NAMIBIA UNIVERSITY OF SCIENCE AND TECHNOLOGY

Groundwater management around tailings storage facilities in Namibia's arid uranium mining region

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Thesis submitted in fulfilment of the requirements for the Doctorate degree in Natural Resource Science at the Namibia University of Science and Technology

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2025 NOVEMBER

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List of Acronyms

AC:	activated carbon
As:	arsenic
Ca^{2+}	calcium
CCHEN:	Chilean Nuclear Energy Commission
Cd	Cadmium
Cl^-	chlorine
DO:	Dissolved Oxygen
EC:	Electrical conductivity
GDP:	Gross Domestic Product
Gos:	graphene oxides
GPS:	Global Positioning System
GSN:	Geological Survey of Namibia
HCL:	Hydrochloric acid
HDC:	Higher Degrees Committee
HNO_3:	Nitric acid
IAEA:	International Atomic Energy Agency
ICP-OES:	Inductively Coupled Plasma — Optical Emission Spectrometry
IOCG-U:	Olympic Dam Iron Oxide Copper Gold-Uranium
ISL:	in-situ leaching
IWRM:	Integrated Water Resources Management
K^+	potassium
LDHs:	layered double hydroxides
Mg^{2+}	magnesium
MME:	Ministry of Mines and Energy
MOFs:	metal–organic frameworks
N02-	nitrite
N03-	nitrate
NAWQA:	National Water Quality Assessment
NEA:	Nuclear Energy Agency
NUST:	Namibia University of Science and Technology
OECD	Organisation for Economic Co-operation and Development
Pb:	Lead

pH:	Power of Hydrogen
PhD:	Doctor of Philosophy
PPE:	Personal protective equipment
SDG:	Sustainable Development Goals
SEMP:	Strategic Environmental Management Plan
TDS,	Total dissolved solids
TSF:	Tailiing storage fascility
U	uranium
UN:	United Nations
UNESCO:	United Nations Educational, Scientific, and Cultural Organisation
USA:	United states of America
USGS:	U.S. Geological Survey
VSMOW	Vienna Standard Mean Ocean Water
WHO:	World Health Organisation
ZVI:	zeolites and zero-valent iron
	sulphate

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"I can do all things through him who strengthens me"

Philippians 4:13

Dedication

To my beloved parents, Mr. Ben //Areseb and Mrs. Magritha Van Neel,
whose unwavering love and support have been my foundation.

To my husband, Mr. Enrico Afrikaner,
for your endless encouragement, support and strength throughout this journey.

To my children, Mr. Elrico Jayden Afrikaner and Ms. Elrica Jayda Afrikaner,
may this achievement inspire you to pursue your dreams with passion and resilience.

This thesis is dedicated to all of you, my greatest source of inspiration and love.

Abstract

Groundwater in arid regions has become increasingly vulnerable to stressors such as climate variability, intensive abstraction, and mining. In Namibia's uranium province (situated in the Erongo region), where mining has persisted for several decades, groundwater resources are subject to dual pressures. This includes legacy contamination from older mining operations and emerging risks from newer mines. This study provides an integrated assessment of uranium occurrence in arid regions of Namibia, groundwater quality, hydrogeochemistry, isotopic composition, and radiological risks in the vicinity of uranium mine tailings. This study includes both field-based sampling and long-term monitoring records. Building on this, the study investigates the hydrogeochemical and isotopic characteristics of groundwater from two uranium mines, one older and one newer, to evaluate spatial variability, contamination patterns, and recharge processes. Sixteen boreholes were sampled and analysed for major ions, trace metals, and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and radiological risks. Results revealed elevated concentrations of metals and cations near the oldest mine. This is indicative of prolonged geochemical alteration and anthropogenic impact. Isotopic enrichment indicated evaporation-driven concentration and a limited contribution from modern recharge. In contrast, groundwater near the newer mine exhibited a broader isotopic range. This reflects both evaporation of mine-influenced waters and mixing with relatively unaltered local groundwater. Severe and spatially variable degradation was observed at the oldest mine, with elevated salinity (mean TDS 20,897 mg/L), chloride (mean 8,685 mg/L), and radium-226 (up to 721.9 mBq/L). Long-term monitoring revealed declining trends in pH (Tau = 0.51, p = 0.0000011), electrical conductivity (Tau = 0.6089, $p < 0.000001$), sodium (Tau = −0.240, p = 0.0238), sulphate(Tau = −0.2685, p = 0.0105), and nitrate (Tau = −0.2890, p = 0.007), but increasing TDS (Tau = 0.30, p = 0.00054) and radium-226 (Tau = 0.49, p = 0.0004) , pointing to persistent legacy contamination. The newer mine displayed more uniform groundwater chemistry but showed increasing trends in EC (Tau = 0.556, p = 0.0318), TDS (Tau = 0.5111, p = 0.049), nitrate (Tau = 0.733, p = 0.0042), calcium (Tau = 0.556, p = 0.0318), and potassium (Tau = 0.644, p = 0.0123) within a decade of operation. This indicates early-stage geochemical alteration in the groundwater system. At both sites, uranium and radium-226 frequently exceeded World Health Organisation drinking water guidelines, highlighting significant chemical and radiological risks. Collectively, these findings meet the research aim by demonstrating how mining legacies, hydrogeological settings, and climate-driven water balance interact to shape groundwater vulnerability. The study establishes a critical baseline for monitoring and offers evidence to inform policy development, risk assessment, and sustainable groundwater management in uranium-rich arid environments.

Keywords: uranium mining, groundwater quality, hydrogeochemistry, stable isotopes, radiological risk, arid regions, Namibia

CHAPTER 1: GENERAL INTRODUCTION

1.1 Background

Water is a fundamental component of all life systems. Its availability, quality, and management are critical for safeguarding human health, sustaining ecosystems, and supporting socio-economic development (Bhushan, 2020; Mishra et al., 2021; Luque-Villa & Gonzalez-Mendez,2022: Onwudiegwu & Izah, 2025). Groundwater represents the most significant global freshwater reserve; yet, quality data are limited (Lapworth et al., 2021; Misstear et al., 2023). Of the 120 countries with water quality information, only 71 provide systematic assessments of groundwater quality (Lapworth et al., 2018; Misstear et al., 2023) . Groundwater's role is especially vital in arid and semi-arid regions, where surface water is scarce or unreliable.

In Africa, groundwater is the primary resource for domestic supply, agriculture, and industrial development (Gurmessa et al., 2022; De Bont & Börjeson, 2024; Silva-Caceres et al., 2024). If managed sustainably, groundwater can make a substantial contribution to the continent's development agenda. In Southern Africa, groundwater is particularly critical in rural and mining-intensive areas. However, industrial activities, including mining, increasingly threaten groundwater quality, reducing its suitability for consumption and ecological use (Verlicchi & Grillini,2020; Masindi & Foteinis, 2021; Lalumbe & Kanyerere, 2022). Effective water resource management thus requires understanding both natural and human-induced factors influencing groundwater vulnerability, a concern that is particularly urgent in Namibia, where aridity and limited surface water make groundwater indispensable.

Namibia is one of the driest countries in sub-Saharan Africa, with approximately 60% of the population relying on groundwater for domestic, agricultural, and industrial use (Hamutoko et al., 2016; Mupambwa et al., 2019; Lohe et al., 2021; Mapani et al., 2023). Continuous monitoring is therefore essential for assessing water quality, detecting emerging threats, and evaluating management strategies.

The Omaruru-Swakop River Basin, spanning the Erongo, Khomas, and Otjozondjupa regions, is characterised by groundwater-fed systems, ephemeral rivers, and springs that provide critical water supplies. Key ephemeral rivers, including the Khan, Swakop, Omaruru, and Ugab, flow only during episodic rainfall but support domestic water supply, farming, and industrial activities in urban centres such as Swakopmund, Walvis Bay, Arandis, Henties Bay, Omaruru, and Uis.

The mining industry contributed 13.3% to Namibia's GDP in 2024, and in the Erongo region, uranium mining represents a key industrial activity (Namibia Chamber of Mines, 2024). Since the resurgence of uranium prices in 2017, Namibia has strengthened its position in the global market, with uranium production growing by 5% in 2024 (Namibian Chamber of mines, 2024). Namibia is the third-largest global producer, hosting two major mines in the Erongo region (Wilde, 2023; Namibia Chamber of Mines, 2024; Lithon, 2025). The oldest mine, which has been operating since 1976 and is majority-owned by China National Uranium Corporation Limited, produced 2 600 tonnes of uranium oxide in 2024. The newest mine, commissioned in 2016 and primarily owned by China General Nuclear Power Corporation (CGNPC), produced 5 232 tonnes the same year (Namibia Chamber of Mines, 2024)

The proximity of these mines to critical alluvial and crystalline aquifers raises environmental and health concerns. Uranium and its decay products, along with mining-induced hydrogeochemical changes, pose a threat to groundwater resources in this arid environment. These risks necessitate a multidisciplinary investigation into the dynamics of groundwater quality near uranium mine tailings.

This thesis addresses these concerns through an integrated approach combining hydrogeochemical assessments and stable isotopic analysis. The study examines the occurrence, environmental impacts, and remediation strategies of uranium in groundwater under arid conditions, evaluates spatial and temporal variations in hydrochemistry, identifies changes in water sources and potential contamination pathways using isotopic and hydrogeochemical indicators, assesses spatio-temporal patterns in radionuclide concentrations. Through this comprehensive investigation, the thesis aims to enhance understanding of uranium-related groundwater contamination and provide evidence-based guidance for water resource management and policy in Namibia and other arid mining regions.

1.2 Study area

The study area is situated at an elevation of approximately 400–600 m above sea level and receives an annual rainfall of 0–50 mm, with an average evaporation rate of 1000–1250 mm per year (Lohe et al., 2021; Atlas of Namibia Team, 2022). Geologically, the Damara Sequence dominates the area, and uranium mineralisation within occurs as the mineral uraninite associated with alkali feldspar (alaskite) of the intrusive Damara granites (Shanyengana et al., 2020; Li et al., 2022; Wilde, 2023).

Based on geological lithology and groundwater flow characteristics, Namibia is divided into 12 hydrogeological regions (Figure 1-1). The study area falls within the Swakop Upper Omatako

groundwater basin, which supplies water to the uranium mines and the coastal towns of Swakopmund and Henties Bay.

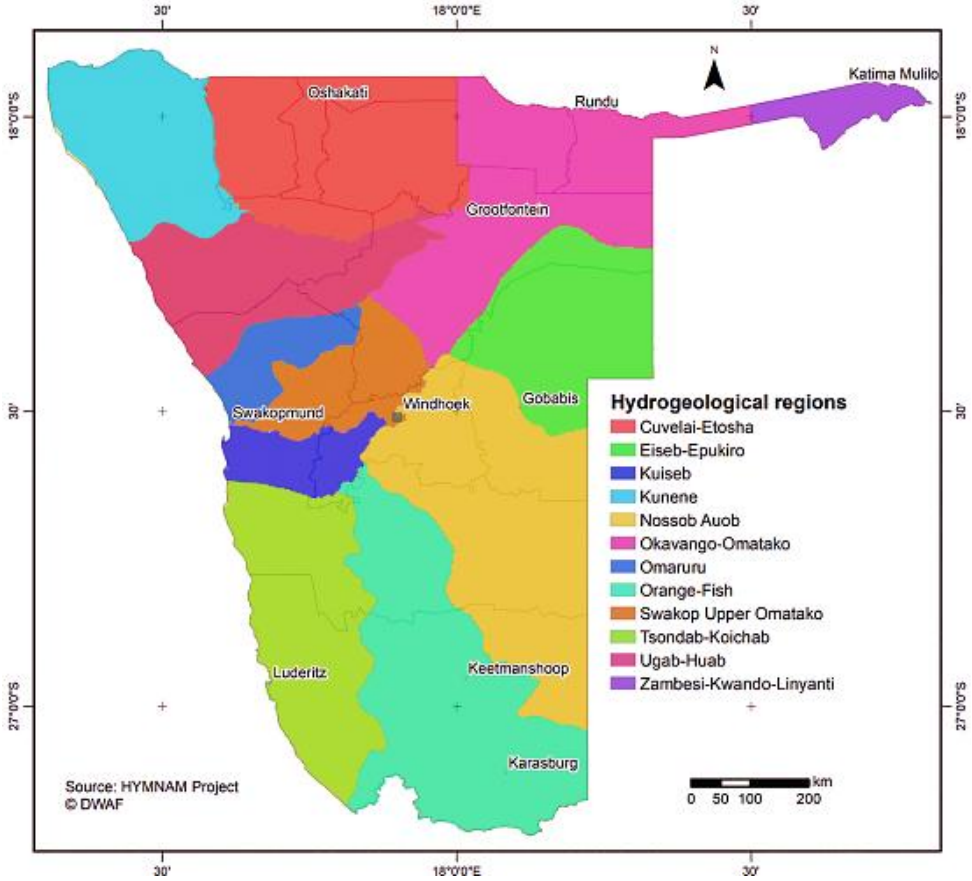


Figure 1-1 Groundwater basins of Namibia (adapted from Lohe et al., 2021, based on Hydrogeological Mapping of Namibia (HYMNAM) project data).

Although the regional aquifer contains zones of relatively high yield, the geological formations within the study area generally provide limited groundwater (Lohe et al., 2021). This apparent contradiction reflects the arid climatic conditions of Namibia, where low and episodic recharge, high evapotranspiration losses, and the presence of low-permeability layers constrain aquifer replenishment (Uugulu & Wanke, 2020; Zeelie, 2020). In addition, abstraction in certain areas exceeds the sustainable safe yield, while elevated salinity and dissolved mineral concentrations further limit the usable groundwater resources (Ihemba & Esterhuyse, 2020; Amwele et al., 2021; Mapani et al., 2023). Given the low groundwater potential, it is critical to safeguard the scarce water resources.

A total of sixteen downstream monitoring boreholes were sampled, comprising eight from the oldest uranium mine and eight from the newer mine. Selection of boreholes was guided by their spatial proximity to the tailings storage facilities (TSFs) and their alignment with probable groundwater flow

paths. The locations and characteristics of these boreholes are presented in Figures 1-2 and 1-3, with additional details provided in Tables 1.1 and 1.2.

Table 1.1 Locations and characteristics of boreholes at the oldest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	Distance from TSF (m)	Jun-24			Oct-24			Mar-25		
									Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)
T3	22°26′36.13″	15°1′40.73″	9.41	612	0.59	7	612.59	123	7.16	2.25	605.43	7.36	2.05	605.23	7.34	2.07	605.25
X02	22°28′22.80″	14°59′28.97″	53.44	564	0.56	30	564.56	3460	13.39	40.05	551.17	13.39	40.05	551.17	13.42	40.02	551.14
X05	22°28′12.47″	15°0′0.68″	49.45	561	0.55	25	561.55	2450	4.95	44.5	556.6	5.05	44.4	556.5	4.95	44.5	556.6
X21	22°29′9.35″	14°59′37.03″	49.57	544	0.53	30	544.53	3790	21.47	28.1	523.06	21.77	27.8	522.76	20.74	28.83	523.79
L10	22°28′42.38″	15°0′56.20″	49.48	540	0.52	25	540.52	1665	11.98	37.5	528.54	10.88	38.6	529.64	11.96	37.52	528.56
N01A	22°27′21.46″	15°2′36.13″	52.11	603	0.59	25	603.59	510	0.1	52.01	603.49	0.1	52.01	603.49	0	52.11	603.59
N09	22°26′43.94″	15°3′20.81″	10.43	591	0.57	8	591.57	1100	3.83	6.6	587.74	3.08	7.35	588.49	3.41	7.02	588.16
N11	22°25′57.68″	15°2′52.66″	49.38	619	0.62	25	619.62	450	4.83	44.55	614.79	4.68	44.7	614.94	4.77	44.61	614.85

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - rest water level (m)

Table 1.2 Locations and characteristics of boreholes at the newest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	Distance from TSF (m)	Jun-24			Oct-24			Mar-25		
									Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (m asl)
GW 14	22°36′7.87″	15°0′36.74″	99.49	496	0.51	40	496.51	60	34.4	96.05	462.11	35.79	63.7	460.72	33.74	65.75	462.77
GW 16	22°36′39.38″	15°1′37.87″	119.93	491	0.35	80	491.35	170	54.4	65.53	436.95	53.55	66.38	437.8	52.19	67.74	439.16
GW 37	22°37′2.17″	15°1′50.56″	100.05	478	0.51	70	478.51	560	47.41	52.64	434.1	46.68	53.82	431.83	45.48	54.57	433.03
GW 17	22°37′19.54″	15°1′25.58″	99.87	469	0.48	80	469.48	310	60.5	39.37	408.98	58.02	41.85	411.46	54.14	45.73	415.34
GW 11	22°37′37.34″	15°0′57.63″	98.9	464	0.51	70	464.51	585	43.41	55.49	426.1	41.19	57.71	423.32	40.29	58.61	424.22
GW 31	22°37′19.71″	15°0′22.21″	106.42	466	0.54	80	466.54	340	31.91	74.48	434.63	32.56	73.86	433.98	81.09	24.91	385.45
GW 12	22°36′55.61″	15°0′7.71″	120.48	472	0.52	90	472.52	320	80.9	39.58	391.62	79.88	40.6	392.64	33.03	87.45	439.49
GW 30	22° 35' 40.16″	15° 0' 39.16"	101.8	498	0.52	80	498.52	900	33.24	68.56	465.28	32.55	69.25	465.97	23.46	78.34	475.06

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - rest water level (m)

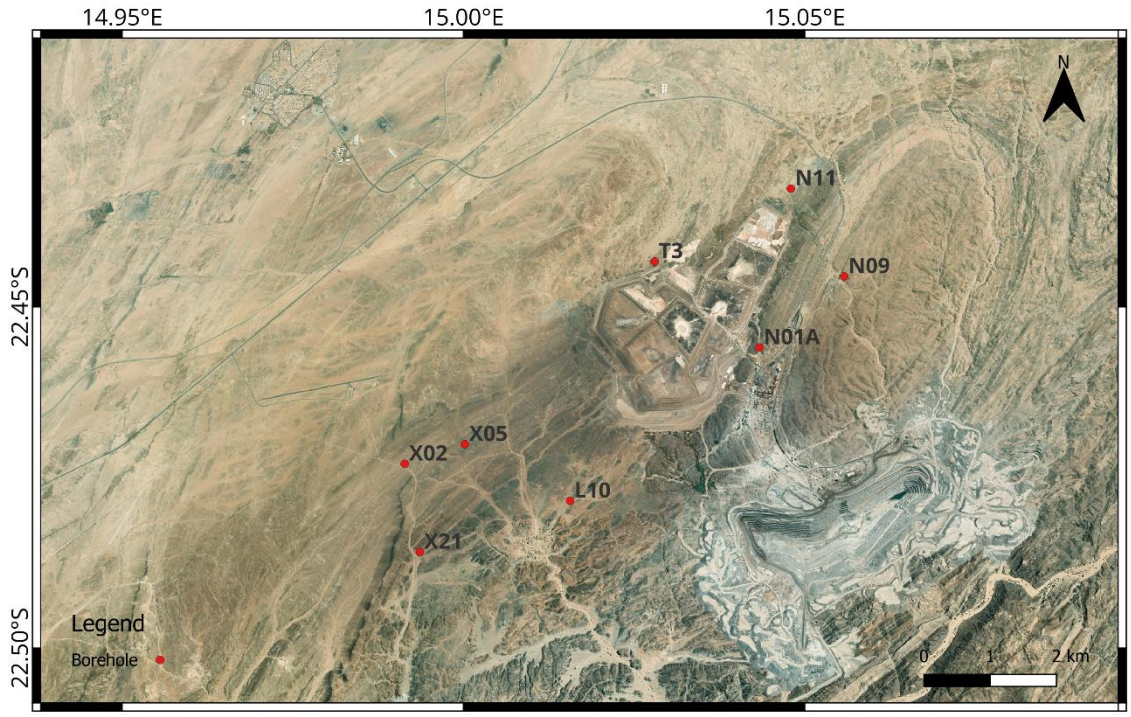


Figure 1-2 Location of boreholes at the oldest uranium mine (QGIS version 3.40.5 2025)

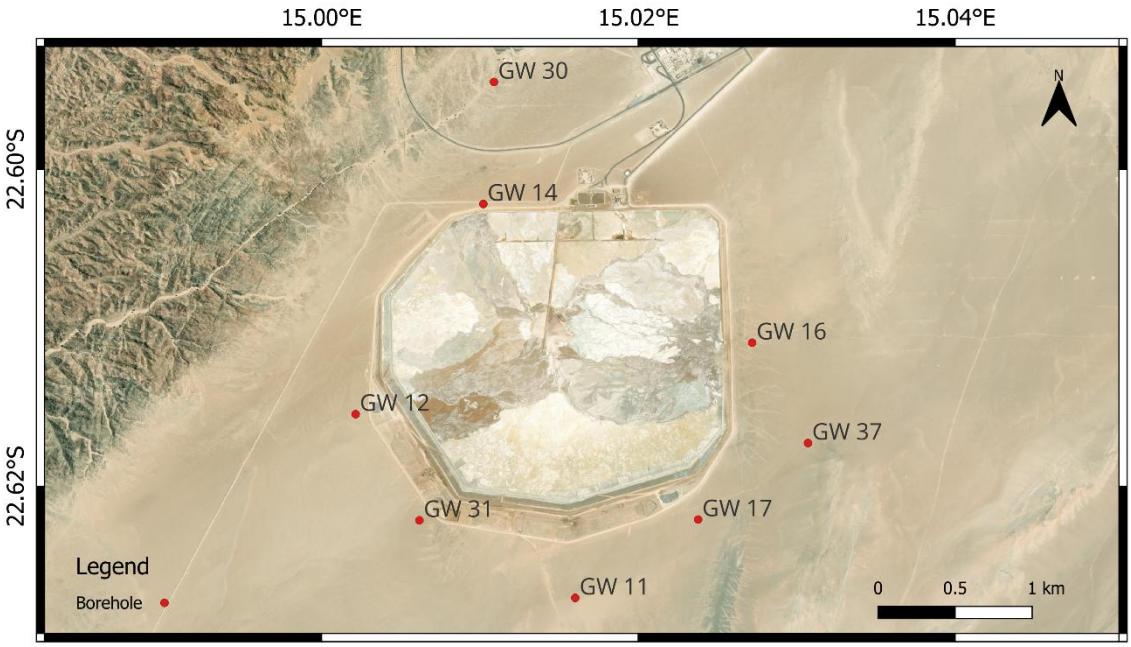


Figure 1-3 Location of boreholes at the newest uranium mine (QGIS version 3.40.5 2025)

1.3 Problem Statement

The growing population in Namibia's Erongo Region has increased the demand for drinking water, intensifying pressure on already limited groundwater resources. If not properly managed, these critical resources, which support both human consumption and ecological sustainability, are at risk of overexploitation and contamination. While uranium mining activities in the region contribute significantly to economic development, they also pose potential threats to groundwater quality, particularly through the leaching of contaminants from tailings storage facilities (Hamutoko et al., 2014; Abiye & Shaduka, 2017; Musiyarira et al., 2017; Mathuthu et al., 2021). Although existing mines have implemented groundwater management measures, there remains insufficient scientific evidence to evaluate the long-term effectiveness of these strategies or to determine whether they require improvement or redesign.

The lack of continuous, detailed groundwater monitoring further limits the ability to detect subtle but potentially important changes in groundwater quantity and quality. This gap constrains efforts to fully understand how mining activities may influence groundwater systems over time, particularly in areas where recharge is limited, and aquifer vulnerability varies.

Communities near uranium mining operations in arid Namibia rely heavily on groundwater for domestic use, agriculture, and livelihoods. However, they often lack access to scientifically validated information on the status and safety of their water sources. The study area encompasses both fossil groundwater stored in crystalline aquifers, which are effectively non-renewable, and alluvial aquifers that are periodically recharged by upstream rainfall. This hydrogeological context underscores the urgency of safeguarding irreplaceable water resources from contamination.

This research aims to address gaps in long-term groundwater quality monitoring around uranium mine tailings storage facilities. By analysing historical groundwater data, the study seeks to improve understanding of spatial and temporal variations in water quality, assess potential contamination risks, and support more effective groundwater management practices. Particular emphasis is placed on protecting groundwater resources that sustain baseflows into the Khan and Swakop Rivers and ensuring that water quality meets safe drinking-water standards.

1.4 Philosophical argument to demonstrate the novelty of the study

The novelty of this research lies in its conceptual framing of groundwater in the Erongo Region as a vulnerable and finite socio-ecological resource within an arid mining landscape. Philosophically, the study adopts a systems-oriented perspective. Rejecting the view of groundwater quality as a series of isolated measurements and instead recognising it as the cumulative outcome of long-term anthropogenic pressures, limited natural recharge, and the contrasting behaviours of fossil and alluvial aquifers. This framing exposes a critical gap in existing research, where groundwater investigations around uranium mines have typically been event-based, short-term, or narrowly focused on compliance monitoring (Hamutoko et al., 2014; Abiye & Shaduka, 2017; Mathuthu et al., 2021; Wilde, 2023). By contrast, this study positions groundwater sustainability as both a scientific and ethical imperative, particularly given that parts of the aquifer system contain fossil water that cannot be replenished on human timescales. This conceptual shift emphasises safeguarding irreplaceable water reserves rather than routine quality assessment, thereby introducing a distinct rationale for examining long-term trends in trace metal and radionuclide concentrations.

