	0.024	0.320	0.344
Thickener dam 3	0.000	0.080	0.140	0.130	1300	0.001	0.016	0.280	0.296
Thickener dam 3	0.010	0.080	0.150	0.140	1400	0.001	0.017	0.300	0.317
Treated water sump dam	0.000	0.100	0.170	0.180	1800	0.002	0.022	0.340	0.362
Treated water sump dam	0.000	0.140	0.160	0.170	1700	0.002	0.021	0.320	0.341
Treated water sump dam	0.000	0.070	0.170	0.160	1600	0.002	0.020	0.340	0.360
Treated water sump dam	0.000	0.100	0.140	0.140	1400	0.001	0.017	0.280	0.297
Treated water sump dam	0.000	0.110	0.200	0.190	1900	0.002	0.024	0.400	0.424

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Laboratory	0.000	0.120	0.140	0.160	1600	0.002	0.020	0.280	0.300
Laboratory	0.000	0.130	0.150	0.170	1700	0.002	0.021	0.300	0.321
Laboratory	0.000	0.070	0.170	0.180	1800	0.002	0.022	0.340	0.362
Christopher office	0.000	0.130	0.200	0.180	1800	0.002	0.022	0.400	0.422
Christopher office	0.000	0.140	0.210	0.200	2000	0.002	0.025	0.420	0.445
Christopher office	0.000	0.090	0.240	0.210	2100	0.002	0.026	0.480	0.506
Boardroom	0.000	0.120	0.160	0.190	1900	0.002	0.024	0.320	0.344
Boardroom	0.000	0.110	0.190	0.200	2000	0.002	0.025	0.380	0.405
Boardroom	0.000	0.110	0.200	0.210	2100	0.002	0.026	0.400	0.426
Office 2	0.000	0.130	0.180	0.190	1900	0.002	0.024	0.360	0.384
Office 2	0.000	0.130	0.170	0.200	2000	0.002	0.025	0.340	0.365
Office 2	0.000	0.130	0.160	0.210	2100	0.002	0.026	0.320	0.346
Office 3	0.000	0.070	0.230	0.170	1700	0.002	0.021	0.460	0.481
Office 3	0.000	0.130	0.200	0.180	1800	0.002	0.022	0.400	0.422
Office 3	0.000	0.130	0.190	0.170	1700	0.002	0.021	0.380	0.401
Kitchen	0.000	0.160	0.170	0.150	1500	0.002	0.019	0.340	0.359
Kitchen	0.000	0.150	0.160	0.140	1400	0.001	0.017	0.320	0.337
Kitchen	0.000	0.150	0.150	0.160	1600	0.002	0.020	0.300	0.320
Office 1	0.000	0.120	0.230	0.250	2500	0.003	0.031	0.460	0.491
Office 1	0.000	0.090	0.200	0.210	2100	0.002	0.026	0.400	0.426
Office 1	0.010	0.080	0.190	0.210	2100	0.002	0.026	0.380	0.406
Laboratory Office	0.000	0.130	0.190	0.170	1700	0.002	0.021	0.380	0.401
Laboratory Office	0.000	0.150	0.200	0.180	1800	0.002	0.022	0.400	0.422
Laboratory Office	0.000	0.150	0.210	0.190	1900	0.002	0.024	0.420	0.444
Reception	0.000	0.130	0.240	0.190	1900	0.002	0.024	0.480	0.504
Reception	0.000	0.110	0.210	0.200	2000	0.002	0.025	0.420	0.445
Reception	0.000	0.190	0.230	0.230	2300	0.002	0.029	0.460	0.489
Control room	0.000	0.130	0.130	0.160	1600	0.002	0.020	0.260	0.280
Control room	0.000	0.120	0.140	0.150	1500	0.002	0.019	0.280	0.299
Control room	0.000	0.120	0.160	0.150	1500	0.002	0.019	0.320	0.339
Control room	0.000	0.060	0.060	0.090	900	0.001	0.011	0.120	0.131

Description of the Area	Electra Measurements			Surface contact			Annual Equivalent Inhalation Dose (1µm)	External Gamma Dose	Total Effective Dose
	α	β	Dose Rate (1m)						
	Bq.cm ⁻²		µSv.h ⁻¹	Bq.cm ⁻²	Bq.m ⁻²	Bq.m ⁻³	mSv.year ⁻¹		
Sludge pump station basement	0.000	0.110	0.070	0.110	1100	0.001	0.014	0.140	0.154
Sludge pump station basement	0.000	0.110	0.110	0.140	1400	0.001	0.017	0.220	0.237
Sludge pump station basement	0.000	0.150	0.120	0.130	1300	0.001	0.016	0.240	0.256
Sludge pump station basement	0.000	0.150	0.140	0.130	1300	0.001	0.016	0.280	0.296
Sludge pump station basement	0.000	0.080	0.160	0.170	1700	0.002	0.021	0.320	0.341
Sludge pump station basement	0.010	0.150	0.170	0.190	1900	0.002	0.024	0.340	0.364
Sludge pump station basement	0.000	0.120	0.160	0.170	1700	0.002	0.021	0.320	0.341
Sludge pump station basement	0.000	0.080	0.170	0.190	1900	0.002	0.024	0.340	0.364
Sludge pump station basement	0.000	0.030	0.180	0.200	2000	0.002	0.025	0.360	0.385
Sludge pump station basement	0.000	0.110	0.190	0.210	2100	0.002	0.026	0.380	0.406
Sludge pump station basement	0.000	0.100	0.200	0.190	1900	0.002	0.024	0.400	0.424
Sludge pump station basement	0.000	0.260	0.230	0.240	2400	0.002	0.030	0.460	0.490
Average	0.001	0.093	0.162	0.170	1698	0.002	0.021	0.324	0.346
Maximum	0.010	0.260	0.240	0.250	2500	0.003	0.031	0.480	0.506
Minimum	0.000	0.030	0.060	0.090	900	0.001	0.011	0.120	0.131
90 th Percentile	0.010	0.148	0.200	0.200	2000	0.002	0.025	0.400	0.425

5.2.4 Untreated Water

Workers at the Water Treatment Plant are not expected to come in direct contact with the untreated water (through immersion) or to ingest some of the untreated water either as a source of water or unintentionally. Direct ingestion of water or external gamma radiation as a result of the untreated water is, therefore, not considered a viable exposure route for worker exposure.

To evaluate the potential contribution of the untreated AMD Water, the following is assumed. It is only certain workers operating in certain sections of the Water Treatment Plant that may potentially come in contact with untreated AMD Water. The only potential exposure routes of concern are accidental ingestion of water and the inhalation and ingestion of water vapour that may be present. Assuming that a specific worker as the most exposed person working at the plant ingests 50 mL AMD Water in this way every hour for 2,000 per year. This equates to a water ingestion rate of 100 L.year⁻¹.

Table 4.3 presents the water ingestion doses to different age groups, which shows that an adult AMD Water ingestion rate of 600 L.year⁻¹ would result in an ingestion dose of about 0.4 mSv.year⁻¹. This means the 100 L.year⁻¹ ingestion rate would result in an annual ingestion dose of about 0.07 mSv.year⁻¹. Even an ingestion rate of 150 L.year⁻¹ (or 75 mL per day) would still result in an ingestion dose of less than 0.1 mSv.year⁻¹.

5.2.5 Maintenance Activities

Section 3.9.2 describes the maintenance activities that are required at the Water Treatment Plant, with additional information presented in AECOM (2015a). Specific lines that need maintenance or repair are taken out of operations, without affecting the other operating lines in the process. Flushing of components is done when in maintenance mode, while pigging is done for those components that transfer sludge into the system.

No data is available at this stage to estimate what the level of contamination would be in different components of the system, which will differ for those in contact with AMD water, treated water or sludge generated during the water treatment process. It might be that the dose rates are similar to those observed during the normal operating conditions (see Section 5.2.2), but shorter exposure periods and thus lower dose rate levels for the maintenance activities.

It is, therefore, proposed that dose rate measurements be taken during the maintenance activities until it can be demonstrated with certainty that the maintenance activities performed in the different sections of the plant meet the necessary regulatory compliance criteria. The procedures to follow can be included in the Method Statement and safety files for approvals before maintenance work commences (see Section 6.3).

5.2.6 Discussion

The most recent results available for worker exposure suggest that on average, the exposure levels are in the order of 0.35 mSv.year⁻¹ (with the 90th percentile of 0.43 mSv.year⁻¹), which is above the dose constraint of 0.25 mSv.year⁻¹ for members of the public (as workers). However, if the background value of 0.2 mSv.year⁻¹ is subtracted from the measured values, then it is clear that the Water Treatment Plant itself makes little contribution to the total effective dose to workers at the plant.

The results showed that under normal operating conditions workers at the Water Treatment Plant do not have to be registered as Occupationally Exposed Persons (OEP), with a non-controlled area classification for all areas of the plant. The standard 2,000 hours per annum occupancy was assumed, which means that more realistic occupancy factors can be defined for each section of the plant that will reduce the

calculated exposure even further (see Section 6.3). In addition, the treated water released to the Blesbok Spruit does not pose a radiation exposure condition to the workers.

It is unlikely that a worker at the Water Treatment Plant would ingest a significant volume of untreated AMD Water regularly. Assuming conservative conditions, the potential water ingestion dose is less than less than $0.1 \text{ mSv}\cdot\text{year}^{-1}$.

No data are available for worker radiation exposure conditions during maintenance activities, although it is expected to be lower than during normal operating conditions due to shorter exposure periods. In addition, equipment and components are flushed during maintenance, while pigging is applied in pipelines used to transfer sludge. It is proposed that surveys be conducted during maintenance activities.

5.3 Sludge Management

5.3.1 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. 3 Shaft, No. 4 Shaft or the deep sludge disposal boreholes. Therefore, the HDS itself is not handled during the emplacement operation and workers also do not come in direct contact with the sludge. This means that occupational exposure of workers to the sludge disposal operation is not possible and, therefore, does not pose a radiation exposure condition to workers during normal operating conditions.

5.3.2 Maintenance Activities

All maintenance activities associated with the sludge disposal operations are done at the surface after pumps and pipelines are extracted from the shaft. Workers are not expected to go down in the shafts themselves for maintenance activities.

Like the Water Treatment Plant itself, no data is available at this stage to estimate what the level of contamination would be in the pumps or pipelines extracted from underground for maintenance. Therefore, it is proposed that dose rate measurements be taken during the maintenance activities until it can be demonstrated with certainty that the maintenance activities performed on the pumps and pipelines meet the necessary clearance criteria. This should include the collection of samples of scales that might have accumulated on any of the equipment for full-spectrum analysis (see Section 6.3).

5.3.3 Discussion

Workers involved in the sludge disposal operations are limited to maintenance activities of the pumps and pipelines, which are done at the surface. Workers do not have to be registered as Occupationally Exposed Persons (OEP), but a survey programme is proposed to gather data to estimate the level of contamination that can be expected on the pumps and pipelines during maintenance activities, including full-spectrum analysis of scales accumulated on equipment.



6 Conclusions and Recommendations

6.1 General

Consistent with the purpose and objective of the assessment (see Section 2.3.3), this report evaluated and presented the radiological public and worker safety assessment for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations. The primary objective was 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 was 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.

6.2 Conclusions

6.2.1 Public Safety Assessment Analysis

The following conclusions were drawn from the public safety assessment analysis for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, which can be divided into the Water Treatment Plant and the sludge disposal operations:

- Due to the physical security measures implemented and maintained at the Water Treatment Plant, uncontrolled public access is not possible, with the result that the plant itself does not serve as a source of radiation exposure to members of the public.
- The release of treated water to the Blesbok Spruit may serve as a source of radiation exposure to members of the public. 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 reduces the total effective dose to less than $20 \mu\text{Sv}\cdot\text{year}^{-1}$.
- Given the current understanding of the sludge disposal operation in the Eastern Basin void, along with the associated hydrogeological and coupled geochemical conceptual model, a complete Source-Pathway-Receptor linkage, with the public as the final receptor, remains uncertain and may only materialise after 10,000 years. For a realistic set of parameter values, the expected water ingestion dose for this timeframe is less than $1,000 \mu\text{Sv}\cdot\text{year}^{-1}$.

6.2.2 Worker Safety Assessment Analysis

The following conclusions were drawn from the worker safety assessment analysis for the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, which can be divided into the Water Treatment Plant and the sludge disposal operations, including normal operations and accident conditions:

- Given the observed and expected radiation exposure conditions associated with the DWS Eastern Basin Water Treatment Plant and Sludge Management Operations, workers do not have to be registered as OEP.

- The treated water is discharged by gravity from the treated water sump into the Blesbok Spruit, with the result that workers are not further exposed to the treated water (i.e., no radiological impact to workers). This means that all areas at the DWS Eastern Basin Water Treatment Plant can be classified as uncontrolled areas (see Section 2.2.7).
- The results from the surface contamination and gamma survey suggest that on average, the exposure levels are in the order of $0.35 \text{ mSv}\cdot\text{year}^{-1}$ (with the 90th percentile of $0.43 \text{ mSv}\cdot\text{year}^{-1}$), which is above the dose constraint of $0.25 \text{ mSv}\cdot\text{year}^{-1}$ for members of the public (as workers). However, if the background value of $0.2 \text{ mSv}\cdot\text{year}^{-1}$ is subtracted from the measured values, then it is clear that the Water Treatment Plant itself makes little contribution to the total effective dose to workers at the plant.
- No data are available for worker radiation exposure conditions during maintenance activities, although it is expected to be lower than during normal operating conditions due to shorter exposure periods. In addition, equipment and components are flushed during maintenance, while pigging is applied in pipelines used to transfer sludge. It is proposed that surveys be conducted during maintenance activities.

6.2.3 General Conclusion

The full-spectrum radioanalysis of the sludge reveals radionuclide levels exceeding $500 \text{ Bq}\cdot\text{kg}^{-1}$, which surpasses the threshold for exemption from regulatory controls. Additionally, the projected radiation doses to the public, including non-OEP workers, exceed the dose constraint of $250 \mu\text{Sv}\cdot\text{year}^{-1}$. As a result, it cannot be confidently recommended to grant exemption from regulatory controls as stipulated in Regulation 388 and detailed in Section 2.2 of this report. Section 6.3 offers specific recommendations aimed at obtaining a more complete record of activity concentrations in the sludge, as well as untreated and treated water, to enhance confidence in the assessment results.

6.3 Recommendations

Due to historical mining and associated disturbed underlying geology, ingress of water from the surface and the subsequent abstraction of water to maintain the ECL, the conceptual hydrogeological and coupled geochemical model of the Eastern Basin is considerably more complex than what is portrayed by Exigo Sustainability (2017b). This led to the development of a comprehensive hydrogeological flow and contaminant migration model by Artesium (2024b), which provided significant insight into understanding the sludge disposal operations.

- It is recommended that the model developed by Artesium (2024b) be maintained and updated as required with improved monitoring data and information, which will lead to a greater level of certainty in the sludge disposal operation.

The Directive by DWS (Ref: 16/2/7/C231/C068) already requires the implementation of a comprehensive geohydrological and geochemical monitoring programme, with a wide spectrum of variables to be assessed on a daily and weekly basis (including Uranium). Therefore:

- It is recommended that this monitoring be continued in line with the Directive and to the satisfaction of the DWS.

In addition to recommended monitoring, it is recommended that the following be included in the monitoring programme to facilitate radiation protection for workers and members of the public and to comply with the NNR recommendation for baseline monitoring as outlined in RG-002:

- Full-spectrum analysis, including total uranium and thorium, of the AMD water abstracted from the

Eastern Basin. The full spectrum analysis (U-238, U-235, Th-232 and their progeny) should be repeated annually, while the total uranium and thorium analysis should be repeated monthly.

- Full-spectrum analysis, including total uranium and thorium, of the sludge generated in the water treatment plant. Since the sludge contains a high volume of moisture, the liquid and solids fractions of the sample should be analysed separately. The full-spectrum analysis (U-238, U-235, Th-232 and their progeny) should be repeated annually, while the total uranium and thorium analysis should be repeated monthly.
- Full-spectrum analysis, including total uranium and thorium, of the treated water before released to the Blesbok Spruit. The full spectrum analysis (U-238, U-235, Th-232 and their progeny) should be repeated biannually, while the total uranium and thorium analysis should be repeated monthly.

No data is available for potential exposure to workers during maintenance activities at the Water Treatment Plant and the sludge disposal operations.

- It is recommended that radiation surveys (e.g., gamma dose rate and surface contamination) be performed during scheduled maintenance activities until it can be demonstrated with certainty that there is no contamination on equipment and components above the clearance levels for release of the material into the public domain.



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Appendix A: Radionuclide and Element Dependent Data

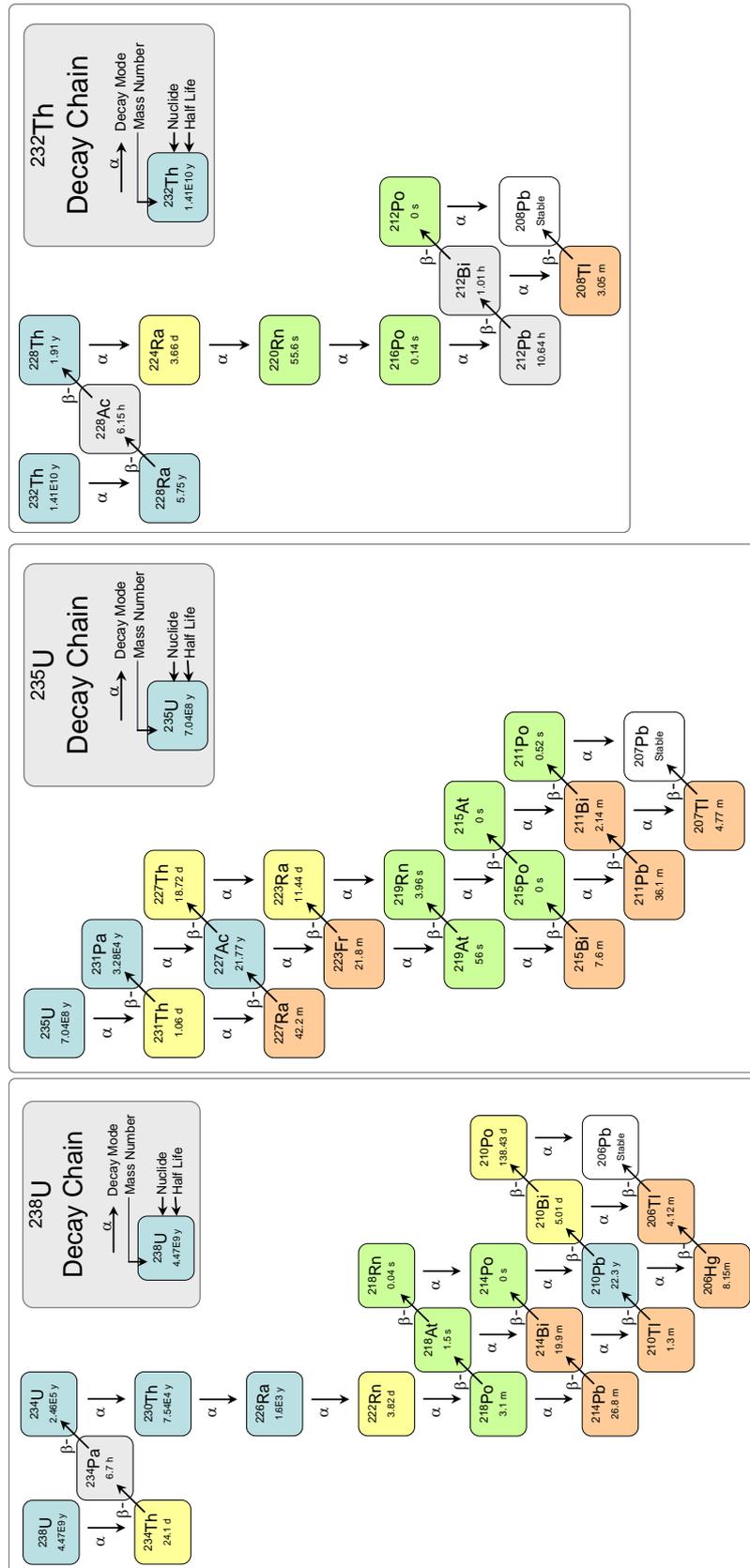


Figure A 1 Schematic illustrations of the U-238, U-235, and Th-232 decay chains.

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

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

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

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

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

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

Appendix B: Necsa Radioanalytical Laboratory Results

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Date: **2016-10-13**
 Report number: **RS2016-4006-01**
 Pages: **3**
 Order no.: **Arconsa-Necsa-001/2016**

Final Analysis Report

Radioactivity analysis of water

Compiled by: **A Rasutha**

Checked by: **N Sono**

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② Company Secretary First Corporate Secretaries (Pty) Ltd

REG 2000/003735/06

Job number: **RS2016-4006-01** Page 2 of 3

1. SERVICE
 Analysis of water samples for gross alpha/beta-activity and for selected radionuclides in the uranium and thorium decay series.
 Number of samples received: 1
 Date samples received: 2016-09-07

2. SAMPLE PREPARATION AND ANALYSIS

Method	Description	Completed	Assayer	Technical Signatory
WIN-121	Filtration of suspended solids	2016-10-04	L Seshoka	O Mathekga
WIN-161	Gross alpha/beta-analysis	2016-10-10	Q Daniels	E Nhlapo
WIN-124	Radium by alpha spectrometry	2016-10-13	A Mokgalane	C Zwane
WIN-145	Uranium by alpha spectrometry	2016-10-13	C Zwane	A Rasutha
WIN-142	Thorium by alpha spectrometry	2016-10-13	N Sono	A Rasutha
WIN-129	Polonium-210 by alpha spectrometry	2016-10-13	T Kota	A Rasutha

Results indicated in **bold in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory.*

3. RESULTS

3.1 Results are attached as an appendix to this report.
 3.2 Reported results relate only to the sample portions tested.
 3.3 The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities. Errors associated with unavoidable differences between particle energies of the calibration standards and samples, are not accounted for in the reported uncertainty which is mainly based on counting statistics. The reported uncertainty may therefore be an underestimation of the true uncertainty.

4. QUALITY ASSURANCE

4.1 RadioAnalysis is a SANAS accredited laboratory (Testing Laboratory T0111) based on ISO/IEC Standard 17025. All analytical methods are documented in the RadioAnalysis Quality System.
 4.2 Results in this report were obtained from one or more individual test reports produced by accredited or non-accredited methods.

- Test reports containing results obtained from methods included in the SANAS Schedule of Accreditation, are verified and signed by SANAS Technical Signatories for those methods.
- Test reports containing results obtained from methods not included in the SANAS Schedule of Accreditation, are verified and signed by qualified competent analysts for those methods. Results reported for non-accredited methods are indicated in bold.

 4.3 The compiled report is checked by a person other than the compiler for accuracy of data transcription.
 4.4 The RadioAnalysis Laboratory keeps the original signed hard copy of this report on record for three years.

Job number: **RS2016-4006-01** Page 3 of 3

APPENDIX 1: ANALYTICAL RESULTS

Activity concentrations of nuclides in filtered samples

Unit: mBq/L

Field Code	Treated Water		
Lab Code	RS2016-4006X001		
Nuclide	Value	Unc.	MDA
²³⁸ U	34.8	4.1	1.3
²³⁴ U	60.1	5.5	1.3
²³⁰ Th	29.0	6.5	22
²²⁶ Ra	25.4	3.9	1.6
²¹⁰ Po	9.06	3.24	3.2
²³⁵ U	1.60	0.19	0.061
²²⁷ Th	5.42	2.47	5.3
²²³ Ra	-0.65	1.4	1.8
²³² Th	3.98	1.78	2.2
²²⁸ Th	9.98	3.26	7.5
²²⁴ Ra	< MDA		5.7
Gross alpha	340	130	390
Gross beta	1320	140	380

*Results indicated in **bold** in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory

Notes:

1. If a measured value (**Value** column) was recorded, it is reported regardless if the value is less than the minimum detectable activity concentration (**MDA** column) or even if the value is negative. In the case where a value could not be obtained, a less than MDA ("**<** MDA") will be indicated.
2. The reported uncertainty (**Unc.** column) is quoted at 1 sigma (or coverage factor k = 1). The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements. No uncertainty value is reported if a less than MDA ("**<** MDA") is indicated in the **Value** column.
3. The minimum detectable activity concentration (**MDA** column) is calculated with a 95% confidence level.
4. A value is reported with 3 significant digits if it is greater than the MDA value and the associated uncertainty will be reported the same precision. If a value is less than the MDA, the value and its associated uncertainty are reported with 2 significant digits regardless of their respective magnitudes. A MDA value is always reported with 2 significant digits.

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Contact: **Mr ID Kruger**
 Company: **ARCONSA**
 Address: **P O Box 34118**

Glenstantia
0010

Date: **10 November 2016**
 Report number: **RS2016-4005-01**
 Pages: **3**
 Your reference: **Arconsa-Necsa-001/2016**

Analysis Report

Radioactivity analysis of solids

Compiled by: **MJ Raven**

Checked by: **N Seaga**

The views and opinions of authors expressed in this report do not necessarily state or reflect those of Necsa. The liability of Necsa is limited to the "General Conditions of Sale", which is available on request.

1. SERVICE

Analysis of solid samples for gross alpha and beta analysis and for selected radionuclides in the uranium and thorium decay series.
 Number of sample(s) received: 2
 The sample(s) were received on: 2016-09-07
 Purchase order received on: 2016-09-30

2. SAMPLE PREPARATION AND ANALYSIS

*Results indicated in **bold** in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory*

Method	Description	Completed	Assayer	Verified by
WIN-114	Dry, mill and homogenise samples	2016-10-05	E Molhabane	O Mathekga
WIN-138	Gross alpha/beta analysis on solids	2016-10-13	S Zhou	E Nhlapo
WIN-167	Uranium/Thorium by neutron activation analysis	2016-11-03	A Sathekge	N Seaga
WIN-101	²²⁶ Ra, ²²⁸ Ra, ²²⁸ Th, ⁴⁰ K by gamma spectrometry	2016-11-03	R Gaven	A Sathekge
WIN-158	²¹⁰ Pb by low energy gamma spectrometry	2016-10-25	M Rapetsoa	A Sathekge

3. RESULTS

- 3.1 Results are attached as an appendix to this report.
- 3.2 Results report are related only to sample portions tested.
- 3.3 The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities. Errors associated with unavoidable differences between particle energies of the calibration standards and samples, are not accounted for in the reported uncertainty which is mainly based on counting statistics. The reported uncertainty may therefore be an underestimation of the true uncertainty.
- 3.4 ²³⁴U activity was derived from the ²³⁸U activity, by using natural isotopic ratio

4. QUALITY ASSURANCE

- 4.1 RadioAnalysis is a SANAS accredited laboratory (Testing Laboratory T0111) based on ISO/IEC Standard 17025. All analytical methods are documented in the RadioAnalysis Quality System.
- 4.2 Results in this report were obtained from one or more individual test reports produced by accredited or non-accredited methods.
 - Test reports containing results obtained from methods included in the SANAS Schedule of Accreditation, are verified and signed by SANAS Technical Signatories for those methods.
 - Test reports containing results obtained from methods not included in the SANAS Schedule of Accreditation, are verified and signed by qualified competent analysts for those methods.
 - The individual test reports are available upon request
- 4.3 The compiler is the Technical Expert for all the methods.
- 4.4 The compiled report is checked by a person other than the compiler for accuracy of data transcription.
- 4.5 The RadioAnalysis Laboratory keeps the original signed hard copy of this report on record for three years.

APPENDIX 1: ANALYTICAL RESULTS

Activity concentrations of nuclides

Unit: Bq/kg

Field code	Soil			Soil (Sludge)		
	RS2016-4005X001					
Lab code	RS2016-4005X001			RS2016-4005X002		
Nuclide	Value	Unc.	MDA	Value	Unc.	MDA
²³⁸ U	115	3	0.62	503	12	0.63
²³⁴ U	116	3	0.63	507	12	0.63
²²⁶ Ra	1180	40	59	538	31	59
²¹⁰ Pb	1820	110	270	< MDA		220
²³² U	5.29	0.14	0.029	23.1	0.5	0.029
²³² Th	18.3	1.1	1.6	< MDA		3.7
²²⁸ Ra	< MDA		120	76	26	77
²²⁸ Th	< MDA		170	< MDA		160
⁴⁰ K	760	118	300	300	110	330
Gross alpha	8020	1220	1900	2870	710	1300
Gross beta	2780	150	230	958	86	150

*Results indicated in **bold** in this report were obtained from methods that are not included in the SANAS Schedule of Accreditation for this laboratory*

Notes:

- 1. If a measured value (Value column) was recorded, it is reported regardless if the value is less than the minimum detectable activity concentration (MDA column) or even if the value is negative. In the case where a value could not be obtained, a less than MDA (< MDA) will be indicated.
- 2. The reported uncertainty (Unc. column) is quoted at 1 sigma (or coverage factor k = 1). The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements. No uncertainty value is reported of a less than MDA (< MDA) is indicated in the Value column.
- 3. The minimum detectable activity concentration (MDA column) is calculated with a 95% confidence level.
- 4. A value is reported with 3 significant digits if it is greater than the MDA value and the associated uncertainty will be reported the same precision. If a value is less than the MDA, the value and its associated uncertainty are reported with 2 significant digits regardless their respective magnitudes. A MDA value is always reported with 2 significant digits.

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RADIOACTIVITY ANALYSIS TEST REPORT

Quotation number	SOQ0000339	Purchase order number	ACS-000-P03-2024
Report number	JOB00002321-01	Report date	2025/01/31

1 Particulars of the customer

Customer name	Aquism Consulting (Pty) Ltd	Contact person	Dr. Japie van Blerk
Address	109 Bosduif Crescent Wierda Park 0157	Tel:	082 806 6159
		Email:	aquism@netactive.com

2 Sample Information

Sample descriptions	Sludge		
Sample receipt date	2024/11/14	Number of samples	01

3 Laboratory Environmental Conditions

Temperature	12 °C – 30 °C	Relative Humidity	0 – 80%
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4 Test Results

Sample Number: JOB00002321X001		Customer ID: ERB Sludge				
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
YRGI-0307	RA-QMS-WIN-0226	NO	U-238	Bq/kg	178	5
YRGI-0307	RA-QMS-WIN-0226	NO	U-234	Bq/kg	179	5
YRGI-0305	RA-QMS-WIN-0101	YES	Ra-226	Bq/kg	985	32
YRGI-0309	RA-QMS-WIN-0158	NO	Pb-210	Bq/kg	< 240	
YRGI-0307	RA-QMS-WIN-0226	NO	U-235	Bq/kg	8.19	0.23
YRGI-0307	RA-QMS-WIN-0226	NO	Th-232	Bq/kg	3.40	0.56
YRGI-0305	RA-QMS-WIN-0101	YES	Ra-228	Bq/kg	118	32
YRGI-0305	RA-QMS-WIN-0101	YES	Th-228	Bq/kg	< 78	
YRGI-0305	RA-QMS-WIN-0101	YES	K-40	Bq/kg	447	137

4.1 Explanatory notes

- A result with its associated uncertainty is reported only if it is greater than the minimum detectable activity (MDA) of the relevant test measurement, else the minimum detectable activity value will be reported with a less than symbol (<) in front of the value.
- Minimum detectable activity is reported with a confidence level of 95%. Measurement of uncertainty is reported with a coverage factor of k=1
- The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements.
- Results indicated in bold were obtained from methods that are not included in the SANAS schedule of Accreditation for this laboratory.

Job Card Number: **JOB00002321**

Purchase Order Number: **ACS-000-P03-2024**

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5 Date(s) of performance of laboratory activities

Method / Activity	Date completed	Analyst
RA-QMS-WIN-0114	2024-12-04	L Seshoka
RA-QMS-WIN-0226	2024-01-20	MA Satheke
RA-QMS-WIN-0101	2024-12-23	MA Satheke
RA-QMS-WIN-0158	2024-12-17	K Hotane
Report compilation	2025-01-31	MA Satheke

5.1 Explanatory notes

- The date of completion is the date on which the total number of samples have been completed by an activity or method.

6 OPINIONS AND INTERPRETATIONS

- None

7 Disclaimers

Results relate only to samples tested as received from client. Necsa are not liable for errors that are due to sampling and transport of samples by external parties. The results, opinions and/or interpretations expressed are based only on the samples received and tests performed. Opinions and interpretations are outside of the scope of SANAS accreditation. Results indicated in bold were obtained from methods that are not included in the SANAS schedule of Accreditation for this laboratory. Reports issued by NECSA shall not be reproduced, except in full, without the written approval of NECSA. Only the original version of this report, as kept by NECSA, shall be used in case of a dispute.

Compiler
 MA Satheke – Senior Technician

Technical Signatory
 MMF Seaga – Section Head

Authoriser
 EN Moalosi – Manager


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END OF REPORT

Job Card Number: **JOB00002321**

Purchase Order Number: **ACS-000-P03-2024**

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RADIOACTIVITY ANALYSIS TEST REPORT

Quotation number	SOQ00000337	Purchase order number	ASC-000-PO3-2024
Report number	JOB00002320-01	Report date	2025/01/31

1 Particulars of the Customer

Customer name	AQUISIM CONSULTING (PTY) LTD	Contact person	Dr Japie Van Blerk
Address	109 BOSDUIF CRESCENT WIERDAPARK 0157	Tel:	082 806 6159
		Email:	aquisim@netactive.co.za

2 Sample Information

Sample descriptions	Liquid samples	Number of samples	04
Sample receipt date	2024/11/12		
Sampling date	Not Applicable		

3 Laboratory Environmental Conditions

Temperature	12 °C – 30 °C	Relative Humidity	0 – 80%
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4 Test Results

Sample ID: JOB00002320 X001		Customer ID: AMD Water				
Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
YRRC-0510	RA-QMS-WIN-0145	Yes	234U	mBq/L	596	46
YRRC-0510	RA-QMS-WIN-0145	Yes	235U	mBq/L	25.9	2.0
YRRC-0510	RA-QMS-WIN-0145	Yes	238U	mBq/L	563	44
YRRC-0511	RA-QMS-WIN-0142	Yes	227Th	mBq/L	<9.0	
YRRC-0511	RA-QMS-WIN-0142	Yes	228Th	mBq/L	<9.9	
YRRC-0511	RA-QMS-WIN-0142	Yes	230Th	mBq/L	30.1	6.4
YRRC-0511	RA-QMS-WIN-0142	Yes	232Th	mBq/L	<6.5	
YRRC-0506	RA-QMS-WIN-0124	Yes	223Ra	mBq/L	<11	
YRRC-0506	RA-QMS-WIN-0124	Yes	224Ra	mBq/L	<7.9	
YRRC-0506	RA-QMS-WIN-0124	Yes	226Ra	mBq/L	353	19
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross alpha	mBq/L	891	90
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross Beta	mBq/L	<850	

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Job Card Number: [JOB00002320](#)

Purchase Order Number: [ASC-000-PO3-2024](#)

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RADIOACTIVITY ANALYSIS TEST REPORT

Sample ID: JOB00002320 X002	Customer ID: ERB Eff
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Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
YRRC-0510	RA-QMS-WIN-0145	Yes	234U	mBq/L	516	45
YRRC-0510	RA-QMS-WIN-0145	Yes	235U	mBq/L	21.7	1.9
YRRC-0510	RA-QMS-WIN-0145	Yes	238U	mBq/L	472	42
YRRC-0511	RA-QMS-WIN-0142	Yes	227Th	mBq/L	<14	
YRRC-0511	RA-QMS-WIN-0142	Yes	228Th	mBq/L	<12	
YRRC-0511	RA-QMS-WIN-0142	Yes	230Th	mBq/L	50.4	10.1
YRRC-0511	RA-QMS-WIN-0142	Yes	232Th	mBq/L	9.07	3.14
YRRC-0506	RA-QMS-WIN-0124	Yes	223Ra	mBq/L	<11	
YRRC-0506	RA-QMS-WIN-0124	Yes	224Ra	mBq/L	<25	
YRRC-0506	RA-QMS-WIN-0124	Yes	226Ra	mBq/L	184	15
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross alpha	mBq/L	1010	120
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross Beta	mBq/L	1440	120

Sample ID: JOB00002320 X003 **Customer ID: ESW-01**

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
YRRC-0510	RA-QMS-WIN-0145	Yes	234U	mBq/L	67.8	8.1
YRRC-0510	RA-QMS-WIN-0145	Yes	235U	mBq/L	1.39	0.25
YRRC-0510	RA-QMS-WIN-0145	Yes	238U	mBq/L	30.2	5.5
YRRC-0511	RA-QMS-WIN-0142	Yes	227Th	mBq/L	10.9	3.7
YRRC-0511	RA-QMS-WIN-0142	Yes	228Th	mBq/L	<11	
YRRC-0511	RA-QMS-WIN-0142	Yes	230Th	mBq/L	67.2	12.1
YRRC-0511	RA-QMS-WIN-0142	Yes	232Th	mBq/L	12.3	3.0
YRRC-0506	RA-QMS-WIN-0124	Yes	223Ra	mBq/L	<12	
YRRC-0506	RA-QMS-WIN-0124	Yes	224Ra	mBq/L	<18	
YRRC-0506	RA-QMS-WIN-0124	Yes	226Ra	mBq/L	<6.0	
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross alpha	mBq/L	243	39
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross Beta	mBq/L	956	90

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Job Card Number: [JOB00002320](#)

Purchase Order Number: [ASC-000-PO3-2024](#)

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Sample ID: JOB00002320 X004 Customer ID: ESW-03

Service Code	Method	Accredited	Parameter	Units	Activity	Uncertainty
YRRC-0510	RA-QMS-WIN-0145	Yes	234U	mBq/L	321	24
YRRC-0510	RA-QMS-WIN-0145	Yes	235U	mBq/L	13.3	1.0
YRRC-0510	RA-QMS-WIN-0145	Yes	238U	mBq/L	289	22
YRRC-0511	RA-QMS-WIN-0142	Yes	227Th	mBq/L	<7.6	
YRRC-0511	RA-QMS-WIN-0142	Yes	228Th	mBq/L	<9.1	
YRRC-0511	RA-QMS-WIN-0142	Yes	230Th	mBq/L	34.7	7.1
YRRC-0511	RA-QMS-WIN-0142	Yes	232Th	mBq/L	10.3	2.6
YRRC-0506	RA-QMS-WIN-0124	Yes	223Ra	mBq/L	<10	
YRRC-0506	RA-QMS-WIN-0124	Yes	224Ra	mBq/L	<8.2	
YRRC-0506	RA-QMS-WIN-0124	Yes	226Ra	mBq/L	<9.0	
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross alpha	mBq/L	501	72
YRAB-0202	RA-QMS-WIN-0161	Yes	Gross Beta	mBq/L	1400	110

4.1 Explanatory notes

(a) A result with its associated uncertainty is reported only if it is greater than the minimum detectable activity (MDA) of the relevant test measurement, else the minimum detectable activity value will be reported with a less than symbol ("<") in front of the value.

(b) Minimum detectable activity is reported with a confidence level of 95%. Measurement of uncertainty is reported with a coverage factor of k=1

(c) The uncertainty is calculated mainly from counting statistics and it is not the standard deviation obtained from replicate measurements.

(d) The method for gross alpha/beta-activity is intended to merely be a screening technique and gives only a first order estimate of total activities.

(e) Results indicated in bold were obtained from methods that are not included in the SANAS schedule of Accreditation for this laboratory.

5 Date(s) of performance of laboratory activities

Method / Activity	Date completed	Analyst
RA-QMS-WIN-0121: Filtration of suspended solids	2024-12-13	HO Mathekga
RA-QMS-WIN-0161: Gross alpha/beta-analysis	2025-01-29	NN Lebepe
RA-QMS-WIN-0124: Radium by alpha spectrometry	2025-01-30	N Yawa/MA Mokgalane
RA-QMS-WIN-0145: Uranium by alpha spectrometry	2025-01-30	NN Lebepe
RA-QMS-WIN-0142: Thorium by alpha spectrometry	2025-01-30	TM Mokatse
Report Compilation	2025-01-31	NN Lebepe

5.1 Explanatory notes

(a) The date of completion is the date on which the total number of samples have been completed by an activity or method.

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Job Card Number: **JOB00002320**

Purchase Order Number: **ASC-000-PO3-2024**

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Job Card Number: **JOB00002320**

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6 Opinions and Interpretations

(a) None

7 Disclaimers

Results relate only to samples tested as received from client. NECSA is not liable for errors that are due to sampling and transporting of samples by external parties. The results, opinions and/or interpretations expressed are based only on the samples received and tests performed. Opinions and interpretations are outside of the scope of SANAS accreditation. Reports issued by NECSA shall not be reproduced, except in full, without the written approval of NECSA. Only the original version of this report, as kept by NECSA, shall be used in case of a dispute.

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 NN Lebepe
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END OF REPORT

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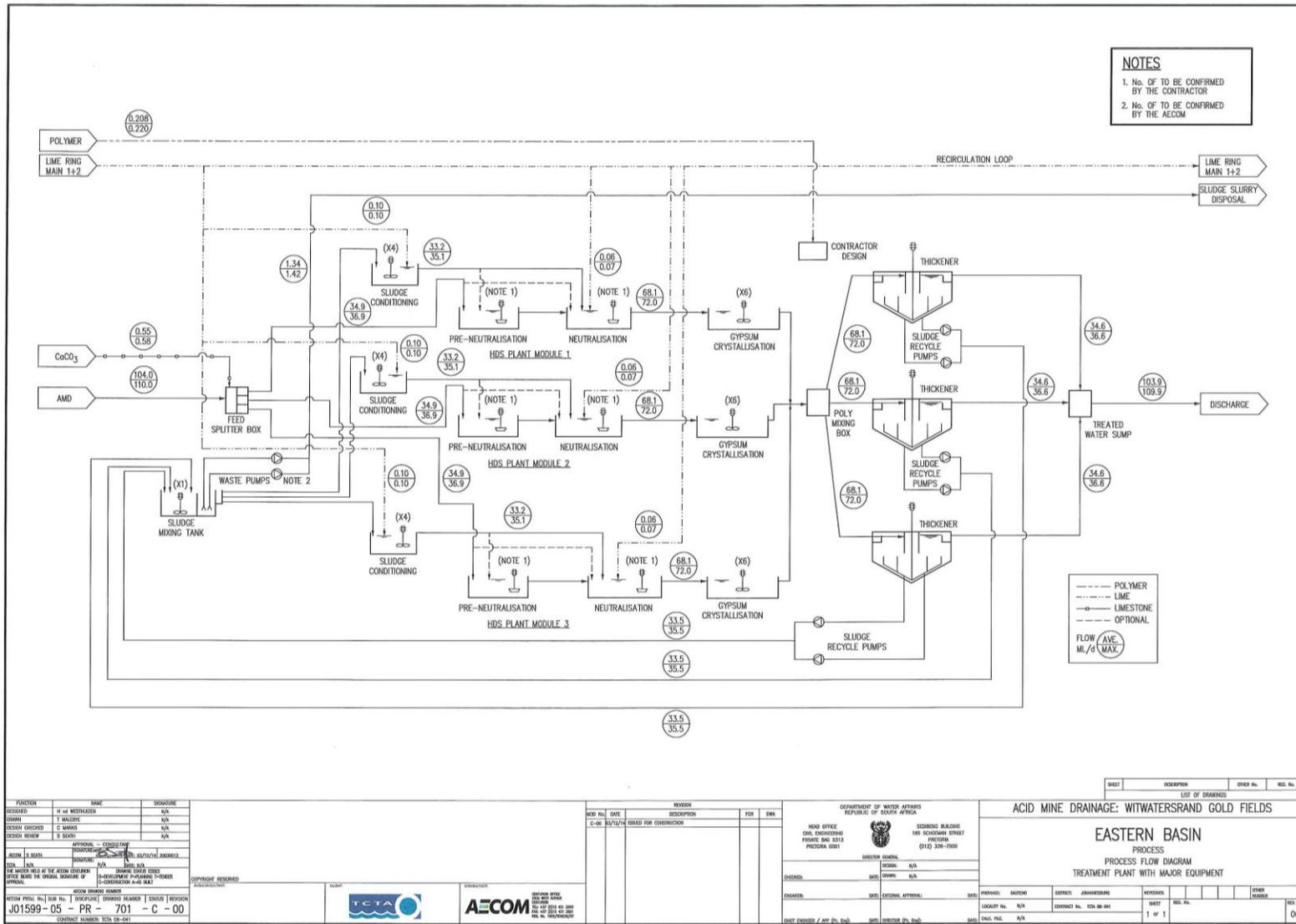


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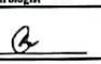
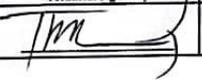
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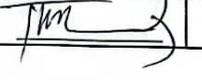
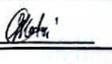
Purchase Order Number: **ASC-000-PO3-2024**

Appendix C:
Process Flow Diagram for the DWS Eastern Basin Water
Treatment Plant



Appendix D:
Calibration Certificates used for the Contamination and Dose
Rate Survey at the DWS Eastern Basin Water Treatment Plant

Calibration Certificate		Certificate No : CQ-KVG-24/9389		Page 1 of 3	
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Job card details					
Question Number : SOQ0000430-1		Purchase Order Number : CASH			
Job Card Number : JOB0001874					
1. Particulars of the customer			Instrument details		
Customer Name : MJC Radiological and Environmental Services			Manufacturer : Thermo Scientific		
Address : Casa Uvengo 106, Lillierona Boulevard, Uvongo KZN, 4270			Instrument Make : RadEye G-10 Gamma Survey Meter		
Contact Person : Gcimumazi Sibanyoni			Instrument Ser No : 0575		
			Calibration Range : From: 2,0 µSv/h to 10,0 mSv/h		
			MTE Number : 0575		
1.1. Details of the Calibrated Instrument					
Date of Receipt : 18-Oct-24		Expiry Date : Jan-26		(Week 1)	
Date of Calibration : 02-Nov-24		Date of Issued Certificate : 02-Nov-24			
2. Details of the calibration					
2.1. Environmental conditions		Temperature : 24.2 °C (Allowable limits (20 °C ± 5 °C))	Atmospheric Pressure : 872.1 mBar (700 to 900) mBar	Relative Humidity : 35.8 % (10 to 90) %RH	
2.2. Calibration procedure		CAL-QMS-WIN-0027 Calibration Spreadsheet : RadEye G-10 Gamma Survey Meter			
3. Calibration procedure					
3.1. The instrument was calibrated for gamma radiation from ¹³⁷ Cs. The instrument was positioned, with the shutter closed, (where applicable) in the radiation beam with the axis of the probe normal to the beam axis.					
3.2. In order to evaluate the instrument's response to variation in radiation energy it was also exposed to radiation from ²⁴¹ Am.					
3.3. The effective point of measurement was taken at a point at the center of the cross marked at back of the instrument.					
3.4. The pre-calibration checks were satisfactory and there was no visible damage. And there were no batteries in the instrument.					
4. Instrument background reading					
The instrument reading in a low background area was <0.25 µSv/h The instrument background reading was 0.13888888888889 µSv/h					
		Calibration Laboratory ISO 17025:2017			
Calibrated by: B Ramaphakela	Checked by: T.M. Ramashidzha	Approved by: E.N. Moalosi			
Metrologist	Technical Signatory	Laboratory Manager			
					

Calibration Certificate		Certificate No : CQ-KVG-24/9389		Page 2 of 3	
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5. Variation of response to radiation energy					
For Am-241 the instrument reads high by a factor 1,706 and is not suitable for measuring X- or gamma ray energies below 60keV. An acceptable response factor is between 0.67 and 1.5					
6. Results of the energy response factor					
True Ambient Dose Equivalent Rate µSv/h		Instrument readings µSv/h		factor	
²⁴¹ Am	¹³⁷ Cs	²⁴¹ Am	¹³⁷ Cs	1,763	
50,070	50,038	90,91	51,54		
Scales used for measurements		10 - 100 µSv/h		10 - 100 µSv/h	
The energy response factor is calculated by means of the instrument's readings for ²⁴¹ Am and ¹³⁷ Cs when exposed to the indicated exposure rates as follows:					
Factor = $\frac{\text{Instrument reading for Am}}{\text{Instrument reading for Cs}} \times \frac{\text{True Cs exposure rate}}{\text{True Am exposure rate}}$					
8. Results					
Scale	Instrument reading before adjustment µSv/h	Instrument reading after adjustment µSv/h	True Ambient Dose Equivalent Rate µSv/h	% Deviation from true exposure rate (%)	Uncertainty of Measurements (%)
0 - 10 µSv/h	2,17	2,17	2,00	8,44	16
	5,28	5,28	5,00	5,53	16
	8,31	8,31	8,00	3,81	16
10 - 100 µSv/h	20,95	20,95	20,03	4,59	12
	51,54	51,54	50,04	3,00	12
	81,55	81,55	80,13	1,77	12
100 - 1000 µSv/h	206,60	206,60	200,46	3,06	12
	514,20	514,20	500,56	2,72	12
	828,30	828,30	801,83	3,30	12
Scale	Instrument reading before adjustment µSv/h	Instrument reading after adjustment µSv/h	True Ambient Dose Equivalent Rate µSv/h	% Deviation from true exposure rate (%)	Uncertainty of Measurements (%)
1 - 10 mSv/h	2,06	2,06	2,00	2,93	12
	5,14	5,14	5,00	2,72	12
	8,20	8,20	8,01	2,46	12
Average deviation from true exposure rates:				3,69	
		Calibration Laboratory ISO 17025:2017			
Calibrated by: B Ramaphakela	Checked by: T.M. Ramashidzha	Approved by: E.N. Moalosi			
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* % Deviation from the true exposure rate is defined by:

$$\% \text{ Deviation} = \left[\frac{\text{Measured exposure rate} - \text{True exposure rate}}{\text{True exposure rate}} \right] \times 100$$

9. Acceptable deviations
 Individual deviations must be within $\pm 25\%$ and the average deviation within $\pm 15\%$.

10. Uncertainty of measurements
 The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$ providing a level of confidence of approximately 95 %, the uncertainty of measurement has been estimated in accordance with the principles defined in the JCGM GUM-6: 2020, Guide of Uncertainty of Measurement, ISO, Geneva, 2020

11. Traceability
 The measurements results are traceable to the National Measurements Standard for air Kerma.

12. Check source measurements
 No check source was supplied

13. Disclaimers
13.1. Validity of Calibration
 The measurement results recorded in this certificate were correct at the time of calibration. The subsequent accuracy will depend on factors such as care, handling and frequency of use. It is recommended that recalibration be undertaken at an interval that will ensure that the instrument remains within the desired limits. This certificate may not be reproduced other than in full without written approval of the issuing laboratory. The reported results relate only to the items calibrated.

13.2. Recognition of the certificates
 The South African National Accreditation System (SANAS) is a member of the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition (MRA). This arrangement allows for the mutual recognition of calibration data by member accreditation bodies worldwide.

13.3. Explanatory Notes
Calibration frequency
 In the Republic of South Africa in accordance to hazardous substance act 15 of 1973 (updated 26 February 1993) the expiry date is 7 months after the date of calibration for radiography and 14 months after the date of calibration for general use. In other countries this may be different and it is the responsibility of the user to ascertain legal requirements of the country where the instrument is used.

—end of calibration certificate—

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Job Card Details
 Quotation Number : SOQ0000430-1 Purchase Order Number : CASH
 Job Card Number : JOB00001874

1. Particulars of the customer	Instrument Details
Customer name : MJC Radiological and Environmental Services	Manufacturer : Thermo Scientific
Address : Casa Uvongo 106, Lilliecrona Boulevard, Uvongo KZN, 4270	Instrument Make : RadEye SX Serial Number : 51475
Contact Person : Gcinumuzi Sibanyoni	Calibration Range : Up to 7.5 kBq
Calibration of : RadEye SX with a Dual Scintillation Probe DP2R-4A	MTE Number : 51475.11332 Probe Serial No : 11332

2. Calibration Dates and Frequency
 Date of Issue : 02 November 2024 Expiry Date : Jan 2026 (week 1)
 Date of Receipt : 18 October 2024 Calibration Frequency : 14 Months
 Date of Calibration : 02 November 2024

3. Calibration Information			
3.1. Environmental condition	Temperature	Atmospheric Pressure	Relative Humidity
Contamination Laboratory	24,6°C	875.4 mBar	42 %
Calibration track room	24,4°C	875.4 mBar	34,5 %
3.2. Calibration procedure	CAL-QMS-WIN-0030		
3.3. Calibration spreadsheet	RadEye SX		

4. Instrument setup
 4.1. The instrument parameters were set as follows:

Parameter	Setting Before	Setting After
High voltage setting	780 V	860 V
Threshold C1 (Gross value)	40 mV	40 mV
Threshold C2	2150 mV	2150 mV
Threshold C3 (Alpha)	2200 mV	2200 mV
Threshold C4	2220 mV	2220 mV
Units	Bq/cm ²	Bq/cm ²
Overload countrate	50000 cps	50000 cps
Overload current	40µA	40 µA
Deadtime C1	6 µs	6 µs
Deadtime C2	6 µs	6 µs
Deadtime C3	6 µs	6 µs
Deadtime C4	6 µs	6 µs
Time Out	100 s	100 s
Sigma Factor	6	6
Phase Fade out	ON	ON
Window	R1-R2;R3	R1-R2;R3

		Calibration Laboratory ISO 17025:2017
Calibrated by: B Ramaphakela	Checked by: T.M. Ramashidza	Approved by: E.N. Moalosi
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Calibration Certificate Certificate No : CQ-KVG-24/9388 Page 2 of 3

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4.2. The high voltage was determined as described in the instrument manual.
4.3. The optimum value was found to be 860 V and the calibration was carried out at this setting.
4.4. The pre-calibration checks were satisfactory, e.g. there was no visible damage, and the instrument settings were checked, and the batteries were not in good condition.

5. Background during calibration

		Background during calibration	
5.1. Alpha background	: 0,01 cps	Alpha background	: 0,008 Bq/cm ²
5.2. Beta Background	: 21,8 cps	Beta Background	: 2,164 Bq/cm ²

6. Calibration constants

6.1. The response to 100 mm x 100 mm certified extended area sources was determined for two beta emitting nuclides and one alpha emitting nuclide.
6.2. The detector (without the plastic cap and metal shield) was positioned over the source with its front face parallel to the source and 4mm from the source.
6.3. The results are summarized in the table below.

Nuclide	Maximum Energy MeV	Instrument function	Net counts per		Uncertainty of Measurements %	%E2 π	PAR Percentage Activity Response
			3.7 Bq/cm ²	0.37 Bq/cm ²			
⁹⁰ Sr/ ⁹⁰ Y	2,27	β	35,67	-	14	29,62	19,68
⁵⁴ Co	0,71	β	29,18	-	14	26,64	16,10
²⁴¹ Am	5,54	α	-	2,26	14	27,70	12,47

Notes:

- The instrument response for ¹⁴C is negligible.
- The instrument response in net cps (excluding background) to a beta contamination level of 3.7 Bq/cm² is given in column 4. Two efficiencies are given for the two given energies. The user of the instrument must select the appropriate response factor. This will be determined by the energy closest to that of the contamination under investigation.
- The instrument's response in net counts per second (excluding background) to an alpha level of 0.37 Bq/cm² is given in column 5.
- %E2 π refers to the efficiency of the detection of particles emitted from the surface of the source towards the detector.
- PAR is the percentage surface activity response and can be used to calculate surface contamination as follows:

$$\text{Surface activity (Bq/cm}^2\text{)} = \left[\frac{\text{Measured count rate} - \text{background count rate}}{\text{Probe area (cm}^2\text{)} \times \text{PAR}} \right] \times 100$$

NOTE: The effective probe area is 49 cm²

sanas Calibration Laboratory 1203		
Calibrated by: B Ramaphakela Metrologist	Checked by: T.M Ramashidzha Technical Signatory	Approved by: E.N Mososi Laboratory Manager

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6. Linearity response check

6.1. The instrument's response to known exposure rates from ¹³⁷Cs radiation (with the detector shield in place) was 649 cps per 1 mR h (10 μ Sv h)
6.2. The instrument's average deviation from linearity was -2.6 cps between 50 and 3500 cps.

7. Rejection Factor

7.1. Alpha rejection factor for a beta source : 0,000421408
7.2. Beta rejection factor for an alpha source : 0,12
Acceptable rejection factors are:
Alpha rejection factor : $\leq 0,01$
Beta rejection factor : $\leq 0,30$

8. Check source measurement
No check source was supplied

9. Uncertainties of measurements
The uncertainties of measurement were estimated not to exceed 14%.
The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2 providing a level of confidence of approximately 95 %, the uncertainty of measurement has been estimated in accordance with the principles defined in the JCGM GUM 6: 2020, Guide of Uncertainty of Measurement, ISO, Geneva, 2020

10. Measurements Traceability
The calibration is traceable to the national measuring standards for Surface Emission Rate and Air Kerma.

11. Disclaimers

11.1. Recognition of the certificates
The South African National Accreditation System (SANAS) is a member of the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition (MRA). This arrangement allows for the mutual recognition of calibration data by member accreditation bodies worldwide.

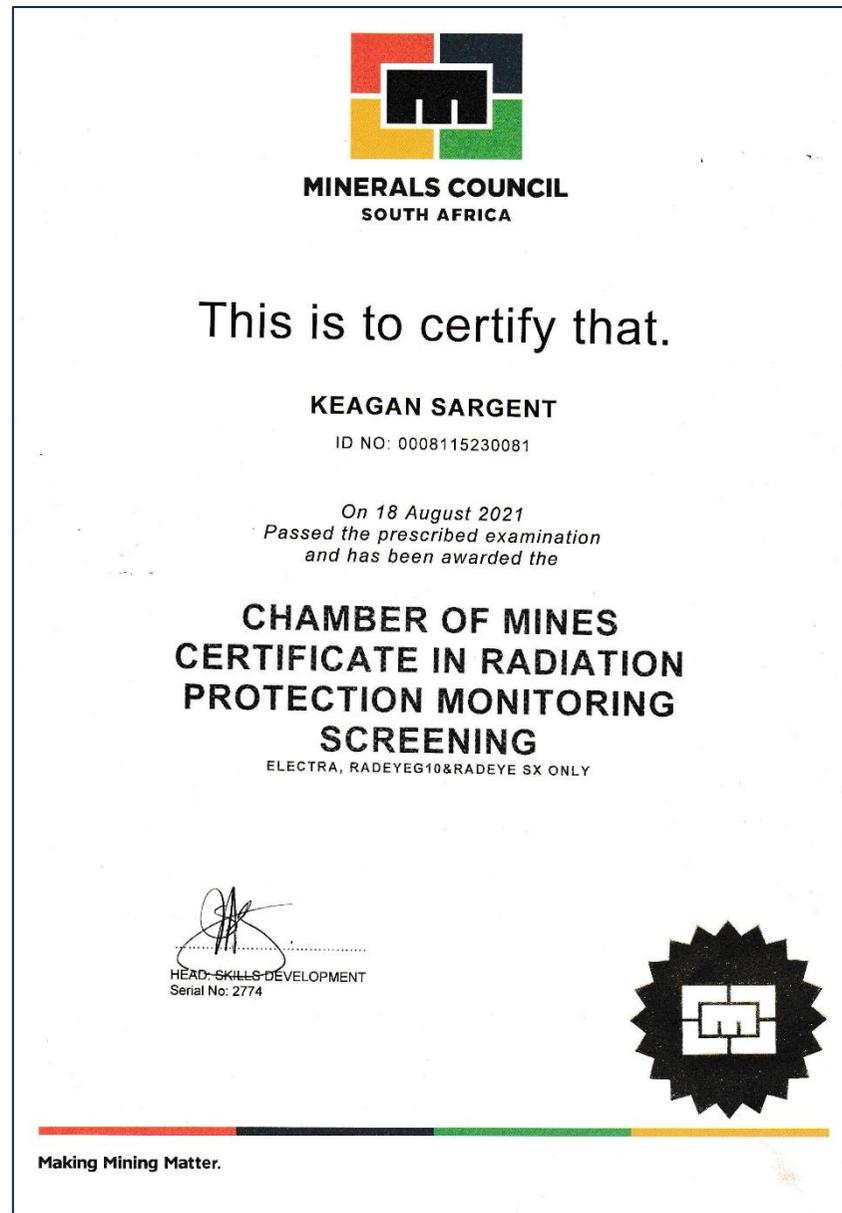
11.2. Validity of Calibration
The measurement results recorded in this certificate were correct at the time of calibration. The subsequent accuracy will depend on factors such as care, handling and frequency of use. It is recommended that recalibration be undertaken at an interval that will ensure that the instrument remains within the desired limits. This certificate may not be reproduced other than in full without written approval of the issuing laboratory. The reported results relate only to the items calibrated.

11.3. Explanatory Notes
Calibration frequency
In the Republic of South Africa in accordance to hazardous substance act 15 of 1973 (updated 26 February 1993) the expiry date is 7 months after the date of calibration for radiography and 14 months after the date of calibration for general use. In other countries this may be different and it is the responsibility of the user to ascertain legal requirements of the country where the instrument is used.

—end of calibration certificate—

sanas Calibration Laboratory 1203		
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Appendix E:
East Rand Basin Numerical Groundwater Model for the Waste
Disposal Flow and Advective Transport Evaluation (Artesium,
2024b)



East Rand Basin Numerical Groundwater Model for the Waste Disposal Flow and Advective Transport Evaluation

**ERB Numerical Groundwater Transport Model and Risk
Quantification at Grootvlei #3 and Grootvlei #4 Shafts**

Technical Report

Project no: 2024-086

Prepared for: ID Kruger Consulting cc

13 March 2025

Artesium Consulting Services

Hydrogeological & Mine Water Solutions

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East Rand Basin Numerical Groundwater Model for the Waste Disposal Flow and Advective Transport Evaluation

ERB Numerical Groundwater Transport Model and Risk Quantification at Grootvlei #3 and Grootvlei #4 Shafts

Technical Report

13 March 2025

Conducted on Behalf of:

ID Kruger Consulting cc

Glenstantia,

Pretoria,

0010

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Hydrogeologists & Mine Water Solutions

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ID Kruger	Idkc

DOCUMENT HISTORY

Report no	Date	Version	Status
2024-086	13 March 2025	1	Final

LIST OF ABBREVIATIONS

Abbreviation	Description
a	Annum
BDL	Below detection limit
DWAF	Department of Water Affairs and Forestry
GW	Groundwater
ha	hectare
mamsl	metres above mean sea level
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mbgl	metres below ground level
Mon	Month/s
P5	5 th Percentile (Lower range)
P50	50 th Percentile (Median)
P95	95 th Percentile (Upper range)
SANS	South African National Standards
SW	Surface Water
TDS	Total Dissolved Solids

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1 INTRODUCTION

Artesium Consulting Services (Pty) Ltd (referred to as ACS) was appointed by ID Kruger Consulting cc and Aquisim Consulting Pty (Ltd), referred to as the Client, to quantify the risk associated with waste disposal in the East Rand Basin (ERB). The ERB (referred to as the site) outcrops to the south-east of Johannesburg and encompasses an area of approximately 720 km². This investigation focused on modelling the advective flow dynamics within the Grootvlei sub-basin, as a result of injection of sludge into Grootvlei #4 shaft and abstraction of groundwater from Grootvlei #3 shaft. Interpreting the simulated mass tracer plume injected into the mine void workings helped characterise the flow characteristics and pathways from the source and possible receptors within the East Rand Basin watershed.

1.1 Objectives

The project objective is to:

- Update the existing numerical groundwater model (AGES, 2006 and Exigo, 2017) by incorporating monitoring data to develop a numerical groundwater transport model to quantify the long-term advective and reactive impacts associated with waste sludge injection/disposal at the Grootvlei #4 Shaft.

1.2 Scope of Work

The scope of work and project timeline is tabulated (Table 1-1) below:

Table 1-1: Summary of the Scope of Work

Scope of Work		Date Completed
1	Sampling & Delivery to Necsa Lab	
1.1	Sampling of sludge and water	Sept-2024
1.2	Submission of sample to Necsa	Nov-2024
2	Necsa Radioanalysis	
2.1	Submission to of samples to Necsa	Nov-2024
2.2	Radioanalysis of samples	Current
3	Analysis and evaluation of monitoring data - 3D Numerical Groundwater Flow & Chemical Mass Transport Models	
3.1	Analysis and evaluation of the groundwater and abstraction monitoring data to be use for model recalibration	Jan-2025
3.2	Update of the conceptual groundwater models with latest data to include updated surface water and groundwater interactions	Jan-2025
3.3	Update of the 3D geometric numerical groundwater flow model (Feflow) based on the monitoring data	Jan-2025
3.4	Recalibration of the groundwater flow model with monitoring data	Feb-2025
3.5	Develop 3D chemical mass tracer transport model	Feb-2025
3.6	Simulation of flow and mass (advective & reactive) scenarios for long-term impact analysis	Feb-2025
3.7	Compilation of GIS maps	Feb-2025
3.8	Compilation of a technical groundwater flow and tracer transport modelling report	Feb-2025

Scope of Work		Date Completed
4	Update of NNR Submission Report	
4.1	Incorporate groundwater modelling results	Pending
4.2	Interpret Necsra radioanalysis results	Pending
4.3	Update report	Pending
4.4	Comment period	Pending
4.5	Finalise report	Pending
5	Submission to NNR	

2 DESCRIPTION OF THE STUDY AREA

2.1 Site Overview

The East Rand Basin (ERB) mining area has been extensively mined since 1886 up to depths of approximately 3.5 km. During active mining the ERB was dewatered (purged) to allow for mining operations to continue. Dewatering was ceased as mines reached their end of life and as a result dewatering rates increased in the remaining operational mines. Until 1991 the bulk of the dewatering from the ERB was conducted from Sallies #1 Shaft with smaller volumes being pumped from the Grootvlei #3 and #4 shafts. Currently, approximately 71 Ml/d of water is abstracted at the Grootvlei #3 shaft. On average 1 614 m³/d of sludge is disposed at the Grootvlei #4 shaft situated approximately 2.2 km (refer to Figure 2-2) to the north-west of Grootvlei #3. The rest of the abstracted water is discharged into the Blesbokspruit. It is assumed the sludge is disposed down the #4 shaft at a depth of 700 mbgl (meters below ground level) via gravity and due to the density (1.4 kg/l), settles at the bottom of the shaft mine void workings. The interaction between the disposal of sludge and abstraction of water from the ERB on the surrounding environment was the focus of this investigation.

2.2 Local Climate

Rainfall data is recorded at the ERB plant (refer to Figure 2-2) and stretched from February 2013 to November 2024. The statistical analysis of the 11 year and 10 month long rainfall record is displayed in Figure 2-1. The Mean Annual Precipitation (MAP) was calculated at 641 mm/a.

Table 2-1: ERB Plant Monthly Recorded Rainfall Statistical Distribution

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Annual
P99	203	170	178	121	55	20	14	3	21	110	225	236	904
P98	199	168	171	119	53	19	13	3	20	108	223	232	893
P95	186	163	151	112	45	17	11	2	15	101	217	220	860
P90	166	154	121	102	34	14	8	1	8	90	208	200	814
P50	111	68	41	46	5	2	0	0	3	42	110	134	641
Average	108	83	66	55	14	5	2	0	5	47	121	140	622
P05	40	11	27	13	0	0	0	0	0	10	58	69	386

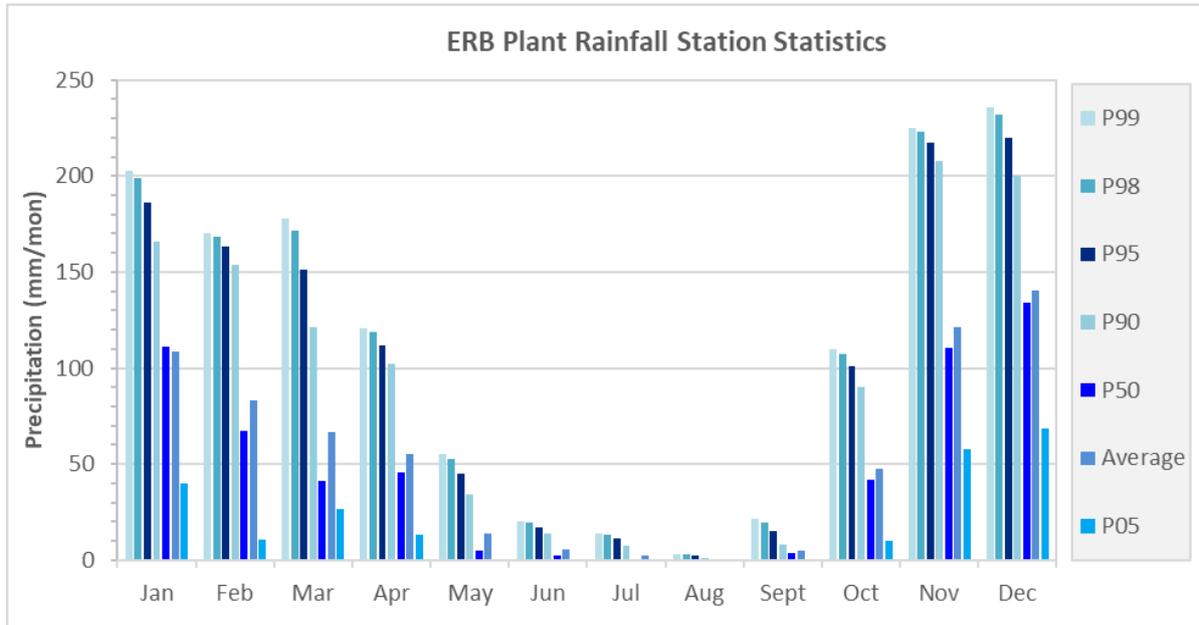


Figure 2-1: Statistical Monthly Distribution for Rainfall Data Recorded at the ERB Plant

2.3 Topography and Drainage

The topography data for the model boundary was derived from the 2628BC, 2628CB, and 2628DA 1:50 000 topographical map sheets (NGI, 2024). The topographical map in Figure 2-3 displays that the Grootvlei #4 Disposal shaft is situated at approximately 1 580 mamsl with the area sloping towards the south-east and towards Grootvlei #3 Abstraction Shaft. The Blesbokspruit drains the area to the east of the ERB plant. The Blesbokspruit River flows from north to south across the model boundary and drains the area to the east of the plant. Regionally, the area slopes from the high-lying (>1 650 mamsl) model boundary towards the two main catchment exit points situated at approximately 1 510 mamsl) in the south-west.