The philosophical contribution also lies in addressing the scarcity of continuous, high-resolution groundwater data, which has historically limited the ability to detect subtle but consequential changes in water quality. Rather than treating these data limitations solely as methodological constraints, the study reframes them as symptoms of a deeper institutional and scientific gap: the absence of integrated, long-term groundwater evidence to evaluate the effectiveness of existing mine-water management practices. This argument provides a novel justification for systematically analysing historical monitoring datasets to reveal temporal and spatial patterns that would otherwise remain obscured.

Furthermore, the study adopts a community-centred lens, acknowledging that downstream users, such as livestock farmers and olive producers, depend on groundwater but often lack scientifically validated information on the safety of their supplies. This introduces a socio-hydrological dimension that is seldom foregrounded in Namibian uranium-mining research. By situating groundwater as both a public-health necessity and a foundation for rural livelihoods, the study advances a philosophical position that groundwater assessment must extend beyond technical evaluation to considerations of environmental justice and equitable resource access. Collectively, these conceptual positions demonstrate the novelty of the research: it offers a holistic, ethically grounded, and system-level examination of groundwater vulnerability in a region where mining pressures, limited recharge, and insufficient monitoring converge to pose risks to both ecological sustainability and human well-being.

1.5 Research objectives

This study aims to assist in managing groundwater resource quality in the study area. The specific objectives of the research are;

i. To review the occurrence, environmental impacts and remedial methods of uranium in groundwater within arid environments.
ii. To assess the hydrogeochemistry of the groundwater both spatially and temporally around the chosen uranium mine tailings in Namibia.
iii. To analyse stable isotopic signatures ($\delta^{2}H$ and $\delta^{18}O$) and hydrogeochemical parameters to identify changes in water source and potential contamination pathways.
iv. To assess trace elements and radiological risks around uranium mine tailings in Namibia

1.6 Research questions

The proposed PhD thesis will address the following research questions:

i. What is the current state of knowledge on the occurrence and impacts of uranium in groundwater systems in arid environments?
ii. What is the hydrogeochemistry around tailings facilities with respect to spatio-temporal (1982-2025) variations of groundwater quality of the chosen uranium mines in Namibia?
iii. How do isotopic signatures and hydrogeochemical characteristics reflect the impact of uranium mining on groundwater systems in the Uranium Province of Namibia?
iv. How do trace element concentrations and radiological hazards vary between groundwater at legacy and newly developed uranium mine tailings in Namibia?

1.7 Significance of the Study

Groundwater is a vital resource for sustaining livelihoods in Namibia, especially in arid regions where surface water is scarce. This study addresses the urgent need to understand and manage the impacts of uranium mining on groundwater systems in such vulnerable environments.

By reviewing the occurrence, environmental impacts, and remedial measures for uranium contamination, the research provides a consolidated scientific foundation for informed decision-making. The assessment of groundwater hydrochemistry and stable isotopes ($\delta^{2}H$ and $\delta^{18}O$) will enhance understanding of spatial and temporal variations in water quality, helping to trace contamination pathways and detect changes in water sources.

Analysis of spatio-temporal trends in radionuclide concentrations around uranium mine tailings will generate empirical evidence of contamination risks, supporting regulatory monitoring and environmental protection efforts.

Beyond its local relevance, the findings and modelling framework can be applied to other arid regions facing similar hydrogeological and mining challenges, contributing to a broader understanding of dryland hydrogeology.

Ultimately, this research equips policymakers, water managers, and mining operators with actionable insights to minimise environmental risks while ensuring the long-term sustainability and safety of groundwater resources. It also serves as a scientific reference for future studies on the environmental impacts of mine tailing facilities across Namibia.

1.8 Limitations of the Study

This study was subject to several logistical constraints. Specific physico-chemical analyses, particularly radionuclide measurements, could not be conducted within Namibia due to limited local analytical capacity. Consequently, samples were analysed at North-West University in South Africa, which introduced delays related to sample transportation, laboratory processing, and turnaround times.

Furthermore, although permission was granted by the Ministry of Agriculture, Fisheries, and Land Reform (MAWLR) to utilise its field equipment, reliance on shared resources occasionally resulted in scheduling challenges that affected the timing of fieldwork activities.

Despite these constraints, the study was carefully designed to ensure the objectives are achieved, and the findings remain robust and scientifically meaningful.

1.9 Thesis outline

The thesis will discuss each objective in a separate chapter, each presented as a manuscript. Each chapter is introduced separately, and a reference list is provided at the end.

The outline will be as follows.

Chapter 1: This chapter presents an introduction to the research topic and includes a detailed overview of the study area.

Chapter 2: This chapter provides a comprehensive literature review on the presence and behaviour of uranium in arid environments, with a focus on its geochemical occurrence, mobilisation, and impacts on groundwater quality. It also examines documented environmental and human health risks

associated with uranium contamination. Various remediation and management strategies used globally to mitigate uranium pollution in groundwater systems are discussed, highlighting their applicability in arid regions such as Namibia. **This manuscript is published in the Journal of Hydrology: Regional Studies.**

Chapter 3: This chapter investigates the spatial and temporal patterns of groundwater quality around selected uranium mine tailings in Namibia. Using field sampling and historical groundwater data, the study evaluates trends in physicochemical parameters and identifies areas of potential contamination. The analysis offers insight into how mining activities impact groundwater quality over time and across various locations within the study area. **This manuscript has been submitted to the Physics and Chemistry of the Earth Journal, Manuscript Number: JPCE-D-25-01863. An international interdisciplinary journal that publishes peer-reviewed collections of thematic issues with an emphasis on rapid dissemination of research findings.**

Chapter 4: This chapter focuses on the hydrogeochemical and isotopic analysis of groundwater to determine sources, flow paths, and contamination mechanisms associated with uranium mining. Stable isotopes ($\delta^{2}H$ and $\delta^{18}O$) and key hydrogeochemical indicators are utilised to trace groundwater origins, assess mixing processes, and identify potential pathways of contamination. The chapter highlights how isotopic and geochemical data complement traditional water quality analyses in understanding groundwater dynamics. **This manuscript (Manuscript number: HSJ-2025-0661.R1) is under second review following major review by journal reviewers for the Hydrological Sciences Journal, special issue: Contribution of isotope hydrology to water sciences in Africa: Revisiting foundations and exploring new research trends.**

Chapter 5: This chapter assesses the trace-element contamination and radiological risks associated with uranium mine tailings in Namibia's Uranium Province. It provides essential evidence to inform groundwater management strategies, reduce mining-induced impacts, and protect scarce water resources in arid regions. **This manuscript (Manuscript Number: JPCE-D-25-01854) is under review at Physics and Chemistry of the Earth, an international interdisciplinary journal that publishes peer-reviewed collections of thematic issues with an emphasis on rapid dissemination of research findings.**

Chapter 6: This chapter synthesises the key findings from all chapters, highlighting how the research objectives were achieved and what new insights were generated regarding groundwater quality and radiological risks associated with uranium mine tailings in Namibia. It emphasises the broader scientific contributions, management implications, and relevance of the study to arid mining environments. Additionally, the conclusion presents recommendations for policy, groundwater protection, and future research directions.

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CHAPTER 2: GROUNDWATER IN ARID ENVIRONMENTS: A REVIEW OF URANIUM OCCURRENCE AND IMPACTS

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Abstract

Study region: This review focuses on major uranium-producing arid regions, including Australia, Chile, Kazakhstan, the USA, Niger, South Africa, and Namibia. These regions are globally significant not only for their uranium deposits but also because communities rely heavily on groundwater as a primary drinking water source.

Study focus: The paper synthesises existing knowledge on the occurrence of uranium in groundwater across these arid environments, examining its impacts on water quality and associated health risks. It further evaluates available remediation technologies and considers their applicability under diverse hydrogeological and socio-economic settings. Unlike previous studies limited to individual sites or countries, this review provides a cross-regional comparison that integrates hydrochemical, radiological, and remediation perspectives.

New hydrological insights for the region: The analysis reveals recurring hydrogeochemical challenges in arid uranium provinces, particularly the limited application of isotopic tracers, radio-nuclide monitoring, and advanced groundwater modelling. By comparing case studies

across continents, the review identifies consistent knowledge gaps and emphasises that remediation strategies must be tailored to local hydrogeology and cost constraints. This synthesis presents a novel global perspective on understanding uranium-related groundwater risks in arid regions and outlines a roadmap for future research and adaptive water management.

Keywords: Groundwater, arid environments, uranium pollution, groundwater quality, remediation, health risks

2.1 Introduction

Groundwater contamination is a pressing global issue that threatens human health and ecosystems, arising from both natural processes and anthropogenic activities such as industrial waste, mining, urbanisation, and agriculture (Akhtar et al., 2021, Li et al., 2021, Karunanidhi et al., 2022, Jibitha and Sabu, 2023). In arid regions, groundwater is particularly scarce due to limited recharge, yet it remains the primary source of drinking water worldwide, relied upon by nearly three billion people (Famiglietti and Ferguson, 2021, Benaissa et al., 2023, Zhang et al., 2024, Elsaidy et al., 2025). Its natural protection, favourable bacteriological quality, and accessibility make safeguarding groundwater resources a global priority.

Uranium is a naturally occurring, toxic, and radioactive heavy metal with an average crustal abundance of 3 ppm, though concentrations in uranium-rich provinces can reach up to 500 ppm (Stumpf et al., 2020, Smedley and Kinniburgh, 2022, Ighalo et al., 2024). When mobilised through erosion, dissolution, or acid mine drainage, uranium contaminates groundwater and poses severe health risks. Globally, guidelines and standards for uranium in drinking water vary considerably and remain relatively recent in development. The World Health Organisation recommends a guideline of 30 µg/L in drinking water, yet elevated levels remain widespread, with exposure linked to kidney damage, neurological effects, and increased cancer risks (Lapworth et al., 2021, Smedley and Kinniburgh, 2022, Vengosh et al., 2022).

Around the world, a number of arid regions host uranium deposits, notably in Australia, Chile, Kazakhstan, the USA, Niger, Namibia, and South Africa, where mining activities heighten contamination risks (Ma et al., 2020, Mathuthu et al., 2021, Smedley and Kinniburgh, 2022, Ibrayeva et al., 2025). In these environments, groundwater contamination is aggravated by solute concentration through evaporation and poorly managed waste disposal, which mobilise uranium and associated radionuclides into aquifers (Smedley and Kinniburgh, 2022, Vengosh et al., 2022, Ibrayeva et al., 2025). Research conducted in the mid-20th century in the United States, Canada, and Europe established a link between radon exposure and lung cancer (Nilsson and Tong, 2020, Ngoc et al., 2022, Richardson et al., 2022, Ruano-Ravina et al., 2023). In Namibia, Mathuthu et al. (2021) observed that isotopic ratios of uranium ($^{234}U/^{238}U$) in groundwater samples were below unity (<1), suggesting that the uranium originated from mining activities rather than natural sources. The rising global demand for uranium has led to increased mining activities, intensifying the need to assess groundwater pollution in arid regions. The Organisation for Economic Co-Operation and Development (OECD) (2025) report serves as a cornerstone reference in uranium research, offering the most comprehensive and authoritative account of global resources, production, and demand. Its detailed synthesis of market

dynamics, policy developments, and environmental and social considerations makes it an essential source for evaluating both the status and the broader impacts of uranium mining worldwide.

This review provides a comprehensive synthesis of uranium contamination in groundwater, particularly in arid regions, where recharge limitations and geochemical conditions exacerbate the vulnerability. Unlike previous studies that focus on isolated sites or individual aspects, this work integrates uranium occurrence and remediation approaches across multiple uranium provinces. By highlighting underrepresented regions such as Africa, the study addresses critical knowledge gaps and advances understanding of groundwater risks in mining-affected arid environments.

2.2 A review of uranium occurrence and impacts

2.2.1 Australia

Australia is one of the largest global uranium producers, alongside Kazakhstan (Herrmann, 2023, Britt and Czarnota, 2024, OECD, 2025). Approximately 90 % of Australia's uranium reserves are found in hematite breccia complexes and unconformity-related deposits (International Atomic Energy Agency, 2020; Hiatt et al., 2021). Figure 2.1 highlights the spatial clustering of deposits across Australia, particularly in the Northern Territory, South Australia, and Western Australia. It illustrates the major deposit categories as defined by the International Atomic Energy Agency (2020), with symbols and colours representing different deposit types (e.g., surficial fluvial valley intrusive plutonic and others). The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources, and Production" (2020).

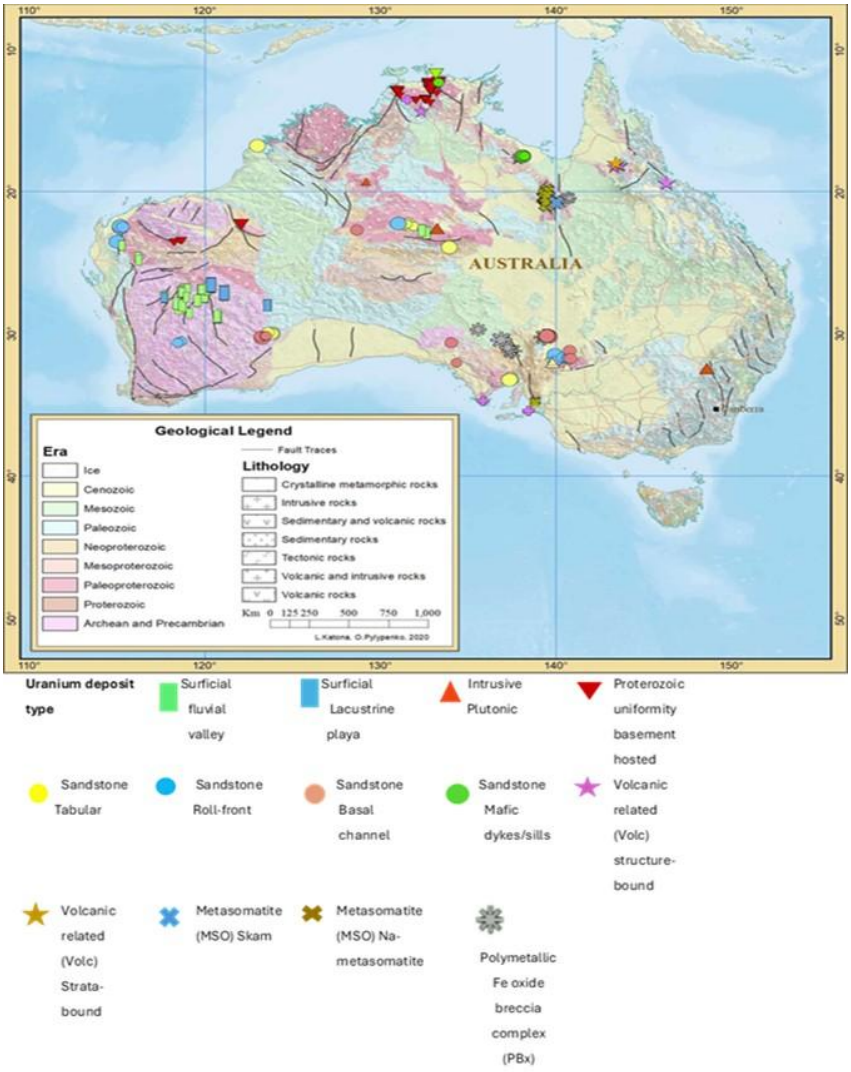


Figure 2-1 Geographic distribution of uranium deposit types in Australia

Significant uranium deposits in Australia include the Olympic Dam Iron Oxide Copper Gold-Uranium (IOCG-U) deposit in South Australia and the unconformity-related deposits of Ranger, Jabiluka, Nabarlek, and Koongarra in the Northern Territory. Other notable deposits include Kintyre in Western Australia and Yeelirrie (Gigon et al., 2019, Reid, 2019, Courtney-Davies et al., 2020, OECD, 2025). Most of the countries' uranium mines are found in Western Australia (4 mines) and Southern Australia (4 mines) (OECD, 2025).

The International Atomic Energy Agency (2020) and Herrmann (2023) note that uranium mining in Australia is governed by a complex regulatory framework that operates at both the federal and state/territory levels. Proponents of uranium mines are required to undertake rigorous and comprehensive environmental impact assessment processes that incorporate public comments on the proposal, as per the requirements of Australia’s Commonwealth and relevant state or territory

legislative frameworks (OECD, 2025). Aboriginal Land Rights and Native Title laws ensure that Aboriginal peoples' cultural and land concerns are respected in approval processes (OECD, 2025). Mining is a key driver of Western Australia's economy, with the Yilgarn Craton hosting significant uranium concentrations primarily associated with carnotite in calcrete formations (Drummond et al., 2021, Ralph et al., 2020, Ralph et al., 2024). Mining operations in Western Australia face notable radiological challenges, with 19 sites identified where workers were exposed to naturally occurring radioactive materials (Ralph and Cattani, 2021). Average worker radiation doses increased by 32.4 %, reaching 0.94 mSv in 2019–20, a level close to regulatory intervention thresholds (Ralph and Cattani, 2021). While natural uranium concentrations in groundwater are generally below 5 µg/L, elevated levels above the WHO (World Health Organisation) guideline of 30 µg/L were observed in granitic terrains and uranium-rich zones in Australia (Smedley and Kinniburgh, 2022). Groundwater near uranium deposits in Koongarra, exhibits uranium concentrations as high as 440 µg/L (Smedley and Kinniburgh, 2022). The consumption of water contaminated with uranium has been associated with adverse health effects, including kidney damage (Guéguen and Frerejacques, 2022, Horvit and Molony, 2022, Anderson et al., 2025), particularly in Western Australia (Rajapakse et al., 2019). However, it is essential to note that the Australian government supports the development of a sustainable uranium mining industry that adheres to the highest global environmental and safety standards (OECD, 2025).

2.2.2 Chile

Uranium exploration in Chile began in the early 1950s, with the first deposits discovered at Estación Romero in northern Chile (International Atomic Energy Agency, 2020, OECD, 2025). In 1965, Chile established the Chilean Nuclear Energy Commission (CCHEN) to address issues related to atomic energy and radioactive materials (OECD, 2025). The commission was tasked with advising the government on matters related to nuclear energy and overseeing radioactive materials (Gutiérrez, 2014, International Atomic Energy Agency, 2020, OECD, 2025). The distribution of uranium deposits in Chile is shown in Figure 2.2. The symbols and colours represent different uranium deposit categories (e.g., volcanic-hosted, surficial, intrusive, and others), with the legend adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production"(2020).

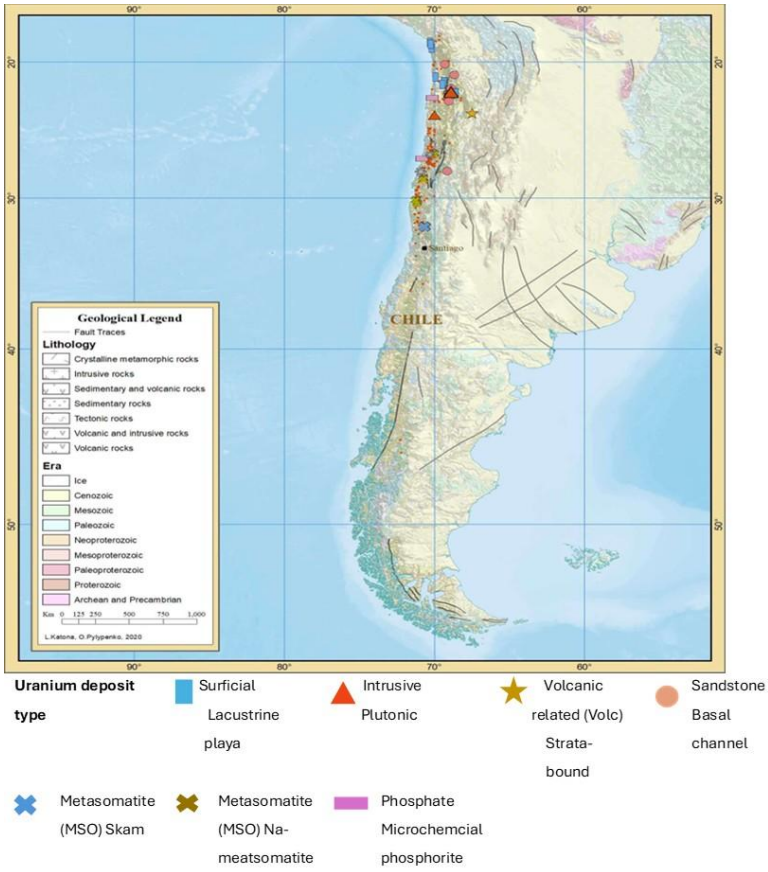


Figure 2-2 Uranium deposits of Chile showing the distribution of major deposit types as defined by the International Atomic Energy Agency (2020)

Chile's uranium resources were estimated at 1448 tonnes of uranium (tU) as of January 2017, comprising 561 tU of reasonably assured resources and 886 tU of inferred resources (International Atomic Energy Agency, 2020). Significant uranium-bearing deposits are hosted within Chile's Paleozoic Coastal Batholith (Collao et al., 2019, OECD, 2025). These deposits include surface uranium resources of 68.8 tU, metasomatic deposits of 1762.8 tU, Cenozoic volcanic deposits of 100 tU, and unconventional deposits totalling 1798 tU (Collao et al., 2019, OECD, 2025).

Although limited literature exists on the effects of uranium on groundwater quality, the Chilean government has made significant strides in enhancing environmental and mining regulatory standards (Ghorbani and Kuan, 2017, OECD, 2025). These efforts include enacting the Environmental Basics Law in 1994 and establishing the Ministry of Environment in 2010 to oversee and enforce environmental policies (Ghorbani and Kuan, 2017). These policies covered the protection of the public, animal health, national protected areas, landfills and residue disposal. Chile has not reported any exploration and development expenditures for uranium since 2016 (OECD, 2025).

2.2.3 Kazakhstan

Kazakhstan accounts for 40 % of global uranium production, solidifying its position as a key player in the international uranium market (Kenzhetaev et al., 2021, Britt and Czarnota, 2024). Kazakhstan has abundant natural resources, including metal ores, natural gas, minerals, and oil reserves (International Atomic Energy Agency, 2020, Kayukov et al., 2020). Despite its resource wealth, the country's vast territory and diverse economic activities result in an uneven and insufficient water supply, posing challenges to sustainable economic development (Alimbaev et al., 2021, Adenova et al., 2023). Mining and metallurgical industries form the backbone of Kazakhstan's economy (Alimbaev et al., 2020). Uranium mining in the country began in the 1940s, with significant deposits identified in nine regions (Kayukov et al., 2020, OECD, 2025). These deposits are primarily found in branching vein networks and in layers of sandstone formations. Figure 2.3 highlights Kazakhstan's significant reserves, which host some of the world's largest in-situ recovery operations. It illustrates the spatial extent and types of uranium deposits as defined by the International Atomic Energy Agency (2020). Symbols and colours indicate different deposit categories, with the legend adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020)

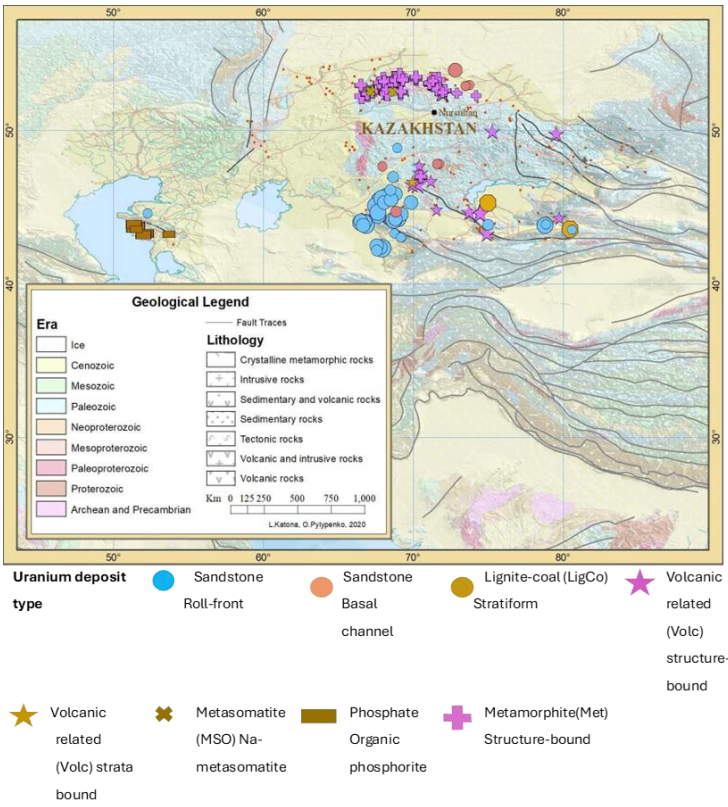


Figure 2-3 Uranium reserve distribution across the uranium provinces of Kazakhstan.

Kazakhstan employs in-situ leaching (ISL) mining techniques at 26 sites operated by 13 uranium mining companies (Kenzhetaev et al., 2021, OECD, 2025). Although ISL is considered cost-effective and environmentally favourable, it releases uranium, thorium, radium, radon, and their decay products into the environment. This process alters groundwater chemistry, resulting in pollution (Zhanbekov et al., 2019, OECD, 2025).

Uranium mining and milling activities in Kazakhstan's northern and southern regions have led to significant environmental pollution, including elevated radioactivity levels in water sources (Kayukov et al., 2020, Subbotin et al., 2024, Aumalikova, 2025, Ibrayeva et al., 2025). The southern region, in particular, faces high pollution levels, with radionuclide concentrations in natural environments and groundwater undergoing considerable changes (Mukhamedzhanov et al., 2019, Beisenova, 2020, Bakhtin et al., 2025, Ibrayeva et al., 2025). Key contributors to groundwater pollution include open-air storage of radioactive waste, uranium ore processing, open-pit mining, and transportation (Kayukov et al., 2020, Aumalikova, 2025, Ibrayeva et al., 2025). Tleuova et al. (2023) recommend intensive monitoring of water supply wells in industrial and uranium mining areas in southern Kazakhstan to mitigate these impacts.

Kazakhstan faces severe environmental challenges, with over 21 billion tons of accumulated waste and an annual increase of 1 billion tons, underscoring the urgent need for long-term waste management programs to support sustainable social and economic development (Alimbaev et al., 2021, Aumalikova, 2025, Ibrayeva et al., 2025). The impacts of uranium mining are particularly concerning, as studies report elevated disease prevalence in villages near active deposits, such as those in Syrdarya province, and radioactivity levels at production sites, surrounding soil, and wastewater that exceed national standards (Zhanbekov et al., 2019, Kayukov et al., 2020). Intensive mining and agricultural practices have further contributed to widespread groundwater pollution, with areas like Mailuu-Suu experiencing exacerbated contamination from naturally occurring radionuclides and trace elements (Liu et al., 2021, Adenova et al., 2023, Egemberdieva and Kamchybekova, 2024, Egemberdieva, 2025, Ibrayeva et al., 2025). Anthropogenic activities have altered natural conditions, resulting in temperature-driven changes in groundwater quality, depletion of available water resources, and a decline in overall water availability (Osipov et al., 2020, Adenova et al., 2023, Adenova et al., 2025). In-situ leaching and other mining practices underscore the urgent need for improved groundwater monitoring and sustainable resource management to mitigate environmental and public health risks.

2.2.4 United States of America (USA)

Uranium is found in various deposits across the USA, as shown in Figure 2.4. The figure presents the major deposit categories as defined by the International Atomic Energy Agency (2020), with symbols and colours representing types such as sandstone-hosted, volcanic, intrusive, and other classifications. The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020). It highlights the concentration of deposits in the western United States, particularly in states such as Wyoming, New Mexico, and Texas, which host significant sandstone-hosted resources.

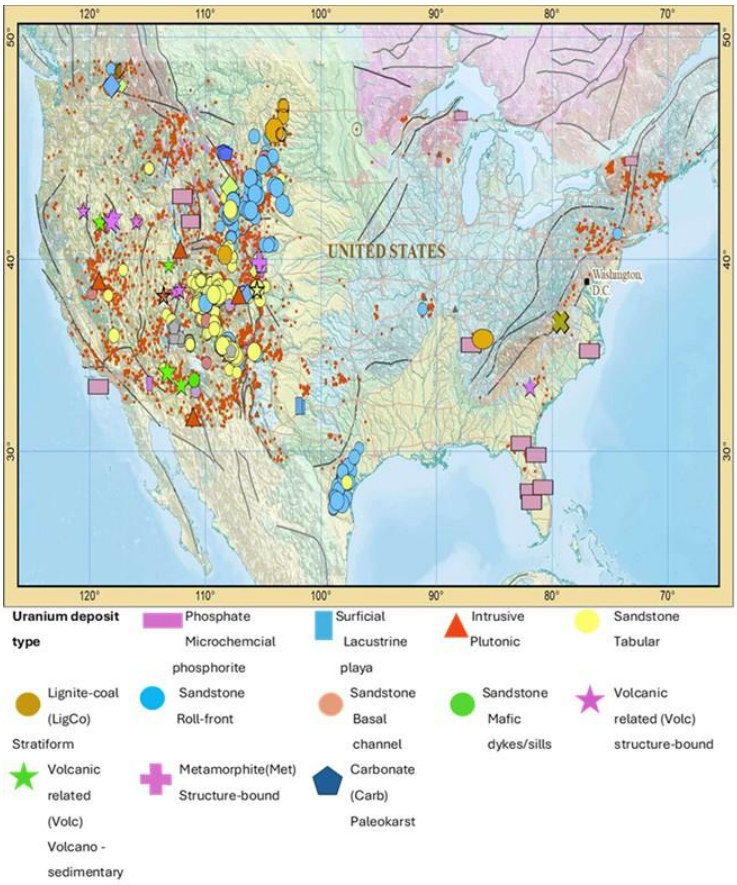


Figure 2-4 Distribution of different uranium deposit types in the United States

Significant sources of uranium pollution stem from mining, milling, tailings disposal, coal combustion, and phosphate fertilisers derived from uranium-rich rocks (Burow et al., 2017, Gardner et al., 2023, Padhi et al., 2023, Fegadel and Lynch, 2024). Major uranium mining areas include the Colorado Plateau, which encompasses regions of New Mexico, Arizona, Colorado, and Utah (Winde et al., 2017). Arizona's Grand Canyon contains some of the highest-grade uranium deposits (0.6 % uranium oxide) in the USA (Bern et al., 2022, Tillman et al., 2021).

Despite over three decades of uranium mining, federal regulations addressing worker health and environmental protection were implemented only recently, leading to illnesses and fatalities among workers and contamination near communities and water sources (Gilles, 2020, Redvers et al., 2021, Winde et al., 2017). In 2012, the federal government imposed a 20-year moratorium on uranium mining near the Grand Canyon, suspending operations until 2032 due to insufficient information on environmental impacts, except where valid mining rights already existed (Tillman et al., 2021, Halbleib, 2023).

The legacy of uranium mining in the USA is significant, with many abandoned uranium mines concentrated in the western states (Hoover et al., 2017, De Pree, 2020, Ingram et al., 2020). Remediation efforts for contaminated sites are estimated to have cost approximately USD 5 billion (Winde et al., 2017, Dinis and Fiúza, 2021). Since 2015, former miners and millers have received compensation amounting to USD 774 million, a financial burden that could have been avoided with earlier regulatory measures (Winde et al., 2017). Groundwater quality has been systematically monitored across the USA since 1991 by the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) program (Burow et al., 2017, Tillman et al., 2021, Belitz et al., 2022, Lindsey et al., 2023). Due to geogenic and anthropogenic activities, uranium concentrations in groundwater exceed 30 µg/L in arid western states, raising human health concerns in these areas (Balaram et al., 2022, Smedley and Kinniburgh, 2022). However, it is noteworthy that even in states without anthropogenic activities, aquifers such as the High Plains and Central Valley, uranium concentrations in groundwater can surpass drinking water standards due to natural geological factors (Ingram et al., 2020, Lopez et al., 2021, Balaram et al., 2022, Mine and Ziegler, 2022, June 20). Due to anthropogenic activities, uranium concentrations in groundwater in the San Joaquin Valley, California, have increased over time, posing significant health risks to local populations (Burow et al., 2017, Tisherman et al., 2023). The health impacts of uranium contamination in the USA include kidney disease and a potential link to congenital disabilities associated with uranium exposure (Vengosh et al., 2022). These findings emphasise the critical need for enhanced monitoring and stricter regulatory frameworks to safeguard public health.

Rural and tribal populations in the USA face disproportionately higher exposure to uranium contamination from abandoned hard-rock mines than other groups (Lin et al., 2020, Redvers et al., 2021, Martinez-Morata et al., 2022, Madrigal et al., 2024). This is primarily due to inadequate infrastructure for water access, which often necessitates the consumption of unregulated water sources. This vulnerability highlights the need for targeted interventions to enhance water access and quality in these underserved communities.

Existing studies' recommendations emphasise the need for increased water quality monitoring nationwide, particularly in areas with elevated uranium levels. Moreover, ensuring access to safe drinking water in rural regions with high uranium concentrations is paramount. Public education campaigns targeting these communities should raise awareness about the health risks associated with consuming unregulated water. Such community engagement initiatives are crucial for mitigating health risks and fostering proactive measures to address uranium contamination.

2.2.5 Africa

Africa contributes significantly to the global uranium market, accounting for approximately 16 % of global production (OECD, 2025). Uranium mining on the continent dates back to the 1920s, reflecting its long-standing role in the industry (Kinnaird and Nex, 2016). The continent hosts a diverse array of uranium deposits, distributed across several countries, including Namibia, Niger, Mali, Malawi, and South Africa (Kinnaird and Nex, 2016, Bezuidenhout, 2021, Sanusi et al., 2022, Wilde, 2023, Mwalongo et al., 2024, OECD, 2025). Notable deposit types include Archaean quartz-conglomerate-hosted gold-uranium deposits in South Africa, Neoproterozoic end-orogeny sheeted leucogranites and small intrusive granitic stocks in Namibia, Mesozoic sandstone-hosted roll-front and calcrete deposits in Niger and Mali, as well as alluvial deposits in Mali (Kinnaird and Nex, 2016, Bezuidenhout, 2021, Frimmel, 2023, Wilde, 2023). Figure 2.5, adapted from Kinnaird and Nex (2016), illustrates the distinction between primary deposits (formed directly from magmatic or hydrothermal processes) and secondary deposits (derived from weathering, sedimentary processes, or reworking).

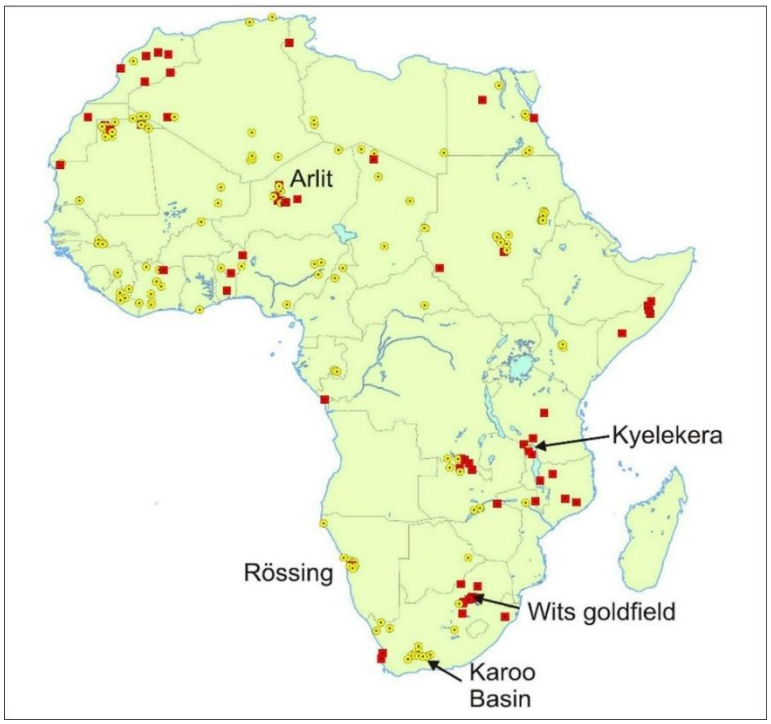


Figure 2-5 Distribution of primary and secondary uranium deposits in Africa

Namibia, Niger, and South Africa are the leading producers of uranium in Africa (International Atomic Energy Agency, 2020, Wilde, 2023, Mwalongo et al., 2024, OECD, 2025). Despite their substantial contributions to the global uranium supply, the continent faces challenges related to water resource management. Over the past three decades, efforts to improve water and sanitation infrastructure have advanced; however, inadequate management of domestic and industrial waste continues to pose significant threats to groundwater quality and availability (Lapworth et al., 2018, Foster et al., 2020, Bruce and Limin, 2021, Omohwovo, 2024).

Niger

Niger is a landlocked country situated between the savannah and desert biomes, characterised by a scorching and arid climate (Sacré Regis M. et al., 2020; Adamou et al., 2021; Almouctar et al., 2024). Uranium was first discovered in Niger in the late 1950s by French surveyors (Volberding and Warner, 2018, Adamson, 2021, LeBlanc, 2022, OECD, 2025). Today, Niger ranks as one of the top global producers of uranium, contributing approximately 5 % of the world's uranium supply (Mamadou et al., 2022, Soumaila, 2023). The country's uranium deposits are primarily found in mid-grade ore within sandstone formations (Winde et al., 2017, International Atomic Energy Agency, 2020, Bohari et al., 2022, Mamadou et al., 2022, OECD, 2025). Figure 2.6 highlights the concentration of deposits in Niger, particularly in the Tim Mersoi Basin. The Tim Mersoï uranium province holds one of the

world's largest reserves of U, the Djado and Emi Lulu basins, located in the Palaeozoic formation, exhibit significant uranium potential (Mamadou et al., 2022, OECD, 2025).

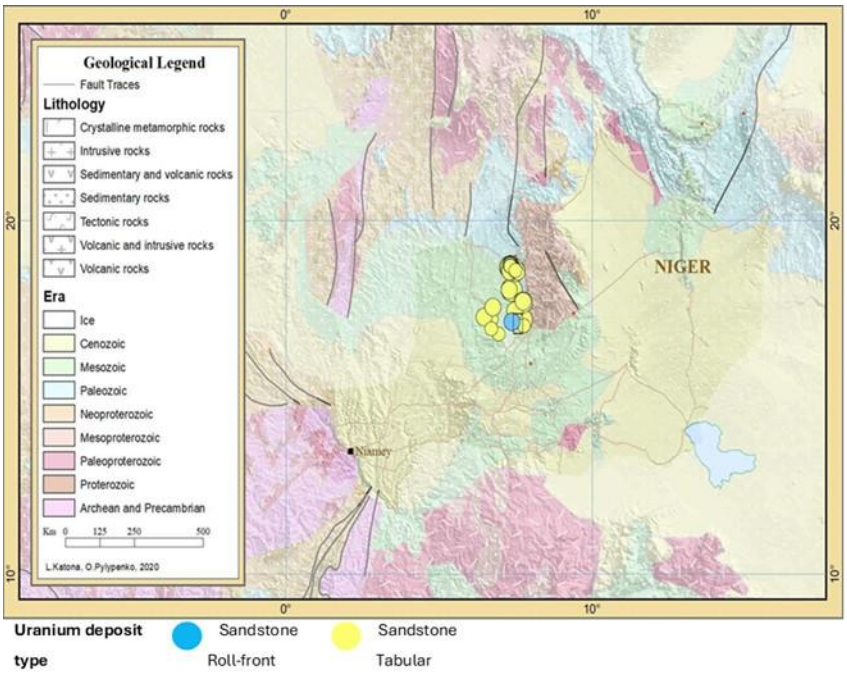


Figure 2-6 Uranium deposits in Niger showing the distribution of major deposit types as defined by teh International Atomic Energy Agency (2020)

Since 2011, several foreign companies have halted exploration activities in Niger due to geopolitical tensions (International Atomic Energy Agency, 2020). As reported by the OECD (2025), Orano's mining operations prioritise environmental protection, maintaining ISO 14001 certification and reducing water use by 35 % through the AMAN project despite increased production. The company supports local communities with free healthcare facilities, housing, education, and agricultural initiatives. Sustainability efforts include building an 8 MW solar power plant and advancing remediation plans for Cominak's closure to ensure safety, social support, and sustainable land use (OECD, 2025). At Dasa, environmental assessments indicate limited impact on nearby populations and livelihoods. However, despite being one of the largest producers of uranium globally, the country has a notable lack of studies on the impact of uranium mining on groundwater quality.

South Africa

As shown in Figure 2.7, South Africa hosts significant uranium deposits, primarily in the Karoo Uranium Province, the Witwatersrand Basin, the Springbok Flats Basin, Intrusives, and Namaqualand surficial uranium deposits (Makubalo et al., 2020, Pretorius et al., 2020, Raji et al., 2021, Moshupya et al., 2022). The figure shows the distribution of uranium deposit types as defined by the International Atomic Energy Agency (2020), with symbols and colours representing different categories. The legend is adapted from the IAEA's "World Uranium Geology, Exploration, Resources and Production" (2020).

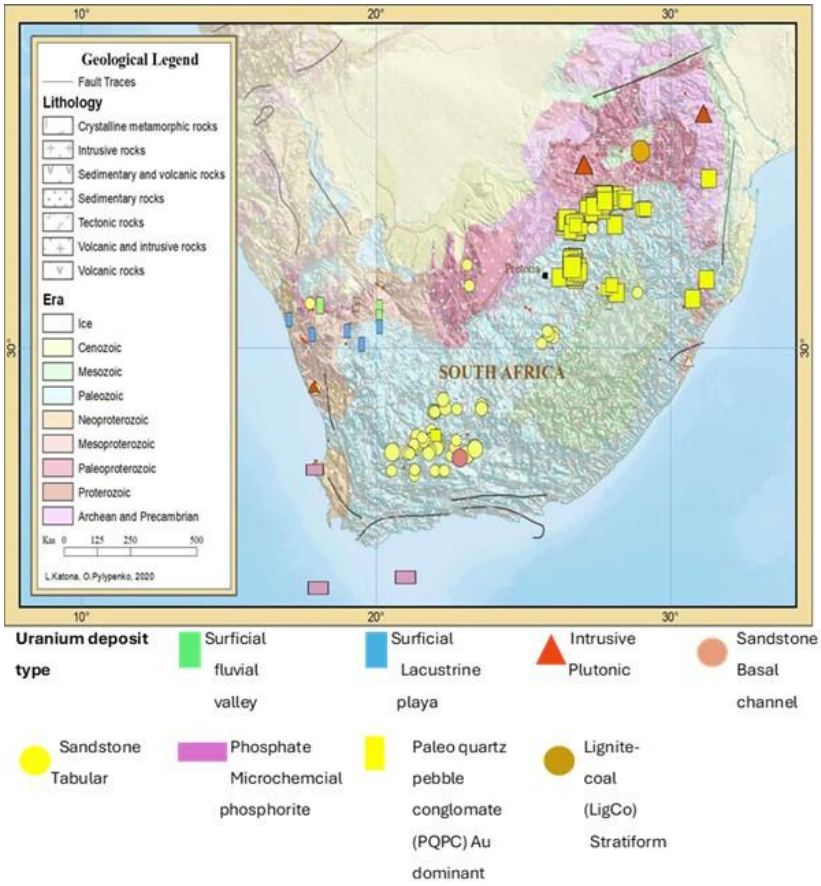


Figure 2-7 Major uranium deposits in South Africa.

The Northern Cape Province in South Africa is an arid region where groundwater is the sole drinking water source, like most arid regions in the world (Lalumbe and Kanyerere, 2022, Abdessamed et al., 2023). Uranium mining in the province has caused elevated levels of uranium in the groundwater, averaging 0.155 mg/L, which is 5 times higher than the drinking water quality guideline (Makubalo and Diamond, 2020). Uranium bioaccumulates in plants, particularly grasses, thereby posing a risk to livestock and potentially leading to significant human exposure through the consumption of

mutton and sheep organs, which serve as dietary staples (Lalumbe and Kanyerere, 2022, Cui et al., 2023, Duhan et al., 2023).

Groundwater in Namaqualand, located within the Northern Cape Province, undergoes complex geochemical processes such as parent rock weathering, which result in unique groundwater chemistry (Adadzi, 2020, Makubalo and Diamond, 2020, van Gend et al., 2021). When compared to South Africa's drinking water quality standards, data from Namaqualand showed that 41 % of samples exceeded the gross alpha standard derived from uranium isotopes (Abiye and Shaduka, 2017)(Gross Alpha Activity (pCi/L)=Uranium Concentration (µg/L)× 0.67) (Scott et al., 2023). In their study, Smedley and Kinniburgh (2022) reported uranium concentrations in Namaqualand groundwater ranging from 1.3 to 5100 µg/L due to evaporation and secondary uranium mineralisation. Hence, they recommended that groundwater be treated before consumption, as uranium levels exceeded the acceptable water quality standards. Mining companies in South Africa are required to use resources responsibly, rehabilitate exploration sites, and comply with environmental management plans through regular inspections (OECD, 2025). Companies must also engage with affected communities during the application process for mining rights and implement Social and Labour Plans.

Namibia

Uranium was first discovered in Namibia in 1928 near the Rossing deposit (World Nuclear Association, 2023, Namibia Uranium Association, 2024, OECD, 2025). The Rossing mine, the country's first operational uranium mine, began production in 1976 under Rio Tinto. Namibia is now the third-largest global supplier of uranium (Namibia Uranium Association, 2024, OECD, 2025). Figure 2.8 shows the different types of uranium deposits in the country. Currently, only Rossing, Langer Heinrich, and Husab are operational, while the Trekkopje mine remains under care and maintenance, alongside six ongoing exploration projects (Namibia Uranium Association, 2024).

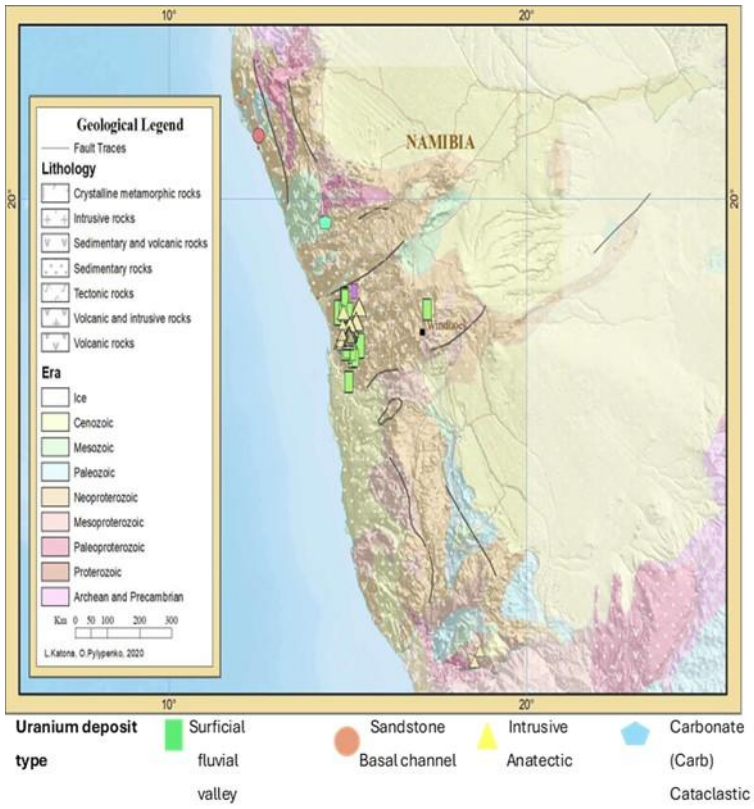


Figure 2-8 Uranium deposits in Namibia, illustrating the distribution of major deposit types as defined by the International Atomic Energy Agency (2020).

In 2023, Namibia produced 8283 tonnes of uranium, marking a 24.5 % increase from the previous year (Namibia Chamber of Mines, 2024). However, the region's location in the Namib Desert presents challenges due to limited groundwater resources and vulnerable aquifers (Hamutoko et al., 2014, Lohe et al., 2021, Atlas of Namibia Team, 2022). Namibia has low-grade uranium ore, ranging from 80 to 540 ppm U3O8, and the country hosts both primary and secondary deposits (Wilde, 2023, Namibia Uranium Association, 2024, OECD, 2025).

The uranium mines in Namibia have made significant efforts to monitor groundwater quality in their surrounding areas, as reported in their annual reports and supported by the Air and Water Quality working group of the Uranium Association of Namibia (Namibia Uranium Association, 2024). Uranium mining operations, in collaboration with the line Ministries, maintain active monitoring of key environmental concerns (Musiyarira et al., 2017, Namibia Uranium Association, 2024, OECD, 2025). Emphasis is placed on adopting best practices and exchanging experiences through participatory approaches to environmental planning and management, alongside the promotion of effective waste management strategies (OECD, 2025). However, in the uranium province, Kringel et al. (2010) reported uranium concentrations in groundwater ranging from 2 µg/L to 528 µg/L near the Rossing uranium mine, Langer Heinrich mine, and Swakop River valley levels that exceed the WHO guideline value of 30 µg/L and thus raise health concerns (World Health Organization, 2022). Unable to confirm whether the elevated levels were due to pollution, they recommended further studies to determine whether the high uranium concentrations stemmed from contamination or natural sources. Similarly, Hamutoko et al. (2014) concluded that the groundwater in the Khan and Swakop rivers (located in the uranium province) was unfit for human consumption based on its hydrochemistry, uranium levels, and radionuclide content due to natural dispersion rather than anthropogenic activities. They recommended further analysis of other aquifers in the uranium province to assess their suitability for water supply. Mathuthu et al. (2021) indicate that the average values of absorbed dose rate (D= 118.11 nGyh−1) and annual effective dose equivalent for ingestion (Hin= 1.26 mSvy−1) in groundwater samples exceeded the thresholds recommended by UNSCEAR, pointing to a potential radiological hazard. Their isotopic ratio analysis further suggests that the uranium present in the groundwater is primarily associated with mine seepage contamination rather than natural geological sources. These results emphasise that seepage water constitutes a significant radiological risk to both human health and the environment due to the elevated hazard parameters identified.