SITE LAYOUT AND LOCALITY MAP

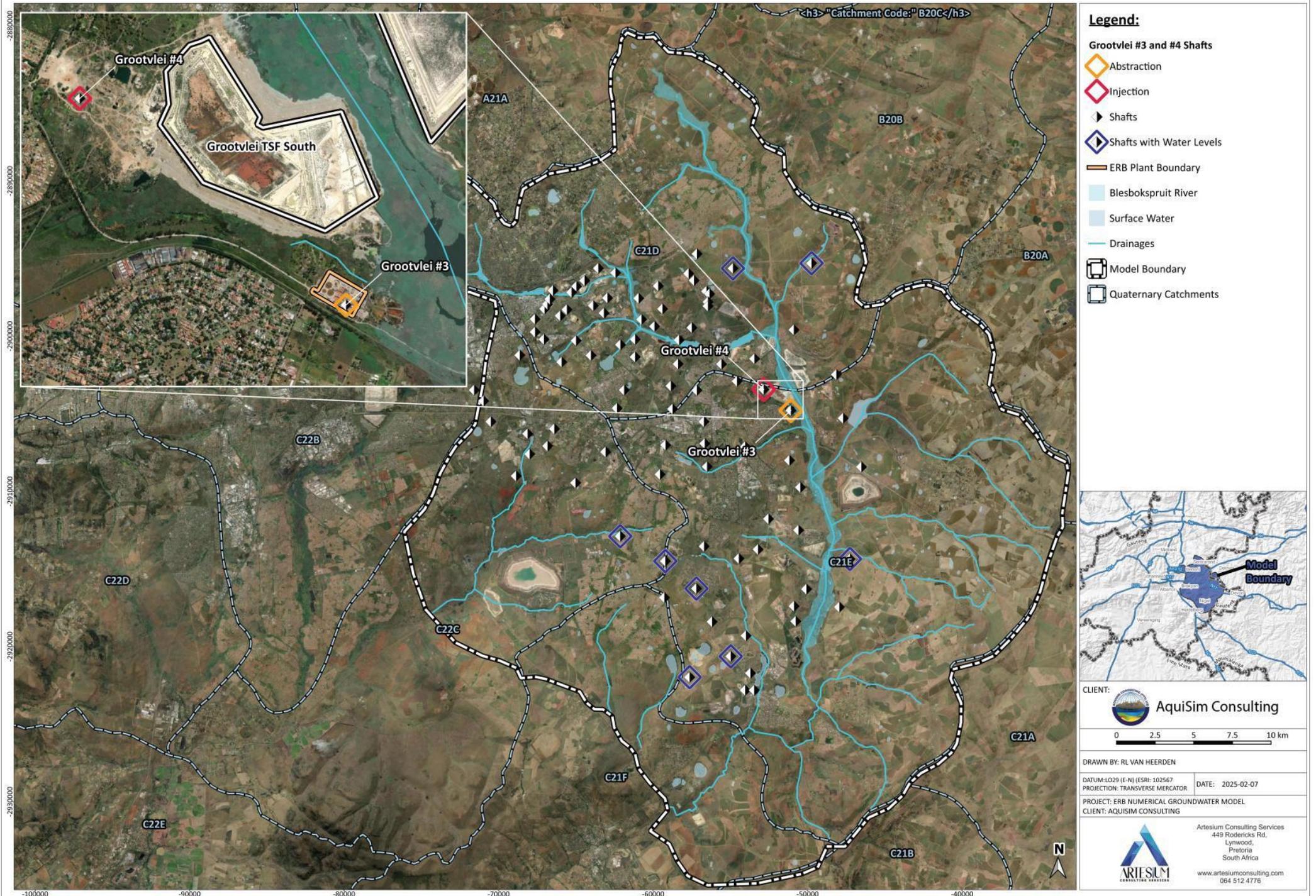


Figure 2-2: Site Layout and Locality Map

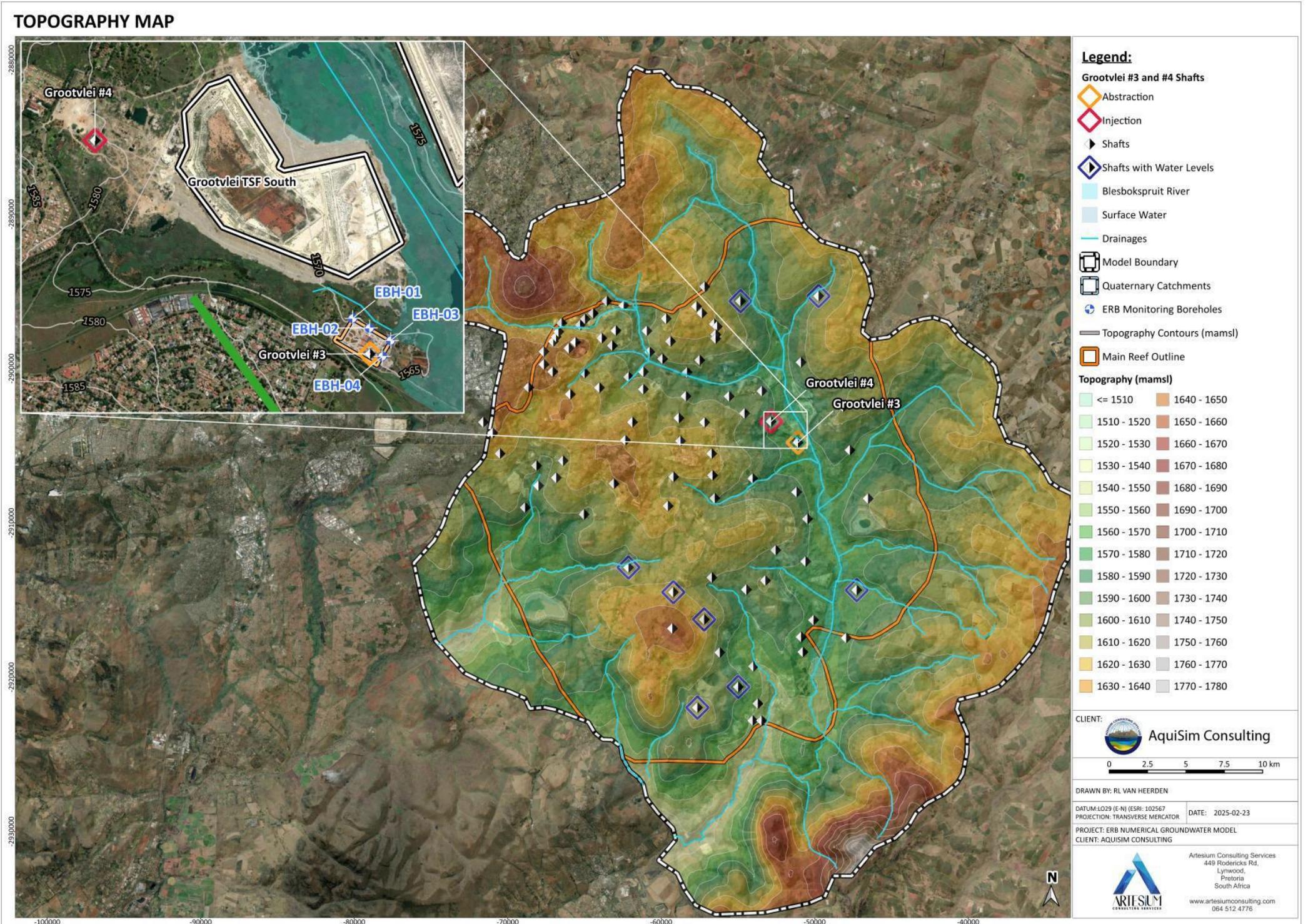


Figure 2-3: Topography Map

2.4 Geology of the East Rand Basin

The local geological setting was derived from the Council for Geoscience (CGS) 2628AB, 2628AD, 2628BA, and 2628BC 1:50 000 Geological Map Series sheets. The geology map within the model domain can be seen displayed in Figure 2-4. The geological cross section was adapted from Lubbe et al., (2007) and is displayed in Figure 2-5. It should be noted that the purpose of this investigation was not to map in detail the sub-surface geology but rather correlate the structural geology of the basin with deep and shallow groundwater flow paths. The structural geology helped construct a numerical groundwater flow model.

The complex geological setting as adapted from Lubbe et al., (2007) can be best summarised in Table 2-2.

Table 2-2: Lithological Succession for the CGS 1:50 000 Map Sheet 2628AB adapted from Lubbe et al., (2007)

Supergroup	Group	Subgroup	Formation	
Quaternary deposits				
Karoo	Ecca		Vryheid (Pv)	
	Dwyka (C-pd)			
Transvaal	Pretoria		Hekpoort (Vh)	
			Boshoek (Vbo)	
			Timeball Hill (Vti)	
			Rooihoogte (Vrh)	
	Angular Unconformity			
	Chuniespoort	Malmani		Eccles (Ve)
				Lyttleton (Vly)
				Mote Christo (Vmo)
				Oaktree (Voa)
				Black Reef (Vbr)
Angular Unconformity				
Ventersdorp	Platberg (Rpl)		Undifferentiated	
Witwatersrand	Central Rand	Turfontein	Mondeor (Rmo)	
			Elsburg (re)	
			Kimberley (Rki)	
		Johannesburg (Rjo)	Undifferentiated	
	Angular unconformity			
	West Rand	Jeppesfontein (Rj)		Elandslaagte (Rel)
				Palmietfontein (Rpf)
		Government (Rg)		Tusschenin (Rts)
				Coronation (Rco)
				Promise (Rpr)
Hospital Hill (Rh)		Undifferentiated		
			Orange Grove (ror)	
Angular Unconformity				
Bryanston Gneiss (Zbr) and Zesfontein Granodiorite (Ze)				

Mining in Witwatersrand Supergroup quartzites, shale and conglomerates followed the deformed sedimentary rocks of the ERB, more specifically, the Main Reef (situated in the Johannesburg Subgroup) and the Kimberley Reef that forms part of the Turfontein Subgroup. Witwatersrand sediments were deposited onto the granitic basement and were deformed by syndepositional forces which refer to stresses imposed onto the sediments while they are deposited and before they have lithified into rock.

The undifferentiated Johannesburg Subgroup consists mainly of quartzite and conglomerate. The Nigel Reef is the pebble marker containing chert, quartzite and porphyry and forms the of the basal part of the Mian Reef (Johannesburg Group). From the conceptual cross-section (Figure 2-5) the thickness of the Johannesburg Group underlying the Grootvlei #3 and #4 shafts is inferred to be approximately 200 m.

Should you drill deeper past the Johannesburg Subgroup, the Jeppestown Subgroup would be intersected for ~80 m until the basement Halfway House Granites are intersected. However, the thickness of the Jeppestown Subgroup can vary to be as thick as 520 m. Various (<40 m²) outcrops of the basal granites are observed within the ERB footprint and consisted of varying textures of light brown to cream reddish leucocratic fine- to medium-grained granite (Opperman et al., 2005). The authors observed that the granites do not intrude into the Witwatersrand Supergroup. The Krugersdorp Formation was deposited onto the Intrusive norite/granophyre and consists of an approximately 130 m thick sheet of coarse-grained quartzite. The bird member would account for approximately 40 m of that thickness.

Extensive lava flows of the Ventersdorp Supergroup overlaid the Witwatersrand Supergroup. However, due to the reef being poorly developed and of little to no economic value, the Supergroup was not extensively mapped within the model domain. A long period of erosion occurred following the deposition of the much younger Karoo sediments onto the Black Reef Formation Quartzites.

The Vredefort impact structure and the forming of the Johannesburg Dome influenced the deposition of pre-Palaeozoic sediments of the Karoo Supergroup. Horizontally underlain by the Dwyka Group and Vryheid Formation. Characteristic of the surface landscape within the East Rand Basin is the high-lying areas associated with sub-outcropping volcanosedimentary sequence of the Ventersdorp Supergroup, and the dolomites of the Malmani Subgroup underlay the flat topographies and wetlands of the basin.

Dykes and sills of various ages ranging from Archaean to Jurassic intruded into the Transvaal Supergroup and Witwatersrand Supergroup sedimentary rocks. The intrusive rocks come in the form of Syenite, Diabase and Ilmenite dykes that fed into sills crosscutting the Malmani Dolomites. The Modder East Dyke was digitized from the CGS 1:50 000 geological map series aeromagnetic survey (2628AB, 2628AD, 2628BA, 2628BC) and strikes south-east to north-west and was emplaced almost vertically. The CGS map sheets had a gap in the survey data (refer to Figure 2-6) and it was not clear if this dyke extends as a single structure to the north-west of the model boundary. The Modder Dyke is situated to the west and is parallel to the Modder East dyke. The pre-Transvaal faulting observed on the geological map (Figure 2-4) was georeferenced from in the cross-section adapted from (Lubbe et al., 2007).

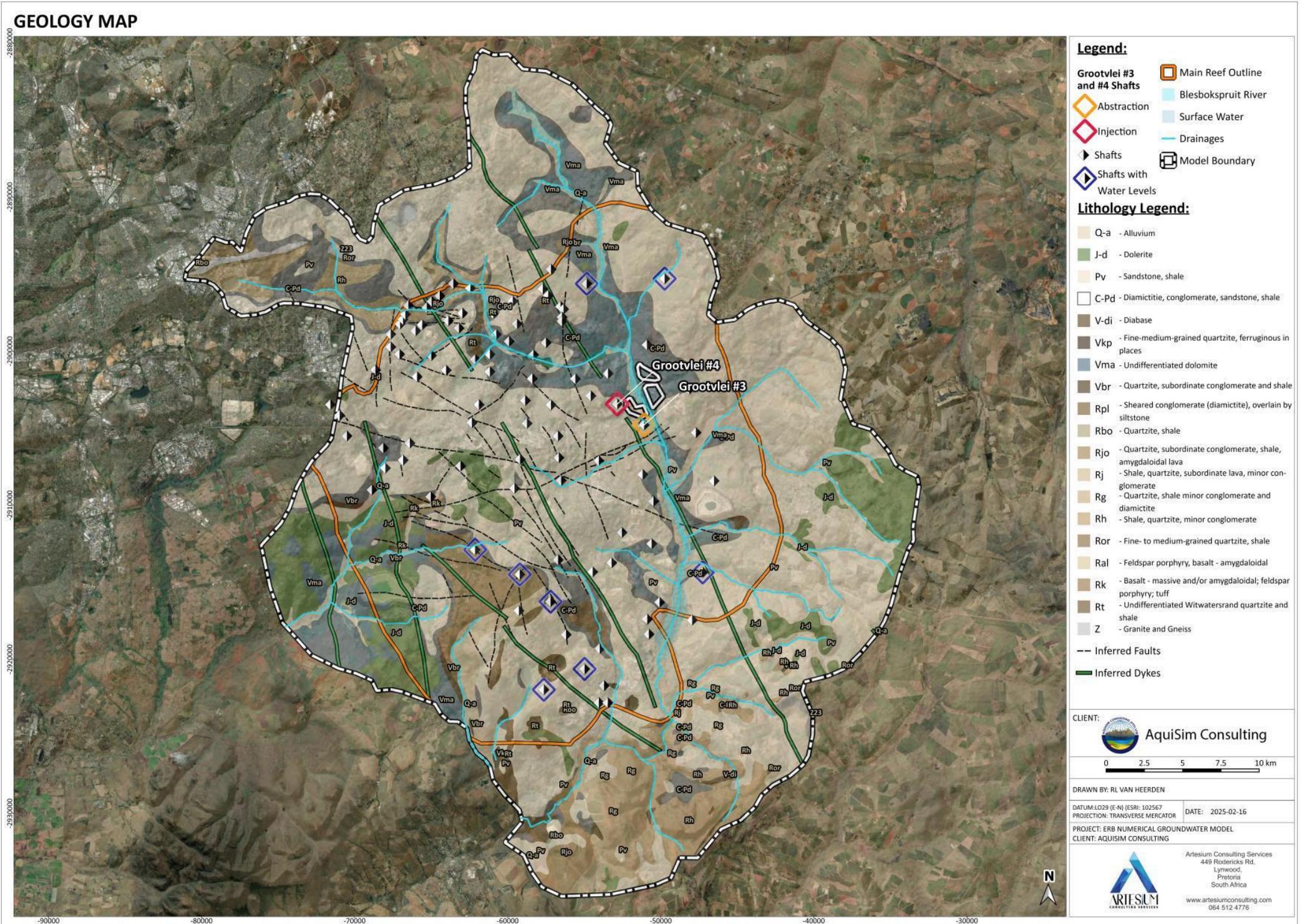


Figure 2-4: Geology Map adapted from 1:50 000 CGS Geological Map Series

GEOLOGICAL CROSS SECTION ADAPTED FROM 1:50 000 CGS GEOLOGICAL MAP EXPLANATION (2628AB BENONI)

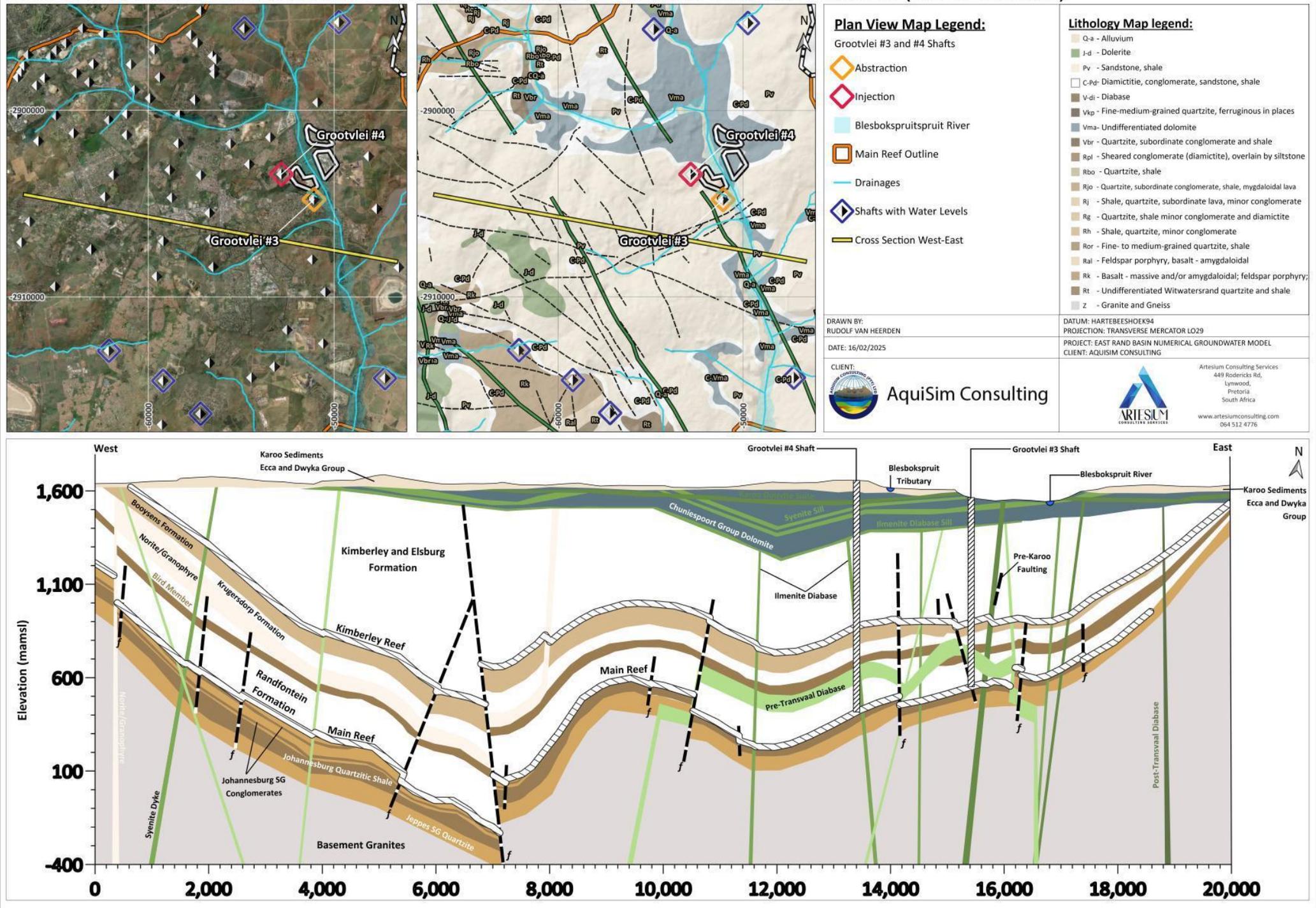


Figure 2-5: Geological Cross-section adapted from Lubbe et al. (2007)

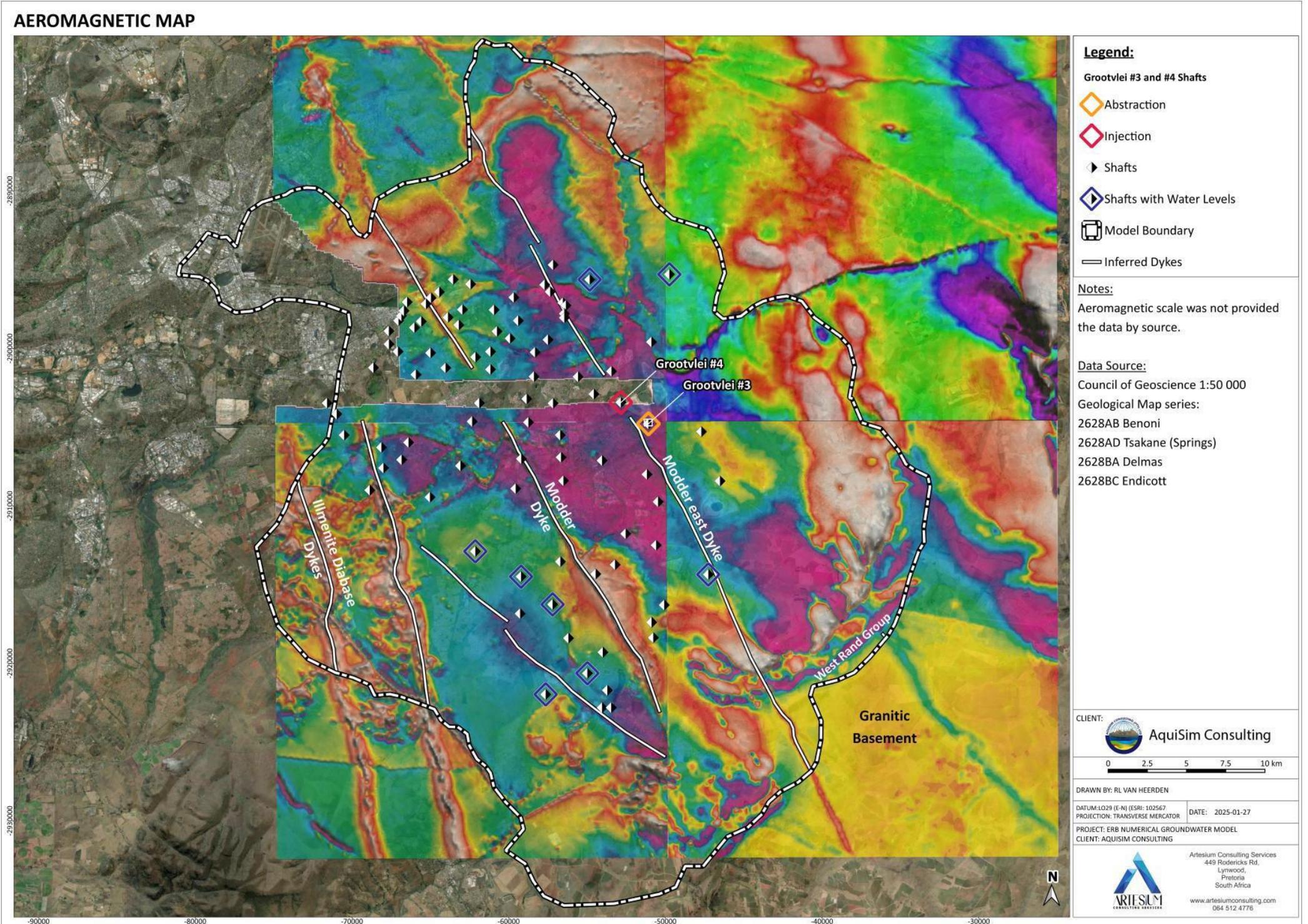


Figure 2-6: Aerial Magnetic Map Adapted from CGS 1:50 000 Geological Map Series

2.5 Hydrogeology of the East Rand Basin

The ERB falls within the Vaal Water Management Area (WMA) bordering the Limpopo WMA to the north-west and the Olifants WMA to the north-east (DWS, 2016). The model domain stretches across the quaternary catchments C21D, C21E, C21F, and C22C with the details for the respected catchments summarised in Table 2-3.

Table 2-3 Quaternary Catchment A21C and C22A Information

Quaternary Catchment	Total Area (km ²)	Recharge (mm/a)	Current use (l/s)	Rainfall (mm/a)	Groundwater level s(mbgl)
C21D	445.8	5.7	26.7	698	16.7
C21E	628.2	5.1	7.0	690.7	14.9
C21F	426.6	6.2	18.7	703.7	11.2
C22C	465.2	6.3	0.9	683.8	11.3

The 1:500 000 Hydrogeological Map Series sheet 2526 Johannesburg (Barnard & Baran, 1999) is displayed in Figure 2-8. The Blesbokspruit and beneath the ERB plant is underlain by Karst type (c5) aquifer with typical borehole yields of > 5 l/s. The main aquifer within the model domain is the Chuniespoort Group (dolomites) that were deposited in westward dipping synform known as the Potchefstroom Synclinorium (Foster, 1988). The majority of the model domain is situated on top of an Intergranular and fractured type aquifer (d2) with typical borehole yields between 0.1 and 0.5 l/s. The author Barnard and Baran (1999) identified the major zones for groundwater as the following:

- Basins of weathering occurring mostly in igneous rocks.
- Joints and fractures in competent arenaceous rocks related to tensional or compressional stresses and off-loading.
- Solution channels and fractures in the carbonate rocks (differentiated dolomite) of the Chuniespoort Group in the dolomite aquifer that underlies the Karoo Sediments to the east of the site (refer to Figure 2 7).
- Joints and fractures occurring in contact zones related to the heating and cooling of country rock, caused by the intrusion of dykes and sills. Modder east and Modder dyke that strikes south-east to north-west.
- Fractures in transitional zones between weathered and unweathered rocks.
- Along contact zones between sedimentary or volcanosedimentary sequences (Ventersdorp Supergroup). Contacts may be:
 - Open;
 - Weathered or fractured along unconformities;

- Fractured along dynamic contacts zones;
- Fractured due to heating and cooling along large extrusive events (Ventersdorp lava flows).
- Faults and associated shear zones as is evident in the major structures within the basin such as the northwest-southeast oriented fold axis, the Springs monocline (refer to cross-section Figure 2-5) that strikes from northwest to southeast, a number of left-lateral faults and anastomosing faults, and thrust faults that are mainly oriented north-south.

Groundwater recharge to the Main Reef and Kimberley Reef are expected to occur via the following main pathways.

- Recharge from surface rainfall via dissolution channels (sinkholes and dolines) in the dolomite (refer to Figure 2-7).
- Recharge from surface water (rainfall) ingress through underground workings.
- The shaft annulus would act as a conduit for surface water to recharge the deeper groundwater.
- Deep basin flow across regional catchments.
- Direct recharge or constant recharge boundary via the Blesbokspruit River.



Figure 2-7: Visible Sinkholes from Sattelite Imagery (Esri, 2025)

From previous hydrochemistry and isotope studies conducted by (Exigo, 2017) it was concluded that the main recharge mechanism is surface water recharging the basin via dissolution channels in the dolomite and the underground workings. The footprints of the underground workings are now known at the time of this study. The sinkholes (especially to the east of the site) could be mapped via satellite imagery (Figure 2-7). The sinkholes could have formed as a result of collapsed shallow mine workings or from weathered dolomite and resulting sinkholes and/or dolines that formed. It was assumed that the main reef outcrop due to the reef being extensively mined out, would also act as a preferential pathway for surface water to recharge the basin.

The basin and lower-dolomite aquifer is semi-confined by an aquitard (Karoo Dolerite Suite) that was emplaced into the surrounding strata, along with ilmenite and diabase sills. The aquitard therefore separates the main dolomite aquifer into an upper (unconfined) and lower (semi-confined) aquifer system. It was assumed that the ERB was regionally semi-confined and locally connected to surface via recharge received from the Blesbokspruit and associated recharge pathways via dolomite dissolution channels. The shafts penetrate through the confining layer into the lower semi-confined aquifer. The degree of weathering of the shaft infrastructure is not known and it is assumed that they reach up to the Main Reef and Kimberley Reef.

2.5.1 Radiological Count of the East Rand Basin

From a desktop background the existing radiological count status map of the model domain can be seen displayed in Figure 2-9. The map data was georeferenced from the CGS 2628AB, 2628AD, 2628BA, and 2628BC 1:50 000 Geological Map Series sheets. The survey recorded four radiometric channels namely; total count, potassium (red), thorium (blue), and uranium (green). The following conclusions were made with regards to the radiological count in the model domain:

- Higher concentrations were observed along mining activity such as Tailings Storage Facilities (TSF's) and open diggings (open cast mine workings). To the north-west of the Grootvlei #3 and #4 shafts, higher intensity signatures were detected correlating with other shaft locations. The shaft localities throughout the model domain correlated with increased radiometric counts.
- A higher signature of Thorium was identified in the middle TSF situated 3 km to the north of the Merryvale #5 shaft and to the south of the N17 in the vicinity of Daggafontein. Another such signature was identified on a rehabilitated TSF situated to the west of the Merryvale #5 shaft.
- Ebotse Golf and Country Estate had a high signature. The Benoni Country Club is situated directly to the east and borders the aforementioned golf estate and had the inverse signature, possibly attributed to the two golf courses irrigating from two separate surface/groundwater sources, with the inverse radiometric counts. The source of the irrigation for these golf courses are not known.
- Surface water features had high radiometric counts. The evaporative pans would concentrate radiological material as they have a higher evaporation rate compared to recharge rate. Certain surface water features like the Pomula Park Nature Reserve dam and the Vanryn Dam had low

radiometric signature compared to the other surface water bodies.

- Elevated levels of Uranium (red) is evident along the footprint of the Blesbokspruit River.
- Intermediate concentrations of radiometric concentrations were identified along fluvial pathways in the south-east part of the model domain.
- Various linear anomalies are situated to the north-east of the model boundary and are associated with the Klapperkop Quartzite Member of the Pretoria Group.