In Namibia, most rivers are ephemeral or seasonal, characterised by infrequent yet often intense flow. These seasonal floods can influence uranium concentrations in alluvial aquifers through the mobilisation of contaminants and dilution (Balaram et al., 2022, Geris et al., 2022, Smedley and Kinniburgh, 2022). This can dilute the concentration of uranium in groundwater, but it can also transport contaminants into groundwater. These rivers' alluvial aquifers and sand beds represent vital water sources for local communities, particularly subsistence farmers, highlighting the importance of understanding surface-groundwater interactions in assessing water quality and contamination risks. In a study by Abiye and Shaduka (2017), the main findings reported indicate that uranium contamination in the Gawib shallow aquifer system is a direct result of seepage from unlined

uranium tailings. The high permeability of the alluvial aquifer facilitates the movement of groundwater in this arid region, thereby enhancing the spread of contamination. Their study further highlights the risk of uranium migration into the deeper aquifer system and downstream into the Swakop River, with the potential to extend as far as the Atlantic Ocean through seasonal flash flood events.

2.3 Remediation

Numerous polluted sites worldwide have been identified as requiring uranium remediation (Dinis and Fiúza, 2021, Akash et al., 2022, Arfasa et al., 2022, Balaram et al., 2022). Examples include Kazakhstan, due to in-situ mining in the northern and southern regions (Zhanbekov et al., 2019, Kayukov et al., 2020, Subbotin et al., 2024, OECD, 2025); the United States, particularly in California's San Joaquin Valley (Gardner et al., 2023, Padhi et al., 2023); South Africa, notably in the Northern Cape (Makubalo and Diamond, 2020; Smedley and Kinniburgh, 2022); and Namibia, around the unlined tailings dams of uranium mines (Abiye and Shaduka, 2017, Mathuthu et al., 2021). Without proper closure plans or rehabilitation projects, mining sites continue to be significant sources of environmental pollution, with groundwater contamination being a primary concern.

Regulators utilise various technologies to control contamination, with remediation enhancing uranium recovery from groundwater while supporting environmental protection and resource efficiency (Dinis and Fiúza, 2021, Balaram et al., 2022, Gandhi et al., 2022). Groundwater remediation requires dynamic, adaptive approaches due to continuously changing subsurface conditions and site-specific complexities (Naseri-Rad et al., 2022, Warner et al., 2023). These methods can be broadly classified into three categories: chemical, physical, and biological remediation (Motlagh et al., 2020; Dinis and Fiúza, 2021).

2.3.1 Chemical remediation

Ion exchange technology has effectively reduced radionuclide levels in water (Dinis and Fiúza, 2021, Ighalo et al., 2024). This method is relatively simple to develop and operate, is cost-effective and has a long lifespan (Alexandratos, 2021, Gandhi et al., 2022, Zhang et al., 2023, Zimmermann et al., 2025). As illustrated in Figure 2.9, contaminated water is filtered and passed through an ion exchange resin, where ion exchange processes remove the contaminants (Barman et al., 2023, Gandhi et al., 2022b; Ighalo et al., 2024).

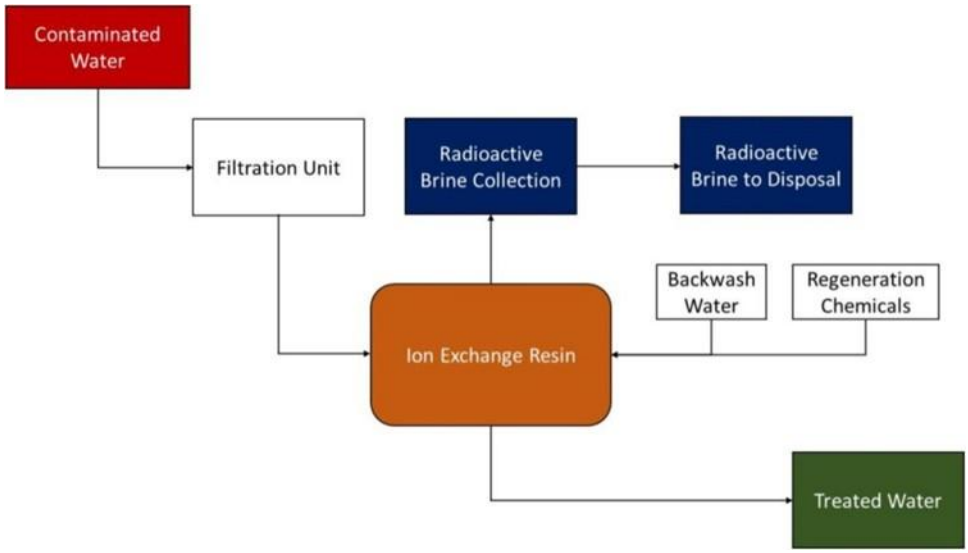


Figure 2-9 Schematic representation of the ion exchange process in uranium recovery, adapted from Dinis and Fiúza (2021).

Ion exchange resins with high exchange capacity are widely used for removing contaminants like uranium, particularly in countries such as South Africa and Australia (Ighalo et al., 2024). However, the concentrated wastewater produced by this process must be treated, stored, or disposed of properly to prevent further pollution (Liu et al., 2021, Banayan Esfahani et al., 2023, Hamza et al., 2024). A significant limitation of ion exchange is its high sensitivity to pH levels, which affects uranium concentration polarisation and speciation (Quinn et al., 2020, Gopalakrishnan et al., 2024, Ighalo et al., 2024). Additionally, the presence of certain cations, due to their hydration radius and high mobility, can reduce uranium removal efficiency (Chen et al., 2022, Gandhi et al., 2022, Hao et al., 2025).

Permeable reactive barrier (PRB)

Permeable reactive barriers (PRB) are an in-situ remediation technique that can be used independently or in combination with other remediation methods (Torres and Gómez, 2020, Akhtar et al., 2021, Singh et al., 2023). This process is passive, sustainable, and remarkably effective for remediating migrating groundwater plumes, as illustrated in Figure 210 (Torres and Gómez, 2020, Budania and Dangayach, 2023, Sakr et al., 2023, Singh et al., 2023). A barrier containing reactive materials facilitates geochemical reactions that remove pollutants from groundwater (Torres and Gómez, 2020, Li and Liu, 2022, Sakr et al., 2023, Meky et al., 2025). The reactive materials employed in this process include activated carbon (AC), zeolites and zero-valent iron (ZVI), which are the most widely used (Bilardi et al., 2023, Singh et al., 2023, Wu et al., 2024).

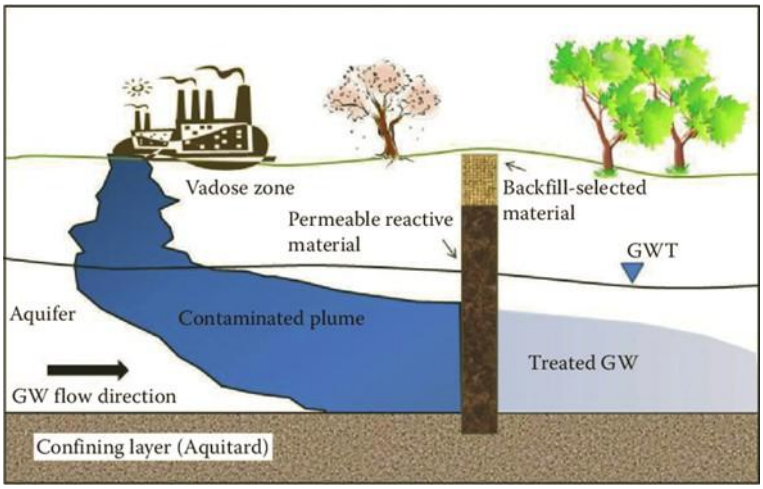


Figure 2-10: Schematic representation of the permeable reactive barrier (PRB) process for groundwater remediation, adapted from Naidu and Birke (2015)

However, the successful implementation of PRBs requires careful site selection, with numerical models typically employed to determine groundwater flow patterns and volumes before a barrier is installed (Guo et al., 2024, Wang et al., 2024, Jiang et al., 2025). Under ideal conditions, PRBs can remain effective for decades, providing a reliable means of removing radionuclide isotopes from groundwater over an extended period (Kwak et al., 2024, Meky et al., 2025, Sakr et al., 2023, Sánchez Hidalgo et al., 2025). Less expensive reactive media can be utilised to reduce costs, and the technology is continuously evolving, with ongoing research into new reactive materials and alternative construction methods (Dayanthi et al., 2024, Ren et al., 2024, Sánchez Hidalgo et al., 2025)

2.3.2 Physical remediation

Membrane filtration

Membrane filtration technologies, such as nanofiltration, ultrafiltration, and reverse osmosis, are capable of separating uranium from water (Dinis and Fiúza, 2021, Gandhi et al., 2022, Ighalo et al., 2024). Ultrafiltration employs low-pressure membranes that are energy-efficient; it is less effective at separating low molecular weight species or dissolved salts (Urošević and Trivunac, 2020, Joshi et al., 2022, Giacobbo et al., 2023). Reverse osmosis, although chemical-free and environmentally friendly, requires high energy input and is constrained by slow water production rates and the need for pre-filtration (Shalaby et al., 2022, Abushawish et al., 2023, Harby et al., 2024, Ighalo et al., 2024). Nanofiltration, though effective in removing heavy metals and salts, requires high-energy membranes and has a relatively short lifespan (Covaliu-Mierlă et al., 2023, Nompumelelo et al., 2023, Mahmoud and Mostafa, 2023, Ighalo et al., 2024).

However, challenges such as membrane fouling, scaling, high energy demand, and material degradation continue to drive research focused on sustainable materials and optimisation strategies for membrane filtration (Chen et al., 2022, Akinyemi et al., 2023, Ilyas and Vankelecom, 2023, Osman et al., 2024). Despite these limitations, membrane filtration is gaining attention as a uranium remediation process due to its high efficiency, low cost, and compact space requirements (Chen et al., 2022, Gandhi et al., 2022, Ilyas and Vankelecom, 2023, Ighalo et al., 2024).

Adsorption

Adsorption is recognised as one of the most effective approaches for removing uranium from water because of its high efficiency, simplicity, and cost-effectiveness (Jun et al., 2021, Gandhi et al., 2022, Verma and Kim, 2022, Ighalo et al., 2024, Liu et al., 2025). In an adsorption process, extraction rates of 70–90 % for uranium were achieved using TiO2 microsphere-infused alginate beads (Bhoria et al., 2021, Ighalo et al., 2024). A wide range of adsorbents has been explored, including clay minerals, metal oxides, layered double hydroxides (LDHs), graphene oxides (GOs), and metal–organic frameworks (MOFs) (Mohapi et al., 2020, Bhoria et al., 2021, Akhtar et al., 2024). Nonetheless, significant challenges persist in scaling these technologies for large-scale applications, necessitating ongoing research aimed at enhancing adsorbent performance and advancing sustainable, cost-effective solutions (Raji et al., 2023, Satyam and Patra, 2024).

2.3.3 Biological remediation

Bioremediation

Bioremediation methods, such as bioleaching, bioreduction, and biosorption, are employed to remove uranium from polluted environments (You et al., 2021, Akash et al., 2022, Ighalo et al., 2024). This technology utilizes microorganisms to degrade pollutants into harmless components, making it one of the most environmentally friendly remediation techniques (Motlagh et al., 2020, Mukherjee et al., 2021, Gandhi et al., 2022; Muttaleb and Ali, 2022; Kuppan et al., 2024). It is typically used in situ to treat groundwater contamination, with natural bioremediation relying on both aerobic and anaerobic bacteria (Rossi et al., 2021, Madison et al., 2023, Skinner et al., 2024). Bioremediation faces significant limitations, including biological specificity, environmental variability, site heterogeneity, scalability challenges, and regulatory hurdles (Patel et al., 2022, Kuppan et al., 2024b; Mahanayak, 2024). When enzymes are employed, additional constraints arise from their low stability under variable pH and temperature conditions, challenges in separating them from the reaction medium, and limited reusability (Somu et al., 2022, Ekeoma et al., 2023).

Phytoremediation

Phytoremediation is another effective method, particularly suited for treating low concentrations of pollutants.

In this process, plants and microbes remove environmental pollutants by accumulating them in the plant's root systems, as depicted in Figure 2.11 (Dinis and Fiúza, 2021, Mitra et al., 2021, Raklami et al., 2022, Khatoon et al., 2024). This method is ideal for the remediation of tailings material (Acosta-Núñez et al., 2025). However, selecting the appropriate plant species for phytoremediation can be challenging due to various factors involved in uranium remediation (Gandhi et al., 2022, Huang et al., 2022, Kafle et al., 2022, Amabogha et al., 2023). Additionally, this process has limitations, as the contaminant must be located near the surface and within the reach of the plant roots (Kafle et al., 2022, Khan et al., 2023; J. Wang and Aghajani Delavar, 2023).

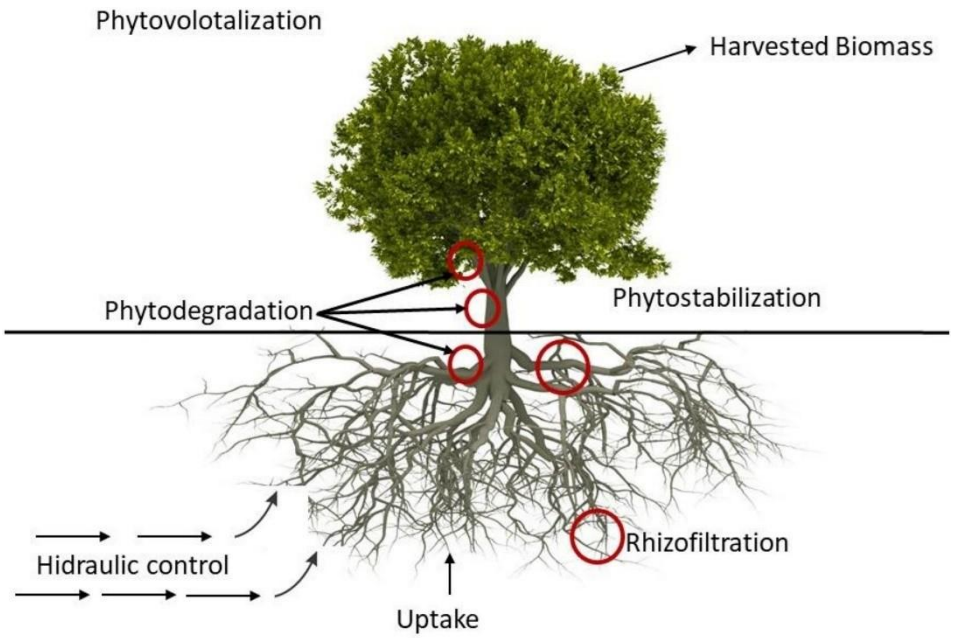


Figure 2-11 Schematic representation of the phytoremediation process for uranium-contaminated soils and water adapted from Dinis and Fiúza (2021).

Significant experience has been gained in remediation technologies; however, these technologies are costly when applied to large-scale contaminated sites. While well-developed technologies for groundwater contaminated with radionuclides exist, many challenges remain to be addressed. Uranium pollution remediation is receiving increasing global attention, and the development of processes and procedures within the nuclear industry could serve as a model for broader applications. A key challenge across all technologies is the safe disposal of the liquid and solid waste produced after

treatment. Membrane filtration and ion exchange are among the most efficient techniques for uranium removal compared to other remediation methods. Various modelling tools are available to simulate the behaviour of uranium and other contaminants in groundwater systems. Commonly used groundwater simulation programs, including MODFLOW, MT3DMS, RT3D, FEFLOW, and MODPATH, allow for accurate contaminant transport modelling when model objectives are clearly defined and flow processes are thoroughly characterised (Chowdhury and Rahnuma, 2023, Kumar and Gour, 2021). For radiological risk assessment at uranium-impacted sites, tools such as AMBER, GoldSim, NORM, Legacy Site Assessment, PRG-dose calculator, and RESRAD-OFFSITE have been employed (Bello et al., 2022, Branko et al., 2022, Pepin et al., 2022). Comparative studies between these models emphasise the need to select context-specific tools and, where appropriate, integrate multiple modelling approaches to support effective remediation planning (Kumar and Gour, 2021).

2.4 DISCUSSION

Groundwater contamination from uranium mining in arid regions is a challenge of both local and global relevance, and the present findings contribute to bridging this knowledge gap. The United States, for example, possesses extensive records, while many other regions remain underrepresented. This imbalance highlights the need for broader global assessments of uranium contamination in arid regions.

Country experiences reflect this uneven knowledge base. In Australia, integrated and interdisciplinary approaches are needed to evaluate the spatial and socio-environmental impacts of uranium mining. Chile has strengthened regulatory frameworks, but groundwater quality near mines remains underexplored. Kazakhstan, facing acute water scarcity, must adopt stronger policies to balance resource use with aquifer protection. In the United States, despite extensive datasets, continued baseline monitoring is crucial for tracking changes during and after mining operations. In Africa, limited monitoring of uranium exposure has allowed long-term environmental and health risks to persist, resulting in significant financial burdens for remediation. Evidence from Niger shows mining consumes significant groundwater reserves, while studies in South Africa call for robust epidemiological assessments and institutional mechanisms for risk reduction. Namibia has advanced groundwater monitoring through industry-led initiatives, but the absence of peer-reviewed publications restricts scientific validation and broader application.

Sustainable uranium mining depends on effective tailings and water management supported by collaborative research and technological innovation. Overreliance on single remediation methods should be avoided in favour of integrated, cost-effective strategies. Comprehensive water quality

monitoring, geological and hydrochemical investigations, and the development of modelling-based tools are critical for understanding uranium transport processes and improving groundwater resource management.

2.5 CONCLUSION

The findings of this study highlight the persistent environmental and health risks associated with uranium mining and reveal critical gaps in global groundwater monitoring, particularly in underrepresented regions such as Africa, South America, and Central Asia. By synthesising previous studies, this work provides new insights into the uneven distribution of uranium contamination knowledge and highlights regions where scientific evidence is urgently needed.

The study demonstrates that sustainable uranium mining requires an integrated, multidisciplinary approach that combines hydrochemical, geological, and epidemiological assessments to evaluate contamination risks and guide effective mitigation strategies accurately. Practical implications include the need for cost-effective and complementary remediation technologies, advanced modelling tools to predict contaminant transport, and strengthened regulatory frameworks to safeguard both water resources and public health. Importantly, this research emphasises the value of international collaboration among scientists, policymakers, and industry stakeholders to establish robust monitoring networks and implement adaptive management strategies. By addressing data gaps and promoting evidence-based interventions, the findings provide a roadmap for mitigating the long-term impacts of uranium mining on groundwater resources, supporting both local community safety and broader environmental sustainability.

Future studies should expand peer-reviewed datasets in underrepresented regions, refine monitoring frameworks, develop innovative remediation technologies, and evaluate long-term water management effectiveness. By addressing data gaps and promoting evidence-based interventions, these efforts provide a roadmap for mitigating uranium mining impacts on groundwater, safeguarding both local communities and environmental sustainability.

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CHAPTER 3: SPATIO-TEMPORAL VARIATIONS OF GROUNDWATER QUALITY AROUND URANIUM MINE TAILINGS: A CASE STUDY FROM THE URANIUM PROVINCE OF NAMIBIA

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Abstract

Groundwater in uranium mining regions is highly susceptible to both chemical and radiological contamination, yet spatio-temporal variations remain poorly documented in Namibia. This study presents a comparative analysis of the oldest and newest uranium mines, using long-term monitoring data from 1982-2025 for the older mine and 2016-2025 for the newer mine. The tailings storage facility (TSF) of the oldest mine is unlined, whereas the TSF of the newer mine incorporates a modern lining system. Sixteen strategically positioned boreholes (eight per site) were analysed for pH, electrical conductivity (EC), total dissolved solids (TDS), major ions, nitrate, uranium, and radium-226.

Statistical methods applied include the Mann-Kendall trend test, Sen's slope estimator, and the Mann-Whitney U test. Descriptive and spatial analyses were used to identify patterns and assess variability. The results indicate that groundwater in the oldest mine exhibited severe and spatially heterogeneous degradation, with elevated salinity (mean TDS: 20,897 mg/L), chloride (mean: 8,685 mg/L), and radium-226 concentrations (up to 721.9 mBq/L). Long-term trends revealed decreasing EC, sodium,

sulphate, and nitrate levels, whereas TDS and radium-226 continued to increase, signifying persistent legacy contamination. Piper diagram analysis over three decades (1990s, 2000s, and 2010s) shows that groundwater at the oldest mine remains predominantly Ca-Mg-Cl in type, with only minor increases in sulphate and sodium, indicating a limited but measurable influence from mining activities.

In contrast, groundwater from the newest mine displayed more uniform geochemical characteristics, though statistically significant upward trends were detected for EC, TDS, nitrate, calcium, and potassium, indicating early geochemical alteration within a decade of operation. At both sites, uranium and radium-226 concentrations frequently exceeded World Health Organisation drinking water guidelines. These findings demonstrate that legacy contamination from unlined TSFs can persist for decades, whereas lined modern systems, though more protective, are not immune to early-stage deterioration. Continuous, integrated hydrogeochemical and radiological monitoring is essential for early detection of contamination trends and for informing effective groundwater protection strategies. Proactive management at newer operations is therefore critical to prevent the long-term degradation observed at legacy sites and to contribute to achieving Sustainable Development Goal 6 (Clean Water and Sanitation) in mining-affected arid regions.

Keywords: spatio-temporal variations, uranium mining, groundwater pollution, hydrogeochemistry, radionuclides

3.1 Introduction

Groundwater is fundamental to global water security, yet its sustainable management remains a serious challenge, particularly in mining regions across Africa (Artwell Kanda et al., 2021; Alexander & Ndambuki, 2023; Ahmad Zainuri et al., 2024). Addressing this challenge requires a comprehensive understanding of groundwater systems, robust long-term monitoring networks, and the effective integration of groundwater governance into broader water resource management frameworks (Karunanidhi et al., 2022; Misstear et al., 2023; Mseli et al., 2024; Mustaq Shaikh & Farjana Birajdar, 2024). Groundwater in uranium mining regions worldwide is highly susceptible to both chemical and radiological contamination (Cho et al., 2019; Manoj et al., 2019; Ibrayeva et al., 2025). This susceptibility fluctuates both temporally and spatially and depends on the contaminant load as mining operations progress.

Across Africa, groundwater supports urban and rural livelihoods, agricultural productivity, and economic development (Lapworth et al., 2018; Chávez García Silva et al., 2020; Foster et al., 2020; De Bont & Börjeson, 2024). Despite its critical importance, groundwater resources in sub-Saharan Africa remain poorly characterised and inadequately managed due to limited monitoring networks, scarce data, and growing contamination risks (Twinomucunguzi et al., 2020; Danert & Healy, 2021; Kombo et al., 2023). Sustained monitoring of groundwater quality is therefore vital not only to ensure sustainable utilisation but also to safeguard public health (Karunanidhi et al., 2022; Lapworth et al., 2023; Alam et al., 2024). Regular and systematic assessments facilitate the detection of temporal and spatial variations in water chemistry, the identification of emerging contaminants, and the evaluation of long-term health risks, even in areas where groundwater has traditionally been considered safe (Gejl et al., 2019; Singh et al., 2021; Li et al., 2022; Huang et al., 2024; Okolo et al., 2025).

In Namibia's Erongo Region (Figure 3-2), surficial uranium deposits hosted within Cenozoic paleochannels represent significant low-grade uranium resources (Chudasama et al., 2019; Wilde, 2023; Mwalongo et al., 2024).

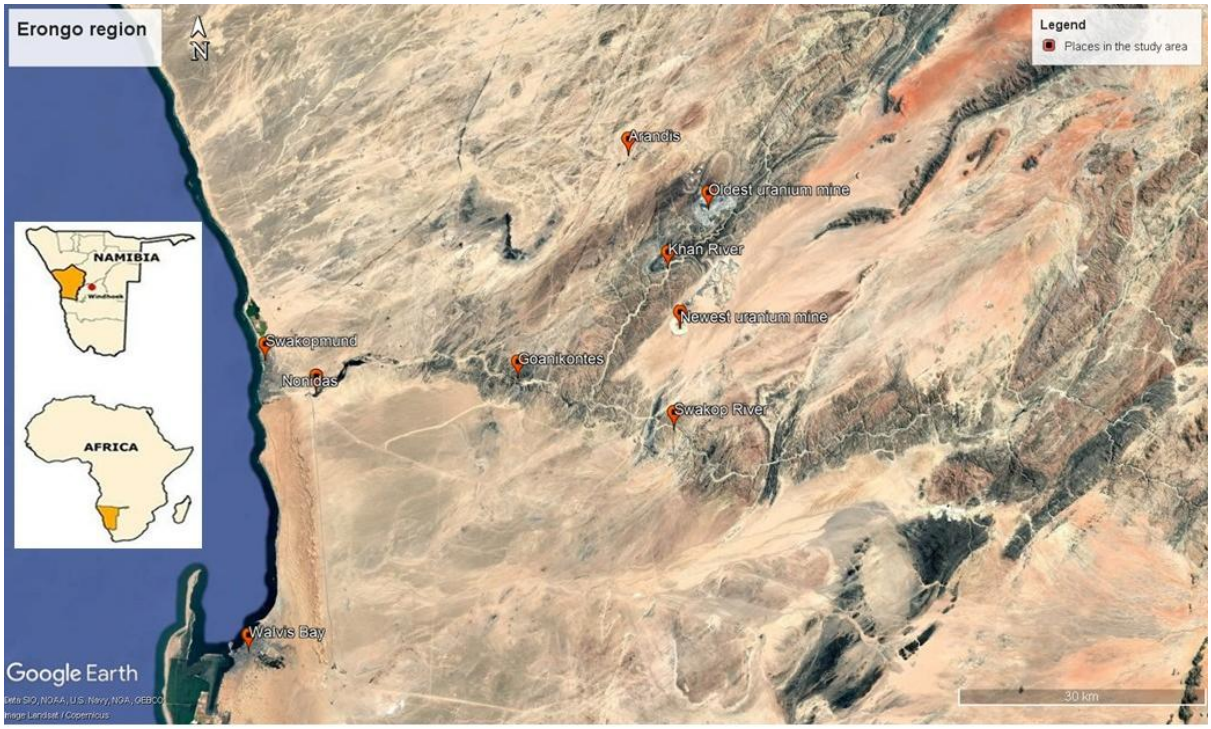


Figure 3-1 The study area in the Erongo region of Namibia.

These deposits, formed through carbonate cementation and evolving groundwater geochemistry, are strongly influenced by groundwater flow interacting with uranium-enriched source rocks (Jia et al., 2020; Wilde, 2023; Cho et al., 2024). Uranium mining in this region (Figures 3-1 and 3-2) has generated significant hydrogeological impacts, particularly concerning groundwater quality (Hamutoko et al., 2014; Abiye & Shaduka, 2017; Mathuthu et al., 2025). Elevated concentrations of uranium and other radionuclides have been detected in groundwater, raising concerns about contamination risks to agriculture and local communities (Hamutoko et al., 2014; Abiye & Shaduka, 2017; Musiyarira et al., 2017; Mathuthu et al., 2021). In areas downstream of the uranium mines, particularly at Goanikontes and Nonidas (Figure 3-1), groundwater is at high risk of contamination, threatening olive cultivation. Airborne dust from tailings storage facilities (TSFs) also poses a substantial health risk to nearby populations, especially in Arandis (Gomo et al., 2022; Salgado-Almeida et al., 2024; Shi et al., 2023; Su et al., 2024). These long-term impacts are compounded by Namibia's fragmented and insufficient legal framework for mine rehabilitation, which hampers effective environmental protection (Musiyarira et al., 2017; Salom & Kivinen, 2020; Kadir Jaelani et al., 2022).

Although prior studies have highlighted the environmental and health risks posed by uranium mining (Abiye & Shaduka, 2017; Mathuthu et al., 2021; Wilde, 2023), few have examined the spatial and temporal variability of groundwater quality near uranium mine tailings. Understanding these

variations is critical for evaluating cumulative exposure risks and developing informed groundwater management strategies, including real-time monitoring and predictive modelling. This study addresses this gap by investigating the spatiotemporal dynamics of groundwater quality around one of Namibia's oldest and newest uranium mines. The findings provide key insights for sustainable groundwater management in mining-impacted environments, directly supporting the objectives of Sustainable Development Goal 6 (Clean Water and Sanitation).

3.2 Methods

This study was conducted in compliance with Namibia's national water regulations, with field activities supervised by the Ministry of Agriculture, Fisheries, Water, and Land Reform (MAFWLR) the designated custodian of national water resources. All ethical and regulatory requirements were adhered to, in accordance with the Water Act No. 54 of 1956 and the Water Resources Management Act No. 11 of 2013.

Groundwater data were obtained from multiple sources. Historical datasets were provided by the mining companies, covering 1982-2023 for the oldest mine and 2016-2023 for the newest mine. These records facilitated a long-term assessment of groundwater quality trends at the older mine across four decades (1982-2025). In contrast, the newer mine dataset encompassed a shorter period of nine years (2016-2025). Consequently, temporal trend analysis was applied only to the oldest mine, while cross-site comparative analyses were used to evaluate dispersion patterns and spatial differences in contamination. This approach allowed for the assessment of both legacy impacts at the older site and emerging hydrogeochemical effects at the newer operation.

3.2.1 Study Area

The study area is situated in the central Erongo Region of Namibia, within the Uranium Province (Figure 3-1 and 3-2). This hyper-arid region, with an aridity index of less than 0.02, receives very low annual rainfall, typically below 50 mm while experiencing high average annual evapotranspiration rates of 2 200-2 500 mm. These high evapotranspiration rates result in a persistent negative water balance (Lohe et al., 2021; Atlas of Namibia Team, 2022; Coetzee, 2023). Temperatures remain elevated throughout the year, with average maximum values ranging from 25°C to 40°C (Lohe et al., 2021; Atlas of Namibia Team, 2022; Shiweda et al., 2023). In this water-scarce environment, groundwater is the principal source of water for communities, mining operations, and ecological systems, given the near absence of perennial surface water resources (Hamutoko et al., 2014; Lohe et al., 2021; Mathuthu et al., 2021).

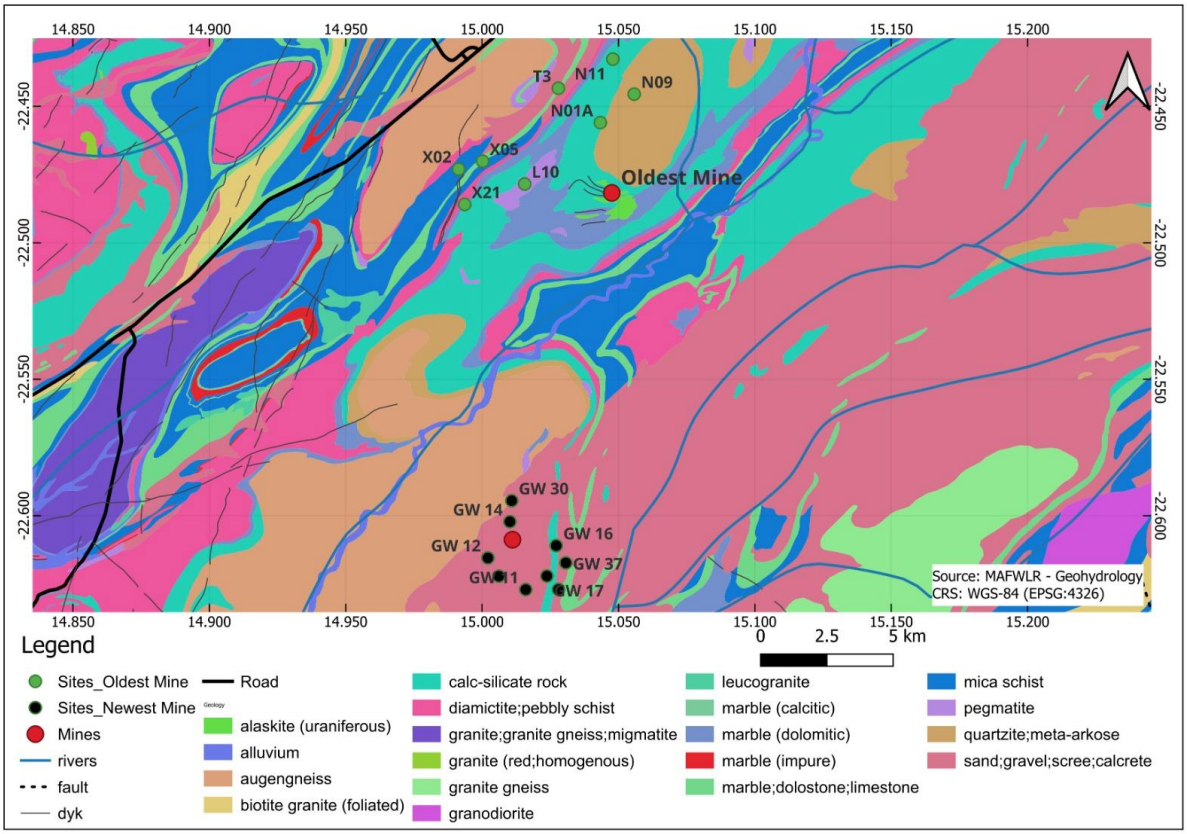


Figure 3-2 The local geology in the study area (Uranium Province of Namibia) situated in the Erongo region (QGIS version 3.40.10 2025)

The geological framework of the study area is dominated by Damaran granitic intrusives and metasedimentary units, which are closely associated with uranium mineralisation in the region (Chudasama et al., 2019; J. Chen et al., 2021; Wilde, 2023). The primary uranium sources are alaskite bodies linked to granitic intrusives of the Damara Belt to the east, while younger deposits are associated with post-Cretaceous tectonic uplift (Figure 3-2). Subsequent weathering and leaching processes facilitated the mobilisation of uranium into palaeochannel systems (Hamutoko et al., 2014; Bowell & Davies, 2017; Chen et al., 2021; Wilde, 2023). The aquifers comprise low-yield fractured Damara Supergroup metasediments (Rössing Formation calc-silicates and alaskites) with minor unconfined Khan River alluvium, highly vulnerable to uranium mine dewatering (Lohe et al., 2021).

The region is further characterised by Tertiary palaeodrainage systems buried beneath unconsolidated Cenozoic sediments that function as significant groundwater reservoirs (Chudasama et al., 2019; Wilde, 2023; Al Saud, 2025). These sediments host extensive surficial uranium mineralisation, including some of the world's largest calcrete-type uranium deposits (Chudasama et al., 2019; Hamutoko et al., 2014; Shanyengana et al., 2020; Wilde, 2023). These deposits are geologically young,

generally not older than the Miocene, and their genesis is strongly linked to climatic fluctuations, evaporative concentration, and pedogenic acidification processes (Wilde, 2023).

The two uranium mines examined in this study are located in the south-central segment of the Damara Orogenic Belt (Figures 3-1 and 3-2), near the Welwitschia Lineament, a major structural feature believed to influence both groundwater flow and mineralisation patterns (Shanyengana et al., 2020; Li et al., 2022). Uranium mineralisation in the study area occurs predominantly within alaskite intrusions emplaced into the calc-silicate rocks of the Rössing Formation, where uranium is mainly present as uraninite, with minor secondary uranium minerals (Shanyengana et al., 2020; Wilde, 2023). These granitic bodies, derived from sedimentary protoliths, display varying degrees of alteration that enhance uranium mobility under favourable hydrogeochemical conditions (Shanyengana et al., 2020; Wilde, 2023).

The region has been the focus of continuous uranium exploration and mining for several decades. The older of the two mines began operations in 1976 using open-pit methods and an unlined tailings storage facility (TSF), posing potential contamination risks to underlying aquifers. In contrast, the newer mine, operational since 2016, employs a TSF lined with a 1 mm high-density polyethylene (HDPE) barrier, specifically designed to prevent seepage and minimise environmental impacts.

3.2.2 Sampling and Field Measurements

Groundwater samples were collected from 16 boreholes, eight at each mine site. Borehole selection was based on their spatial proximity to the TSFs and alignment along predicted groundwater flow paths. Borehole characteristics and locations are illustrated in Figures 3-3 and 3-4 and summarised in Tables 3.1 and 3.2. Primary field sampling and in situ measurements were conducted during 2024 and 2025.



Figure 3-3 Location of boreholes at the oldest uranium mine in Namibia (QGIS version 3.40.5 2025

Table 3.1 Locations and depths of boreholes at the oldest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Borehole water level (m)	Distance from TSF (m)	Ground elevation (masl)	Collar height (m)	Collar elevation (masl)	Static water level (masl)
T3	22°26′36.13″	15°1′40.73″	9.41	7.29	123	612	0.59	612.59	605.3
X02	22°28′22.80″	14°59′28.97″	53.44	13.4	3460	564	0.56	564.56	551.16
X05	22°28′12.47″	15°0′0.68″	49.45	5	2450	561	0.55	561.55	556.55
X21	22°29′9.35″	14°59′37.03″	49.57	21.3	3790	544	0.53	544.53	523.23
L10	22°28′42.38″	15°0′56.20″	49.48	11.60	1665	540	0.52	540.52	528.92
N01A	22°27′21.46″	15°2′36.13″	52.11	0.07	510	603	0.59	603.59	603.52
N09	22°26′43.94″	15°3′20.81″	10.43	3.44	1100	591	0.57	591.57	588.13
N11	22°25′57.68″	15°2′52.66″	49.38	4.76	450	619	0.62	619.62	614.86

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - borehole water level (m)

*masl=meters above sea level

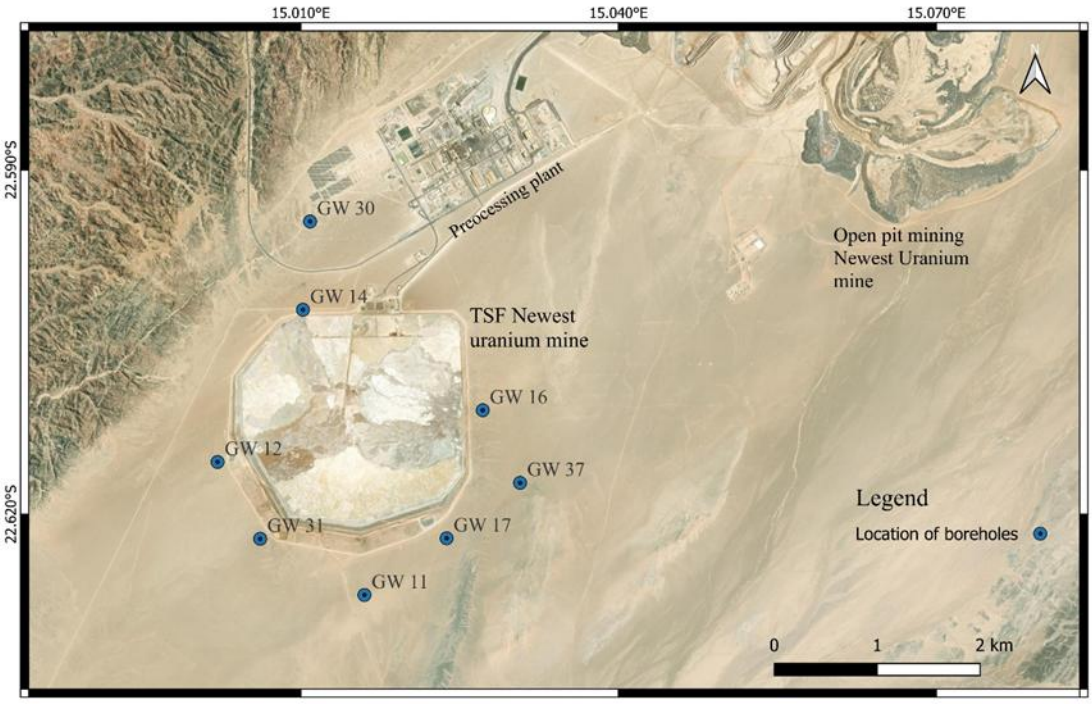


Figure 3-4 Location of boreholes at the newest uranium mine in Namibia (QGIS version 3.40.5 2025).

Table 3.2 Borehole locations and depths of the newest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Borehole water level (m)	Distance from TSF (m)	Ground elevation (masl)	Collar height (m)	Collar elevation (masl)	Static water level (masl)
GW 14	22°36′7.87″	15°0′36.74″	99.49	34.64	60	496	0.51	496.51	461.87
GW 16	22°36′39.38″	15°1′37.87″	119.93	53.38	170	491	0.35	491.35	437.97
GW 37	22°37′2.17″	15°1′50.56″	100.05	46.52	560	478	0.51	478.51	431.99
GW 17	22°37′19.54″	15°1′25.58″	99.87	57.55	310	469	0.48	469.48	411.93
GW 11	22°37′37.34″	15°0′57.63″	98.9	41.63	585	464	0.51	464.51	422.88
GW 31	22°37′19.71″	15°0′22.21″	106.42	48.52	340	466	0.54	466.54	418.02
GW 12	22°36′55.61″	15°0′7.71″	120.48	64.60	320	472	0.52	472.52	407.92
GW 30	22° 35' 40.16″	15° 0' 39.16"	101.8	29.75	900	498	0.52	498.52	468.77

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - borehole water level (m)

*masl=meters above sea level

At each borehole, in situ physicochemical parameters including pH, electrical conductivity (EC), and GPS coordinates were measured using a calibrated AQUAREAD AP-5000 multiparameter probe. Borehole depths were determined with a dip meter. The spatial distance between each borehole and its corresponding tailings storage facility (TSF) was calculated using Google Earth Pro (version 7.3.6). Coordinates were mapped, and straight-line distances from each borehole to the nearest point along the tailing's boundary were determined.

To ensure representative sampling, all boreholes were purged prior to sample collection to remove stagnant water and obtain samples reflective of in situ aquifer conditions. Field procedures adhered to the standard quality control protocols of the respective mining operations, which included collecting duplicate samples from selected boreholes.

At the older uranium mine, borehole depths ranged from 9.41 m to 53.44 m, primarily accessing shallow alluvial aquifers with static water levels between 523.23 masl and 614.86 masl. In contrast, boreholes at the newer uranium mine were substantially deeper, ranging from 98.9m to 120.48 m, and intersected confined or semi-confined aquifers with static water levels between 407.92 masl and 468.77 masl. Groundwater samples were collected in pre-cleaned polyethylene bottles. At each borehole, four separate samples were collected for anion, cation, trace metal, and radionuclide analyses. Samples designated for cation, trace metal, and radionuclide determinations were acidified immediately after collection with dilute nitric acid. Duplicate samples were obtained from each borehole for quality assurance. All samples were preserved at 4°C in a portable refrigerator to maintain chemical stability during transport and storage prior to laboratory analysis.

3.2.3 Laboratory Analyses

Primary water samples were analysed for total dissolved solids (TDS), chloride (Cl^-), fluoride (F^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), uranium (U), and radium-226 (Ra-226). Analyses were conducted at the Analytical Laboratory in Windhoek. Cations and trace metals were quantified using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Instrument calibration was carried out by a certified PerkinElmer technician at regular maintenance intervals. Quality control procedures included the use of analytical blanks, sample replicates, and certified reference materials

Anions were determined using a combination of analytical methods: chloride by titration, fluoride by ion-selective electrode, sulphate by turbidity analysis, and nitrate using a UV-Vis spectrophotometer and Meck test kit. Radionuclide analyses were performed at the Centre for Applied Radiation Science and Technology (CARST), North-West University, South Africa, using a / detector to measure Ra-226

concentrations. Samples were analysed after achieving secular equilibrium to ensure accuracy in radionuclide quantification.

3.2.4 Data Processing

Data analysis was performed using R software (version 4.3.0) and Microsoft Excel (version 2502). Spatial visualisation of borehole locations and sampling networks was conducted in QGIS (version 3.28). Long-term groundwater quality trends (1982-2025) at the oldest uranium mine were evaluated using the non-parametric Mann-Kendall trend test and Sen's slope estimator. Hydrogeochemical facies were visualised using Piper diagrams generated with DIAGRAMME (version 9.20). For comparative analyses between the oldest and newest uranium mines, the Mann-Kendall test, two-sample t-test, and Mann-Whitney U test were employed. These statistical methods were selected for their robustness and suitability in interpreting environmental and hydrochemical datasets. The maps of the local geology and location of boreholes were visualised with QGIS versions 3.40.10 and 3.40.5 respectively.

3.3 Results

3.3.1 Long-term trends (1982-2025) at the older uranium mine

Spatial Variations

Spatial variation in groundwater quality parameters across the sampled boreholes near the TSF of the oldest uranium mine was assessed using descriptive statistical methods. Results were compared against the World Health Organisation (WHO) and Namibian Water Quality Guidelines and Standards for Potable Water, as illustrated in Figure 3-5 (Ministry of Agriculture, 2013; World Health Organization, 2022).

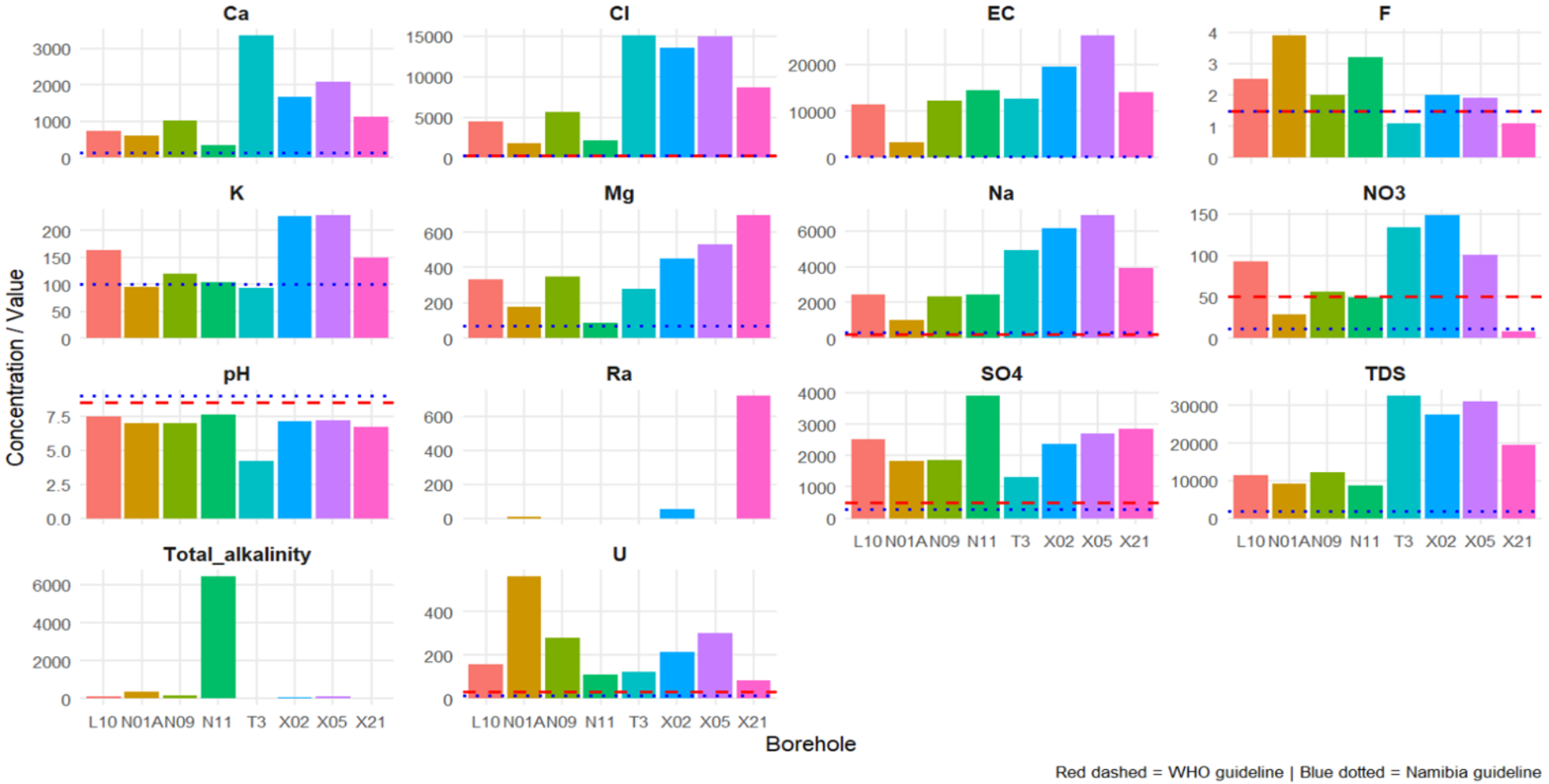


Figure 3-5 Comparison of groundwater quality parameters across boreholes relative to WHO and Namibian Water Quality Guidelines and Standards for Potable Water (Ministry of Agriculture, 2013; World Health Organization, 2022) for the older uranium mine.

The pH of groundwater samples ranged from 4.2 to 7.6, with a mean value of 6.8. Most boreholes exhibited neutral to slightly alkaline conditions, consistent with the World Health Organisation (WHO) operational range of 6.5-8.5 and the Namibian standard of 6-9. However, borehole T3 recorded an anomalously acidic pH of 4.2, falling below both thresholds.

Electrical conductivity (EC) and total dissolved solids (TDS) were consistently elevated, reflecting the high ionic strength of the groundwater. EC values ranged from 3,308.7 mS/m at N01A to 26,326.4 mS/m at X05, with a mean of 14,277.2 mS/m. Correspondingly, TDS concentrations varied between 8,842.1 mg/L and 32,574.3 mg/L (mean = 19,083.0 mg/L). Although the WHO provides no health-based guideline for EC or TDS, values exceeding 1,000 mg/L are generally considered unpalatable. All boreholes exceeded the Namibian potable water limits (<2,000 mg/L TDS and <300 mS/m EC), with particularly high values at T3, X05, and X02. Total alkalinity exhibited substantial variability, ranging from 22.8 mg/L at T3 to 6,454.4 mg/L at N11 (mean = 913.5 mg/L).