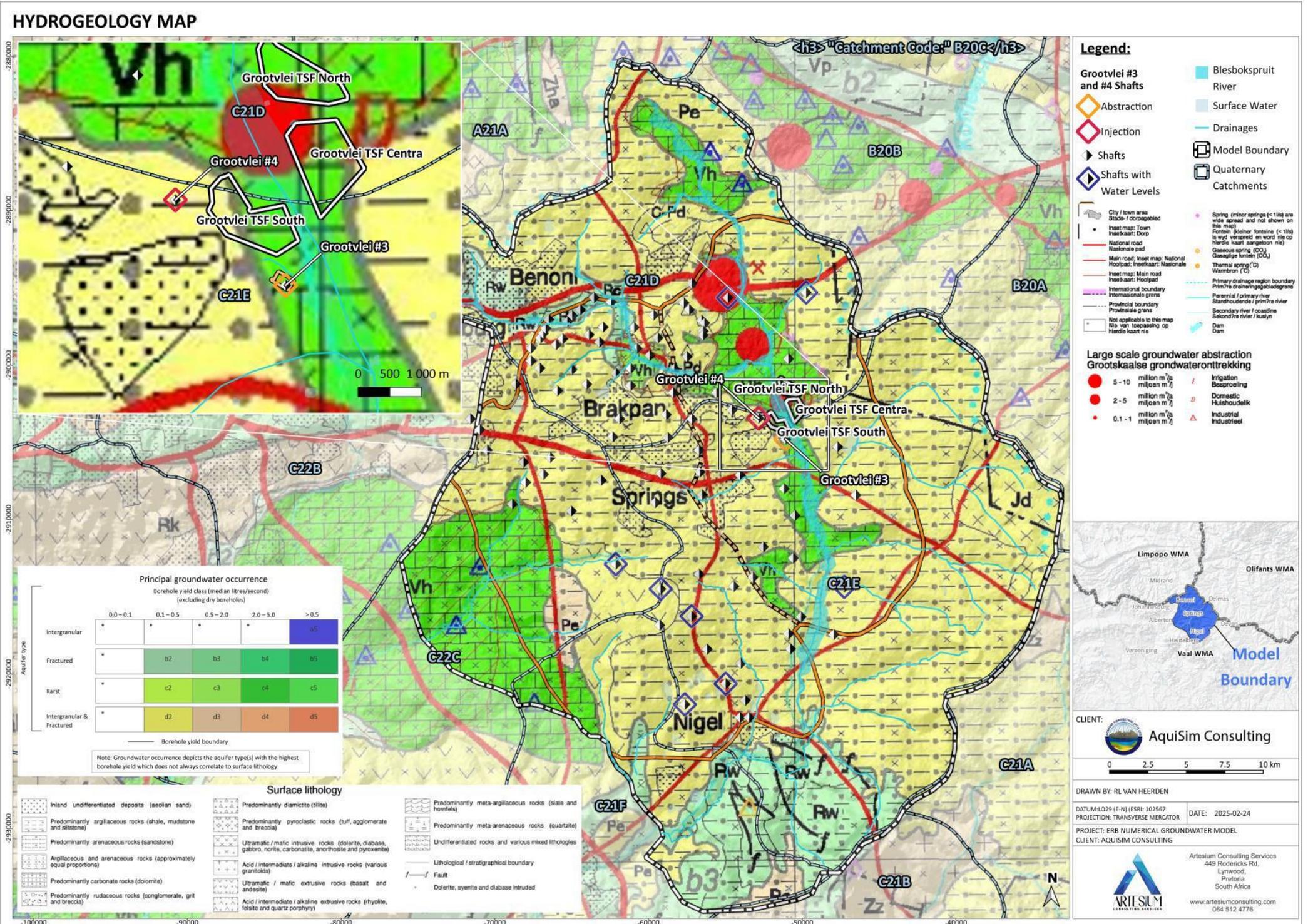


Figure 2-8: Hydrogeology Map

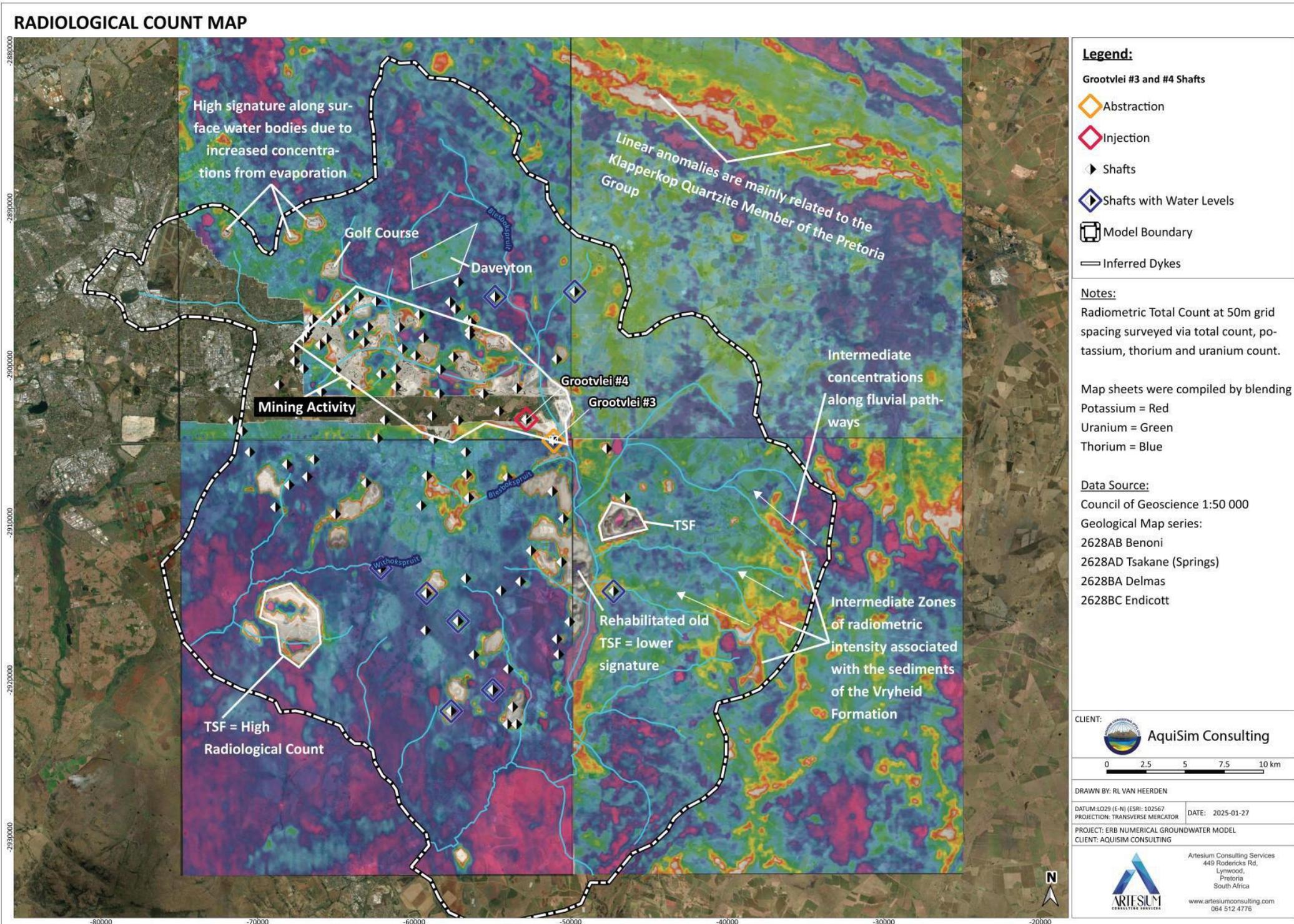


Figure 2-9: Radiological Count Map

3 METHODOLOGY

3.1 Historical Report Review

The following existing data sources were available for the study area and was used to provide background for the numerical groundwater model update:

- Conceptual groundwater flow model of the Far East Rand Basin – Grootvlei sub-catchment Phase I. (AGES Technical Report no.:AG/R/04/11/29, dated November 2004).
- Groundwater flow model of the Far East Rand Basin – Grootvlei sub-catchment Phase II: Calibrated for the Canal Area. (AGES Technical Report.: AS/R/05/04/01, dated April 2005).
- Regional groundwater flow management model for the Far East Rand Basin. (AGES Technical Report no.: AS/R/06/02/10, dated February 2006).
- East Rand Basin Flooding and Sludge Disposal: Flow and Mass Balance Modelling. (Exigo Groundwater specialist report Draft no.: ES15/205 V2, dated 10August 2017).
- Nafasi ERB AMD Water Level Rise Investigation – Risk Assessment. (Artesium SA Technical Report no.: 2022-067, dated 8 November 2022).

3.2 Project Background

- **2003:** A groundwater flow model was developed and calibrated focusing on the surface water groundwater interaction at the Florida Lake sub-catchment in the Central Rand Basin.
- **2004:** A conceptual groundwater flow model in the Grootvlei Mine sub-catchment was developed to qualify the origin of the water that is dewatered at Grootvlei #3 shaft at a rate of 75 000 m³/d. It was identified that 70 % of the water originates from surface water inflow from the Blesbokspruit, Alexander and Cowles Dam. The water balance and saturated state (i.e. shallow water levels) of the Karoo and Dolomite Aquifers indicated that the groundwater inflow component was in the order of 30 % (23 000 m³/d). There was however no detailed piezometric head elevation data to confirm the conceptual groundwater flow model indications. Recommendations were made to confirm the model with the development of monitoring boreholes during the follow up phase.
- **2005:** Seven monitoring boreholes were drilled in the proposed canal area in the Blesbokspruit at Grootvlei Mine's West Pit and Shaft No 9. The monitoring borehole data confirmed that the piezometric head gradients are from the spruit to the groundwater system. The calibrated model indicated that up to 10 000 m³/d, which represents 12 % of the inflow could seep from the canal area. Recommendations were made to extend the surface water drainage or isolation option to Alexander and Cowles Dam.
- **2006:** From the previous Groundwater flow model the most important ingress zones identified was the Cowles Dam 15 000 m³/d (42 %) and the West Pit canal area 10 000 m³/d (28 %), that contributes 70 % of

the ingress volume of 35 000 m³/d. The Blesbokspruit sub-catchment is the most important and accounts for 70 000 m³/d (80 %) of the abstracted volume. The original base flow of the Blesbokspruit is reduced by 42 % from 80 000 m³/d to 46 000 m³/d. The Sallies and Brakpan Basins account for 15 000 m³/d (20%) of the abstracted volume, which originates from both the Blesbok Spruit and the Withok Spruit catchments. The Withokspruit accounts for only 3 000 m³/d (3.5 %) of inflow into the underground mine workings.

- **2017:** A water flow and mass balance model was developed by Exigo (2017) to ERB to determine the dynamics and potential for sludge disposal and the associated potential impacts on the water environment. It was proved with hydrochemistry isotope analysis that 65% of the water pumped from Grootvlei #3 shaft originates from the Blesbokspruit and only 35% comes from the dolomite aquifer. The Erwat Plants to the north and up-gradient of the ERB plant also discharges 140 ML/d of water into the Blesbokspruit. The influence of the sludge disposal is positive as the calcium carbonate in contact with the AMD (Acid Mine Drainage) water has a very long residence time to further buffer pH and the physical filling of the mine void reduces the oxygen levels which would reduce pyrite and uranium leaching.
- **2022:** ACS analysed the rise of water levels in the ERB since from the Grootvlei #3 shaft during February 2022. The analysis was conducted to investigate risk of possible surface and sub-surface decanting, estimate potential timescale to decant, and recommend monitoring and management options. A negative correlation between rate of basin water rise and the basin water level itself was observed. It is proposed that this may be due to the shape of the basin, the concentration of shallow mine voids and subsurface decant into the dolomite aquifers. Decant areas of lowest topographic elevation near canal from Nigel Dam enters Nigel Town (bridge at R42) was identified. By the time decant at surface would occur, significant sub-surface decant will already have taken place. This poses a risk to groundwater aquifer water quality and also to building foundations.

3.3 Grootvlei Shaft Abstraction and Injection Monitoring Data

The Grootvlei #3 shafts main function is to abstract water from the Grootvlei sub-basin in order to keep the Acid Mine Drainage (AMD) from decanting at surface. The abstraction aims to keep the water level in the shaft below the Environmental Critical Level (ECL) situated at 1 470 mamsl. The Nigel #1 shaft was identified as the shaft were decant is most likely to occur, with the shaft top situated at 1 550 mamsl. Dewatering started 01 March 2015 until present, and was provided in daily flow meter readings (daily volumes). The statistical summary of the mentioned data is provided in Table 3-1 with the localities of the shafts displayed in Figure 2-2. The average pumping rate at Grootvlei #3 shaft is 70 250 m³/d. The water is abstracted at approximately 160 mbgl, equating to approximately 1 405 mamsl.

Table 3-1: Grootvlei Shaft Abstraction and Injection Volumes Statistical Analysis

ID	Abstraction Volumes (m ³ /d)	Deposition Volumes (m ³ /d)
Max	104 977	4 053
P99	104 870	3 808
P95	102 741	3 097
P50	70 250	1 614
Average	70 250	1 614
P05	32 751	618
Min	12 686	0

The integrity of the shaft walls is not known, and neither the shaft dimensions (diameter). A study conducted by MacConachie (1959) on typical shaft construction in the East Rand Basin suggested that most of the shafts were constructed with a diameter of 5.4864 m and these dimensions were used for all calculations in the simulations. The degree of weathering of the shaft and possible placement of plugs and access tunnels would effect the flow dynamics between shafts and as a results effect the basin flow pathways. The walls of the shafts were assumed to be relatively weathered in this study, and thus water can be abstracted and injected at various levels (elevations). It was assumed that the total depth of the Grootvlei #3 shaft is equal to the depth of Main Reef at the shaft location (1 172 m).

Grootvlei #4 shaft injects on average 1 614 m³/d of sludge into the shaft at 700 mbgl via unknown mechanism. It was assumed that the sludge is pumped into the shaft and settles via gravity to the bottom of the Grootvlei sub-basin (Figure 3-5). The depth of disposal would indicate that the injection takes place in Kimberley Reef. However, if it is assumed that that the sludge would settle to the lowest point through gravity feed, it would settle in the lowest part of the Grootvlei sub-basin and therefore in the main reef. The exact depth of the shaft is also not known, and it was assumed that the shaft would have been sunk to access both the Main Reef and the Kimberley Reef during active mining. The total assumed depth of Grootvlei #4 shaft is therefore 1 223 m.

3.4 East Rand Basin Hydraulic Heads

The ERB Plant hydraulic heads (surface elevation minus the measured water level) trends are plotted below in Figure 3-1. The Grootvlei #3 shaft displays a deeper calculated hydraulic head compared to the shallow boreholes (EBH-01 – EBH04). EBH-01 – EBH-04 are drilled 20.46, 19.95, 20.17, and 30.38 m deep, respectively. The shaft had an assumed depth of 1 172 m. The shaft has a deeper on average measured hydraulic head compared to the shallow monitoring boreholes despite being within close proximity to each other (EBH-04 is situated 80 m to the east). The lack of drawdown observed in the shallow boreholes proves that the Blesbokspruit is constantly recharging the shallow aquifer.

The Grootvlei #3 shaft water level increased to above the ECL (May 2021) following an increase in rainfall (CRD trend) coupled with a decrease in pumping at the same time. The water level increased to within approximately 15 m of decanting at the Nigel #1 shaft located (16 km) to the south and down-gradient of the ERB Plant. An increase in pumping rates has since decreased the hydraulic head in the basin to within 10 m

above the ECL as of December 2024.

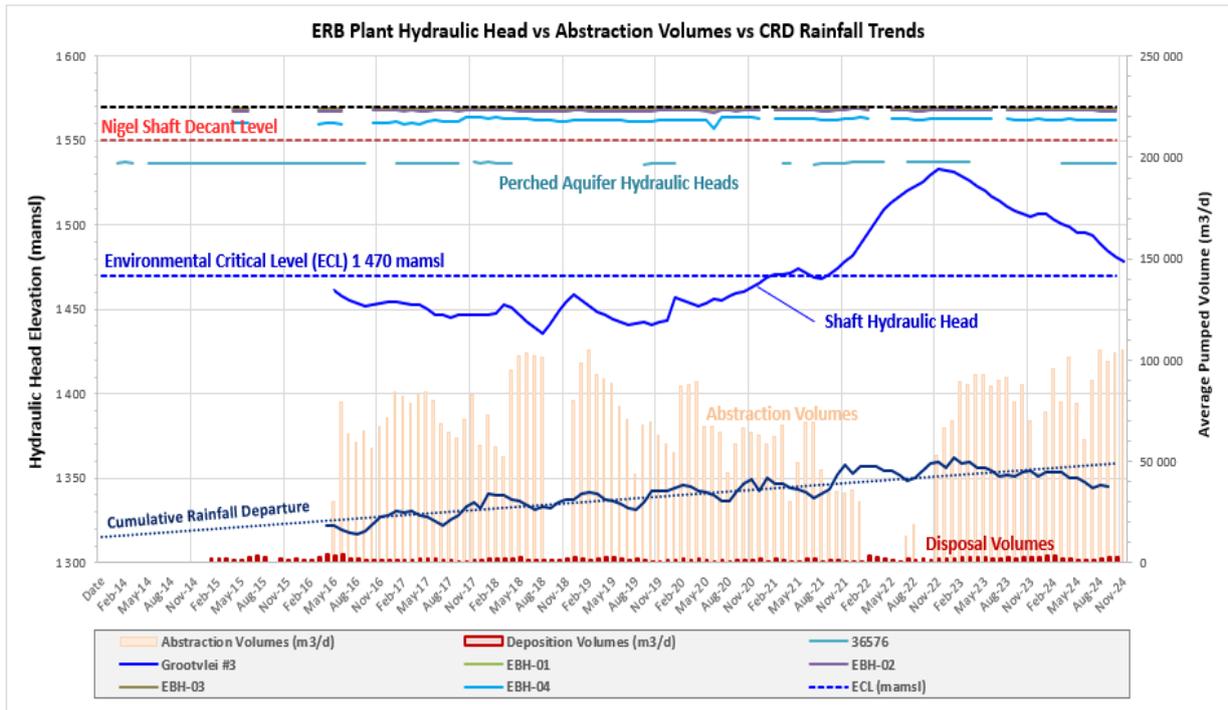


Figure 3-1: ERB Plant Hydraulic Head and Abstraction/Inhection Volumes vs Cumulative Rainfall Trend

The summary of historical monitoring record for the East Rand Basin (within the delineated model boundary) is shown in Table 3-2. The data was gathered from ACS monitoring database, ACS report archives, and additional data was provided by the DWS. The monitoring record was for both shaft and borehole water levels.

Overall, from the total 103 data points, 84 had single data points (i.e. one measured water level on record). Nineteen (19) sites had records stretching on average 2 years, with one borehole (ID: 36576) having a 38 year record and the boreholes at the plant being monitored for the past 10 years. Of the 19 sites with monitoring records, 6 had a decreasing trend of 6 m on average and 13 had an increase in water level of 225 m on average. The higher rise in water level is attributed to the shaft water levels increasing on average 323 m compared to the boreholes that had an average increase of 4 m.

The available long-term monitoring data trends of recorded hydraulic heads for the ERB watershed (Figure 3-1 to Figure 3-3), with the spatial distribution of the sites shown in Figure 2-3 and Figure 3-1. The following was concluded:

- Shaft water levels have increased correlating with the Cumulative Rainfall Departure (CRD) trend.
- The Vlakfontein Deep #2, Vlakfontein#1, and Holfontein #1 shafts show an increasing trend in water levels, however, do not show the seasonal variation in water levels. These shafts also have shallower water levels on average compared to the other deeper shafts

- Borehole water levels are stable over time in boreholes GP00501, GP00502, GP00499, EBH-01, EBH-02, EBH-03, EBH-04.
- The deepest water level (1 514 mamsl) was measured in GP00500 in September 2024, with the borehole displaying a downward trend.
- The boreholes situated in the shallow and perched aquifer system do not display the same seasonal trends as the shafts situated beneath the aquitard

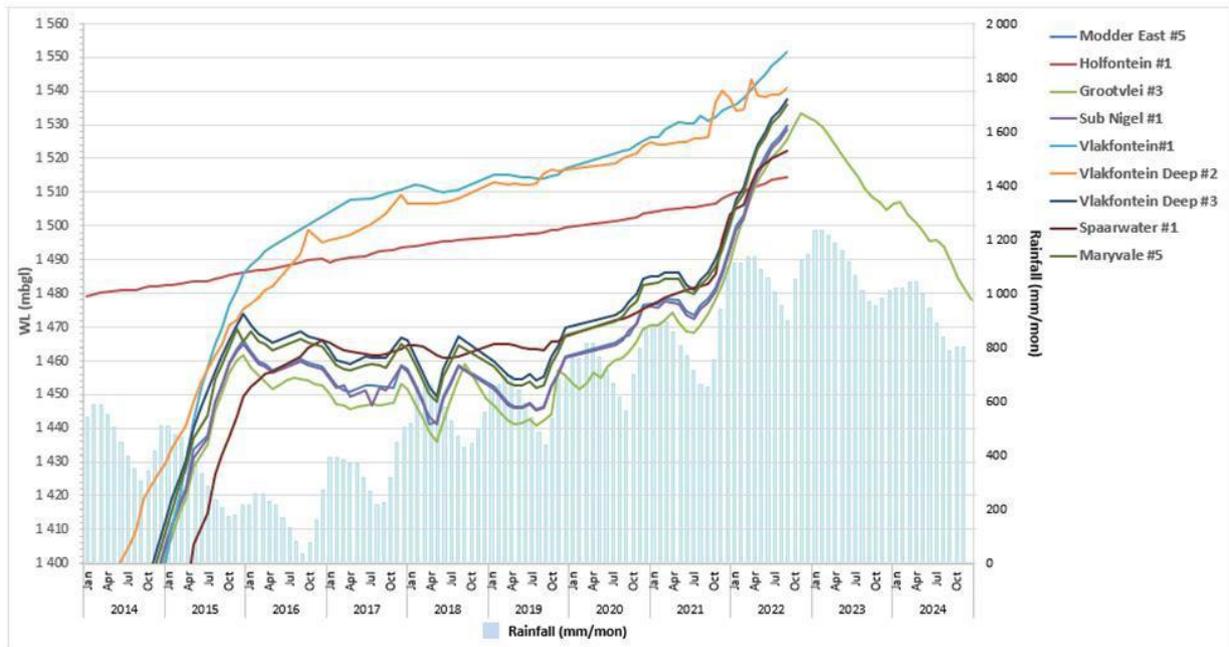


Figure 3-2: Recorded Hydraulic Head Measurements for Shafts Located in the ERB vs CRD Trends

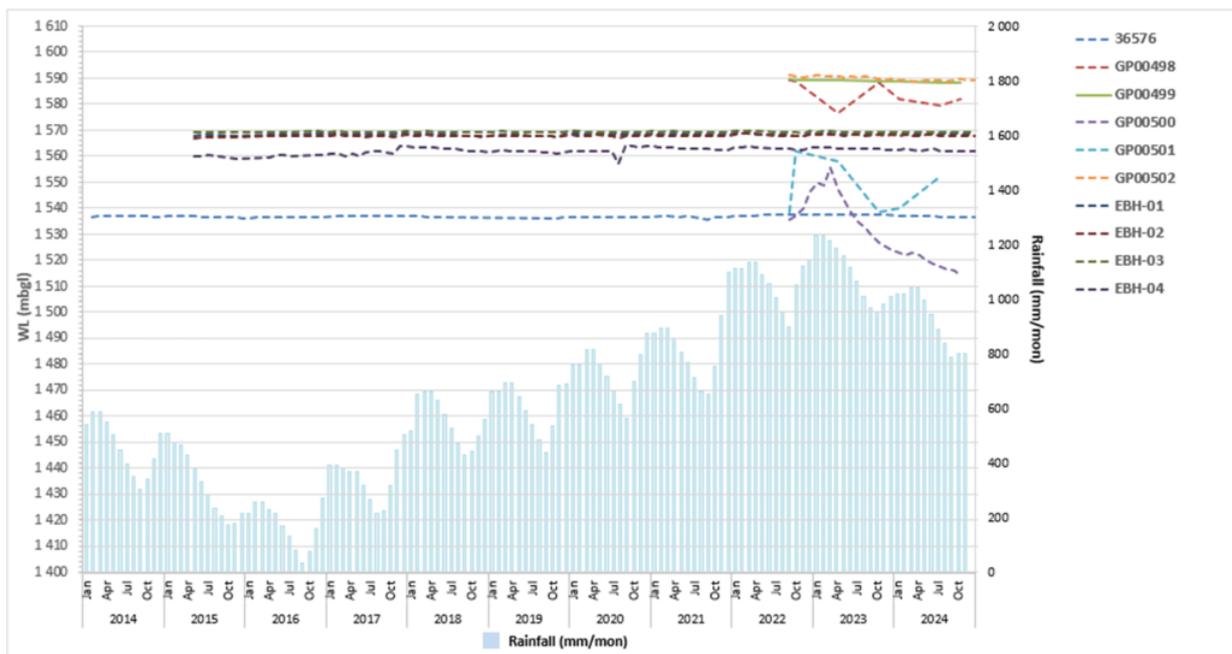


Figure 3-3: Recorded Hydraulic Head Measurements for Boreholes Located in the ERB vs CRD Trend

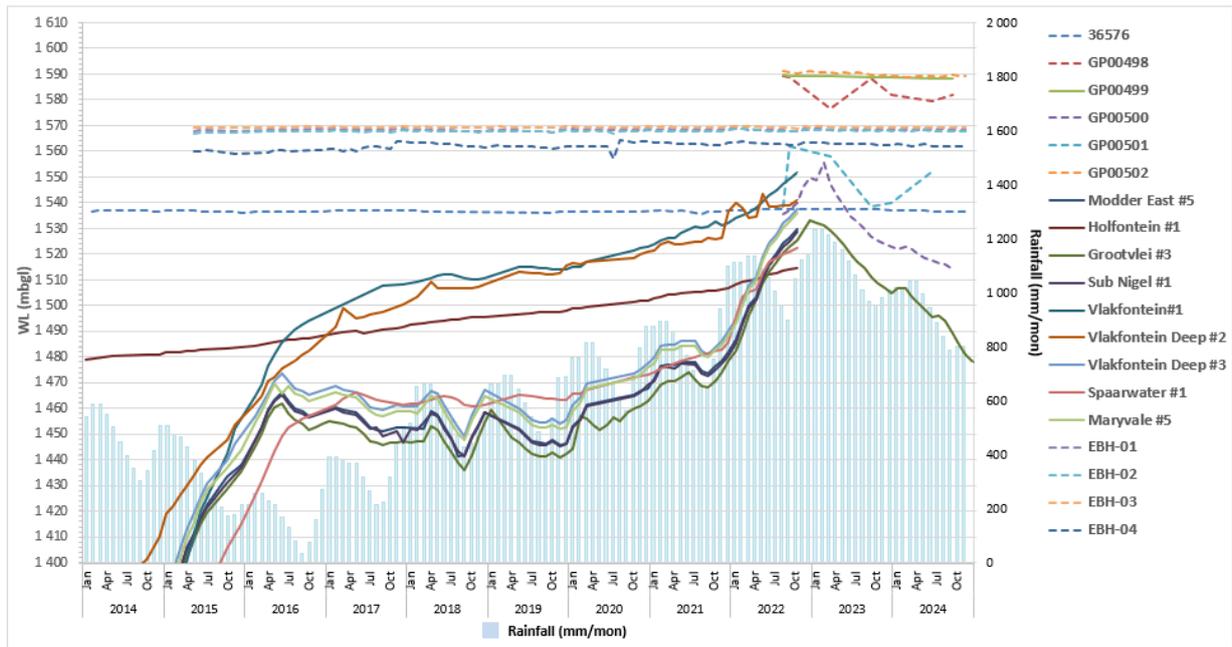


Figure 3-4: Recorded Hydraulic Head Measurements displayed Together to show |Correlation between Deep and Shallow Hydraulic Heads vs CRD Trend

Table 3-2: Water Level Monitoring Database for Boreholes and Shafts within the Model Boundary

Site ID	Site ID	X LO_29	Y LO_29	Z (mamsl)	Average of Hydraulic Head (mamsl)	P95 of Hydraulic Heads (mamsl)	P50 of Hydraulic Heads (mamsl)	Number of Data Points (count)	First Measured Hydraulic Head (mamsl)	Last Measured Hydraulic Head (mamsl)	Difference (m)	Trend First to Last	First Measured Date	Last Measured Date	Record Span (years)
Statistical Analysis for All Data Points															
				Max	1 633	1 633	1 633	3 039	1 633	1 633	483				38
				P95	1 624	1 624	1 624	109	1 624	1 624	288				10
				P50	1 582	1 582	1 582	1	1 582	1 582	0				0
				Average	1 571	1 579	1 572	50	1 551	1 579	28				2
				P05	1 465	1 517	1 465	1	1 232	1 517	0				0
1	36576	-74 013	-2 917 212	-2 917 212	1 537	1 538	1 537	293	1 538	1 537	-1	Decrease	1987/01/20	2024/11/21	38
2	GP00498	-43 650	-2 919 613	-2 919 613	1 584	1 589	1 582	7	1 589	1 582	-7	Decrease	2022/08/14	2024/09/18	2
3	GP00499	-43 638	-2 919 106	-2 919 106	1 589	1 590	1 589	7	1 590	1 588	-2	Decrease	2022/08/14	2024/09/18	2
4	GP00500	-48 000	-2 917 282	-2 917 282	1 532	1 549	1 532	29	1 536	1 514	-22	Decrease	2022/08/17	2024/09/18	2
5	GP00502	-43 295	-2 919 617	-2 919 617	1 590	1 591	1 590	28	1 591	1 589	-2	Decrease	2022/08/17	2024/11/13	2
6	EBH-03	-50 951	-2 904 699	-2 904 699	1 569	1 570	1 569	103	1 569	1 569	0	Decrease	2015/05/01	2024/11/28	10
7	GP00501	-48 098	-2 916 338	-2 916 338	1 548	1 561	1 546	6	1 538	1 552	14	Increase	2022/08/14	2024/06/20	2
8	Modder East #5	-54 828	-2 895 624	-2 895 624	1 449	1 521	1 460	105	1 046	1 530	483	Increase	2012/06/26	2022/10/19	10
9	Holfontein #1	-49 742	-2 895 293	-2 895 293	1 496	1 512	1 496	107	1 478	1 515	36	Increase	2012/06/26	2022/10/19	10
10	Grootvlei #3	-51 082	-2 904 784	-2 904 784	1 473	1 528	1 461	3 039	1 185	1 477	293	Increase	2013/09/10	2024/12/10	11
11	Sub Nigel #1	-54 974	-2 920 625	-2 920 625	1 263	1 499	1 196	337	1 046	1 528	483	Increase	2012/06/26	2022/10/19	10
12	Vlakfontein#1	-59 207	-2 914 489	-2 914 489	1 470	1 545	1 515	103	1 143	1 552	409	Increase	2012/08/16	2022/10/20	10
13	Vlakfontein Deep #2	-62 127	-2 912 884	-2 912 884	1 486	1 540	1 512	109	1 295	1 541	246	Increase	2012/08/16	2022/10/20	10
14	Vlakfontein Deep #3	-57 195	-2 916 256	-2 916 256	1 464	1 528	1 468	102	1 225	1 537	312	Increase	2013/11/13	2022/10/20	9
15	Spaarwater #1	-57 635	-2 921 969	-2 921 969	1 424	1 518	1 464	109	1 044	1 522	479	Increase	2012/08/07	2022/10/19	10
16	Maryvale #5	-47 259	-2 914 353	-2 914 353	1 423	1 506	1 408	263	1 369	1 536	167	Increase	2014/12/02	2022/10/19	8
17	EBH-01	-51 193	-2 904 558	-2 904 558	1 568	1 569	1 568	103	1 568	1 568	0	Increase	2015/05/01	2024/11/28	10
18	EBH-02	-51 085	-2 904 620	-2 904 620	1 568	1 568	1 568	103	1 567	1 568	1	Increase	2015/05/01	2024/11/28	10
19	EBH-04	-51 004	-2 904 800	-2 904 800	1 562	1 564	1 562	103	1 560	1 562	2	Increase	2015/05/01	2024/11/28	10
20	GP129	-65 956	-2 901 366	-2 901 366	1 576	1 576	1 576	1	1 576	1 576	0	Single Data Point	2005/08/05	2005/08/05	0
21	GP130	-62 928	-2 901 251	-2 901 251	1 616	1 616	1 616	1	1 616	1 616	0	Single Data Point	2005/08/05	2005/08/05	0
22	GP131	-63 001	-2 901 275	-2 901 275	1 616	1 616	1 616	1	1 616	1 616	0	Single Data Point	2005/08/05	2005/08/05	0
23	GP132	-68 147	-2 906 105	-2 906 105	1 564	1 564	1 564	1	1 564	1 564	0	Single Data Point	2005/08/05	2005/08/05	0
24	GP133	-62 224	-2 904 311	-2 904 311	1 623	1 623	1 623	1	1 623	1 623	0	Single Data Point	2005/08/04	2005/08/04	0
25	GP134	-63 289	-2 907 975	-2 907 975	1 612	1 612	1 612	1	1 612	1 612	0	Single Data Point	2005/08/04	2005/08/04	0
26	GP135	-64 846	-2 909 456	-2 909 456	1 565	1 565	1 565	1	1 565	1 565	0	Single Data Point	2005/08/03	2005/08/03	0
27	GP136	-66 174	-2 910 832	-2 910 832	1 577	1 577	1 577	1	1 577	1 577	0	Single Data Point	2005/08/02	2005/08/02	0
28	GP137	-68 715	-2 911 713	-2 911 713	1 560	1 560	1 560	1	1 560	1 560	0	Single Data Point	2005/08/03	2005/08/03	0
29	GP138	-44 767	-2 911 577	-2 911 577	1 576	1 576	1 576	1	1 576	1 576	0	Single Data Point	2005/07/26	2005/07/26	0
30	GP139	-45 608	-2 911 557	-2 911 557	1 571	1 571	1 571	1	1 571	1 571	0	Single Data Point	2005/07/27	2005/07/27	0
31	GP140	-45 618	-2 911 555	-2 911 555	1 572	1 572	1 572	1	1 572	1 572	0	Single Data Point	2005/07/27	2005/07/27	0
32	GP141	-47 508	-2 914 369	-2 914 369	1 567	1 567	1 567	1	1 567	1 567	0	Single Data Point	2005/07/28	2005/07/28	0
33	GP142	-48 477	-2 915 340	-2 915 340	1 568	1 568	1 568	1	1 568	1 568	0	Single Data Point	2005/07/28	2005/07/28	0
34	GP143	-51 683	-2 913 688	-2 913 688	1 571	1 571	1 571	1	1 571	1 571	0	Single Data Point	2005/07/29	2005/07/29	0
35	GP144	-50 291	-2 909 321	-2 909 321	1 554	1 554	1 554	1	1 554	1 554	0	Single Data Point	2005/07/30	2005/07/30	0