Chloride (Cl^-) concentrations were markedly elevated across all boreholes, ranging from 1,858.2 mg/L at N01A to 15,116.7 mg/L at T3 (mean = 8,308.3 mg/L). These values far surpass both the Namibian limit of 300 mg/L and the WHO taste threshold of approximately 250 mg/L. Fluoride (F^-) concentrations ranged between 1.1 and 3.9 mg/L (mean = 2.2 mg/L), exceeding the WHO and Namibian guideline value of 1.5 mg/L in most boreholes, except T3 and X21. Sulphate (SO_4^{2-}) concentrations ranged from 1,331.0 mg/L to 3,903.6 mg/L (mean = 2,417.1 mg/L), exceeding the Namibian maximum of 300 mg/L and the WHO guideline of 500 mg/L.

Nitrate (NO_3^-) levels displayed pronounced variability, ranging from 8.1 mg/L at X21 to 148.2 mg/L at X02 (mean = 77.0 mg/L). Only boreholes N01A, N11, and X21 recorded concentrations below the WHO limit of 50 mg/L. Sodium (Na^+) concentrations were exceptionally high, ranging from 1,033.6 mg/L to 6,869.6 mg/L (mean = 3,770.4 mg/L), greatly exceeding both the Namibian standard (300 mg/L) and the WHO threshold (200 mg/L). Potassium (K^+) concentrations were moderate (92.4–227.3 mg/L; mean = 147.1 mg/L), though several boreholes exceeded the Namibian guideline of 100 mg/L.

Magnesium (Mg^{2+}) concentrations ranged from 84.7 mg/L to 694.1 mg/L (mean = 362.3 mg/L), while calcium (Ca^{2+}) concentrations ranged from 346.8 mg/L to 3,360.5 mg/L (mean = 1,367.4 mg/L). Both parameters exceeded the Namibian permissible limits (Mg <70 mg/L; Ca <150 mg/L) across all samples.

Uranium (U) concentrations were consistently elevated, ranging from 85.9 µg/L at X21 to 563.7 µg/L at N01A (mean = 229.5 µg/L). These values substantially exceed both the WHO guideline of 30 µg/L and the Namibian limit of 15 µg/L. Radium-226 (Ra-226) showed extreme spatial variability, ranging from 0.2 mBq/L in several boreholes to 721.9 mBq/L at X21 (mean = 98.7 mBq/L). While specific WHO or Namibian limits for Ra-226 are not provided, the gross alpha and beta activity guidelines (0.5 and 1.0 Bq/L, respectively) are applicable; the extremely high concentration at X21 suggests localised radiological contamination with potential health implications if the water is consumed untreated.

Overall, groundwater quality across the monitored boreholes was unsuitable for direct human consumption. Boreholes T3, X05, X02, and X21 exhibited the most severe exceedances, particularly for TDS, chloride, sulphate, sodium, uranium, and radium-226.

Temporal Variations

For visualising and interpreting groundwater chemistry, piper diagrams are used widely (Piper, 1944; Hamutoko et al., 2014). It graphically displays the relative abundance of major cations and anions in water samples. In this study, piper diagrams are used to characterise groundwater composition at the oldest uranium mine, facilitating the temporal shifts in dominant water facies across 3 decades, 1990-1999, 2000-2009 and 2010-2019.

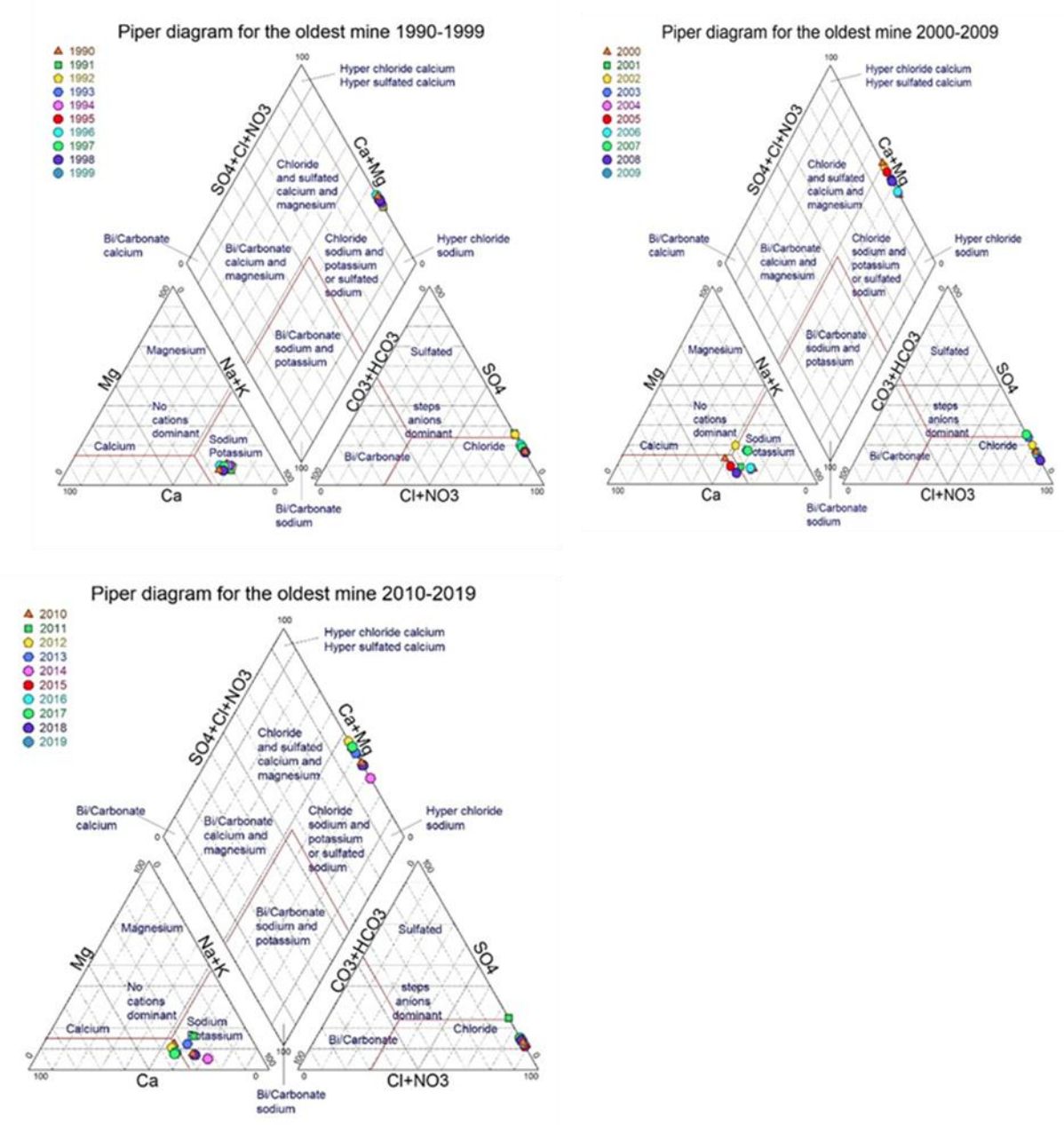


Figure 3-6 Piper diagrams for three decades for the oldest uranium mine.

Illustrations by the piper diagrams for the three decades (Figure 3-6) reveal consistent patterns of major ion composition and water type for the oldest uranium mine. The Piper diagrams for the oldest uranium mine show a consistent dominance of chloride-rich, calcium-magnesium water across the three decades (Figure 3-6). However, there are subtle shifts in both cation and anion composition over time. Indicating a stable Ca-Mg-Cl hydrochemical facies with minimal variability in the 1990s, samples cluster tightly toward the Ca-Mg side of the diamond triangle and the chloride apex of the anion triangle. Suggesting a modest increase in Na-K contributions in the 2000s, the cation field shows a slightly greater spread toward the Na+K corner. The anion field remained firmly chloride dominant (2000s). By the 2010s, the plots show further dispersion in the cation triangle, particularly toward the Na+K. Across all decades, the anion composition remains overwhelmingly chloride rich. There is, however, minor movement toward the sulphate axis in some years during the last decade (2010s). Overall, the mine groundwater chemistry remains consistently chloride-dominated, with a slow but noticeable trend toward greater cation mixing from the 1990s to the 2010s.

Mann-Kendall Trend Analysis

To assess long-term temporal variations in groundwater quality from 1982 to 2025, the non-parametric Mann-Kendall test was applied. Associated p-values (significance) and test statistics (Tau) indicating the direction of trends are presented in Table 3.3. A significant threshold of $p < 0.05$ was adopted to identify statistically significant trends.

Table 3.3 The p-values and test statistics for the mean parameters for the oldest uranium mine

Parameter	Tau	p- value
Mean pH	-0.5108409	0.0000011
Mean EC (mS/m)	-0.6088795	0.0000000
Mean TDS (mg/L)	0.2956810	0.0053725
Mean Total alkalinity (mg/L)	0.1871539	0.0787151
Mean Chloride (mg/L)	0.1501057	0.1538364
Mean Fluoride (mg/L)	0.1977790	0.0599245
Mean Sulphate (mg/L)	-0.2684990	0.0105001
Mean Nitrate (mg/L)	-0.2890365	0.0065083
Mean Sodium (mg/L)	-0.2403101	0.0237883
Mean Potassium (mg/L)	-0.1343205	0.2024996

Mean Magnesium (mg/L)	0.1289641	0.2210180
Mean Calcium (mg/L)	0.2004430	0.0595953
Mean Uranium (µg/L)	-0.0958165	0.3971171
Mean Radium-226 (mBq/L)	0.4871795	0.0003941

The following parameters exhibited statistically significant downward trends between 1982 and 2025: pH (Tau = 0.51, p = 0.0000011), EC (Tau = 0.6089, p < 0.000001), sulphate (Tau = −0.2685, p = 0.0105), nitrate (Tau = −0.2890, p = 0.007), and sodium (Tau = −0.240, p = 0.0238). In contrast, TDS (Tau = 0.30, p = 0.00054) and Ra-226 (Tau = 0.49, p = 0.0004) displayed statistically significant upward trends.

Total alkalinity, fluoride, calcium, and chloride showed weak positive Tau values, suggesting either stable concentrations or insufficient trend strength over the study period. Uranium (Tau = −0.10, p = 0.397) and potassium (Tau = 0.13, p = 0.221) exhibited weak, statistically insignificant tendencies toward decline, indicating no clear temporal evolution. Magnesium also showed a low, non-significant increase (Tau = 0.13, p = 0.221), implying minimal temporal variability.

Although nitrate concentrations at a few boreholes (N01A, N11, and X21) were within acceptable limits, most sites exceeded the WHO guideline value. In addition, all boreholes exhibited elevated concentrations of sulphate, chloride, sodium, calcium, magnesium, and fluoride. Of particular concern were the persistently high TDS levels and exceptionally high Ra-226 activities measured at borehole X21, both of which pose long-term risks to groundwater quality and radiological safety. Overall, these findings indicate that groundwater quality is severely compromised, with widespread exceedances of both national and international standards for multiple parameters.

Sen's Slope Analysis

To assess the direction and magnitude of temporal changes in hydrogeochemical parameters from the 1980s to the 2020s, a non-parametric Sen's slope estimator was applied to decadal groundwater quality data. The analysis revealed both positive and negative slopes across major ions, salinity indicators, and radionuclides, as illustrated in Figure 3-7.

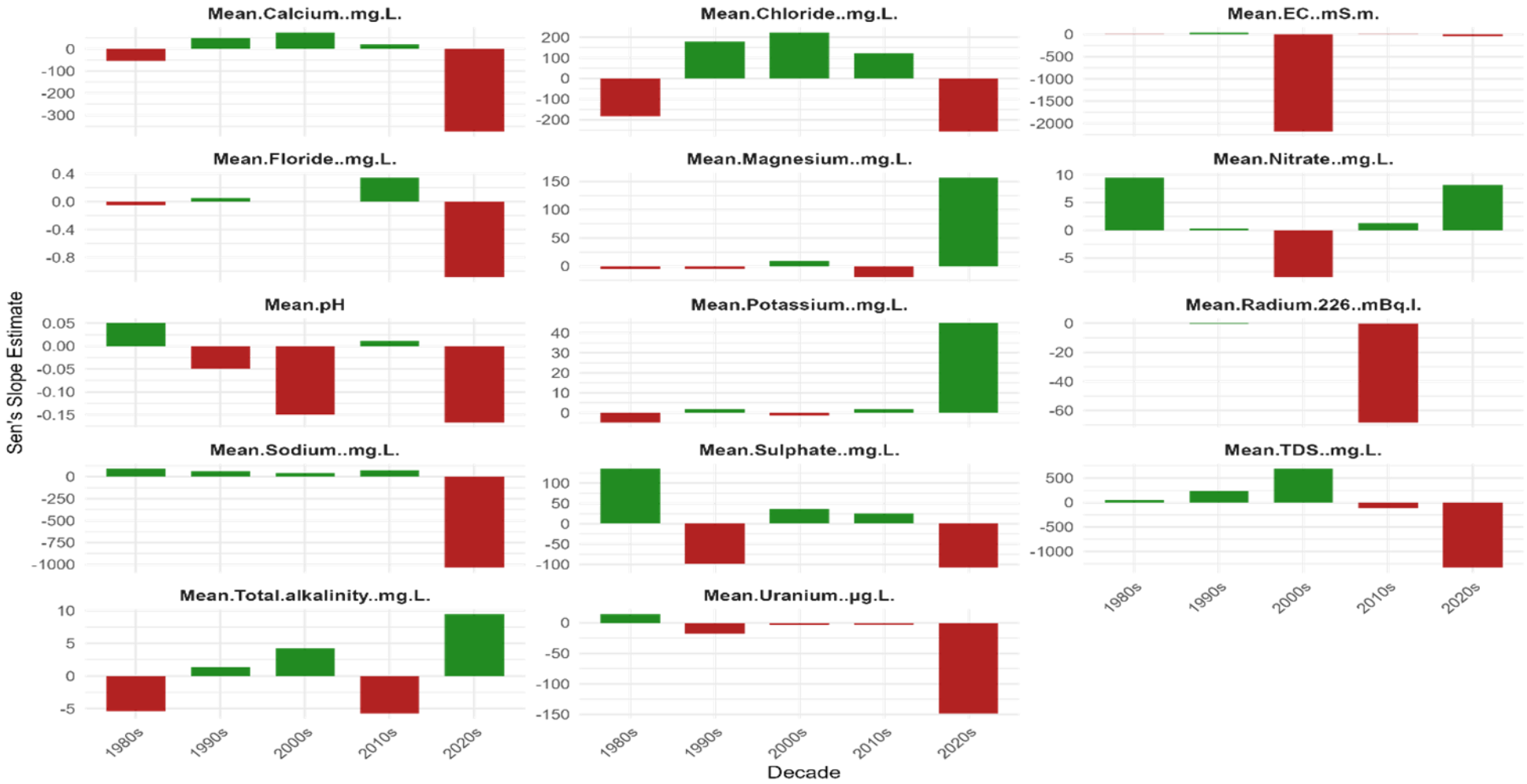


Figure 3-7 Median rate of change per decade for each parameter.

Groundwater pH declined progressively after the 1980s, with the steepest decrease observed during the 2010s (-0.12 units per decade). This ongoing acidification trend suggests contamination originating from the unlined TSF.

Major cations exhibited contrasting temporal patterns. Calcium concentrations increased through the 1990s and 2000s but declined sharply in the 2020s (-280 mg/L per decade). In contrast, magnesium and potassium showed notable increases over the same period (>100 mg/L and >40 mg/L per decade, respectively). Sodium showed a persistent downward trend, with the steepest decline recorded in the 2020s (-950 mg/L per decade).

Anions followed similarly variable trajectories. Chloride concentrations rose markedly during the 1990s and 2000s (>150 mg/L per decade) before declining in the 2010s and 2020s (-200 mg/L per decade). Sulphate increased in the 1980s (+100 mg/L per decade) but decreased steadily thereafter (from -80 to -20 mg/L per decade). Fluoride showed a modest rise in the 2000s followed by a sharp decline in the 2020s (-0.8 mg/L per decade). Nitrate exhibited alternating positive and negative slopes, increasing during the 1980s and 2020s but falling in the 1990s and 2010s. Total alkalinity also displayed cyclic behaviour, peaking in the 2000s (+10 mg/L per decade) before decreasing in the 2010s (-6 mg/L per decade).

Salinity indicators showed notable shifts over time. Both electrical conductivity (EC) and total dissolved solids (TDS) recorded steep negative slopes during the 2010s and 2020s (-2000 mS/m and -1000 mg/L per decade, respectively), reflecting overall reductions in ionic strength.
Among the radionuclides, uranium exhibited the greatest reduction in the 2020s (-150 µg/L per decade), while radium-226 showed a pronounced decline in the 2010s (-80 mBq/L per decade).

Overall, Sen's slope analysis indicated long-term decreases in salinity-related parameters (Na^+, Cl^-, SO_4^{2-}, EC, TDS) and radionuclides (U, Ra-226), particularly over the past two decades. In contrast, increasing Mg^{2+} and K^+ concentrations, accompanied by declining pH, suggest evolving geochemical conditions possibly linked to secondary mineral dissolution or changes in contaminant sources.

3.3.2 Comparison Between the Two Mines

This section presents a comparative assessment of spatial and temporal variations in groundwater quality between Namibia's oldest and newest uranium mines, using hydrogeochemical and radiological indicators. The comparison reveals distinct geochemical signatures influenced by local geology and potential legacy contamination from historical mining operations.

Temporal Variations

To analyse annual changes in groundwater quality at both mine sites, the nonparametric Mann–Kendall trend test was applied. This analysis provides insight into the direction and significance of temporal trends for each parameter. Tables 3.4 and 3.5 present the corresponding test statistics (Tau) and p-values for the oldest and newest mine, respectively. A significance threshold of $p < 0.05$ was adopted to identify statistically significant trends.

Table 3.4 Mann-Kendall result for the oldest uranium mine

Parameter	Tau	p value
Mean pH	0.27602622	0.31930196
Mean EC (mS/m)	-0.2888889	0.28313082
Mean TDS (mg/L)	-0.3888889	0.17530808
Mean Total alkalinity (mg/L)	0	1
Mean Chloride (mg/L)	-0.82222223	0.00128218
Mean Fluoride (mg/L)	-0.3146266	0.24303496
Mean Sulphate (mg/L)	0.24444444	0.37109327
Mean Nitrate (mg/L)	0.66666669	0.01648867
Mean Sodium (mg/L)	-0.44444445	0.11785091
Mean Potassium (mg/L)	0.55555558	0.03182316
Mean Magnesium (mg/L)	0.46666667	0.07363832
Mean Calcium (mg/L)	-0.6111111	0.02856768
Mean Uranium (µg/L)	-0.2	0.8064959
Mean Radium-226 (mBq/l)	-0.19999999	0.70711422

Table 3.5 Table 5 Mann-Kendall results for the newest uranium mine

Parameter	Tau	p value
Mean pH	-0.53201592	0.05186867
Mean EC (mS/m)	0.55555558	0.03182316
Mean TDS (mg/L)	0.51111114	0.04909801
Mean Total alkalinity (mg/L)	0.42222223	0.10740471
Mean Chloride (mg/L)	0.15555556	0.59150505
Mean Fluoride (mg/L)	-0.65996635	0.01344999
Mean Sulphate (mg/L)	0.46666667	0.07363832
Mean Nitrate (mg/L)	0.73333335	0.00420749
Mean Sodium (mg/L)	0.15555556	0.59150505
Mean Potassium (mg/L)	0.64444447	0.01226604
Mean Magnesium (mg/L)	0.42222223	0.10740471
Mean Calcium (mg/L)	0.55555558	0.03182316
Mean Uranium (µg/L)	0.42222223	0.10740471
Mean Radium-226 (mBq/l)	-0.33333331	0.45237035

Distinct patterns in groundwater quality evolution were observed between the two mines based on the Mann-Kendall trend analysis. The oldest mine exhibited predominantly declining trends in conservative ions, particularly chloride (Tau = −0.8222, p = 0.00128) and calcium (Tau = −0.6111, p = 0.0286). In contrast, increasing trends in nitrate (Tau = 0.667, p = 0.0165) and potassium (Tau = 0.556, p = 0.0318) indicate emerging contamination risks, likely associated with anthropogenic influences.

At the newest mine, multiple parameters showed upward trajectories, pointing to a growing contaminant load. Significant positive trends were recorded in electrical conductivity (EC) (Tau = 0.556, p = 0.0318), total dissolved solids (TDS) (Tau = 0.5111, p = 0.049), nitrate (Tau = 0.733, p = 0.0042), calcium (Tau = 0.556, p = 0.0318), and potassium (Tau = 0.644, p = 0.0123).

Both sites exhibited non-significant temporal trends for uranium and radium-226, suggesting minimal long-term variation in radiological contamination within the study period. Nonetheless, their occasional spikes and fluctuating activity levels remain a public health concern, reflecting potential episodic releases or mobilization events.

Statistical Significance of Temporal Trends

To compare mean concentrations across parameters, a two-sample t-test was performed (Table 3.6). The analysis aimed to determine whether statistically significant differences existed between the two mining areas, potentially reflecting differing hydrogeochemical conditions or operational influences. Results indicated that only three parameters pH, TDS, and chloride differed significantly between the two sites at the 95% confidence level ($p < 0.05$). However, parameters such as sulphate, although not statistically distinct, still suggest notable pollution at both mines.

Table 3.6 The summary of the statistical significance of the temporal trends between the two mines.

Parameter	Mean oldest	Mean newest	p value	Significant
pH	6.45	7.14	0.00862	Yes
EC	2299.88	1906.92	0.183	No
TDS	20897.37	13281.76	0.0015	Yes
Total Alkalinity	1972.23	130.14	0.348	No
Chloride	8685.72	5690.73	0.0000247	Yes
Fluoride	3.58	2.23	0.146	No
Sulphate	2454.8	2200.17	0.219	No
Nitrate	53.09	71.76	0.618	No
Sodium	3219.11	3346.18	0.846	No
Potassium	177.69	139.09	0.274	No
Magnesium	486.1	209.2	0.0517	No
Calcium	1330.06	909.97	0.175	No
Uranium	278.19	485.88	0.211	No
Radium-226	1288.15	247.8	0.362	No

Groundwater quality parameters pH, TDS, and chloride differed significantly between the oldest and newest uranium mines. pH levels were significantly higher in the newest mine (mean = 7.14) than in the oldest mine (mean = 6.45; $p = 0.00862$), indicating a shift from more acidic to neutral alkaline conditions.

Salinity indicators showed extreme contrasts. Total dissolved solids (TDS) concentrations were significantly greater in the oldest mine (mean = 20,897.38 mg/L) compared to the newest mine (mean = 13,281.76 mg/L; $p = 0.0015$). Similarly, chloride concentrations were markedly elevated in the oldest mine (mean = 8685.72 mg/L) relative to the newest mine (mean = 5690.73 mg/L; $p = 0.0000247$). These findings suggest more intense salinisation and ionic accumulation in the older mine, consistent with legacy contamination resulting from prolonged groundwater residence times and historical tailings seepage.

Other parameters, including fluoride, sulphate, nitrate, sodium, potassium, magnesium, calcium, uranium, and radium-226, showed differences in mean values between the two mines; however, these differences were not statistically significant at the 5% confidence level ($p > 0.05$). Notably, uranium concentrations were higher in the newest mine (mean = 485.88 µg/L) compared to the oldest mine (mean = 278.19 µg/L; $p = 0.211$), although this difference was not significant, likely due to high variance or variability in sampling depth.

Overall, the statistically significant variations in pH, TDS, and chloride concentrations reflect stronger geochemical alteration processes and a more persistent contamination legacy at the oldest mine. The lack of statistically significant differences in other parameters suggests that hydrogeochemical controls are broadly similar between the two mines. This may reflect comparable environmental management practices, similar geological settings, or limited temporal divergence in contaminant transport dynamics.

Spatial Variations

Groundwater chemistry exhibited clear spatial contrasts between the oldest and newest uranium mines. The oldest mine generally showed higher concentrations and greater spatial heterogeneity across most parameters, including EC, TDS, total alkalinity, and chloride. Table 3.7 presents the descriptive statistics of the evaluated parameters.