Site ID	Site ID	X LO_29	Y LO_29	Z (mamsl)	Average of Hydraulic Head (mamsl)	P95 of Hydraulic Heads (mamsl)	P50 of Hydraulic Heads (mamsl)	Number of Data Points (count)	First Measured Hydraulic Head (mamsl)	Last Measured Hydraulic Head (mamsl)	Difference (m)	Trend First to Last	First Measured Date	Last Measured Date	Record Span (years)
36	GP145	-51 486	-2 922 532	-2 922 532	1 553	1 553	1 553	1	1 553	1 553	0	Single Data Point	2005/08/01	2005/08/01	0
37	GP146	-53 376	-2 922 501	-2 922 501	1 550	1 550	1 550	1	1 550	1 550	0	Single Data Point	2005/08/02	2005/08/02	0
38	GP147	-53 378	-2 922 495	-2 922 495	1 552	1 552	1 552	1	1 552	1 552	0	Single Data Point	2005/08/02	2005/08/02	0
39	GP148	-55 389	-2 920 859	-2 920 859	1 583	1 583	1 583	1	1 583	1 583	0	Single Data Point	2005/08/01	2005/08/01	0
40	GP149	-62 238	-2 912 701	-2 912 701	1 570	1 570	1 570	1	1 570	1 570	0	Single Data Point	2005/08/03	2005/08/03	0
41	GP151	-54 251	-2 895 045	-2 895 045	1 579	1 579	1 579	1	1 579	1 579	0	Single Data Point	2005/08/06	2005/08/06	0
42	GP152	-54 367	-2 893 415	-2 893 415	1 580	1 580	1 580	1	1 580	1 580	0	Single Data Point	2005/08/07	2005/08/07	0
43	cen15	-70 873	-2 912 241	-2 912 241	1 553	1 553	1 553	1	1 553	1 553	0	Single Data Point	2005/09/28	2005/09/28	0
44	cen16	-70 997	-2 911 173	-2 911 173	1 555	1 555	1 555	1	1 555	1 555	0	Single Data Point	2005/09/28	2005/09/28	0
45	cen18	-72 021	-2 909 083	-2 909 083	1 588	1 588	1 588	1	1 588	1 588	0	Single Data Point	2005/09/28	2005/09/28	0
46	cen21	-72 346	-2 907 646	-2 907 646	1 595	1 595	1 595	1	1 595	1 595	0	Single Data Point	2005/09/28	2005/09/28	0
47	cen22	-72 062	-2 907 501	-2 907 501	1 598	1 598	1 598	1	1 598	1 598	0	Single Data Point	2005/09/28	2005/09/28	0
48	cen25	-73 423	-2 908 462	-2 908 462	1 587	1 587	1 587	1	1 587	1 587	0	Single Data Point	2005/09/28	2005/09/28	0
49	cen28	-73 607	-2 908 919	-2 908 919	1 592	1 592	1 592	1	1 592	1 592	0	Single Data Point	2005/09/28	2005/09/28	0
50	cen57	-61 570	-2 888 331	-2 888 331	1 545	1 545	1 545	1	1 545	1 545	0	Single Data Point	2005/09/28	2005/09/28	0
51	cen59	-61 451	-2 888 032	-2 888 032	1 595	1 595	1 595	1	1 595	1 595	0	Single Data Point	2005/09/28	2005/09/28	0
52	cen61	-60 971	-2 888 096	-2 888 096	1 599	1 599	1 599	1	1 599	1 599	0	Single Data Point	2005/09/28	2005/09/28	0
53	cen63	-60 800	-2 888 317	-2 888 317	1 562	1 562	1 562	1	1 562	1 562	0	Single Data Point	2005/09/28	2005/09/28	0
54	cen69	-64 052	-2 910 435	-2 910 435	1 579	1 579	1 579	1	1 579	1 579	0	Single Data Point	2005/09/28	2005/09/28	0
55	cen71	-63 037	-2 909 632	-2 909 632	1 608	1 608	1 608	1	1 608	1 608	0	Single Data Point	2005/09/28	2005/09/28	0
56	cen72	-63 176	-2 909 821	-2 909 821	1 583	1 583	1 583	1	1 583	1 583	0	Single Data Point	2005/09/28	2005/09/28	0
57	cen74	-63 833	-2 910 234	-2 910 234	1 582	1 582	1 582	1	1 582	1 582	0	Single Data Point	2005/09/28	2005/09/28	0
58	cen76	-63 674	-2 909 990	-2 909 990	1 603	1 603	1 603	1	1 603	1 603	0	Single Data Point	2005/09/28	2005/09/28	0
59	cen80	-64 282	-2 910 237	-2 910 237	1 586	1 586	1 586	1	1 586	1 586	0	Single Data Point	2005/09/28	2005/09/28	0
60	cen82	-63 194	-2 910 121	-2 910 121	1 577	1 577	1 577	1	1 577	1 577	0	Single Data Point	2005/09/28	2005/09/28	0
61	cen83	-63 265	-2 909 977	-2 909 977	1 576	1 576	1 576	1	1 576	1 576	0	Single Data Point	2005/09/28	2005/09/28	0
62	cen84	-62 745	-2 910 185	-2 910 185	1 604	1 604	1 604	1	1 604	1 604	0	Single Data Point	2005/09/28	2005/09/28	0
63	cen86	-62 432	-2 910 859	-2 910 859	1 598	1 598	1 598	1	1 598	1 598	0	Single Data Point	2005/09/28	2005/09/28	0
64	cen87	-62 432	-2 910 870	-2 910 870	1 598	1 598	1 598	1	1 598	1 598	0	Single Data Point	2005/09/28	2005/09/28	0
65	cen88	-62 382	-2 910 859	-2 910 859	1 562	1 562	1 562	1	1 562	1 562	0	Single Data Point	2005/09/28	2005/09/28	0
66	cen92	-63 125	-2 912 015	-2 912 015	1 566	1 566	1 566	1	1 566	1 566	0	Single Data Point	2005/09/28	2005/09/28	0
67	cen94	-62 427	-2 911 945	-2 911 945	1 588	1 588	1 588	1	1 588	1 588	0	Single Data Point	2005/09/28	2005/09/28	0
68	cen102	-59 922	-2 896 433	-2 896 433	1 599	1 599	1 599	1	1 599	1 599	0	Single Data Point	2005/09/28	2005/09/28	0
69	cen103	-59 434	-2 895 977	-2 895 977	1 600	1 600	1 600	1	1 600	1 600	0	Single Data Point	2005/09/28	2005/09/28	0
70	cen105	-59 634	-2 895 956	-2 895 956	1 601	1 601	1 601	1	1 601	1 601	0	Single Data Point	2005/09/28	2005/09/28	0
71	cen120	-57 001	-2 887 579	-2 887 579	1 596	1 596	1 596	1	1 596	1 596	0	Single Data Point	2005/09/28	2005/09/28	0
72	cen125	-58 277	-2 888 615	-2 888 615	1 600	1 600	1 600	1	1 600	1 600	0	Single Data Point	2005/09/28	2005/09/28	0
73	cen126	-59 434	-2 895 977	-2 895 977	1 605	1 605	1 605	1	1 605	1 605	0	Single Data Point	2005/09/28	2005/09/28	0
74	cen130	-59 141	-2 890 104	-2 890 104	1 600	1 600	1 600	1	1 600	1 600	0	Single Data Point	2005/09/28	2005/09/28	0
75	cen132	-59 270	-2 890 271	-2 890 271	1 604	1 604	1 604	1	1 604	1 604	0	Single Data Point	2005/09/28	2005/09/28	0
76	cen133	-58 376	-2 886 755	-2 886 755	1 604	1 604	1 604	1	1 604	1 604	0	Single Data Point	2005/09/28	2005/09/28	0
77	cen136	-59 850	-2 890 384	-2 890 384	1 610	1 610	1 610	1	1 610	1 610	0	Single Data Point	2005/09/28	2005/09/28	0
78	cen137	-59 839	-2 890 495	-2 890 495	1 608	1 608	1 608	1	1 608	1 608	0	Single Data Point	2005/09/28	2005/09/28	0
79	cen138	-59 598	-2 890 837	-2 890 837	1 610	1 610	1 610	1	1 610	1 610	0	Single Data Point	2005/09/28	2005/09/28	0

Site ID	Site ID	X LO_29	Y LO_29	Z (mamsl)	Average of Hydraulic Head (mamsl)	P95 of Hydraulic Heads (mamsl)	P50 of Hydraulic Heads (mamsl)	Number of Data Points (count)	First Measured Hydraulic Head (mamsl)	Last Measured Hydraulic Head (mamsl)	Difference (m)	Trend First to Last	First Measured Date	Last Measured Date	Record Span (years)
80	cen140	-59 487	-2 891 003	-2 891 003	1 606	1 606	1 606	1	1 606	1 606	0	Single Data Point	2005/09/28	2005/09/28	0
81	cen141	-59 007	-2 890 890	-2 890 890	1 601	1 601	1 601	1	1 601	1 601	0	Single Data Point	2005/09/28	2005/09/28	0
82	cen144	-60 823	-2 885 481	-2 885 481	1 620	1 620	1 620	1	1 620	1 620	0	Single Data Point	2005/09/28	2005/09/28	0
83	cen145	-59 682	-2 892 012	-2 892 012	1 616	1 616	1 616	1	1 616	1 616	0	Single Data Point	2005/09/28	2005/09/28	0
84	cen148	-59 865	-2 891 414	-2 891 414	1 601	1 601	1 601	1	1 601	1 601	0	Single Data Point	2005/09/28	2005/09/28	0
85	cen149	-59 915	-2 891 392	-2 891 392	1 619	1 619	1 619	1	1 619	1 619	0	Single Data Point	2005/09/28	2005/09/28	0
86	cen150	-60 050	-2 890 429	-2 890 429	1 612	1 612	1 612	1	1 612	1 612	0	Single Data Point	2005/09/28	2005/09/28	0
87	cen154	-63 957	-2 894 025	-2 894 025	1 558	1 558	1 558	1	1 558	1 558	0	Single Data Point	2005/09/28	2005/09/28	0
88	cen156	-64 012	-2 893 879	-2 893 879	1 594	1 594	1 594	1	1 594	1 594	0	Single Data Point	2005/09/28	2005/09/28	0
89	cen163	-62 300	-2 892 782	-2 892 782	1 625	1 625	1 625	1	1 625	1 625	0	Single Data Point	2005/09/28	2005/09/28	0
90	cen164	-62 255	-2 892 584	-2 892 584	1 596	1 596	1 596	1	1 596	1 596	0	Single Data Point	2005/09/28	2005/09/28	0
91	cen165	-62 255	-2 892 591	-2 892 591	1 630	1 630	1 630	1	1 630	1 630	0	Single Data Point	2005/09/28	2005/09/28	0
92	cen166	-62 251	-2 892 594	-2 892 594	1 601	1 601	1 601	1	1 601	1 601	0	Single Data Point	2005/09/28	2005/09/28	0
93	cen167	-61 948	-2 893 381	-2 893 381	1 628	1 628	1 628	1	1 628	1 628	0	Single Data Point	2005/09/28	2005/09/28	0
94	cen168	-61 694	-2 893 119	-2 893 119	1 633	1 633	1 633	1	1 633	1 633	0	Single Data Point	2005/09/28	2005/09/28	0
95	cen170	-61 935	-2 893 378	-2 893 378	1 631	1 631	1 631	1	1 631	1 631	0	Single Data Point	2005/09/28	2005/09/28	0
96	cen172	-67 050	-2 898 619	-2 898 619	1 624	1 624	1 624	1	1 624	1 624	0	Single Data Point	2005/09/28	2005/09/28	0
97	cen201	-74 251	-2 910 315	-2 910 315	1 459	1 459	1 459	1	1 459	1 459	0	Single Data Point	2005/09/28	2005/09/28	0
98	cen555	-60 628	-2 899 078	-2 899 078	1 576	1 576	1 576	1	1 576	1 576	0	Single Data Point	2005/09/28	2005/09/28	0
99	cen592	-68 533	-2 921 974	-2 921 974	1 571	1 571	1 571	1	1 571	1 571	0	Single Data Point	2005/09/28	2005/09/28	0
100	cen603	-74 910	-2 916 787	-2 916 787	1 516	1 516	1 516	1	1 516	1 516	0	Single Data Point	2005/09/28	2005/09/28	0
101	cen604	-74 446	-2 916 298	-2 916 298	1 514	1 514	1 514	1	1 514	1 514	0	Single Data Point	2005/09/28	2005/09/28	0
102	CEN680	-61 510	-2 898 989	-2 898 989	1 576	1 576	1 576	1	1 576	1 576	0	Single Data Point	2005/09/28	2005/09/28	0
103	CEN681	-54 146	-2 899 878	-2 899 878	1 577	1 577	1 577	1	1 577	1 577	0	Single Data Point	2005/09/28	2005/09/28	0

*Shaft Locations marked | blue

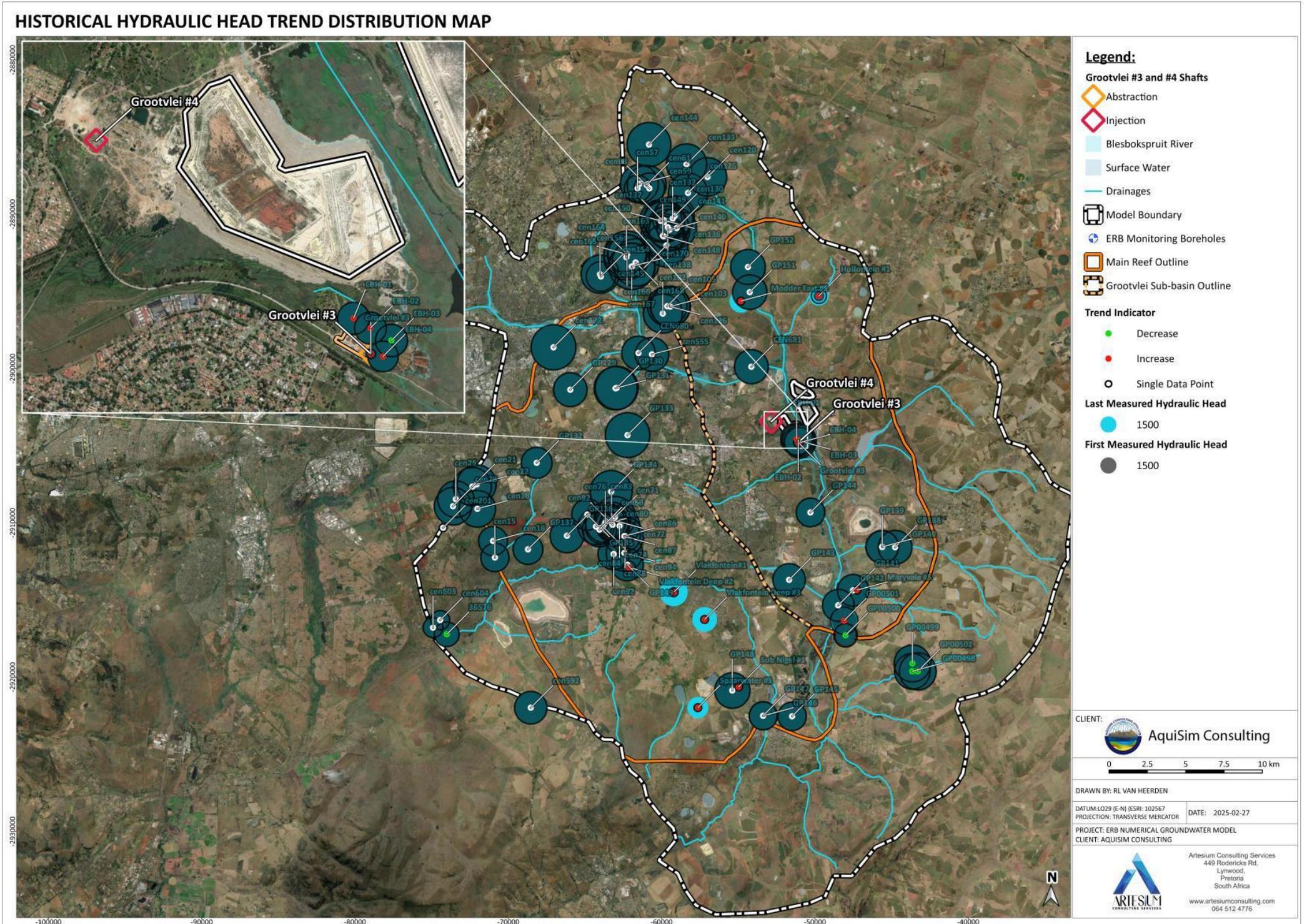


Figure 3-5: Historical Hydraulic Head Trend Distribution Map

3.5 Surface Water Quality Trends and Spatial Distribution

3.5.1 AMD and Effluent Water

Water quality of AMD samples that have been taken from the abstracted water at Grootvlei #3 shaft had stable TDS (Total Dissolved Solids) concentrations. From the TDS values to date, 80% were between 2 034 mg/L and 2 361 mg/L. For sulphate 80% of values were between 968 mg/L and 1 247 mg/L. Although sulphate in plant effluent have varied from being 35% below that of AMD to 21% above, the averages for AMD and effluent are not distinguishable. On average, ERB plant effluent TDS has been 5% lower than AMD TDS.

Variation in AMD iron concentrations observed to date were in contrast with the relative stability of other parameters. The long-term average concentration of 11 mg/l includes concentrations below the detection limit up to elevated concentrations of which 10% were above 41 mg/l (maximum of 82 mg/l). The reasons for the variations may relate to a defined interface between water of different qualities and properties that have been noted at depths that varied between 130 m and 160 m and is near the pump intake (Exigo, 2020). The only other AMD parameters with similar variations are turbidity and suspended solids. In contrast to iron concentrations in the AMD, the iron concentrations in plant effluent have not exceeded 0.3 mg/l and was only detected in 5% of samples taken. Average iron concentration of 11 mg/L in AMD decreasing to below 0.004 mg/l in plant effluent implies that 780 kg/d of iron is disposed (Grootvlei #4 shaft) via the sludge injection, given abstraction and treatment of 71 ML/d.

Manganese is detected constantly in the AMD water and in a relatively narrow range. In monitoring to date, 80% of concentrations were between 2.5 mg/L and 4.4 mg/L and averaged 3.436 mg/L. Manganese in plant effluent has averaged 2.044 mg/L since April 2020. The decrease in concentration implies that 100 kg/d of manganese is disposed of via the sludge.

Uranium was below detection (0.015 mg/L) in most samples taken in the shaft from July 2017 to March 2019. Uranium in the five AMD abstraction samples taken from April 2019 to May 2020 averaged 0.043 mg/L. Uranium was then below detection in twelve samples taken, only detected again on 21 February 2023 at 0.028 mg/L and recently during November 2024 (0.021 mg/L). The detection of U in AMD water seems to be related to the detection of U in plant effluent samples at times. The November 2024 concentrations in AMD water and effluent of 0.021 mg/L also matched exactly. This would imply minimal uranium was disposed of via the sludge and rather goes through plant processes and is deposited into the Blesbokspruit River. It is recommended that the plant SOP is adapted to remove U from the abstracted AMD water.

In AMD, effluent and surface water samples taken on 30 January 2025 uranium was below the detection limit of 0.015 mg/L using the regular ICP-OES method. Samples were however also subjected to ICP-MS analyses and results of 0.016 mg/L (effluent) and 0.009 mg/L (AMD) were obtained. At surface water upstream locations ESW-01, ESW-02 and ESW-04 uranium was not detected. Downstream at ESW-06, uranium of 0.003 mg/L was detected.

At the Central Basin plant, a sample of sludge was taken during a spillage on 29 July 2023. Uranium was not detected in either the water fraction or the leachate of the solids fraction (Artesium, 2023). Together with the above, this corroborates minimal disposal of uranium via the sludge injection.

3.5.2 Surface Water Quality

Water quality of the Blesbokspruit and tributary has been monitored since inception of the plant in 2015. Six locations have been sampled (refer to Figure 3-6). Significant impact due to plant effluent discharge has been observed at the downstream locations ESW-03 and ESW-06. These locations are approximately 700 m and 1.7 km downstream of the plant, respectively. The impact at these locations has been characterised by elevated sulphate concentrations and 80% of values have been between 139 mg/L and 660 mg/L, at times of effluent discharge. In contrast, at the upstream locations ESW-01, ESW-02 and ESW-04, 80% of sulphate concentrations have been between 37 mg/L and 117 mg/L.

The increase in sulphate concentrations from upstream to downstream of plant discharge has been balanced by associated increases in calcium and magnesium concentrations and to a lesser extent sodium. No other increases were observed. Specifically, average iron and manganese concentrations were noted to decrease from upstream to downstream. Impact by sludge would likely reflect in increase in iron concentrations.

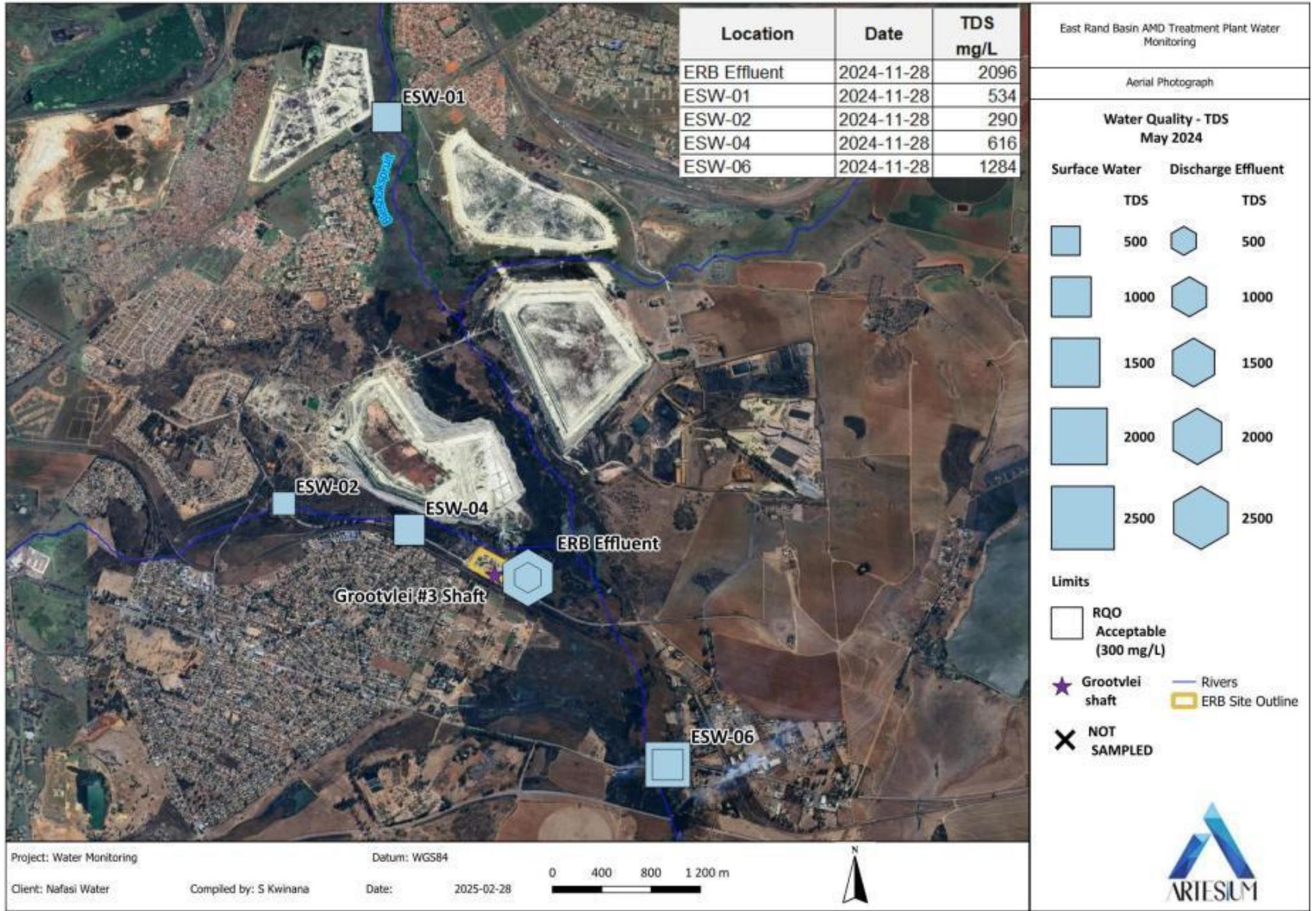


Figure 3-6: ERB TDS Surface Water Quality Results for February 2025

3.5.3 Plant Groundwater Quality

In the ERB plant environmental authorisation (DEA, 2013) under Specific Conditions, Water Quality Monitoring (Item 59), a requirement for installation of shallow monitoring wells around the treatment facility is made. The drilling of four boreholes on the perimeter of the plant in 2015 was in fulfilment of this requirement.

Groundwater quality has not been observed to change significantly over time. An initial TDS of 2 040 mg/L and two values near 1 500 mg/L during 2017 were observed at ERB-01. All other values at ERB-01, ERB-02 and ERB-03 were below 600 m/L. Boreholes EBH-04 has maintained a slightly higher TDS not values have never exceeded 850 mg/L. TDS values during November 2024 varied from 276 mg/L (EBH-01) to 544 mg/L (EBH-04). See Figure 3-7.

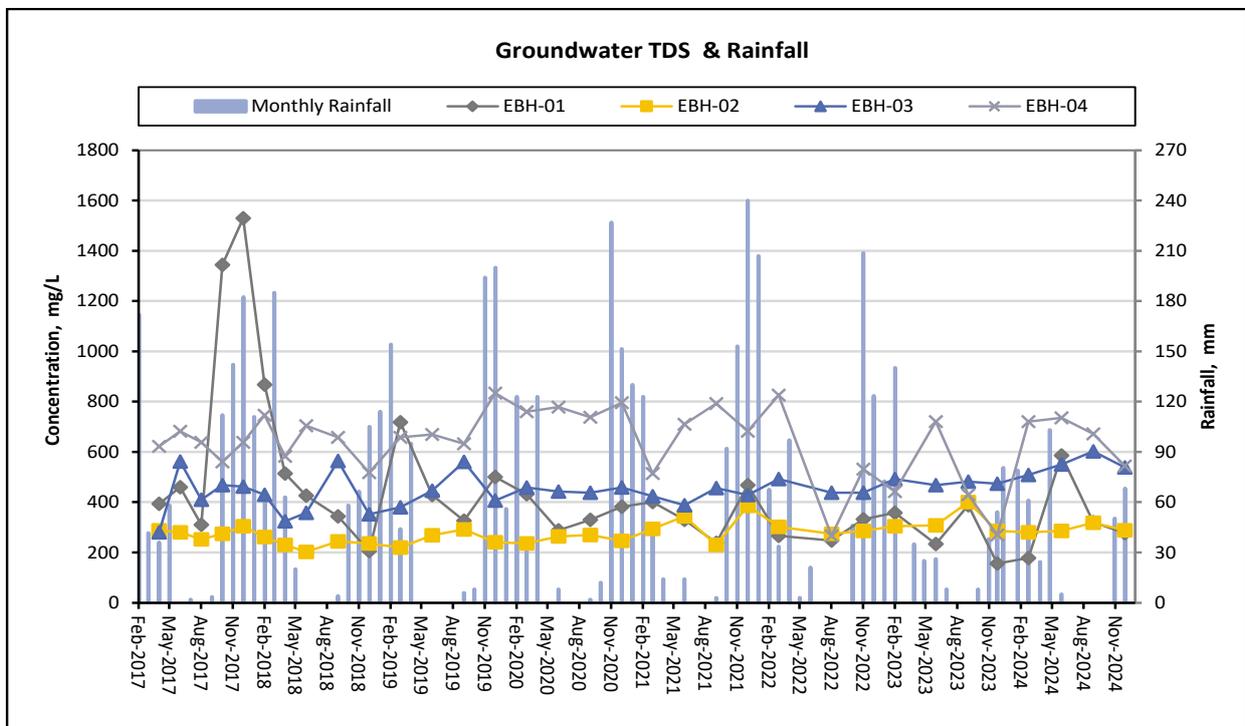


Figure 3-7: Groundwater TDS Trends vs Rainfall Trends

Three metals (iron, manganese and uranium) were identified as critical for monitoring. In terms of these metals the following was noted.

Manganese was detected at EBH-01 (0.02 mg/L), EBH-03 (0.16 mg/L) and EBH -04 (0.24 mg/L) during November 2024. It was not detected at EBH-02. Iron and uranium were not detected at any borehole. These results were similar to historical findings as manganese has been detected in 70% of groundwater samples to date. Only five (2.6%) of these manganese values have exceeded the SANS 241 drinking water limit of 0.4 mg/L and all five instances were before 2018. Iron has been detected in 15% of groundwater samples to date. Only five (2.6%) of these iron values have exceeded the SANS 241 drinking water limit of 2 mg/L and these were sporadically at EBH-01 and EBH-03. Uranium has only been detected in 1 out of 180 groundwater

samples taken to date and this was during 2015. In view of the above results, it was inferred that no impact on groundwater was observed from sludge or AMD water.

3.5.4 DWS Groundwater Database Quality

Groundwater quality data for the area of interest was requested from DWS. A data set for 924 boreholes, mostly located west of the model boundary as far as Rockville, was received. The data dates back to 1970, with 80% of the data covering the years 1983 to 1999. It included five boreholes that are located within the model boundary and also have results for 2024. Seventy other boreholes are located within the model boundary with data older than 1995.

TDS and sulphate concentrations for the five boreholes within the model boundary and with recent results are listed in Table 3-3. These boreholes are less than 7 km apart and located between 1 km and 7 km from the Blesbokspruit (refer to Figure 3-9), and some 10 km south of the ERB plant. Four of the boreholes displayed similar quality in their available data, that covers July 2022 to June 2024. TDS for these boreholes varied between 421 mg/L and 753 mg/L, while sulphate varied between 7 mg/L and 325 mg/L.

At the fifth borehole (1000265505), TDS values varied between 1 580 mg/L and 3 330 mg/L, with elevated sulphate averaging 1 457 mg/L. The borehole is located at the Maryvale mine shaft #5 and likely affected by local historical mining activities. The higher TDS and sulphate concentrations correlates with AMD water and this could also be indicative of the borehole being drilled into the ERB, accessing AMD water.

Table 3-3: TDS and sulphate for five boreholes in DWS data set

DWS Borehole ID	Date Analysed	Total Dissolved Solids as TDS [mg/L]	Sulphate as SO ₄ [mg/L]
1000265488	2024/06/11	677	78
1000265496	2024/06/11	623	80
1000265499	2024/06/11	452	39
1000265501	2024/06/11	565	14
1000265505	2024/03/11	1 570	1 143

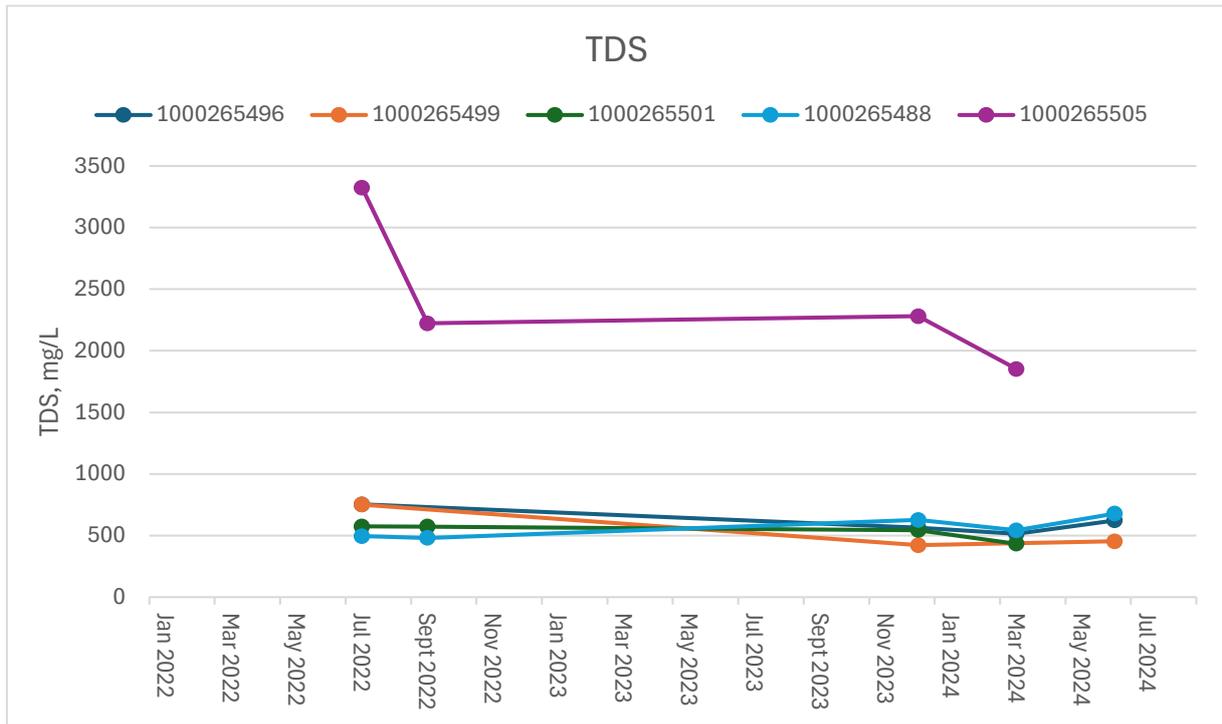


Figure 3-8: TDS for five boreholes in DWS data set.

In terms of the three metals (iron, manganese and uranium) identified as critical for monitoring, the following was noted:

- Iron concentrations at the five boreholes (1000265488, 1000265496, 1000265499, 1000265501, and 1000265505) were all below 0.07 mg/L, well below the SANS 241 drinking water limit of 2 mg/L. No discernible trends were observed.
- Manganese concentrations at borehole 1000265505 (at Maryvale #5 shaft) varied between 2.65 mg/L and 4.2 mg/L and exceeded the SANS 241 drinking water limit of 0.4 mg/L. One concentration of 0.68 mg/L at 1000265496 during July 2022 also exceeded the limit. Subsequent concentrations as well as concentrations at three other boreholes were while below 0.03 mg/L. No uranium results were available in the data set.
- In view of the above results, it was inferred that no impact on groundwater was observed from sludge or AMD water.

DWS GROUNDWATER TDS BUBBLE PLOT DISTRIBUTION MAP

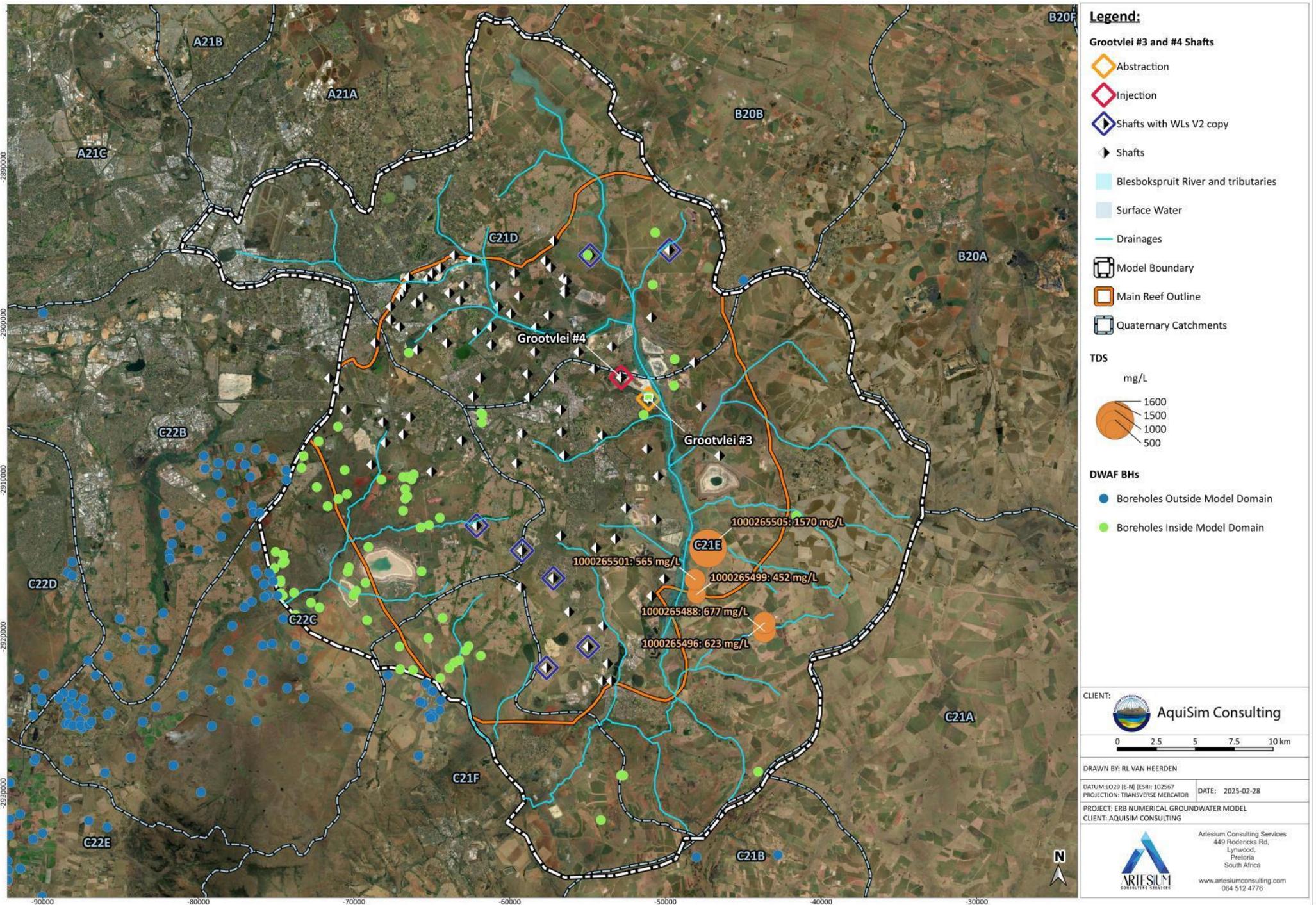


Figure 3-9: Groundwater TDS Bubble Plot Distribution Map

4 AQUIFER CHARACTERISATION

The aquifer classification and vulnerability were assessed using the aquifer system management classification discussed in Parsons and Conrad’s (1995) Explanatory Note for the Aquifer Classification Map of South Africa. The aquifer vulnerability and classification maps are presented in Figure 4-1 and Figure 4-2,

The aquifer system management classification was developed based on the work by Parsons (1995) and Vegter (1995). The aquifer classification map was developed utilising the geohydrological units developed by Vegter (1995) and system management classes developed by Parsons (1995). Table 4-1 below presents the different aquifer classes as described by Parsons and Conrad.