Table 3.7 Descriptive statistics of the spatial data of the oldest and newest mines

Parameter	oldest uranium mine (n=8)				newest uranium mine (n=8)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
pH	6.8	4.2	7.6	1.1	6.9	7.40	7.14	0.19
Electrical conductivity (µS/cm @25˚C))	14277.2	3308.7	26326.4	6636.6	933.47	3777.53	1866.16	1091.78
TDS (mg/L)	19083.0	8842.1	32574.3	10073.0	6956.29	26480.98	13015.32	7667.43
Total alkalinity (mg/L)	913.5	22.8	6454.4	2241.7	46.43	249.40	127.55	72.47
Chlorine (mg/L)	8308.3	1858.2	15116.7	5604.8	2116.50	13096.80	5538.07	4060.45
Fluoride (mg/L)	2.2	1.1	3.9	1.0	1.06	3.25	2.25	0.75
Sulphate (mg/L)	2417.1	1331.0	3903.6	788.4	1272.73	3202.04	2208.06	717.02
Nitrate (mg/L)	77.0	8.1	148.2	50.0	10.07	195.50	69.75	56.04
Sodium (mg/L)	3770.4	1033.6	6869.6	2065.1	1529.07	6402.00	3269.52	1942.91
Potassium (mg/L)	147.1	92.4	227.3	55.2	46.07	364.58	135.03	110.68
Magnesium (mg/L)	362.3	84.7	694.1	194.6	69.33	537.41	205.05	165.32

Calcium (mg/L)	1367.4	346.8	3360.5	982.3	237.83	1985.08	896.83	559.05
Uranium (µg/L)	229.5	85.9	563.7	156.3	63.71	2396.36	485.06	779.97
Radium (mBq/L)	98.7	0.2	721.9	252.5	42.90	701.60	257.62	233.40

Chloride and sulphate concentrations were notably elevated in the oldest mine. Chloride ranged from 1,858 mg/L at borehole N01A to 15,117 mg/L at T3 (mean = 8,308.3 mg/L), compared with a lower mean concentration of 5,538 mg/L in the newest mine. Sulphate levels reached 3,903.6 mg/L at N11 (mean = 2,417 mg/L) in the oldest mine, versus 2,208 mg/L in the newest mine.

pH values reflected contrasting hydrochemical environments between the two sites. In the oldest mine, values ranged from acidic conditions at T3 (4.2) to near-neutral at N11 (7.6), with an overall mean of 6.8, indicating localised acidification near tailings storage facilities (TSFs). In contrast, the newest mine showed a narrower, more buffered range (6.9-7.4; mean = 7.14), suggesting a more chemically stable environment with reduced acid-generating conditions.

Salinity indicators further reinforced these distinctions. In the oldest mine, electrical conductivity (EC) reached 26,326.4 µS/cm at X05 and total dissolved solids (TDS) peaked at 32,574.3 mg/L at T3, both indicating possible tailings leachate influence. The newest mine recorded considerably lower mean values (EC = 1,866 µS/cm; TDS = 13,015 mg/L), though elevated readings at GW14 (EC = 3,777.5 µS/cm; TDS = 26,481 mg/L) point to localised mineralisation zones.

Alkalinity exhibited contrasting behaviour across sites. The oldest mine displayed extreme variability, ranging from 22.8 mg/L at T3 to 6,454.4 mg/L at N11, suggesting strong carbonate buffering and influence from TSF seepage. In comparison, the newest mine showed more moderate and consistent values (46.4–249.4 mg/L; mean = 127.6 mg/L), indicative of a more stable hydrochemical system.

Other parameters showed moderate contrasts. Fluoride concentrations were nearly identical in both mines (oldest = 2.20 mg/L; newest = 2.25 mg/L). Nitrate was slightly higher in the oldest mine (mean = 77 mg/L) compared with the newest (mean = 69.8 mg/L), suggesting limited anthropogenic input from explosives or local habitation. Sodium and potassium concentrations were greater in the oldest mine (Na^+ = 3,770 mg/L; K^+ = 147 mg/L) than in the newest (Na^+ = 3,270 mg/L; K^+ = 135 mg/L),

consistent with enhanced ion exchange processes. Similarly, calcium and magnesium exhibited higher variability and concentrations in the oldest mine (Ca^{2+} = 1,367.4 mg/L; Mg^{2+} = 362.3 mg/L) relative to the newest (Ca^{2+} = 896.8 mg/L; Mg^{2+} = 205.1 mg/L).

Radiological parameters revealed concerning levels across both sites. Uranium concentrations were elevated in both mines, reaching maxima of 563.7 µg/L at N01A (oldest mine) and 2,396.4 µg/L at GW31 (newest mine), indicating active mobilization processes. Radium-226 also displayed strong spatial variability, peaking at 721.9 mBq/L in X21 (oldest mine; mean = 98.7 mBq/L) and 701.6 mBq/L in GW14 (newest mine; mean = 257.6 mBq/L), raising potential radiological safety concerns.

Overall, the oldest uranium mine exhibited higher mean concentrations and greater variability across most parameters (Figure 3-8), particularly EC, TDS, chloride, and calcium, reflecting long-term contaminant accumulation and legacy impacts. In contrast, the newest mine showed more moderate, uniform groundwater chemistry, though elevated uranium and radium levels at select boreholes suggest emerging geochemical alteration and ongoing mining influence.

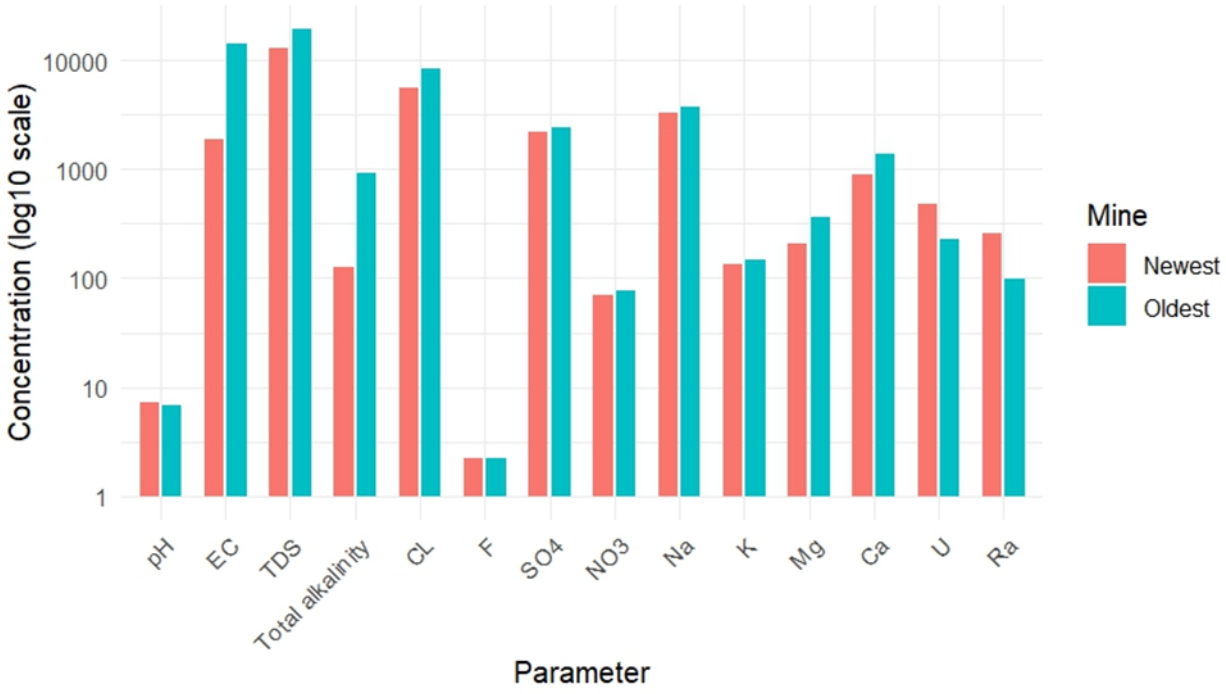


Figure 3-8 Statistical comparison of groundwater quality between the oldest and the newest uranium mines.

The Mann-Whitney U test, a nonparametric alternative that does not assume normality and compares ranked data, was applied to evaluate differences between the two mines. This method accommodates the contrasting distributional characteristics of the datasets, providing a more robust and statistically valid comparison of groundwater quality parameters across the spatially distinct mining sites.

Table 3.8 Results from the Mann-Whitney U test for the oldest and newest mine parameters

Parameter	W	p value
pH	29	0.791694616
EC	62	0.001947528
TDS	48	0.103561871
Total alkalinity	29	0.792895503
CL	42	0.318425067
F	29.5	0.832784637
S04	36	0.713191261
N	35	0.792895503
Na	36	0.713191261
K	40	0.430897044
Mg	47	0.127807601
Ca	42	0.318425067
U	27	0.636502487
Ra	9	0.017287216

The majority of measured parameters did not exhibit statistically significant differences between the two mine sites ($p > 0.05$), as presented in Table 3.8. Specifically, parameters such as pH ($W = 29$, $p = 0.79$), total alkalinity ($W = 29$, $p = 0.79$), chloride ($W = 42$, $p = 0.32$), fluoride ($W = 29.5$, $p = 0.83$), sulphate ($W = 36$, $p = 0.71$), nitrogen ($W = 35$, $p = 0.79$), sodium ($W = 36$, $p = 0.71$), potassium ($W = 40$, $p = 0.43$), calcium ($W = 42$, $p = 0.32$), and uranium ($W = 27$, $p = 0.64$) showed no statistically significant differences in concentration levels between the oldest and newest mines. These results indicate broadly similar groundwater chemistry profiles for these parameters despite temporal and operational differences between the two mining environments.

In contrast, electrical conductivity (EC) ($W = 62$, $p = 0.0019$) and radium-226 ($W = 9$, $p = 0.017$) were significantly different between the two mines. These findings suggest that the spatial distributions of these parameters vary markedly between the oldest and newest mining locations. EC, a proxy for total dissolved solids, highlights substantial contrasts in overall mineralisation or ionic content. Elevated radium levels point to potential radiological influences linked to uranium mining processes, warranting further environmental and health risk evaluation.

TDS ($W = 48$, $p = 0.10$) and magnesium ($W = 47$, $p = 0.13$) approached statistical significance but did not meet the $p < 0.05$ threshold, implying potential trends that merit additional investigation using larger datasets or complementary analytical approaches. Collectively, these results underscore the spatial heterogeneity of groundwater quality parameters in uranium mining environments, with EC and radium-226 showing the clearest distinctions between the two mine sites.

3.4 Discussion

Groundwater quality at the oldest mine demonstrates dynamic hydrogeochemical evolution over time, influenced by natural attenuation, dilution, and prolonged mining activities (Ju et al., 2020; Wang et al., 2023; Liu et al., 2024; Song et al., 2024). Changes in radiological parameters reflect contributions from silicate weathering, carbonate buffering, evaporitic processes, and legacy contamination from tailings (Skierszkan et al., 2020; Lopez et al., 2021; Punia et al., 2021; De Windt et al., 2025). Piper diagram trends further support this interpretation, showing that groundwater at the oldest mine maintains a predominantly Ca–Mg–Cl facies across all decades, with only minor shifts toward the Na+K and sulfate fields in more recent periods. These subtle changes indicate limited but measurable mine-related influence, likely reflecting low-level sulphate seepage from processing and gradual cation exchange processes (Newman et al., 2020). These trends illustrate the complexity of mining-impacted aquifers, where multiple geochemical and operational factors interact to drive temporal and spatial variability (Adamovic et al., 2022; Sikakwe et al., 2024).

The observed spatial heterogeneity in groundwater chemistry between the two uranium mines reflects both natural hydrogeochemical variability and the effects of mining operations consistent with other studies (Adadzi et al., 2022; Bala et al., 2022; Balaram et al., 2022; Bhavya et al., 2023). Variations in pH, salinity, and major ionic composition indicate localised geochemical processes, such as water–rock interactions, mineral dissolution, and leachate contributions from tailings storage

facilities (TSFs) (Cheng et al., 2022; Li et al., 2023; Shi et al., 2023; Zheng et al., 2023). The oldest mine, with its extended operational history, exhibits signatures of legacy contamination, whereas the newest mine displays relatively moderate hydrochemical conditions likely attributed to improved management practices and shorter exposure durations (Dolchinkov et al., 2024; Sahu et al., 2023). These site-specific differences underscore the need for targeted groundwater monitoring, as variability can be pronounced even within the same mining region (Abiriga et al., 2020; Hernandez-Jerez et al., 2023; Verma, 2025).
Attenuation processes such as sorption and reduced leaching appear to mitigate some radiological risks over time, indicating the potential role of natural self-purification mechanisms within the aquifer (Bugai et al., 2022; Liu et al., 2023; Lu et al., 2024). Nevertheless, continuous monitoring remains essential to detect emerging risks, particularly in areas prone to acidification or salinisation (Li et al., 2024).

Comparative analysis reveals apparent differences in hydrogeochemical behaviour and contamination legacy between the two sites. The oldest mine continues to exhibit the cumulative impacts of historical operations, while the newest mine shows early signs of geochemical stress (Dinis & Fiúza, 2021; Mathuthu et al., 2021; Tillman et al., 2021; Bhavya et al., 2023). These distinctions highlight the long-term effects of uranium mining on groundwater systems and emphasise the importance of proactive management in newer operations to prevent similar deterioration. The spatial and temporal contrasts observed also underscore the interplay between aquifer lithology, water–rock interactions, and mine management practices (Chen et al., 2022; Ji et al., 2024; Li & Zhang, 2012). Consequently, remediation and mitigation strategies should be tailored to the specific hydrogeological and operational contexts of each mining site.

The findings have direct implications for groundwater management in uranium-mining regions. Evidence of localized contamination, evolving hydrogeochemical conditions, and potential radiological hazards underscores the urgent need for integrated monitoring frameworks, early-warning systems, and preventive interventions. Management efforts should prioritise the containment of TSF seepage, the treatment of affected water, and the adoption of adaptive strategies that address ongoing geochemical evolution.

Overall, this study highlights the importance of integrating geochemical assessments with operational planning to promote sustainable groundwater use. Effective management requires a balance between

resource extraction and the protection of water resources, particularly in arid regions where groundwater serves as a critical lifeline.

3.5 Conclusion

This study illustrates the progressive evolution of groundwater quality in uranium-mining environments, revealing that legacy operations are characterised by persistent salinity, ion enrichment, and radiological hotspots. In contrast, newer operations, though initially less affected, already exhibit signs of early deterioration. By analysing both long-term and contemporary datasets across multiple groundwater quality parameters, this research addresses a key knowledge gap in understanding the mechanisms of contamination persistence in arid-region aquifers impacted by uranium mining. Piper diagram analysis further supports these findings, showing that groundwater at the oldest mine remains dominated by a Ca–Mg–Cl facies despite subtle increases in sulphate and sodium, indicating a long-term but limited geochemical imprint from mining activities.

The results demonstrate that even modern engineering controls cannot entirely prevent groundwater degradation. Historical contamination remains embedded within aquifer systems, posing sustained risks to water quality and ecosystem health. These findings have critical implications for groundwater protection policies, particularly in regions dependent on subsurface water for domestic and agricultural use.

Future research should integrate hydrogeochemical monitoring with groundwater-flow and contaminant-transport modelling to predict the long-term behaviour of chemical and radiological pollutants. Expanding monitoring networks and incorporating isotopic tracers are recommended to improve source identification and pathway analysis.

Ultimately, long-term groundwater protection in mining-impacted regions depends on sustained, adaptive management that responds promptly to early warning signals. Without such vigilance, the degradation observed at legacy sites risks becoming the inevitable future of today's newly developed uranium mines.

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CHAPTER 4: HYDROGEOCHEMICAL AND ISOTOPIC CHARACTERISATION OF GROUNDWATER IMPACTED BY URANIUM MINING: EXAMPLES FROM NAMIBIA, SOUTHERN AFRICA

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Abstract

Groundwater in arid regions is increasingly threatened by climate variability and uranium mining activities. In Namibia's Uranium Province, groundwater quality is at risk from both legacy and ongoing mining operations. This study investigates the hydrogeochemical and isotopic characteristics of groundwater from two uranium mines, one older and one more recently developed, to assess spatial variability, contamination, and recharge dynamics. Sixteen boreholes were analysed for hydrogeochemical parameters and stable isotopes ($\delta^{18}O$ and $\delta^{2}H$). Elevated metal concentrations and cation anomalies near the oldest mine indicate prolonged geochemical alteration and persistent legacy contamination. Isotopic data reveal evidence of evaporative enrichment and limited modern recharge. In contrast, groundwater from the newest mine displays a wider isotopic range, with both enriched and near-neutral signatures, suggesting evaporation of mine-influenced waters and mixing with less-modified local groundwater. These findings highlight the combined influence of mining legacy and hydrogeological conditions on groundwater quality, offering a vital baseline for future monitoring, policy formulation, and sustainable water resource management.

Keywords: stable isotopes, hydrogeochemistry, groundwater quality, tailings storage facilities, uranium mining, groundwater pollution

4.1 Introduction

The global significance of water quality challenges is underscored by the United Nations Sustainable Development Goals (SDGs), particularly Goal 6, which aims to "ensure availability and sustainable management of water and sanitation for all" (United Nations, 2023). Groundwater is a critical resource for drinking water, agriculture, and industrial activities, supporting over 50% of the global population (Frappart & Merwade, 2022; Karunanidhi et al., 2022; Mutilifa et al., 2024; Zhang et al., 2024). In Africa, effective groundwater management is essential for achieving sustainable development; however, groundwater availability varies significantly across the continent (Gaye & Tindimugaya, 2019; Bayat et al., 2023; De Bont & Börjeson, 2024). While North Africa benefits from high-yielding sedimentary aquifers, Sub-Saharan Africa is dominated by low-yielding basement aquifers (Nwankwo et al., 2020; MacDonald et al., 2021; Scanlon et al., 2022; Mutilifa et al., 2024). In Southern Africa, groundwater plays a vital role in rural water supply and mining operations (Gaye & Tindimugaya, 2019; Ndhlovu & Woyessa, 2021; Mutilifa et al., 2024). Dependence on groundwater varies by country, with Namibia meeting approximately 80% of its water needs from groundwater, compared to 59% in South Africa, 54% in Botswana, and 38% in Zimbabwe (Hamutoko et al., 2016; World Bank Group, 2017; Mutilifa et al., 2024).

Groundwater pollution remains a primary global concern, primarily driven by anthropogenic activities such as industrial discharges, oil spills, and the release of untreated wastewater (Kurwadkar et al., 2020; The Groundwater Foundation, 2022; Basharat et al., 2023; United Nations, 2023). Although natural geochemical weathering of elements such as arsenic, cadmium, and lead contributes to contamination, human activities significantly exacerbate groundwater degradation (Kurwadkar, 2014; Kayastha et al., 2022; Mutilifa et al., 2024; Wali et al., 2024). With severe implications for both human health and ecosystems, groundwater pollution demands integrated prevention strategies, regular monitoring, and sustainable management (Li et al., 2021; Karunanidhi et al., 2022; Lapworth et al., 2023). While remediation remains challenging due to the complexity of subsurface contamination, emerging technologies such as adsorption of contaminants using magnesium-based materials and nanoparticle-assisted removal methods show promise for mitigating pollutants, including uranium (Dinis & Fiúza, 2021; Balaram et al., 2022; Gandhi et al., 2022). For smaller-scale contamination, pump-and-treat systems remain a cost-effective and straightforward solution (Antelmi et al., 2020; Solcova et al., 2022).

Isotopes are classified as either stable or radioactive, depending on whether they undergo natural decay (Fymat, 2019; Xia & Yu, 2019; Ji et al., 2023). The isotopic composition of stable elements is

typically expressed in delta (δ) notation, which compares the ratio of rare to abundant isotopes in a sample relative to a standard reference (Dunn et al., 2017; Xia & Yu, 2019; Skrzypek et al., 2022). Stable isotopes of hydrogen ($\delta^{2}H$) and oxygen ($\delta^{18}O$) are powerful tracers in hydrological studies, providing valuable insights into the origin and movement of water within the hydrological cycle (Hurst & Krishnamurthy, 2019; Persaud et al., 2023; Stadnyk & Holmes, 2023). These isotopes help elucidate interactions between surface and groundwater systems and reveal the influence of meteorological processes such as precipitation patterns, evaporation, recharge mechanisms, and groundwater composition (Mahlangu et al., 2020; Zhang et al., 2021; Modie et al., 2022). By analysing isotopic signatures, researchers can distinguish between water sources and trace subsurface flow pathways (Tweed et al., 2019; Stotler, 2021; Zhou et al., 2023). Moreover, isotopic tracers are instrumental in estimating groundwater residence and contaminant transit times, key indicators of aquifer vulnerability and contamination risk (Cook, 2020; Banks et al., 2021; Persaud et al., 2023). Because isotope behaviour is influenced by physical, chemical, and biological processes, isotopic analysis has become an indispensable tool in hydrogeological research (Alexandre, 2020; Vanhaecke & Costas-Rodríguez, 2021; Teixeira et al., 2022). Environmental isotopes, particularly $\delta^{18}O$ and $\delta^{2}H$, are widely used to assess groundwater pollution, recharge processes, and hydrological connectivity (Nisi et al., 2014; Arumi et al., 2020; Ansari et al., 2023).

In Namibia, groundwater is indispensable for domestic supply, livestock farming, irrigation, and industrial applications (Hamutoko et al., 2016; Lohe et al., 2021; Mutilifa et al., 2024). Consequently, robust groundwater monitoring programs are essential to evaluate management strategies and safeguard this vital resource. Isotopic studies have provided important insights into recharge mechanisms and contamination risks. For instance, stable isotope studies in the Cuvelai-Etosha Basin revealed that deep aquifers are primarily recharged during high-intensity rainfall events, while shallow wells remain vulnerable to evaporative losses (Hamutoko et al., 2016).

Groundwater contamination by uranium and associated radionuclides represents a serious environmental and public health challenge in arid regions. Studies in India, South Africa, and Saudi Arabia have reported uranium concentrations exceeding World Health Organisation (WHO) guidelines (Makubalo & Diamond, 2020; Bala et al., 2022; Pandit et al., 2022). Uranium mobilisation is influenced by water-rock interactions, evaporation, and alkaline, oxic conditions, as well as silicate weathering, bicarbonate complexation, and ion exchange (Bala et al., 2022; Pandit et al., 2022). Contamination patterns are spatially and vertically variable, with shallow aquifers often more affected, typically accompanied by elevated fluoride, nitrate, and radium concentrations (Faraj et al., 2020; Makubalo &

Diamond, 2020). These findings highlight the urgent need for integrated groundwater management strategies and sustained research to protect water resources in arid, mining-impacted regions.

As the most arid country in Southern Africa, Namibia faces the critical challenge of protecting its limited groundwater and surface water resources from both pollution and over-extraction (Lohe et al., 2021; Coetzee, 2023; Mapani et al., 2023). Groundwater quality monitoring is therefore essential for detecting and mitigating contamination risks, particularly around tailings storage facilities (TSFs) associated with mining operations. An isotopic study conducted along a precipitation gradient from the Tsumeb area in the north to the central Waterberg and southeast to Kuzikus/Ebenhaezer found that recharge predominantly occurs between January and March, ranging from 1.4% to 11.4% of annual precipitation depending on location (Uugulu & Wanke, 2020).

Namibia's Uranium Province, located along the central coast, hosts some of the world's largest granite-hosted and calcrete uranium deposits (Chudasama et al., 2019; Mapani et al., 2025). This region supports multiple uranium mining operations that contribute substantially to the national Gross Domestic Product (GDP) (Lohe et al., 2021; Namibian Chamber of Mines, 2023). With an average annual rainfall of only 50 mm, groundwater recharge in this arid zone is minimal, making its conservation critically important (Lohe et al., 2021; Atlas of Namibia Team, 2022).

The two uranium mines investigated in this study maintain groundwater monitoring programs, with results reported annually. However, previous research has raised concerns regarding contamination risks in these mining areas (Abiye & Shaduka, 2017; Musiyarira et al., 2017; Mathuthu et al., 2021). For example, Abiye and Shaduka (2017) reported insufficient mitigation measures at the Langer Heinrich Mine, where an unlined tailings dam has contributed to a pollution plume potentially extending toward the Atlantic Ocean via seasonal Swakop River floods. Similarly, Mathuthu et al. (2021) found uranium isotopic ratios ($^{234}U/^{238}U$) below unity in groundwater samples, suggesting that mining rather than natural processes was the dominant contamination source.

Addressing water scarcity and environmental impacts in Namibia's mining industry requires the implementation of sustainable water management practices (Musiyarira et al., 2017). Tailings consist of finely ground rock residues from uranium extraction mixed with process water (Robertson et al., 2019; Mathuthu et al., 2021; Ikotun et al., 2022), which forms tailings pond water. Uranium tailings in the Namib Desert, where annual precipitation rarely exceeds 50 mm pose a distinct challenge, as the limited natural water availability means that tailings pond water is the primary medium for

contaminant transport. Groundwater contamination downstream and beneath unlined tailings dams remain a major concern, as pollutants can migrate into surrounding aquifers (Mathuthu et al., 2021; Rudakov et al., 2023; Tisherman et al., 2023; Zheng et al., 2023).

This study therefore investigates the hydrochemical characteristics and isotopic composition of groundwater surrounding the tailings storage facilities of two uranium mines in Namibia's Uranium Province. It aims to improve understanding of groundwater sustainability and contamination risks in Namibia's uranium-mining region.

4.1.1 Study Area

The study area lies within an arid climatic zone of the Erongo Region (Figure 4-1), characterised by extremely low annual precipitation (0-50 mm), high average annual evapotranspiration rates (2 200- 2 500 mm) (Lohe et al., 2021; Atlas of Namibia Team, 2022; Coetzee, 2023).