Table 4-1: Modified aquifer system management classification (Parsons and Conrad, 1995)

Aquifer type	Description
Sole source aquifer	An aquifer used to supply 50% or more of urban domestic water for a given area and for which there are no reasonably available alternative sources of water.
Major aquifer region	A high-yielding aquifer system of good quality water.
Minor aquifer region	A moderately-yielding aquifer system of variable water quality.
Poor groundwater region	A low to negligible yielding aquifer system of moderate to poor water quality.
Special aquifer region	An aquifer system designated as such by the Minister of Water Affairs and Forestry, after due process.

Table 4-2 below indicates groundwater usage in South Africa and was developed to inform the sole source aquifers and special aquifers across the country.

Table 4-2: The Aquifer Management System in Relation to The Borehole Prospect Map Of Vegter (1995) and (Parsons & Conrad, 1995)

Accessibility	Exploitability					
	<10%	10% - 20 %	20% - 30 %	30% - 40 %	40% - 50 %	>50%
>60%	poor	minor	minor	major	major	major
40% - 60%	poor	poor	minor	minor	major	major
<40%	poor	poor	poor	minor	minor	major

Q and TQc	major
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The Aquifer vulnerability is based on the map originally compiled by Reynders and Lynch (1993), (Parsons & Conrad, 1995). The classification uses the DRASTIC method of classification that considers the seven factors that affect aquifer characterization:

1. Depth to groundwater;
2. Recharge;
3. Aquifer Media;

4. Soil media;
5. Topography;
6. Impact on vadose zone; and
7. (Hydraulic) Conductivity.

The ERB watershed is inferred to be underlain by a major aquifer system. Considering the Aquifer Vulnerability of South Africa Map (2013) the aquifer region is rated as most vulnerable. Aquifer mass susceptibility can be determined by the product of the classification and vulnerability of an aquifer. The matrix in Table 4-3 shows the different classes in aquifer susceptibility. Based on the description given in the table, the localized aquifer underlying the plant has high susceptibility to mass transport.

Table 4-3: Aquifer Contamination susceptibility classes (Parsons & Conrad, 1995)

Vulnerability Class	Vulnerability Class		
	low (1)	medium (2)	high (3)
Aquifer System Management Class			
poor groundwater region (1)	low susceptibility (1)	low susceptibility (2)	medium susceptibility (3)
minor aquifer region (2)	low susceptibility (2)	medium susceptibility (4)	high susceptibility (6)
major aquifer region (3)	medium susceptibility (3)	high susceptibility (6)	high susceptibility (9)

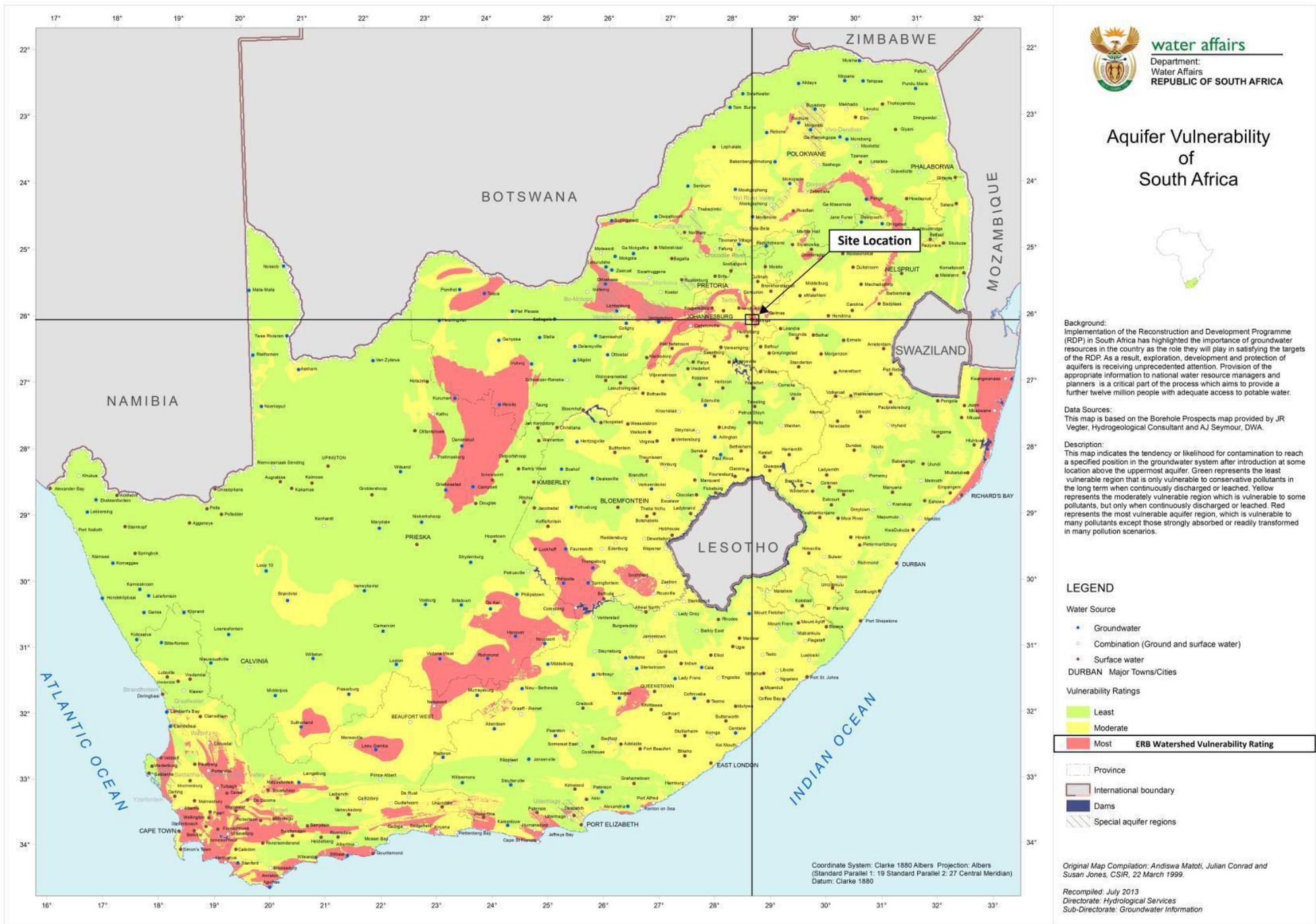


Figure 4-1: Aquifer Vulnerability Map of South Africa

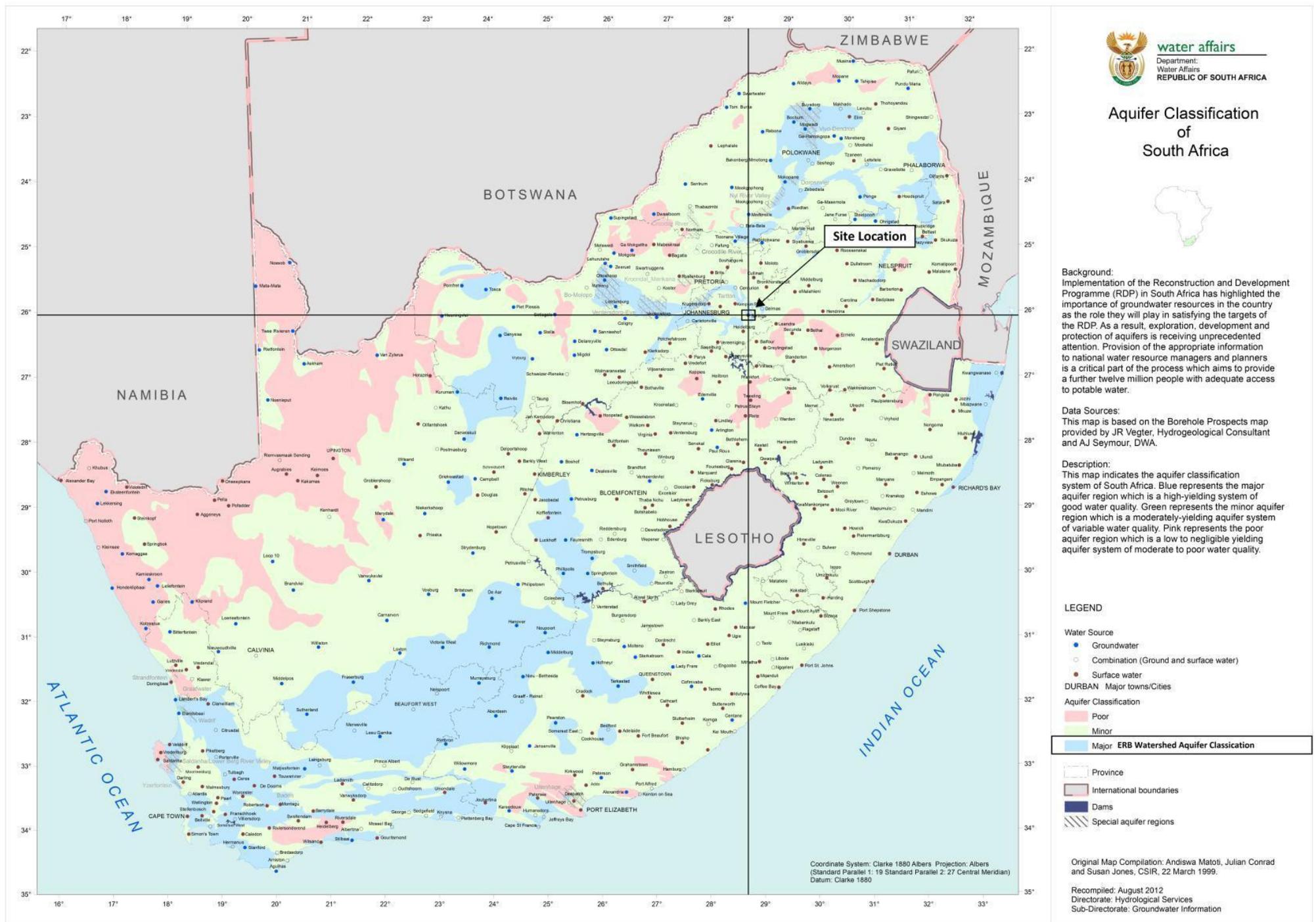


Figure 4-2: Aquifer Classification Map of South Africa

5 HYDROGEOLOGICAL CONCEPTUAL MODEL

A Conceptual Site Model (CSM) was constructed for the ERB delineated sub-catchment (model domain). The CSM displayed in Figure 5-2, with the model domain displayed in Figure 5-1. The following data sources were used to construct model:

- Model topography data was derived from the 1:50 000 topographical map series data of South Africa and the generated Digital Elevation Model (DEM).
- Surface geology and cross sections were derived from the 1:50 000 CGS map sheets (2628AB, 2628AD, 2628BA, and 2628BC), along with the explanation sheets compiled by Lubbe et al., (2007) and Opperman et al., (2005).
- The following data was gathered from reports compiled by AGES, 2006; Exigo 2017; ASA, 2022:
 - previous conceptual models;
 - model layer thickness and hydrogeological property zones;
 - ingress zones;
 - model groundwater and surface water balance volumes;
 - shaft locations and depths; and
 - groundwater recharge values.
- Main reef elevation, and green sill (grid) files from ACS archives.
- Climate data was derived from ACS archives and was recorded on site and provided by Nafasi Plant.
- Hydrochemistry data was summarised from ACS archives, that conducts the monthly monitoring at the plant.

The shape of the ERB was derived from ACS archives along with the Green Sill geometry. The Main Reef had a thickness of 1 m in the model, the Kimberley reef was simulated 500 m above the Main Reef and had the same thickness and hydraulic conductivity assigned to Main Reef. The main reef was represented in the model up to the surface with higher hydraulic conductivity values, as this reef is well developed, and it is assumed to be mined out up to or close to the surface.

The green sill was represented throughout the model domain as an impermeable layer as it is not known where the aquitard will pinch out or outcrop. The dykes in the model domain had an impermeable matrix with the contact zones input as preferential flow pathways utilising discrete features with a thickness of 0.1 m. Three other main flow pathways from surface to deep underground (Witwatersrand Supergroup) were represented in the model domain:

1. Shaft annulus (imposed as a discrete feature);
2. Main Reef outcrop (represented by higher K-values); and
3. Sinkholes underlain by WAD (Weathering After Dolomite input into the model with higher K-values).

The shallow mined out voids or footprint of mined out areas is not known. It was assumed that the dolomites underlying the sinkholes located to the east of the ERB plant would act as an ingress zone and recharge the Witwatersrand Supergroup, and both reefs. The water discharges from the Blesbokspruit at approximately 60 740 m³/d and accounts for 85% of the water pumped from the Grootvlei #3 shaft in the model. It is recommended that the mined-out areas be investigated in order to get a more accurate representation of ingress zones in the ERB.

The goal of the numerical groundwater model was to simulate the interaction or flow dynamics in the Grootvlei Sub-basin as a result of the injection at Grootvlei #4 shaft, and the dewatering from the Grootvlei #3 shaft. This was done to better understand the flow dynamics in the basin, especially the Grootvlei sub-basin.

Water quality of AMD samples that have been taken from the abstracted water at Grootvlei #3 shaft had a TDS concentration between 2 034 mg/L and 2 361 mg/L. The water quality of the injected sludge water was not known, and was estimated at approximately 1 500 mg/L. The estimate was calculated by comparing the liquid phase of the sludge from the Central Rand Basin (CRB) that had a TDS of 2 672 mg/L, and sulphate concentration of 1 635 mg/L (sampled 29 July 2023), with the effluent disposed on the same day that had a TDS concentration of 3 712 mg/L, and sulphate of 2 328 mg/L. ERB effluent has a typical TDS of 2 100 mg/L, and sulphate of 1 050 mg/L. Given, 2 672 mg/L (CRB sludge) divided by 3 712 mg/L (CRB effluent) times the average ERB effluent (2 100 mg/L), ERB TDS sludge mass load equals 1 500 mg/L.

A mass tracer load of 1 000 mg/L was injected as a transient mass tracer plume from Grootvlei #4 shaft. A mass tracer plume was considered as currently the sludge deposited into the #4 shaft had TDS concentrations that are lower than the in-situ AMD water in the Basin (refer to Section 3.5.1). The tracer mass plume of 1 000 mg/L was therefore used for simulations with a background (model domain) concentration of 0 mg/L. This would give the best representation of flow dynamics in the basin.

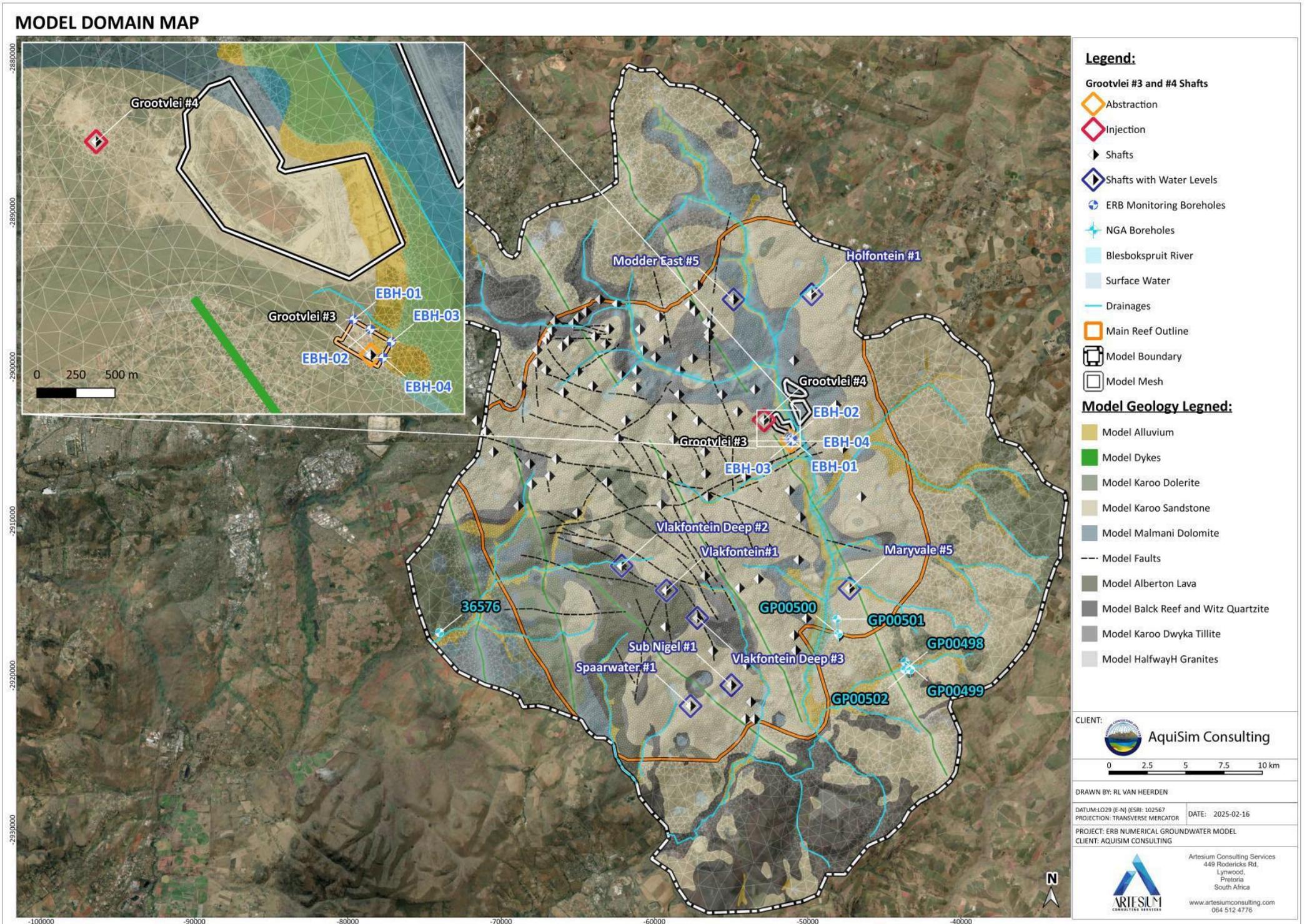
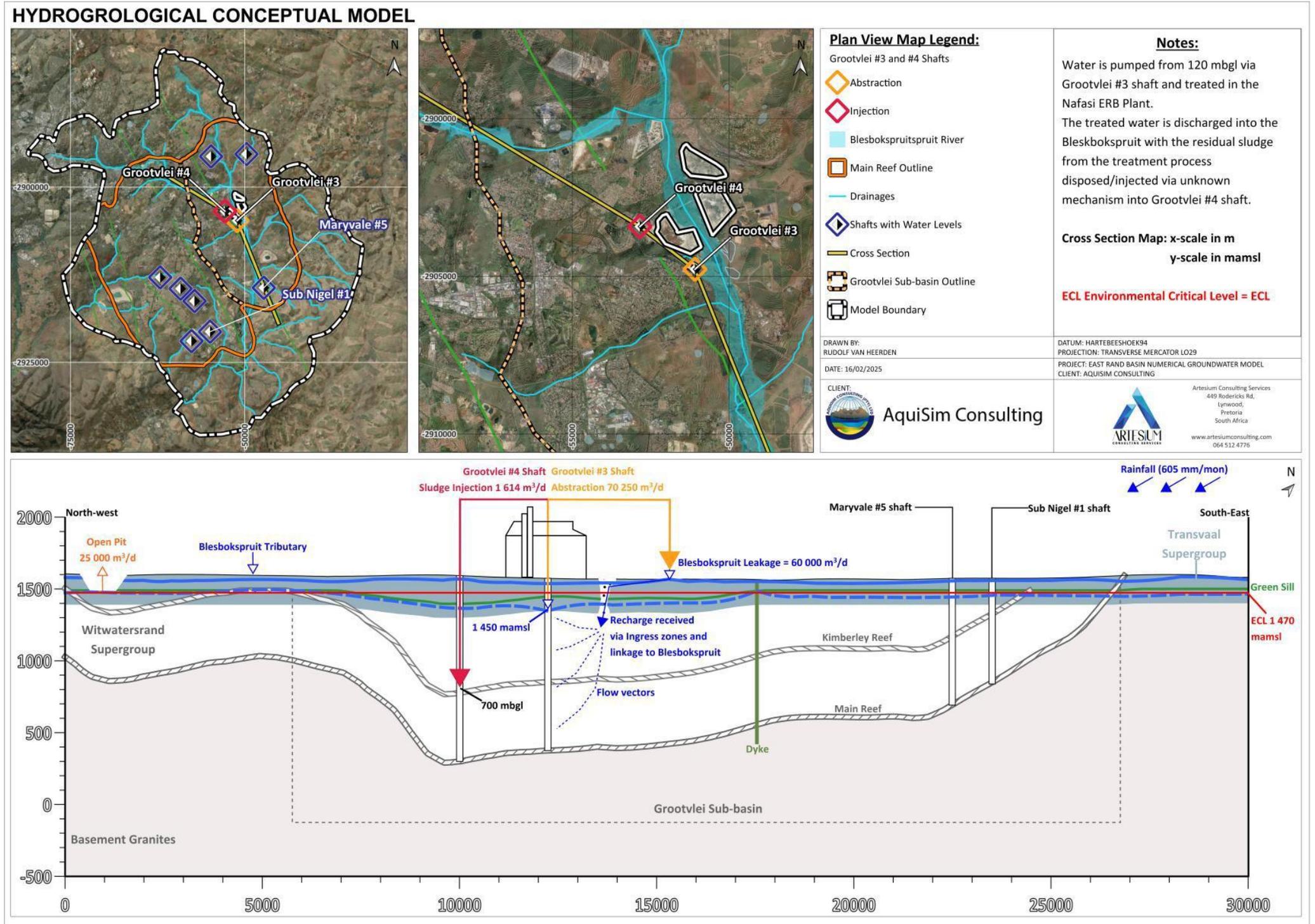


Figure 5-1: Model Domain Map



6 GROUNDWATER NUMERICAL MODEL

The main goal of project was to update the previous numerical model (ACS, 2006) with the latest available monitoring data in order and simulate flow dynamics between the dewatering and injection from Grootvlei #3 and Grootvlei #4 shafts, respectively. The modelling methodology and scenarios is shown in Figure 6-1. The Steady State (SS) and Transient State (TS) calibration discussion is attached in Appendix A, Section 10.

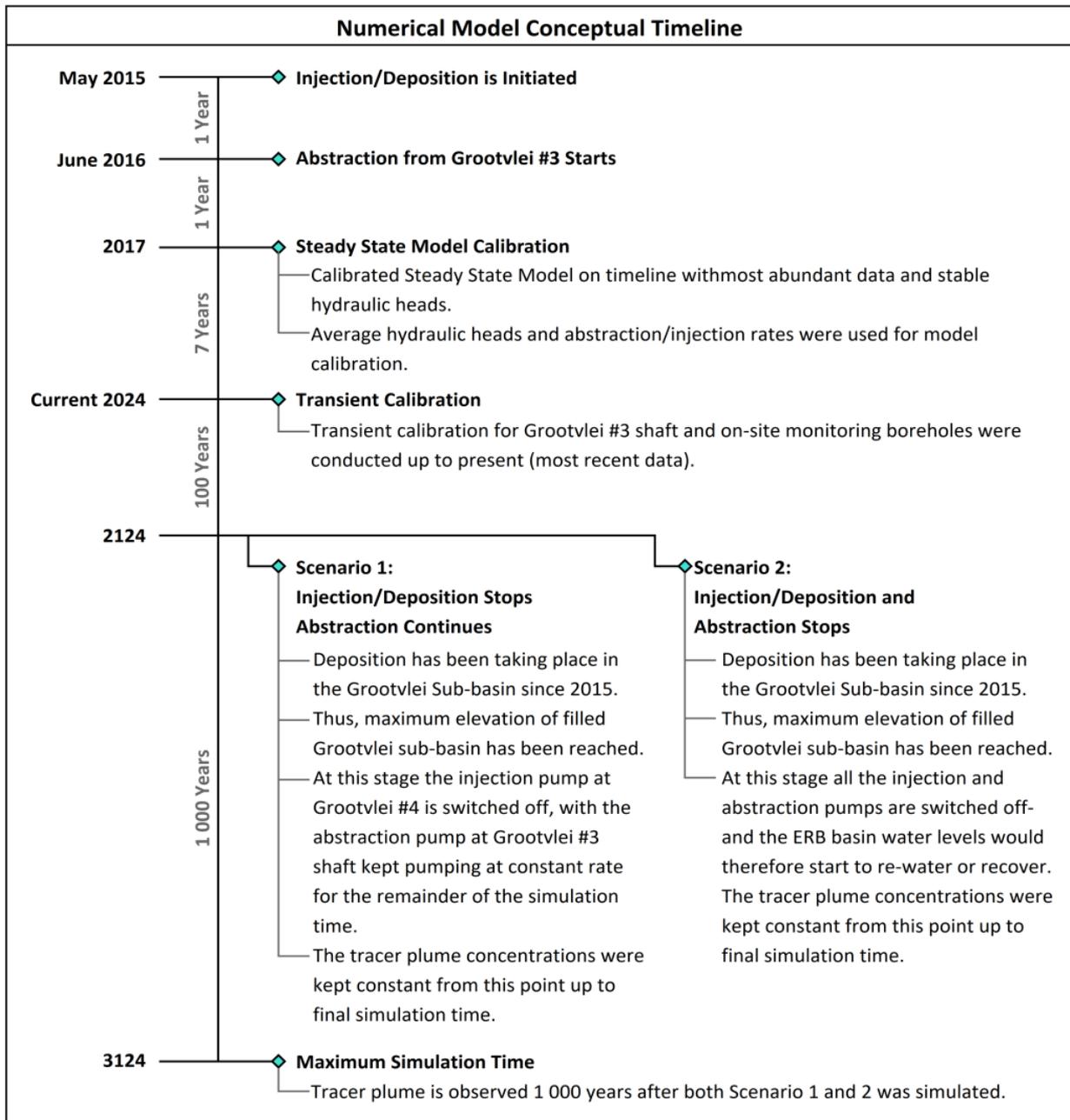


Figure 6-1: Conceptual Model Timeline

6.1 Source Term Analytical Model

An analytical model was prepared to define the source term (geometry) for the Grootvlei sub-basin as shown in Figure 6-1 and Figure 6-2. The analytical model was prepared by sequencing the deposition data on record (from March 2015 to December 2024) and comparing the cumulative deposited volume against the available volume calculated for Main Reef (Grootvlei sub-basin). The volume for Main Reef was calculated assuming a void space of 70%.

The total volume of liquid and solid phase sludge deposited up to date is equal to 75 944 m³, assuming a solid to liquid ratio of 1:10 (i.e. 10% is solids). This volumetric ratio was estimated from a sludge sample collected from the ERB plant.

The total volume for main reef was computed at 259 938 078 m³, given a void space of 70% the available space for deposition will be 181 956 655 m³. Currently the main reef is filled up to approximately 276 mamsl (0.2% capacity) assuming 616 440 m³ (999 t) of sludge solids have been deposited up to date.

After sequencing the deposition rate for 100 years (from March 2015 to March 2115) the total filled volume was calculated at 6 254 345 m³ (821 820 t), filled up to an elevation of 335 mamsl as depicted in Figure 6-2. The spillway depicted in Figure 6-2 is the lowest point in the ridge along the south-western side of the Grootvlei sub-basin. This was assumed as the highest point that the sub-basin could be theoretically filled up to. The current surface area for the source was calculated at 192 ha in the reef with the source growing up to a 1 001 ha after 100 years of deposition, given current deposition rates is sequenced. The source term was simulated according to this growth factor spatially in the simulated groundwater model.

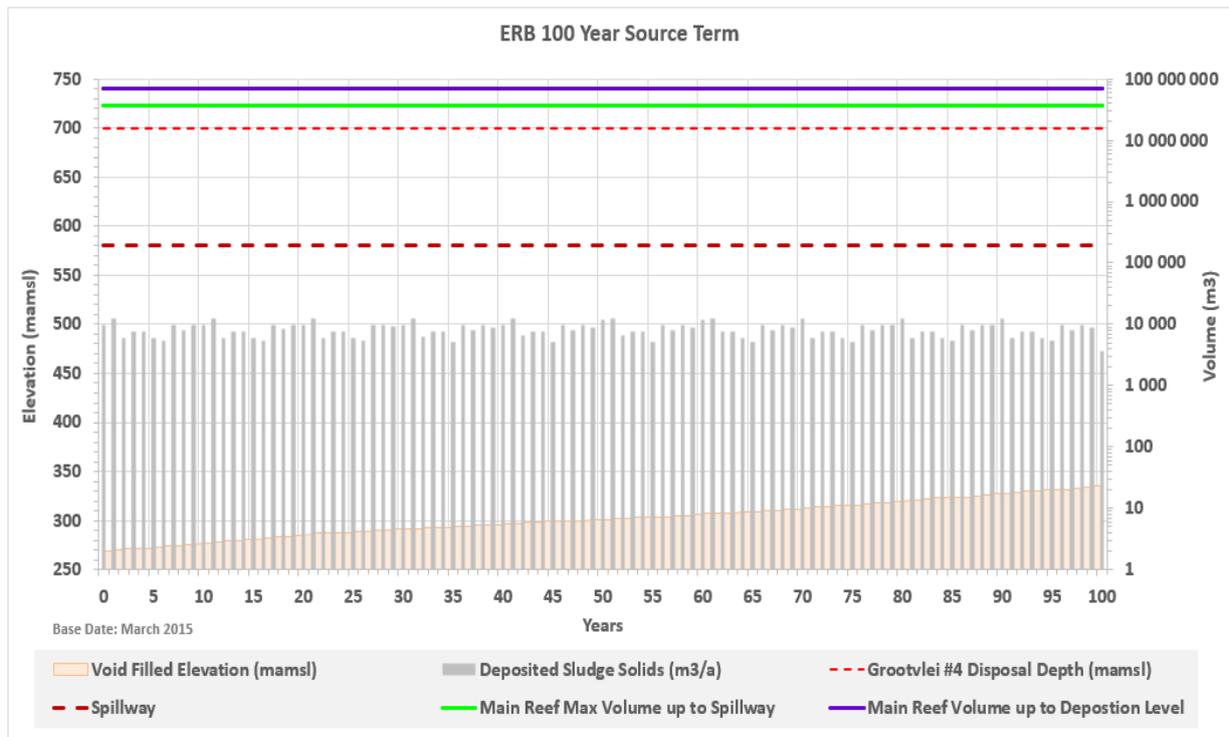


Figure 6-2: ERB 100 Year Source Term Analytical Model

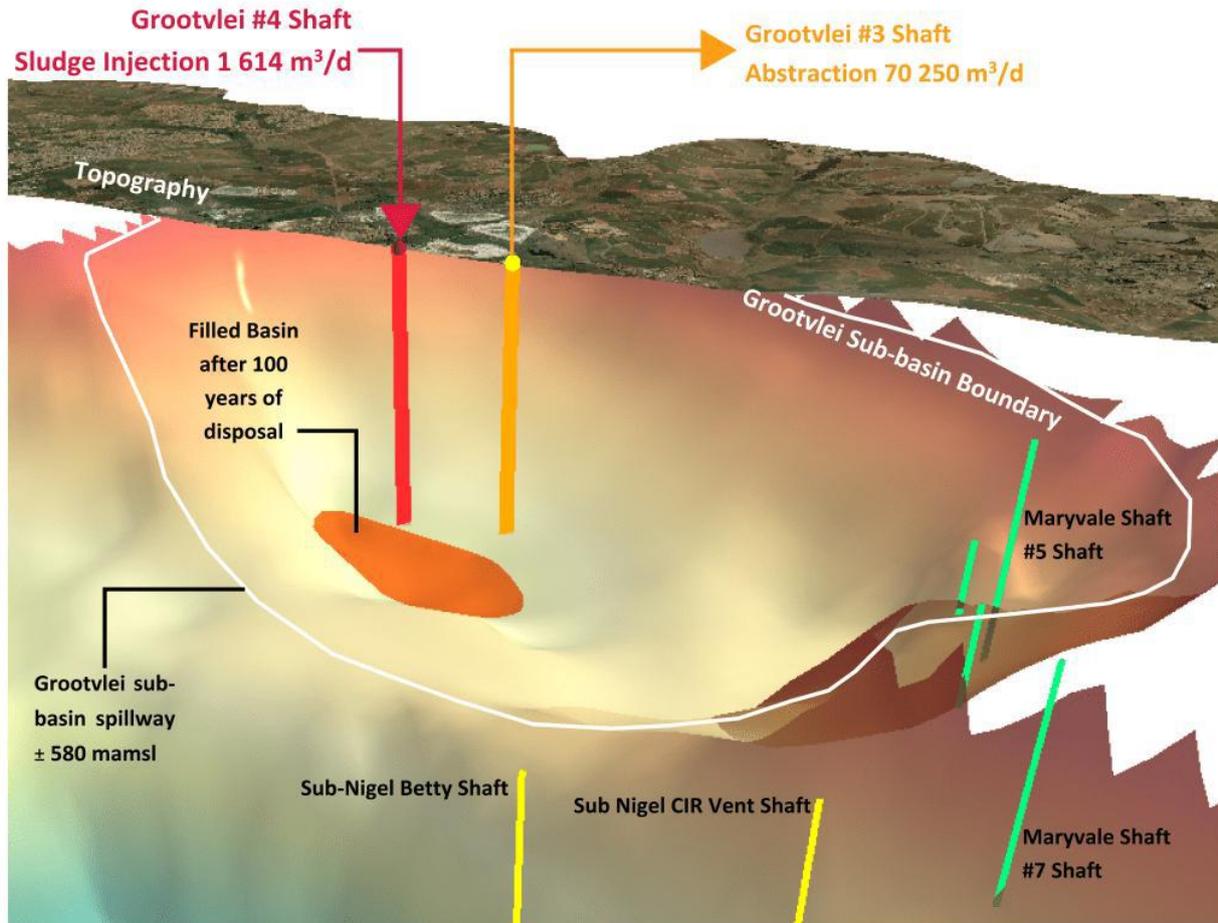


Figure 6-3: Grootvlei Sub-basin Filled Volume After 100 Years Of Simulated Deposition

6.2 Simulated Tracer Mass Plume – Scenario 1

In Scenario 1 the mass tracer was simulated to be deposited as detailed in Section 6.1. The surface area along which the 1 000 mg/L source was added in the model simulations was forward simulated up to 100 years. In order to represent the disposal ending after 100 years. The injection into Grootvlei #4 shaft was then stopped and the dewatering in Grootvlei #3 shaft was kept constant up to a 1 000 years. The resulting mass plume is shown in cross-section and zoomed plan view in Figure 6-4 and Figure 6-5. The simulated steady state flow particle tracking from the Blesbokspruit River footprint to the Abstraction point (Grootvlei #3 shaft) is shown in Figure 6-6.

A hundred years after deposition the tracer plume at the maximum extends approximately 3 430 m to the south-east and approximately 1 000 m upward from the injection point. The upwards extension of the tracer plume can be attributed to the injection taking place from the Witwatersrand Supergroup down towards the Main Reef. The method of injection/deposition was therefore considered conservative as the deposition would in reality take place from the Kimberley Reef downwards, and possibly from the Main Reef downwards. The centre of the tracer plume (1 000 mg/L) was considered to be at the Main Reef elevation. No decant was observed in the Scenario 1 simulation and the plume remained stagnant in place considering the 100 mg/L plume contour.

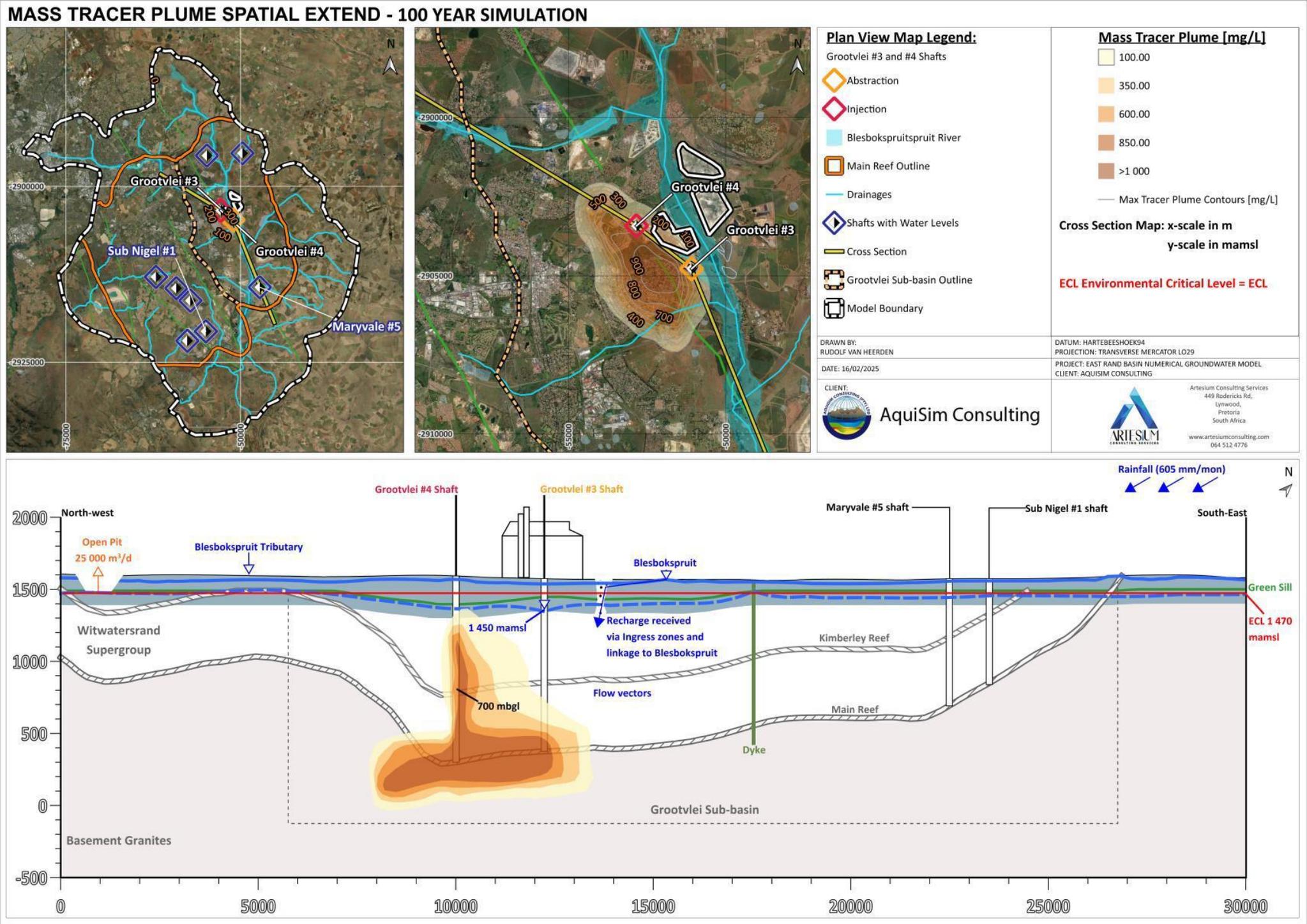


Figure 6-4: Transient Mass Tracer Simulated Plume Results - 100 Years Post Deposition for Scenario 1

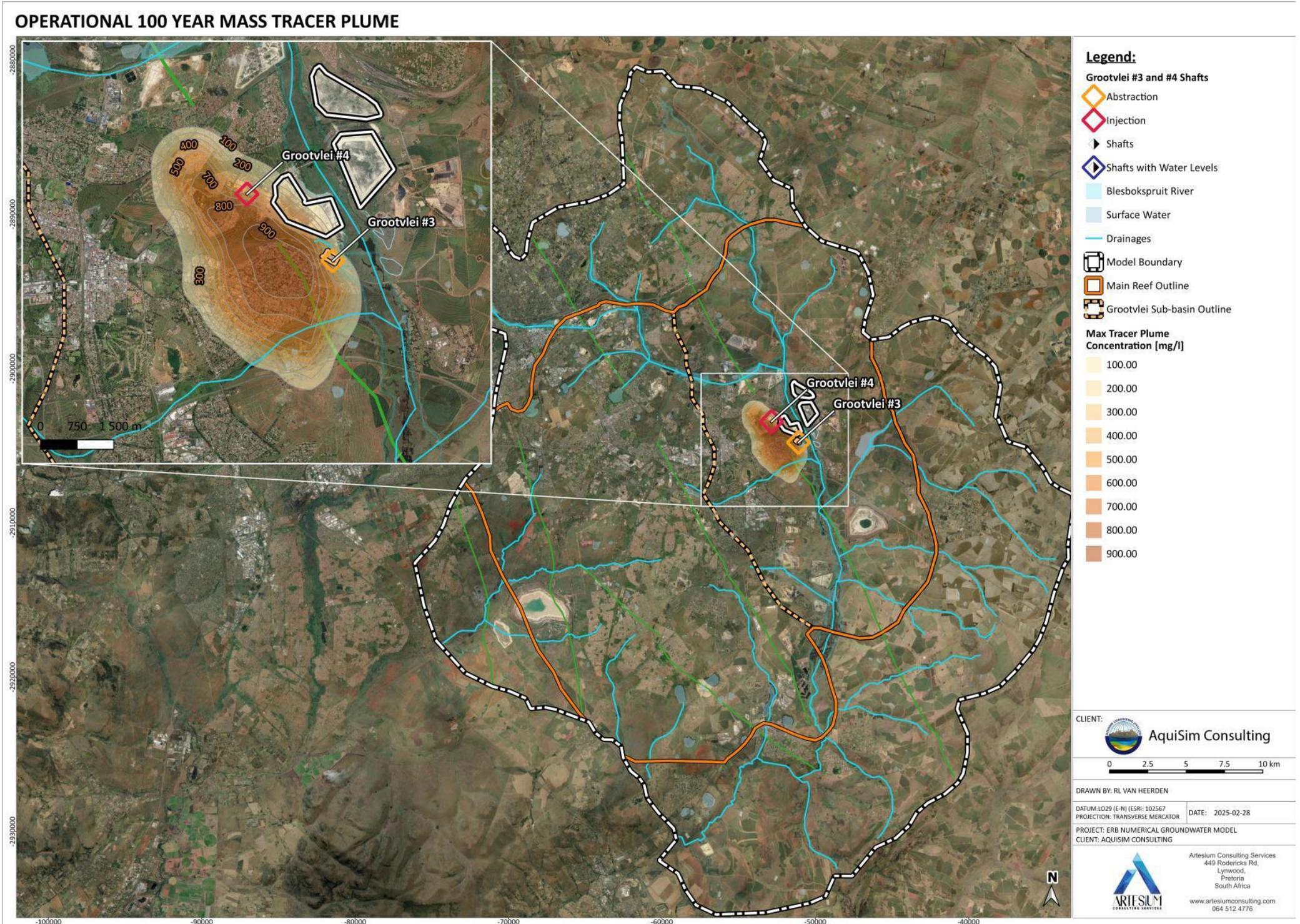


Figure 6-5: Transient Mass Tracer Simulated Plume Results - 100 Years Post Deposition for Scenario 1 – Zoomed in Spatially

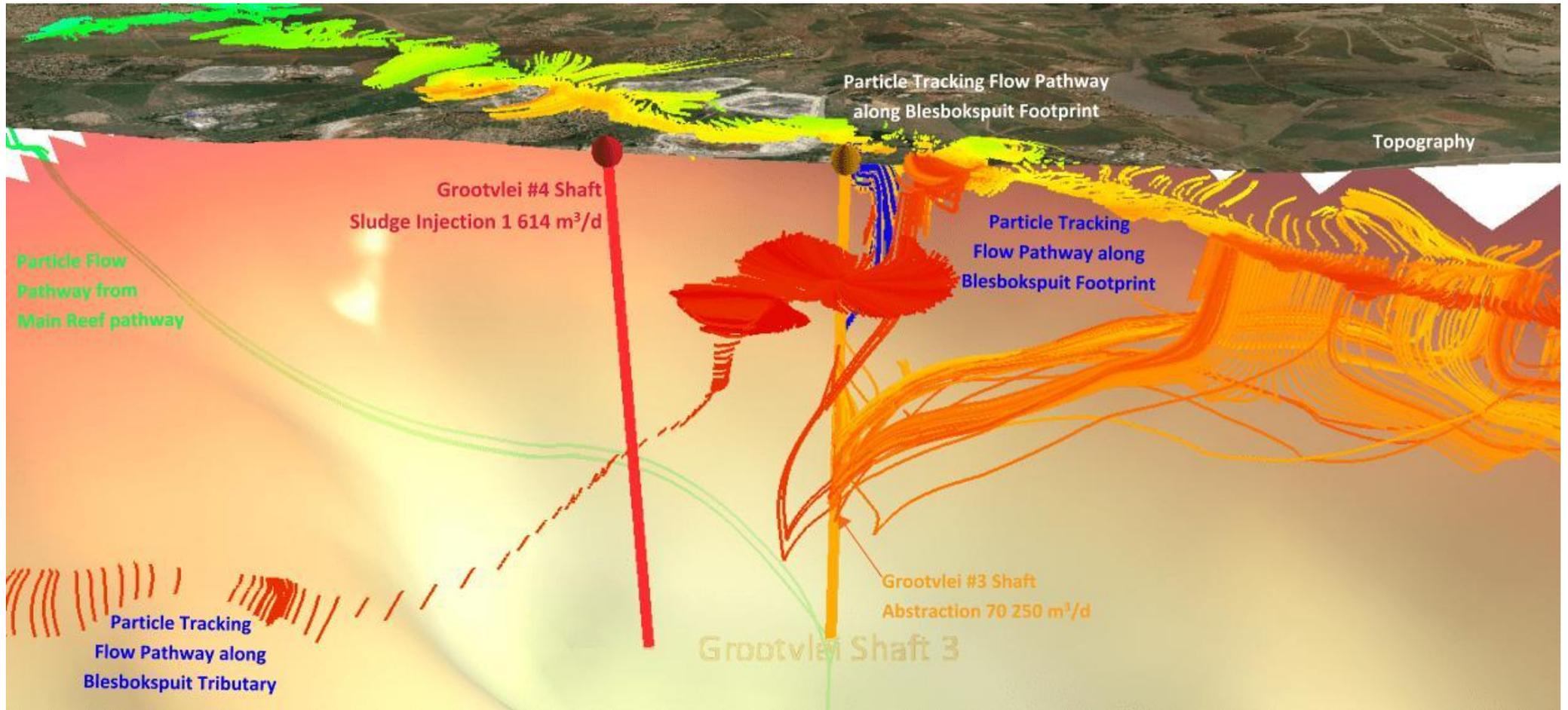


Figure 6-6: Particle Tracking Flow Pathway from Blesbokspuit to Witwatersrand Basin

6.3 Simulated Tracer Mass Plume – Scenario 2

For Scenario 2 the abstraction from Grootvlei #3 shaft was switched off to simulate the possible dereliction of the ERB Plant and subsequently the deposition of sludge was also simulated to stop. After a 1 000 years post deposition the tracer plume had a maximum plume extent of 23 x 10 km. From the disposal zone, the furthest tracer concentration was mapped at 16 km to the south-east of the site.

The plume followed the bathymetry of the Main Reef and three main decant zones were observed as shown in Figure 6-10. It should be noted that the decant zones towards the north-west Main Reef outcrop, and the north-western zone (where the decant surfaces along an open pit currently situated at approximately 100 mbgl), could only be observed when the tracer plume concentration was cut-off at 10 mg/L. When the tracer plume concentration of 100 mg/L is referenced, the only decant point was to the south-east of the ERB plant situated on the Blesbokspruit River footprint between Sub Nigel #1 and Maryvale #5 shafts.

The simulated concentrations for Scenario 2 are shown below in Figure 6-7. The Grootvlei #3 shaft concentration was measured at the same depth disposal is taking place. Given this observation depth, tracer plume concentrations were first detected in 2017 (2 years after deposition started), with the 100 mg/L threshold reached in 2025. The maximum concentration reached in the shaft was simulated at 462 mg/L. After 44 years of pumping (2059) the tracer mass was detected at surface in Grootvlei #3 shaft with concentrations peaking at 4.59 mg/L. The tracer plume reached the green sill boundary around the same time the peak concentrations were detected in Grootvlei #3 shaft, and the mass accumulated at the green sill (aquitard) interface until reaching a peak concentration of 66 mg/L (2021).

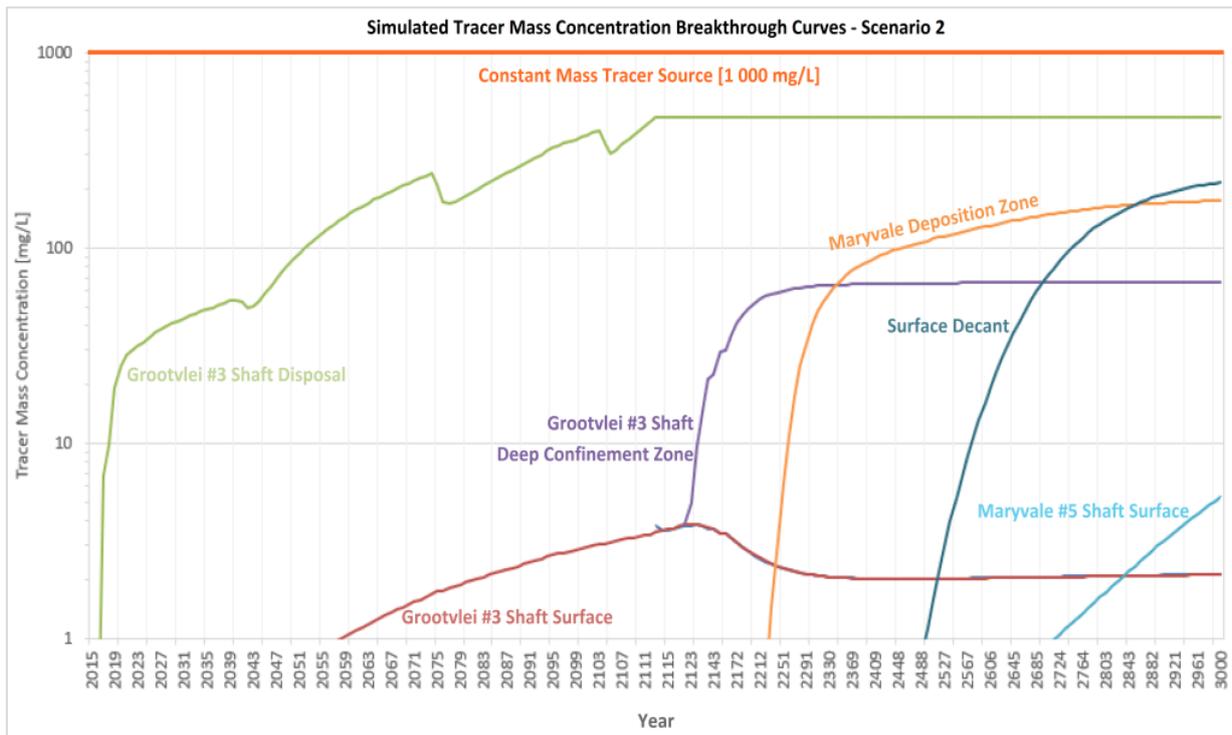


Figure 6-7: Simulated Tracer Mass Concentratio Breakthrough Curves for Scenario 2

The Maryvale #5 receptor was reached 217 years after sludge deposition started and the highest concentration simulated in the model was calculated at 170 mg/L. The tracer plume was detected at surface in the shaft approximately 700 years following deposition. No concentrations were computed to reach the Sub-Nigel #1 shaft in any of the observed locations with depth (i.e. deposition zone, green sill aquitard, or surface).

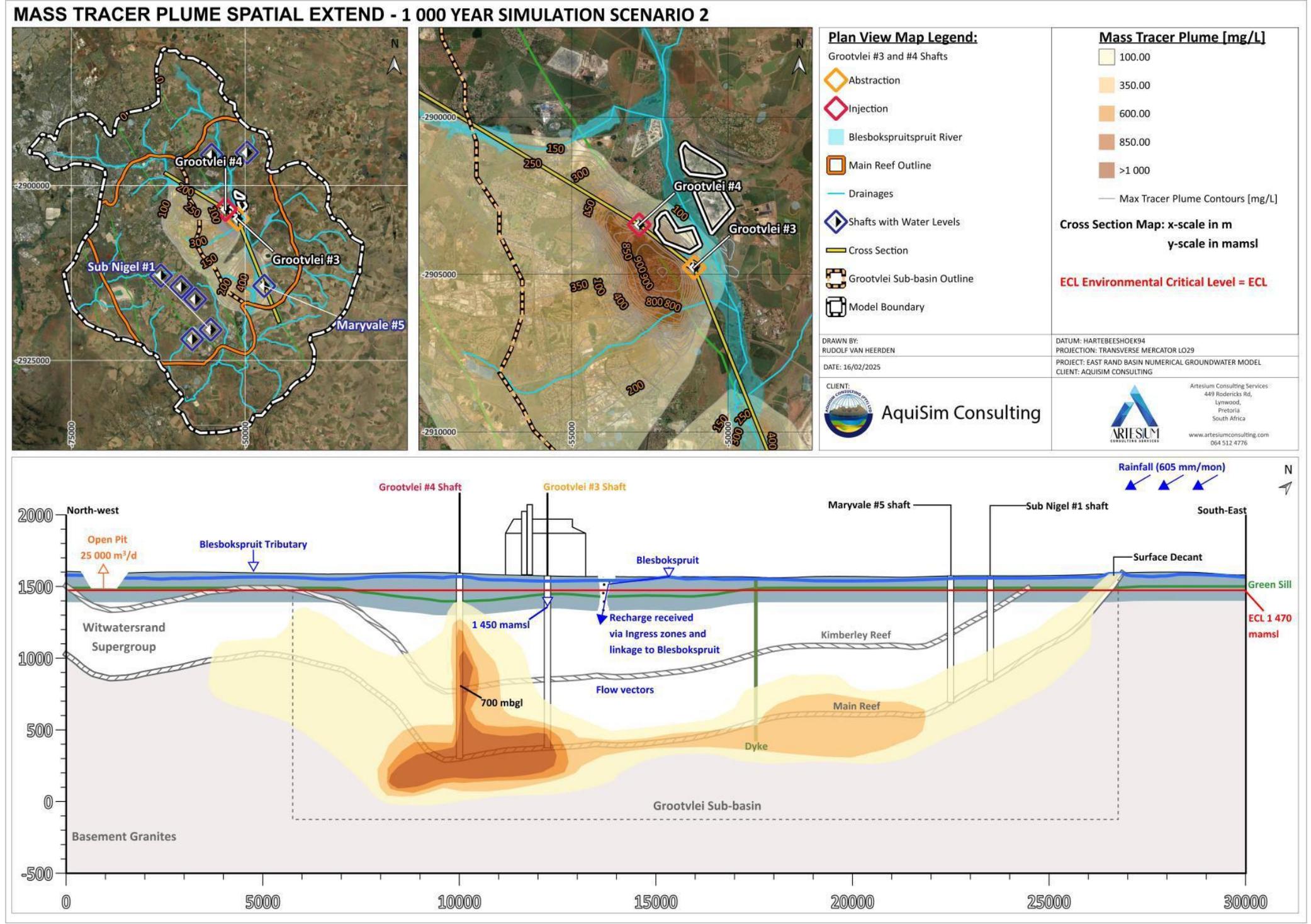


Figure 6-8: Transient Mass Tracer Simulated Plume Results – 1 000 Years Post Deposition for Scenario 2

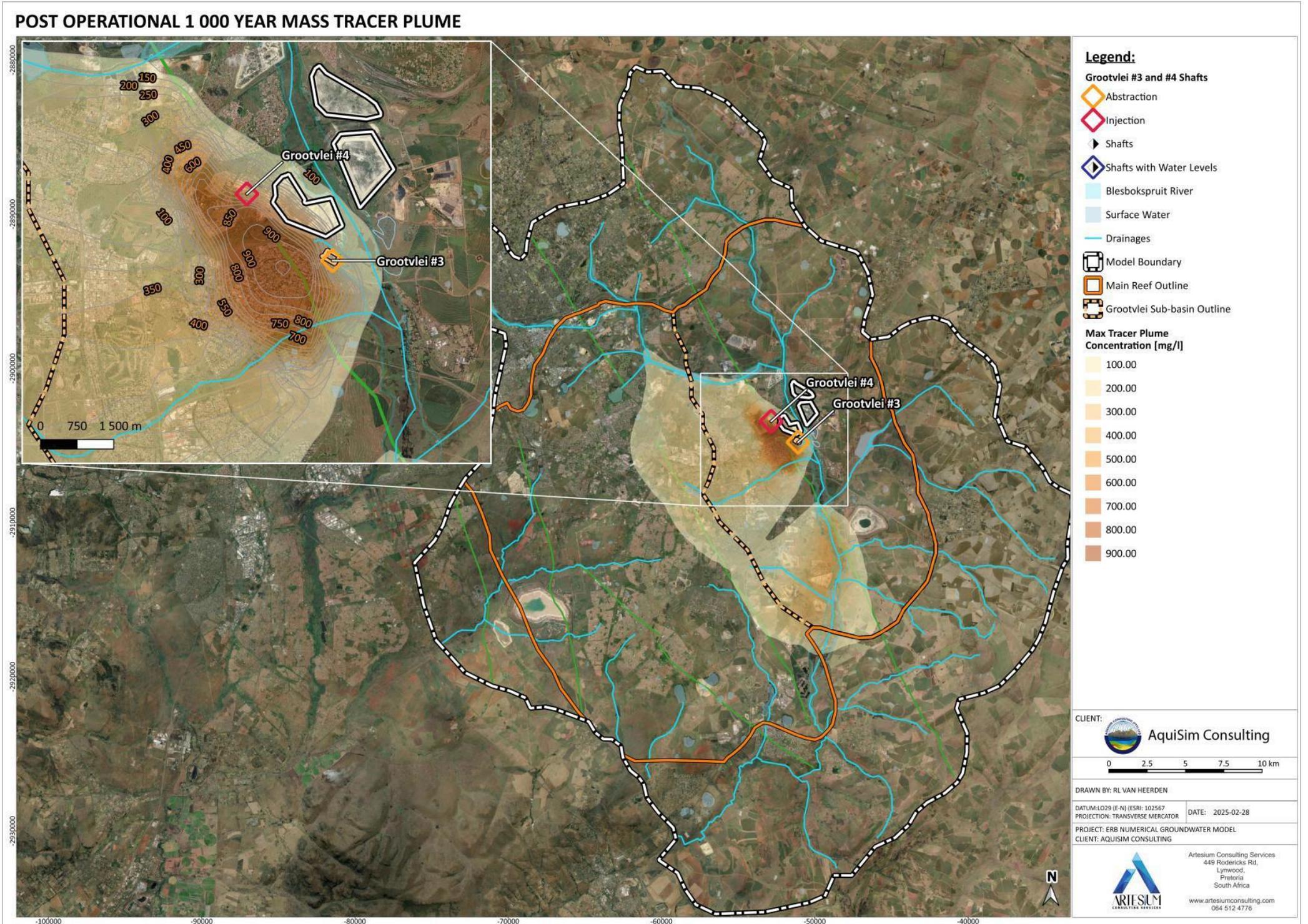


Figure 6-9: Transient Mass Tracer Simulated Plume Results – 1 000 Years Post Deposition for Scenario 2 – Zoomed in Spatially

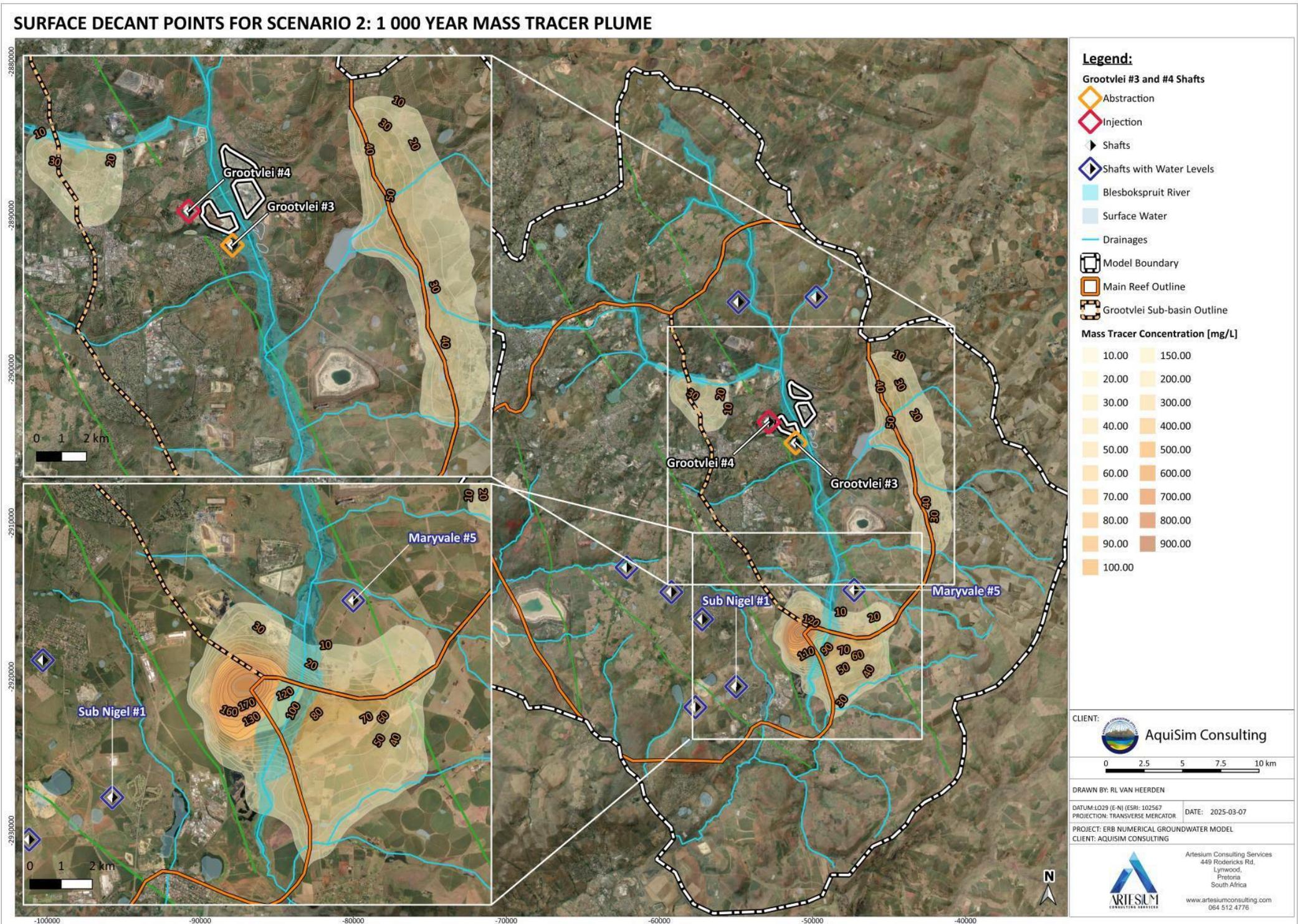


Figure 6-10: Decant Zones from Simulated Tracer Mass Plume – 1 000 Years Post Deposition (Scenario 2)

Table 6-1: Summarised Darcy Flux Calculations

No	Zone	Formation (entity)	Horizontal Hydraulic Conductivity (Kxy)	Vertical Hydraulic Conductivity (Kz)	Horizontal Head Gradient (1)	Vertical Head Gradient (1)	Kinematic Porosity (1)	Horizontal Source-Pathway Distance (m)	Vertical Source-Pathway Distance (m)	Horizontal Source Flow Prdr 2 Tube Surface Area 1 (Disposal Zone) (m2)	Vertical Source Flow Prdr 2 Tube Surface Area 2 (Confinement Zone) (m2)	Horizontal Darcy Flux qxy (m/d)	Vertical Darcy Flux qz (m/d)	Plume Horizontal Flow Rate (m3/d)	Plume Vertical Flow Rate (m3/d)	Flow Vector ratio (qz/qv)	Water volume in storage (mil m3)
1	Disposal Zone	Main Reef Grootvlei Sub-Basin	100	100	2.65E-04	2.65E-08	0.7	3 774	1 225	3 202	12 428 246	2.65E-02	2.65E-06	84.791	32.9	1.00E-04	1.82E+08
2	Confinement Zone (deep)	Wits Quartzite	3.54E-01	3.54E-01	2.65E-04	3.21E-07	0.01	3 774	1 125	3 202	12 428 246	9.37E-05	1.14E-07	0.300	1.414	1.21E-03	1.36E+09
3	Confinement Zone (shallow)	Green Sill Aquitard	5.00E-06	5.00E-08	2.65E-04	8.60E-03	0.01	3 774	1 390	3 202	12 428 246	1.33E-09	4.30E-10	4.25E-06	0.005	3.24E-01	3.64E+07
4	Receptor 1	Grootvlei #3 Shaft Pumping Discrete Shaft	100	100	4.24E-04	4.31E-02	0.7	2 218	365		28	4.24E-02	4.31E+00	0.000	122	1.02E+02	-
5	Receptor 2.a	Sub-Nigel #1 Shaft Surface Decanting	2.6	5.18E-04	5.75E-05	4.12E-04	0.7	17 329	713		28	1.49E-04	2.13E-07	0.000	6.03E-06	1.43E-03	-
6	Receptor 2.b	Sub-Nigel #1 Shaft Sub-Surface Decanting	0.9	7.78E-04	5.75E-05	4.11E-04	0.7	17 329	708	3 202	28	5.17E-05	3.20E-07	0.166	9.05E-06	6.19E-03	-
7	Receptor 3a	Merryvale #5 Shaft Surface Decanting	0.7	0.2	8.12E-05	5.47E-04	0.7	12 267	687		28	5.68E-05	1.09E-04	0.000	3.09E-03	1.92E+00	-
8	Receptor 3b	Merryvale #5 Shaft Sub-Surface Decanting	0.9	7.78E-04	8.12E-05	5.47E-04	0.7	12 267	682	3 202	28	7.31E-05	4.26E-07	0.234	1.20E-05	5.82E-03	-

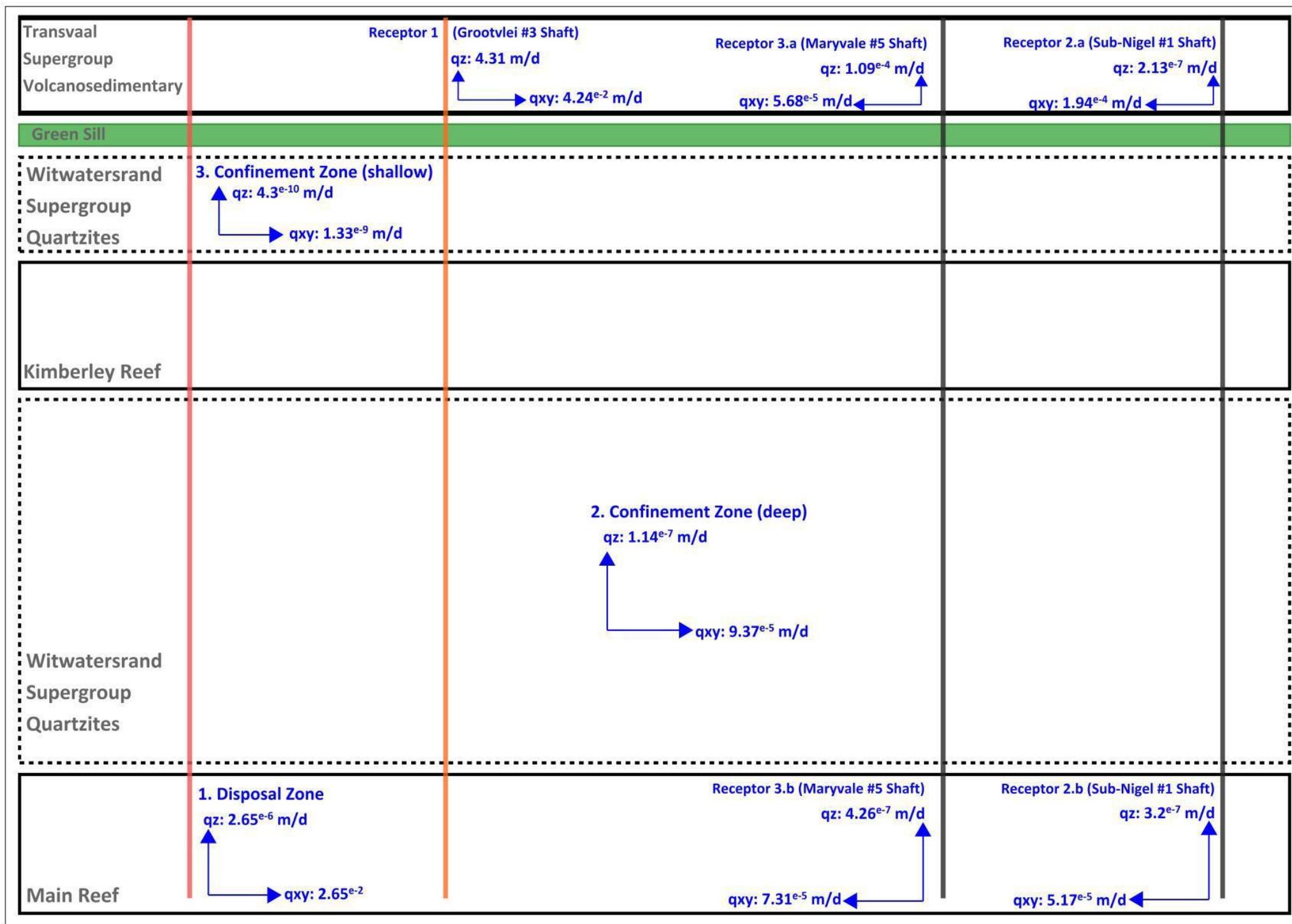


Figure 6-11: Calculated Darcy shown on Modelled Hydrogeological Zones

Table 6-2: Simulated Mass Tracer Concentrat

Observation Point ID	Tracer Source Conc.	Time (y)	Surface (Decant)			Disposal Zone (Main Reef)			Confinement Zone (Shallow)		
			Distance from disposal zone centre (m)	Tracer Peak Concentration at Obs Point (mg/L)	Ratio Peak Conc: Source	Distance from disposal zone centre (m)	Tracer Peak Concentration at Obs Point (mg/L)	Ratio Peak Conc: Source	Distance from source center (m)	Tracer Peak Conc (mg/L)	Ratio Peak Conc: Source
Grootvlei #3 Shaft_Surface	1000	10	1 409	0	0.00E+00	2 350	34	3.40E-02	1 095	0	0.00E+00
Grootvlei #3 Shaft_Surface	1000	100	1 409	3	3.46E-03	2 350	462	4.62E-01	1 095	251	2.51E-01
Grootvlei #3 Shaft_Surface	1000	1000	1 409	2	2.12E-03	2 350	462	4.62E-01	1 095	251	2.51E-01
Nigel #1 Shaft	1000	10	17 329	0	0.00E+00	13 631	0	0.00E+00	13 631	0	0.00E+00
Nigel #1 Shaft	1000	100	17 329	0	0.00E+00	13 631	0	0.00E+00	13 631	0	0.00E+00
Nigel #1 Shaft	1000	1000	17 329	0	0.00E+00	13 631	0	0.00E+00	13 631	0	0.00E+00
Merryvale #5 Shaft	1000	10	12 267	0	0.00E+00	12 267	0	0.00E+00	12 267	1.99	1.99E-03
Merryvale #5 Shaft	1000	100	12 267	0	0.00E+00	12 267	0	0.00E+00	12 267	1	1.46E-03
Merryvale #5 Shaft	1000	1000	12 267	0	0.00E+00	12 267	173	1.73E-01	12 267	0	0.00E+00

6.4 Darcy Flux Calculations

The darcy flux calculation results are shown in Figure 6-11 with the data used for the calculations summarised Table 6-1. Scenario 2 was used to conduct the calculations as this was the most conservative estimate for the mass tracer plume. The horizontal and vertical darcy flux for the disposal zone was calculated at 2.65×10^{-2} and 2.65×10^{-6} m/d, respectively, compared to the deep confinement zone (Witwatersrand Supergroup) that had computed darcy flux values of 9.37×10^{-5} and 1.14×10^{-7} m/d.

The darcy flux calculated in confinement zone is considered low, because of the depth (>1 km) of the Grootvlei sub-basin the flow velocity of the groundwater when observed from surface is considered almost stagnant. The only mechanism increasing the flow velocities within the sub-basin is the pumping from Grootvlei #3 shaft and even when this shaft is simulated to be pumped for 1 000 years, no significant mass was transported to the surface.

7 CONCLUSIONS

From the findings of the model update the following conclusions were made:

1. The current volume of solid sludge deposited is $75\,944\text{ m}^3$ (106 3221.6 tons) assuming a density of $1\,400\text{ kg/m}^3$, with the main reef void volume calculated at 181 mil m^3 . If referred to the Grootvlei sub-basin spillway as the highest point to where sludge can be deposited ($\pm 580\text{ mamsl}$), the reef is currently filled up to 0.2% capacity. The source therefore would have the approximate proportions of $8 \times 2\,240 \times 5\,666\text{ m}$ (Height x Width x Length).
2. If current deposition rates are sequenced for a 100 years, the Grootvlei sub-basin will be filled up to approximately 17% capacity. Noted, that this is not even considering the volume of the Kimberley Reef and associated mined out voids, and the voids from tunnels and associated mine infrastructure voids are also not considered in this calculation. This is just assuming the main reef with a 1 m thickness with 70% void space.
3. The water quality of the injected sludge water was not known, and was estimated at approximately $1\,500\text{ mg/L}$ compared to Central Rand Basin water Qualities, given $2\,672\text{ mg/L}$ (CRB sludge) divided by $3\,712\text{ mg/L}$ (CRB effluent) times the average ERB effluent ($2\,100\text{ mg/L}$), ERB TDS sludge mass load equals $1\,500\text{ mg/L}$. A mass tracer plume $1\,1000\text{ mg/L}$ was therefore considered as currently the sludge deposited into the #4 shaft had TDS concentrations that are lower than the in-situ AMD water in the Basin.
4. The simulations revealed that should pumping from Grootvlei #3 continue, the sludge mass plume would remain relatively stable or stagnant with a footprint of $1\,000\text{ ha}$ at 335 mamsl .
5. The most conservative estimate for a mass tracer plume given 100 years of sludge deposition, after which the pumping from Grootvlei #3 shaft was ceased, had a maximum plume extend of $23 \times 10\text{ km}$ when observed in the disposal zone (at 1.4 km depth), and decants at 3 main zones at surface along

the main reef basin outcrops.

6. The horizontal and vertical darcy flux for the disposal zone was calculated at $2.65e^{-2}$ and $2.65e^{-6}$ m/d, respectively, compared to the deep confinement zone (Witwatersrand Supergroup) that had computed darcy flux values of $9.37e^{-5}$ and $1.14e^{-7}$ m/d.
7. Uranium was below detection (0.015 mg/L) in most samples taken from the shaft (July 2017 to March 2019) and was only detected in five AMD abstraction samples (April 2019 to May 2020) which averaged 0.043 mg/L. The November 2024 concentrations in AMD water and effluent water (0.021 mg/L) matched exactly, which indicates minimal U is disposed of via the sludge as it is not captured by plant processes. Currently, uranium analysis of the sludge is being undertaken, and the results will be analysed by AquSim to quantify the U concentrations associated with disposal.
8. 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 plant and this would only occur if all pumping from Grootvlei #3 shaft is stopped and the water levels within the basin recovers completely.

8 RECOMMENDATIONS

The following is recommended from the findings of the investigation:

1. It is recommended that the plant process SOP's be upgraded to remove uranium from the abstracted AMD water before it is disposed into the Blesbokspruit. This would ensure that the U gets captured within the sludge and is disposed of in the Grootvlei sub-basin. Currently, it appears that the bulk of the U mass possible abstracted from the AMD water is being discharged into the Blesbokspruit River and would eventually accumulate in the reed beds along the drainage system.
2. Even though the disposal within the Grootvlei sub-basin is considered a viable long-term (□ 100 years) solution for disposal of sludge, deposition into the alternative sub-basins should be considered. The sub-basins underlying the Sallies and Vlakfontein Deep shafts are deeper when compared to the Grootvlei sub-basin. This would increase the long-term viability of deposition if practically feasible.
3. It is recommended that the geochemistry of the sludge sampled and analysed, and the radiological risks (conducted by AquSim) be characterised.
4. It is recommended that a density dependent flow numerical model be conducted.
5. The liquid fraction of the deposited sludge be analysed on a quarterly basis to determine if the water quality of said sample fluctuates, if not then the sludge water sample can be sampled on an annual basis and be incorporated into the monitoring protocol.

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10 APPENDIX A: NUMERICAL MODELLING ASSUMPTIONS, MATERIAL PROPERTIES AND CALIBRATION

10.1 Steady State Numerical Model Calibration

The Steady State model (SS Model) was calibrated under current (2017) conditions. The average water levels in 2017 for both the shaft and monitoring boreholes were considered stable for that year, and the average for the year was used for steady state flow calibration. The steady state calibration focused spatially on the injection and abstraction sites and the correlation between the simulated and measured hydraulic heads are summarised in Table 10-1. The model surrounding the injection/abstraction zone was considered calibrated, with a calculated RMSE of 0.7% and a correlation factor of 99%.

The simulated hydraulic heads in the regional shafts (>10 km from Grootvlei #3 and #4 shafts) was higher than measured values, which would be considered conservative when simulating possible decant locations. The presence of plugs, collapsed sidewalls, silted up shafts, plugs, and numerous side-tunnel connections made the calibration of steady state heads at these locations difficult. A more complex geometry with regards to the old mining infrastructure (shafts and tunnels) would have to be incorporated into the model should this calibration need be considered.

Table 10-1: Steady State Model Calibration Summary

Site name	Date	Measured Head (mamsl)	Simulated Head (mamsl)	Residual Error Above or below actual (m) - RE	Absolute Error (m) - AE	Root Square Error (m) - RSE
EBH-01	Average of 2017	1 571	1 575	-5	5	21
EBH-02	Average of 2017	1 572	1 574	-2	2	3
EBH-03	Average of 2017	1 572	1 570	2	2	3
EBH-04	Average of 2017	1 566	1 571	-4	4	17
Grootvlei #3 shaft	Average of 2017	1 449	1 447	2	2	2
Average		1 546	1 547	-1	3	9
Minimum		1 449	1 447	-5	1.58	2.48
Maximum		1 572	1 599	2	136	18 411
Correlation (R)		0.52				
					ME	-1
					MAE	3
					RMSE	0.7%
Minimum Hydraulic Head in Model						1 448
Max Hydraulic Head in Model						1 904

***ME: Mean Error**

****MAE: Mean Absolute Error**

*****RMSE: Root Mean Square Error**

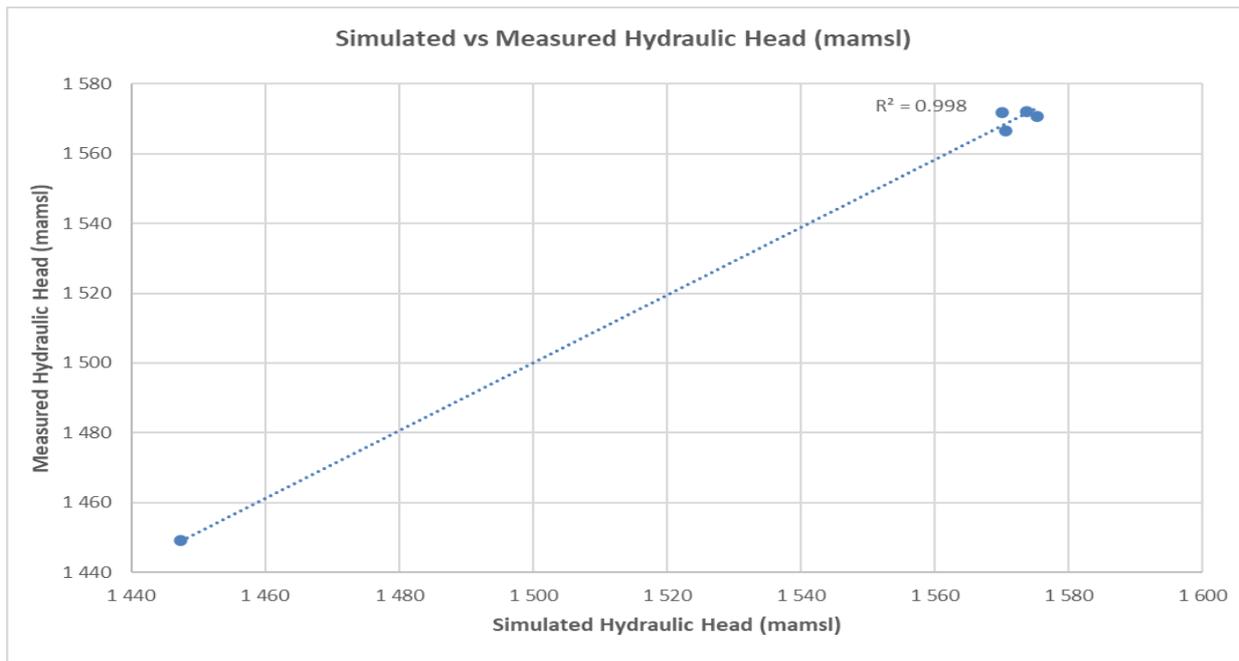


Figure 10-1: Correlation of Simulated vs Observed Hydraulic Heads

10.2 Transient State Model Calibration

The transient state model calibration for Grootvlei #3 shaft is shown in Figure 10-2. The abstraction volumes from the shaft along with transient recharge was simulated. The calibration was considered good, except for the period when pumping stopped post 2022. The simulated hydraulic heads were lower compared to the actual hydraulic heads as the storage in the mine voids and tunnels are high. In reality, after the water levels in Main Reef recovered and the abstraction was continued, the measured water level did not drop in the shaft as simulated in the model. This is because of the amount of water released from storage from the voids of old mine workings (unknown volume). The abstraction would have to dewater these voids over time in order to drop the hydraulic heads in the Main Reef.

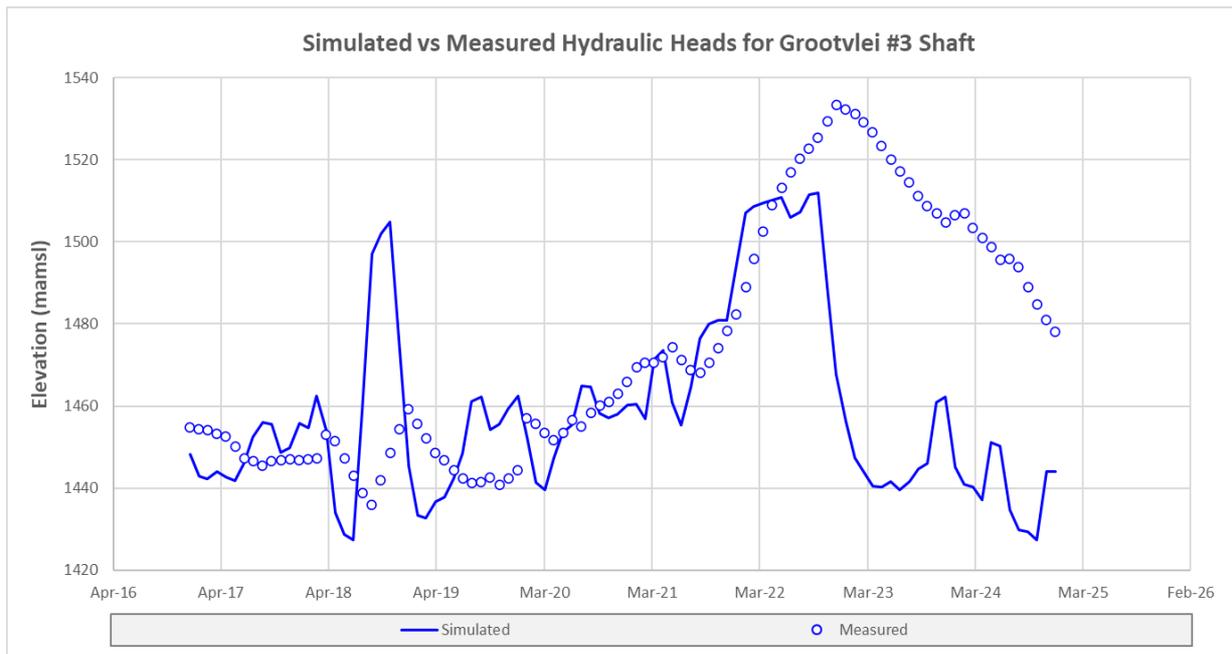


Figure 10-2: Transient State Model Simulated vs Measured Hydraulic Heads for Grootvlei #3 Shaft

10.3 Assumptions and Limitations

The following assumptions were made with listed limitations:

- It was assumed that the Blesbokspruit recharges the semi-confined ERB aquifer via ingress zones. 85% of the water pumped from the Grootvlei #3 shaft is recharge via the Blesbokspruit and does not originate from the dolomite aquifer.
- The system was considered in Steady State in 2017 following a prolonged period of abstraction, the hydraulic heads in the basin was considered stable.
- The accuracy and scale of the assessment will result in acceptable deviations at specific points e.g., individual boreholes and shafts.
- Dykes and faults inferred to be ± 20 m thick, with a contact zones acting as a preferential pathway represented in the model with a discrete feature (0.1 m thick).
- The Kimberley reef bathymetry was not known, and it was assumed that the Kimberley reef is situated 500 m above the Main Reef and would have the same shape (geometry) as the Main Reef.
- It was assumed that both the Main Reef and Kimberley Reef would have a thickness of 1 m, and that they are completely mined out.
- Mine out areas was assumed to be 70% voids
- Shaft depths were unknown, and it was assumed that the shafts were constructed to access Main

Reef, and thus their depths were equal to the depth of Main Reef for each shaft location.

- The integrity of the sidewalls of the shafts were not known, and it was assumed that they would be weathered in a degree.
- No external abstraction from surrounding boreholes were considered.
- The water quality of the regional basin was not known, and it was assumed that the water quality (AMD) water at the Grootvlei #3 and #4 shafts would represent the whole basin.

When assumptions were made or reference values used, a conservative approach was followed aligned with the precautionary principle (NEMA, 1998). A groundwater model is a representation of the real system. It is therefore an approximation, and the level of accuracy depends on the quality of the data that is available. The purpose of the model was not to simulate the actual field conditions (i.e., every dyke and fracture), but to simulate the proposed abstraction from the on-site boreholes and investigate the possible impacts on the surrounding environment. The model input parameters are presented in Table 10-2.

Table 10-2: Model Input Parameter Uncertainty

Input parameter	Source, parameter, or assumption description	Data uncertainty
Topography (DEM)	1:50 000 topographical map series of South Africa was used for the elevation data.	Low
Rivers, streams, drainages	Digitised from topographical maps and aerial imagery (1:50 000 scale), as well as generated from the model DEM, to ensure drainages are placed at appropriate low-lying places in the model topography. Particular care was placed in digitizing the Blesbokspruit with its wide (>500 m) floodplain, and incorporating it into the model.	Low
Lithology	Council for Geoscience 1:50 000 Geological Map Series) 2628AB, 2628AD, 2628BA, and 2628BC Rand.	Moderate
Weathered Zone Thickness	An average depth was used derived from the Murray & Roberts Geological Plan and Profile across the tunnel alignment.	Moderate
Geological structures	Various geological structures were present on the Aerial Magnetic Map, however, there appears to be a gap in the surveyed data, and it was not clear whether this dyke/structure extended past the injection/abstraction site.	High
Ingress Zones	Ingress zones refer to the zones where surface water provided a constant recharge boundary and a zone that is more permeable (higher hydraulic conductivity) is present and would recharge the semi-confined East Rang Basin. The only inferred recharge zone incorporated into the model, was the sinkholes located to the east of the site. In reality multiple ingress zones would be present in the form of old mine workings voids and tunnels, that would act as preferential pathways for surface water to recharge the semi-confined aquifer.	High
Neighbouring Boreholes and pumping rates	No abstraction volumes from neighbouring properties in the ERB watershed was available. No pumping was simulated in the model from neighbouring boreholes within the watershed.	High

Input parameter	Source, parameter, or assumption description	Data uncertainty
Abstraction Volumes (Grootvlei #3 shaft)	Abstraction volumes was received from the client in daily flow rates/volumes.	Low
Injection Volumes (Grootvlei #4 shaft)	Injection volumes was received from the client in daily flow meter readings and the volumes were calculated from them.	Low
Mian Reef and Kimberley Reef Bathymetry	The Main Reef shape (X,Y,Z) data was gathered from the project archives and cross-referenced conceptually with geological cross section Lubbe et al., (2007). The Kimberley Reef was assumed to be 500 m above the Main Reef and has the same geometry.	Moderate
Rainfall	Rainfall data is recorded on-site at the ERB plant and was used for all model simulations.	Low
Steady State Modelling Parameters		
Boundary conditions	Rivers and drainages within the model domain are described by fixed head boundary conditions and they can both take water out of the system and recharge the aquifer system along the perennial drainages.	Low - Moderate
Recharge	The recharge across the model domain was calibrated according to the measured monitoring data (groundwater levels) and according to the seasonal variances in the dewatering rates. The bulk of the recharge received is via the surface water systems recharging the semi-confined aquifer.	Moderate
Initial Hydraulic Heads	The water levels in the ERB are dynamic, and are either recovering or being drawn down from pumping. The initial conditions were therefore not considered and the system was considered in steady state during the 2017 year, when hydraulic heads in the boreholes and shafts (shallow and deeper aquifer) were most stable.	Moderate
Hydraulic Conductivity	The hydraulic conductivity from previous model calibration was used as initial values. The hydraulic conductivity of the mining voids and collapsed zones are high, and it was assumed that the	Moderate
Transient State Modelling Parameters		
Monitoring data	Long-term monitoring data (2017 - 2024) was available for transient calibration. In long term modelling scenarios, the steady state flow and transient tracer mass was used to conduct simulations. The transient calibration was used to test the sensitivity of the model parameters used for input.	Low
Specific Storage	The volume of water that a unit volume of aquifer releases from or takes into storage per unit change in head. $S = S_s \times D$. S_s . The storage available in mine voids are not known, and the transient calibration proved that the deep semi-confined aquifer is highly dependent on this parameter.	High
Transient Mass Tracer Parameters		
Porosity (%)	A conservative porosity value of 7.5% was used across the model domain.	High

Table 10-3: Initial Model Parameters

No	Layer	Selection	Hydraulic Zone	Thickness (m)	Transmissivity (m ² /d)	Avg Hydraulic Conductivity K (m/d)	Hydraulic Conductivity Kx (m/d)	Hydraulic Conductivity Ky (m/d)	Hydraulic Conductivity Kz (m/d)	Ss (1/m)	S (1)	Porosity	Ass_R (mm/a)	Recharge (%)	Recharge (m/d)
1	1	Alluvium	Weathered Zone	5	2.667	0.53	7.00E-01	7.00E-01	2.00E-01	2.00E-02	1.00E-01	7.50E-01	25	4.13%	6.85E-05
2	1	Karoo Dolerite	Weathered Zone	5	1.296	0.259	2.59E-01	2.59E-01	2.59E-01	2.00E-02	1.00E-01	7.50E-01	12	2.00%	3.32E-05
3	1	Dykes	Weathered Zone	5	1.295	0.259	2.59E-01	2.59E-01	2.59E-01	2.00E-02	1.00E-01	7.50E-01	12	2.00%	3.32E-05
4	1	Karoo Sandstone	Weathered Zone	5	8.634	1.727	2.59E+00	2.59E+00	5.18E-04	2.00E-02	1.00E-01	7.50E-01	26	4.30%	7.12E-05
5	1	Karoo Dwyka Tillite	Weathered Zone	5	0.663	0.133	1.99E-01	1.99E-01	3.97E-05	2.00E-02	1.00E-01	7.50E-01	12	2.00%	3.32E-05
6	1	Malmani Dolomite	Weathered Zone	5	26.668	5.334	8.00E+00	8.00E+00	8.64E-04	2.00E-02	1.00E-01	7.50E-01	42	7.00%	1.16E-04
7	1	Black Reef Quartzite	Weathered Zone	5	5.767	1.153	1.73E+00	1.73E+00	3.46E-04	2.00E-02	1.00E-01	7.50E-01	12	2.00%	3.32E-05
8	1	Alberton and other Lava	Weathered Zone	5	0.333	0.067	1.00E-01	1.00E-01	2.00E-05	2.00E-02	1.00E-01	7.50E-01	12	2.00%	3.32E-05
9	1	HalfwayH Granites	Weathered Zone	5	0.333	0.067	1.00E-01	1.00E-01	2.00E-05	2.00E-02	1.00E-01	7.50E-01	18	2.98%	4.93E-05
10	1	Main Reef Outcrop	Weathered Zone	5	155.000	31	3.10E+01	3.10E+01	3.10E+01	2.00E-02	1.00E-01	7.50E-01	18	3.00%	4.97E-05
11	1	Dam River Sediments	Dam/lake sediments	5	2.333	0.467	7.00E-01	7.00E-01	5.18E-05	2.00E-02	1.00E-01	7.50E-01	25	4.13%	6.85E-05
12	1	Ingress Areas	Induced Recharge	5	25.000	5.000	5.00E+00	5.00E+00	5.00E+00	2.00E-02	1.00E-01	7.50E-01	50	8.26%	1.37E-04
13	1	TSF	Induced Recharge	5	0.200	0.040	1.00E-02	1.00E-02	1.00E-01	2.00E-02	1.00E-01	7.50E-01	65	10.74%	1.78E-04
14	2	Karoo Dolerite	Solid and Fractured	109	5.663	0.0519	7.78E-02	7.78E-02	7.78E-05	5.00E-03	5.46E-01	7.50E-01			
15	2	Dykes	Aquitard	109	5.663	0.0519	7.78E-02	7.78E-02	7.78E-05	5.00E-03	5.46E-01	7.50E-01			
16	2	Karoo Sandstone	Solid and Fractured	109	65.506	0.6003	9.00E-01	9.00E-01	7.78E-04	5.00E-03	5.46E-01	7.50E-01			
17	2	Karoo Dwyka Tillite	Solid and Fractured	109	4.338	0.0398	5.96E-02	5.96E-02	5.96E-05	5.00E-03	5.46E-01	7.50E-01			
18	2	Malmani Dolomite	Solid and Fractured	109	0.364	0.0033	5.00E-03	5.00E-03	5.00E-06	5.00E-03	5.46E-01	7.50E-01			
19	2	Black Reef Quartzite	Solid and Fractured	109	37.734	0.3458	5.18E-01	5.18E-01	5.18E-04	5.00E-03	5.46E-01	7.50E-01			
20	2	Alberton and other Lava	Solid and Fractured	109	37.688	0.3454	5.18E-01	5.18E-01	5.18E-05	5.00E-03	5.46E-01	7.50E-01			
21	2	HalfwayH Granites	Solid and Fractured	109	2.191	0.0201	3.01E-02	3.01E-02	3.01E-05	5.00E-03	5.46E-01	7.50E-01			
22	2	Main Reef Pathway	Solid and Fractured	109	54.592	0.5003	7.50E-01	7.50E-01	7.50E-04	5.00E-03	5.46E-01	7.50E-01			
23	2	Open Diggings	Solid and Fractured	109	18.197	0.1668	2.50E-01	2.50E-01	2.50E-04	5.00E-03	5.46E-01	7.50E-01			
24	2	Ingress Areas	Solid and Fractured	109	177.518	1.6267	4.40E-01	4.40E-01	4.00E+00	5.00E-03	5.46E-01	7.50E-01			
25	3 - 4	Karoo Dolerite	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			
26	3 - 4	Dykes	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			
27	3 - 4	Karoo Sandstone	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			
28	3 - 4	Karoo Dwyka Tillite	Aquitard	20	0.001	0.0001	1.00E-04	1.00E-04	1.00E-09	5.00E-07	1.00E-05	7.50E-01			
29	3 - 4	Malmani Dolomite	Aquitard	20	0.058	0.0029	4.32E-03	4.32E-03	4.62E-08	5.00E-07	1.00E-05	7.50E-01			
30	3 - 4	Black Reef Quartzite	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			
31	3 - 4	Alberton and other Lava	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			

ERB Numerical Advective Tracer Transport Model

No	Layer	Selection	Hydraulic Zone	Thickness (m)	Transmissivity (m ² /d)	Avg Hydraulic Conductivity K (m/d)	Hydraulic Conductivity Kx (m/d)	Hydraulic Conductivity Ky (m/d)	Hydraulic Conductivity Kz (m/d)	Ss (1/m)	S (1)	Porosity	Ass_R (mm/a)	Recharge (%)	Recharge (m/d)
32	3 - 4	HalfwayH Granites	Aquitard	20	0.035	0.0017	2.59E-03	2.59E-03	2.59E-08	5.00E-07	1.00E-05	7.50E-01			
33	3 - 4	Main Reef Pathway	Aquitard	20	34.706	1.7353	2.59E+00	2.59E+00	2.59E-02	5.00E-07	1.00E-05	7.50E-01			
34	3 - 4	Ingress Areas	Aquitard	20	11.000	0.5500	5.50E-01	5.50E-01	5.50E-01	5.00E-07	1.00E-05	7.50E-01			
35	3 - 4	Green Sill	Aquitard	20	0.000	0.0000	5.00E-06	5.00E-06	5.00E-09	5.00E-07	1.00E-05	7.50E-01			
36	3 - 4	Ingress Zone	Aquitard	10	20.000	2.0000	2.00E+00	2.00E+00	2.00E+00	5.00E-07	5.00E-06	7.50E-01			
37	5	Karoo Dolerite	Solid and Fractured	100	6.532	0.0653	9.33E-02	9.33E-02	9.33E-03	1.00E-06	1.00E-04	7.50E-01			
38	5	Dykes	Aquitard	100	6.532	0.065	9.33E-02	9.33E-02	9.33E-03	1.00E-06	1.00E-04	7.50E-01			
39	5	Karoo Sandstone	Solid and Fractured	100	39.777	0.398	5.50E-01	5.50E-01	9.33E-02	1.00E-06	1.00E-04	7.50E-01			
40	5	Karoo Dwyka Tillite	Solid and Fractured	100	50.076	0.501	7.15E-01	7.15E-01	7.15E-02	1.00E-06	1.00E-04	7.50E-01			
41	5	Malmani Dolomite	Solid and Fractured	100	4.200	0.042	6.00E-02	6.00E-02	6.00E-03	1.00E-06	1.00E-04	7.50E-01			
42	5	Black Reef Quartzite	Solid and Fractured	100	43.546	0.435	6.22E-01	6.22E-01	6.22E-02	1.00E-06	1.00E-04	7.50E-01			
43	5	Alberton and other Lava	Solid and Fractured	100	25.257	0.253	3.61E-01	3.61E-01	3.61E-02	1.00E-06	1.00E-04	7.50E-01			
44	5	HalfwayH Granites	Solid and Fractured	100	25.257	0.253	3.61E-01	3.61E-01	3.61E-02	1.00E-06	1.00E-04	7.50E-01			
45	5	Main Reef Pathway	Solid and Fractured	100	69.300	0.693	9.90E-01	9.90E-01	9.90E-02	1.00E-06	1.00E-04	7.50E-01			
46	5	Ingress Areas	Solid and Fractured	100	55.000	0.550	5.50E-01	5.50E-01	5.50E-01	1.00E-06	1.00E-04	7.50E-01			
47	6	Wits SG	Solid and Fractured	506	93.586	0.185	1.86E-01	1.86E-01	1.84E-01	4.57E-05	2.31E-02	7.50E-01			
48	6	PO Wits SG	Solid and Fractured	0.1	85.680	857	8.57E+02	8.57E+02	8.57E+02	4.57E-05	4.57E-06	7.50E-01			
49	6	Dykes	Aquitard	506	0.124	2.46E-04	2.46E-04	2.46E-04	2.46E-04	4.57E-05	2.31E-02	7.50E-01			
50	7	Kimberley Reef	Conduit	1	90.000	90.000	9.00E+01	9.00E+01	9.00E+01	5.00E-01	5.00E-01	7.50E-01			
51	7	PO Wits SG	Solid and Fractured	0.1	102.000	1 020.000	1.02E+03	1.02E+03	1.02E+03	5.00E-01	5.00E-02	7.50E-01			
52	7	Dykes	Aquitard	0.1	0.100	1.000	1.00E+00	1.00E+00	1.00E+00	5.00E-05	5.00E-06	7.50E-01			
53	8	Wits SG	Solid and Fractured	500	91.800	0.184	1.84E-01	1.84E-01	1.84E-01	4.63E-05	2.32E-02	7.50E-01			
54	8	PO Wits SG	Solid and Fractured	0.1	71.400	714.000	7.14E+02	7.14E+02	7.14E+02	4.63E-05	4.63E-06	7.50E-01			
55	8	Dykes	Aquitard	500	0.104	2.07E-04	2.07E-04	2.07E-04	2.07E-04	4.63E-05	2.32E-02	7.50E-01			
56	9	Main Reef	Conduit	1	100.000	100.000	1.00E+02	1.00E+02	1.00E+02	5.00E-01	5.00E-01	7.50E-01			
57	9	PO Wits SG	Solid and Fractured	0.1	80.000	800.000	8.00E+02	8.00E+02	8.00E+02	2.53E-02	2.53E-03	7.50E-01			
58	9	Dykes	Aquitard	0.1	0.100	1.00E+00	1.00E+00	1.00E+00	1.00E+00	2.53E-02	2.53E-03	7.50E-01			
59	10	Basement Granites	Solid and Fractured	1 352	2.514	0.002	1.86E-03	1.86E-03	1.86E-03	3.05E-07	4.12E-04	7.50E-01			
60	10	PO Basement Granites	Solid and Fractured	2 300	2.510	0.001	1.09E-03	1.09E-03	1.09E-03	3.05E-07	7.02E-04	7.50E-01			
61	10	Dykes	Aquitard	1 352	0.010	7.43E-06	7.43E-06	7.43E-06	7.43E-06	3.05E-07	4.12E-04	7.50E-01			