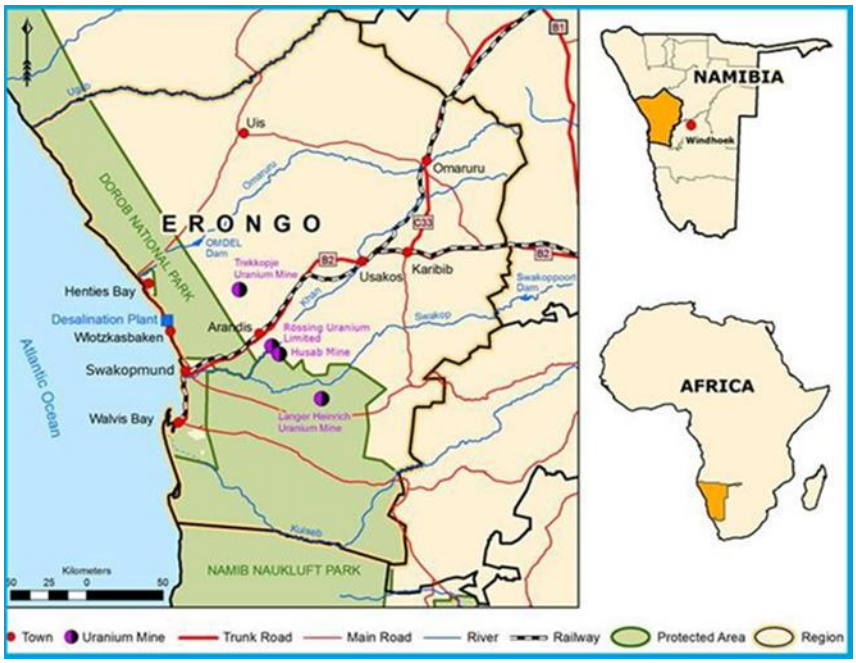


Figure 4-1 Location of the study area in the Erongo region, Namibia, Africa (El Obeid, 2021)

High evapotranspiration rates result in a continuous negative water balance (Lohe et al., 2021; Atlas of Namibia Team, 2022). Temperatures stay elevated year-round, with average maximums varying between 25°C and 40°C (Lohe et al., 2021; Atlas of Namibia Team, 22022; Shiweda et al., 2023). In this water-scarce environment (rainfall occurs sporadically between October and April), groundwater serves as the primary water source for communities, ecological systems and mining due to the near absence of perennial surface water (Hamutoko et al., 2014; Lohe et al., 2021; Mathuthu et al., 2021).

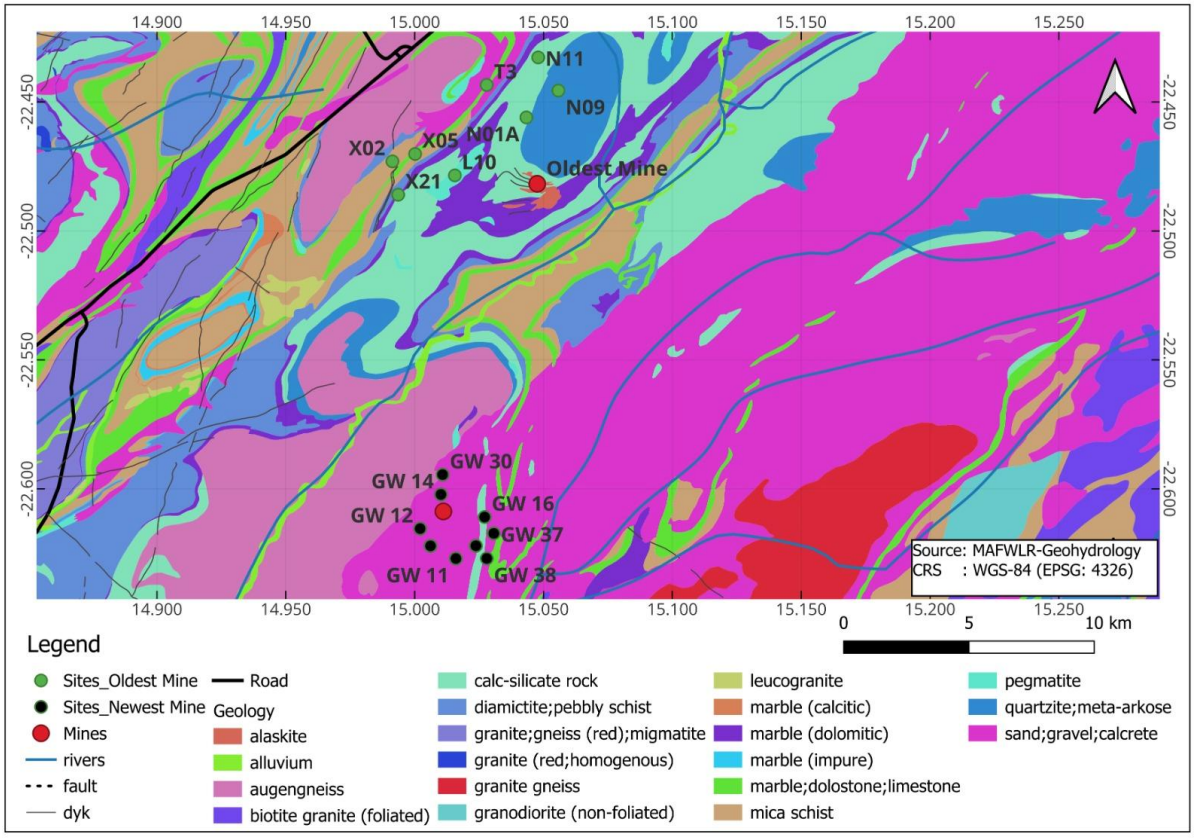


Figure 4-2: Local geology of the study area in the Erongo regin of Namibia (QGIS version 3.40.10 2025)

The study area is dominated by Damaran granitic intrusives and meta-sedimentary units, which are closely associated with uranium mineralisation in the region (Chudasama et al., 2019; Chen et al., 2021; Wilde, 2023). The primary uranium sources are alaskite bodies associated with granitic intrusives of the Damara Belt to the east, whereas younger deposits are associated with post-Cretaceous tectonic uplift and subsequent weathering processes that facilitated the mobilisation of uranium into palaeochannel systems (Hamutoko et al., 2014; Bowell & Davies, 2017; Chen et al., 2021; Wilde, 2023) (Figure 4-2). The region is further characterised by Tertiary palaeo-drainage systems buried beneath unconsolidated Cenozoic sediments, which serve as important groundwater reservoirs (Chudasama et al., 2019; Wilde, 2023; Al Saud, 2025). These sediments host extensive surficial uranium mineralisation, including some of the world's largest calcrete-type uranium deposits (Chudasama et al., 2019; Hamutoko et al., 2014; Shanyengana et al., 2020; Wilde, 2023). These deposits are relatively young, generally no older than the Miocene, and their genesis is closely linked to climatic fluctuations, evaporative concentration, and pedogenic acidification (Wilde, 2023).

Namibia's uranium mining history is characterised by significant mineral exploitation starting in the mid-1970s (Agius et al., 2023). The uranium mining sector has been crucial to Namibia's economy (Shanyengana et al., 2020). However, uranium mining has not been without challenges (Hamutoko et al., 2014; Abiye & Shaduka, 2017; Mathuthu et al., 2021). Studies indicate potential environmental risks, with over 250 abandoned mines posing significant ecological (Salom & Kivinen, 2020). The oldest uranium mine in the study area commenced operations in 1976 and remains the longest-operating open-pit uranium mine in Namibia (Namibian Chamber of Mines, 2023). In 2023, the mine produced approximately 2,920 tonnes of uranium oxide, a 10% increase from the previous year (Namibian Chamber of Mines, 2023). In contrast, the newest uranium mine began export production in 2016 and has since become the second-largest uranium producer globally, recording a total output of 5,318 tonnes of uranium oxide in 2023 (Namibian Chamber of Mines, 2023).

According to annual reports submitted to the Namibian Ministry of Agriculture, Fisheries, Water and Land Reform (MAFWLR), the tailings storage facility (TSF) of the oldest mine covers a basal area of approximately 585 hectares and is situated at an elevation of about 700 metres above sea level. As shown in Figure 4-3, the TSF is unlined, posing potential risks of seepage and groundwater contamination.



Figure 4-3 TSF of the oldest uranium mine in Namibia

The newest uranium mine's TSF is engineered to store up to 186 million cubic meters of tailings over its projected lifespan, which is anticipated to extend until 2036. This facility is lined with a 1 mm high-density polyethylene (HDPE) liner and underlain by a geocomposite, as shown in Figure 4-4. The size of the TSF is 484 ha with a lifespan of 20 years.



Figure 4-4 TSF of the newest uranium mine in Namibia

4.2 Methods

This study employed a mixed-methods approach, integrating both quantitative and qualitative techniques to evaluate the hydrochemical characteristics and isotopic composition of groundwater in the vicinity of TSFs within Namibia's Uranium Province, located in the Erongo Region (Figure 4-1). Groundwater samples were collected during three field campaigns (June 2024, October 2024, and March 2025), representing the early dry, late dry, and late wet seasons, respectively. This design captures seasonal variations in recharge, evaporation, and water-rock interactions that may influence groundwater chemistry. Descriptive statistics (minimum, maximum, and mean) were calculated from the combined dataset across the three sampling campaigns to provide an overall representation of groundwater quality over the study period.

4.2.1 Sampling

A total of sixteen groundwater monitoring boreholes were sampled, eight from the oldest uranium mine (Figure 4-5) and eight from the more recently developed mine (Figure 4-6). Boreholes were selected based on their proximity to the TSFs and alignment with the predominant groundwater flow paths. The locations and characteristics of the sampled boreholes are illustrated in Figures 4-5 and 4-6 and summarised in Tables 4.1 and 4.2.

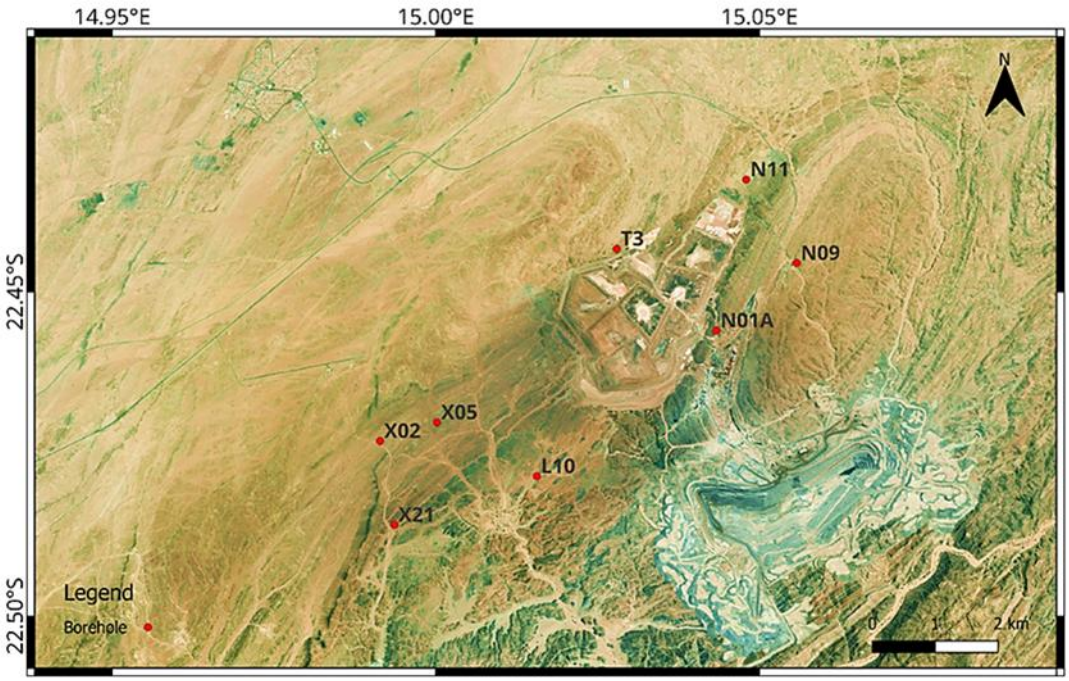


Figure 4-5 Location of boreholes at the oldest uranium mine in Namibia (QGIS version 3.40.5 2025)

Table 4.1 Locations and characteristics of boreholes at the oldest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	Jun-24			Oct-24			Mar-25		
								Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)
T3	22°26′36.13″	15°1′40.73″	9.41	612	0.59	7	612.59	7.16	2.25	605.43	7.36	2.05	605.23	7.34	2.07	605.25
X02	22°28′22.80″	14°59′28.97″	53.44	564	0.56	30	564.56	13.39	40.05	551.17	13.39	40.05	551.17	13.42	40.02	551.14
X05	22°28′12.47″	15°0′0.68″	49.45	561	0.55	25	561.55	4.95	44.5	556.6	5.05	44.4	556.5	4.95	44.5	556.6
X21	22°29′9.35″	14°59′37.03″	49.57	544	0.53	30	544.53	21.47	28.1	523.06	21.77	27.8	522.76	20.74	28.83	523.79
L10	22°28′42.38″	15°0′56.20″	49.48	540	0.52	25	540.52	11.98	37.5	528.54	10.88	38.6	529.64	11.96	37.52	528.56
N01A	22°27′21.46″	15°2′36.13″	52.11	603	0.59	25	603.59	0.1	52.01	603.49	0.1	52.01	603.49	0	52.11	603.59
N09	22°26′43.94″	15°3′20.81″	10.43	591	0.57	8	591.57	3.83	6.6	587.74	3.08	7.35	588.49	3.41	7.02	588.16
N11	22°25′57.68″	15°2′52.66″	49.38	619	0.62	25	619.62	4.83	44.55	614.79	4.68	44.7	614.94	4.77	44.61	614.85

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) – Rest water level (m)

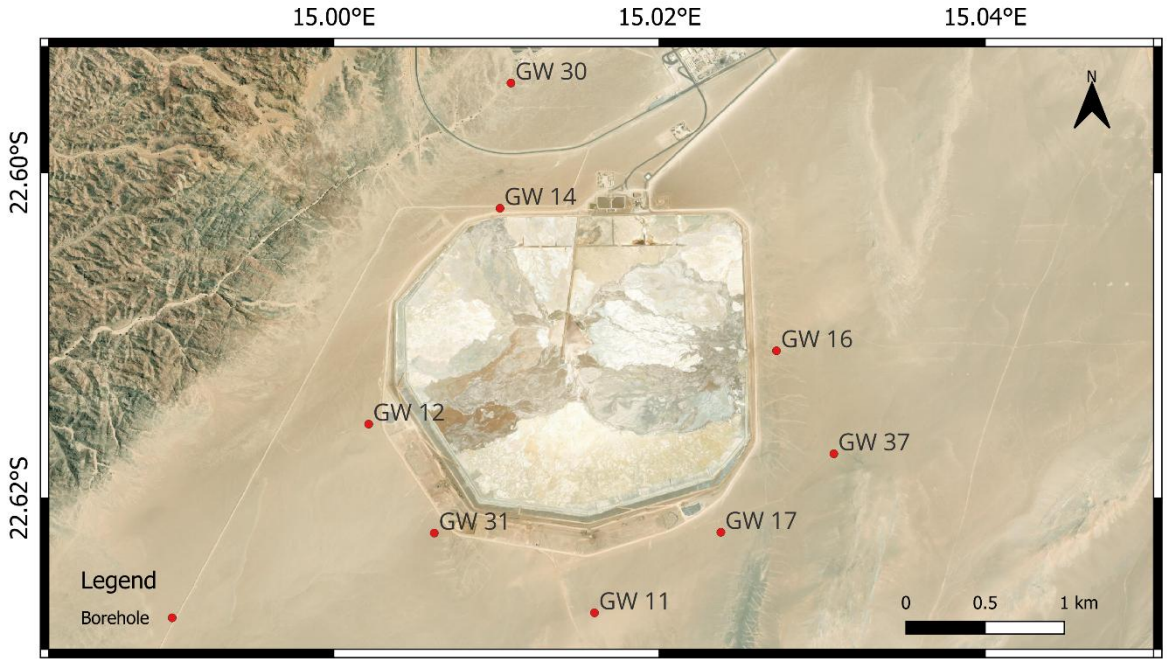


Figure 4-6 Location of boreholes at the newest uranium mine in Namibia (QGIS version 3.40.5 2025)

Table 4.2Borehole locations and characteristics of the newest uranium mine

								Jun-24			Oct-24			Mar-25		
Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	*Rest water level (m)	^Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (m asl)
GW 14	22°36′7.87”	15°0′36.74”	99.49	496	0.51	40	496.51	34.4	96.05	462.11	35.79	63.7	460.72	33.74	65.75	462.77
GW 16	22°36′39.38”	15°1′37.87”	119.93	491	0.35	80	491.35	54.4	65.53	436.95	53.55	66.38	437.8	52.19	67.74	439.16
GW 37	22°37′2.17”	15°1′50.56”	100.05	478	0.51	70	478.51	47.41	52.64	434.1	46.68	53.82	431.83	45.48	54.57	433.03
GW 17	22°37′19.54”	15°1′25.58”	99.87	469	0.48	80	469.48	60.5	39.37	408.98	58.02	41.85	411.46	54.14	45.73	415.34
GW 11	22°37′37.34”	15°0′57.63”	98.9	464	0.51	70	464.51	43.41	55.49	426.1	41.19	57.71	423.32	40.29	58.61	424.22
GW 31	22°37′19.71”	15°0′22.21”	106.42	466	0.54	80	466.54	31.91	74.48	434.63	32.56	73.86	433.98	81.09	24.91	385.45
GW 12	22°36′55.61”	15°0′7.71”	120.48	472	0.52	90	472.52	80.9	39.58	391.62	79.88	40.6	392.64	33.03	87.45	439.49
GW 30	22° 35' 40.16”	15° 0' 39.16"	101.8	498	0.52	80	498.52	33.24	68.56	465.28	32.55	69.25	465.97	23.46	78.34	475.06

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - rest water level (m)

4.2.2 Field Measurements and Sample Collection

On-site physicochemical parameters were measured at each borehole using calibrated instruments: an AQUAREAD AP-5000 multiparameter probe for pH, electrical conductivity (EC), temperature, and GPS coordinates; a HACH 2100Q turbidimeter for turbidity; an OHAUS Starter 400D meter for dissolved oxygen (DO); and a dip meter for depth-to-water measurements. Prior to sampling, each borehole was purged to remove stagnant water and ensure that the collected samples represented in situ groundwater conditions. Duplicate samples were collected at each borehole. Samples destined for laboratory analysis were stored at 4 °C in a portable camping refrigerator to preserve their integrity.

From each borehole, three water samples were collected and filtered through a 0.45 µm cellulose membrane. One set was used for the analysis of major ions and general hydrochemical parameters, including total dissolved solids (TDS), electrical conductivity (EC), redox potential (Eh), dissolved oxygen (DO), chloride (Cl^-), fluoride (F^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), nitrite (NO_2^-), bicarbonate (HCO_3^-), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}). For cation analysis, 250 mL of the sample was acidified with 10% nitric acid (HNO_3) to prevent precipitation and adsorption.

For stable isotope analysis (δ^2H and $\delta^{18}O$), water was collected in 50 mL polyethylene bottles, filtered through a 25 mm syringe filter with a 0.45 µm cellulose acetate membrane, and tightly sealed to prevent evaporation. Isotopic analysis was performed at the Central Veterinary Laboratory in Windhoek using a Picarro Cavity Ring-Down Spectrometer (Model L2130-I). Measurements were expressed relative to the internationally recognised Vienna Standard Mean Ocean Water (VSMOW) reference standard, with all isotope ratios reported as δ-values in per mil (‰).

4.2.3 Laboratory Analysis

Chemical analyses were conducted at the Analytical Laboratory in Windhoek. Cations were measured using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), while anions were analysed using a combination of methods: calculation (bicarbonate), titration (for chloride), ion-selective electrode (for fluoride), turbidimetry (for sulphate), UV–V is spectrophotometry, and the Merck test kit (for nitrate and nitrite). A certified PerkinElmer technician performed instrument calibration during scheduled maintenance intervals. Quality control procedures included the use of analytical blanks, sample replicates, and certified reference materials.

Analytical uncertainty was carefully evaluated using certified reference materials, replicate samples, and charge-balance calculations. The consistent recoveries (within 90-110 %) and low CBE deviations (< ± 5 % for most samples) confirm the robustness of the chemical dataset and the reliability of subsequent hydrogeochemical interpretations. All analyses were conducted in accordance with the laboratory's Standard Operating Procedures (SOPs), based on the Standard Methods for the Examination of Water and Wastewater (AWWA, Latest Edition). Analytical accuracy was evaluated using the ion charge balance error (CBE) method. Of the 48 groundwater samples analysed, 38 samples (79%) fell within the acceptable ±5% CBE threshold, indicating reliable analytical precision. The remaining 10 samples showed slightly higher deviations, but these were not significant enough to affect the overall hydrogeochemical interpretation. Given the consistency of the major ion trends, all samples were included in subsequent analyses.

4.2.4 Data Analysis

Hydrogeochemical data were processed using R software (version 4.3.0) and Microsoft Excel (version 2502) for descriptive and inferential statistical analyses. To assess variations in groundwater quality between the oldest and newest uranium mines, a two-sample t-test was used to test for statistically significant differences in the measured parameters. To avoid temporal pseudo-replication, repeated measurements from the same boreholes across campaigns were averaged, and the resulting mean values per borehole were treated as independent observations in the two-sample t-tests. Hydrogeochemical facies were visualised using Piper diagrams generated with DIAGRAMME (version 9.20), while the spatial distribution of boreholes was mapped in QGIS (version3.40.5). The map of the local geology was visualised with QGIS version 3.40.10.

4.3 Results and Discussion

The following sections present the results of the hydrogeochemical and stable isotope analyses, together with the statistical comparison of groundwater quality between the two uranium mines. The comparative analysis revealed no statistically significant differences in groundwater quality parameters between the oldest and newest uranium mines.

4.3.1 Hydrogeochemistry

Descriptive statistics for the selected hydrogeochemical parameters at both mines are presented in Table 4. 3.

Table 4.3 Summary of the descriptive statistics of the hydrogeochemical parameters.

Parameter	oldest uranium mine (n=8)			newest uranium mine (n=8)		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
pH	5.6	8	7.2	6.7	8.3	7.8
Turbidity (NTU)	32.4	1112	342.4	1.8	53.8	14.1
EC (µS/cm@25C)	6882	37332.7	20616.2	4730.7	38282	17998
TDS (mg/L)	4327	32105	14027.2	4108	26673	13356.5
Eh (mV)	-215.8	112.3	21.2	19.2	135.0	84.9
DO (mg/L)	2.9	6.7	4.7	2.3	6.5	4.7

The oldest uranium mine exhibits a broad pH range, from acidic to highly alkaline. pH values range from 5.6 at borehole N09 to 8 at N11, with a mean of 7.2. Borehole N09, located 1,100 m east of the tailings storage facility (TSF), consistently displays acidic conditions (mean pH = 6.5). In contrast, boreholes T3 (pH = 7.5) and N01A (pH = 7.3) (Figure 4-5) show near-neutral conditions, while the remaining boreholes reflect predominantly alkaline groundwater chemistry.

The newest uranium mine, by comparison, shows a narrower and more stable pH range, indicative of near-neutral to mildly alkaline conditions. Values range from 6.7 at GW16 to 8.3 at GW37, with a slightly lower mean pH of 7.8 (Figure 4-6). This moderate pH range may indicate improved environmental management practices, effective containment systems, and minimal geochemical alteration over time; however, it may also reflect the relatively short operational history of the mine.

The pH variability in the oldest mine is primarily driven by differences in geology and climate, particularly the high evaporation rates characteristic of the arid region (see detailed regional geology in Section 4.1.1). Granitic weathering can produce a wide range of pH values (4.7 to > 8), whereas

carbonate-bearing formations such as marble and limestone yield near-neutral to alkaline conditions (7.6–8.4) (Makubalo & Diamond, 2020; Skierszkan et al., 2020; Wilde, 2023). pH also plays a key role in uranium mobility, with higher pH generally enhancing uranium solubility (Kirby et al., 2020; Filter et al., 2024; Sofronova et al., 2025). Under acidic conditions (pH 2–4), uranium is transported as the hexavalent uranyl cation UO_2^{2+}, often complexed with Cl^- or SO_4^{2-} (Kirby et al., 2020; Baqer et al., 2023). In neutral to alkaline conditions, U(VI) forms stable carbonate and bicarbonate complexes ($UO_2(CO_3)_3^{4-}$, $UO_2(CO_3)_2^{2-}$, and $UO_2(HCO_3)_3^-$), which greatly enhance its mobility (Kalintsev et al., 2020; Foster et al., 2022).

Groundwater turbidity is largely influenced by seepage from TSFs and the geochemical or hydraulic mobilisation of colloidal particles within aquifers (Zhang et al., 2019; Kim et al., 2020; J. Zhang et al., 2022; Fujihara et al., 2024). At the oldest mine, turbidity ranged from 32.43 Nephelometric Turbidity Units (NTU) at borehole T3 to 1,112 NTU at N11 (mean = 342.4 NTU). These elevated levels reflect substantial suspended particulate matter, likely derived from historical mining residues and eroded sediments. In contrast, turbidity in the newest mine was markedly lower, ranging from 1.8 NTU at GW16 to 53.8 NTU at GW14 (mean = 14.1 NTU). The lower turbidity values indicate relatively clear groundwater, possibly due to geological differences where the oldest mining area is dominated by schists that promote turbidity, whereas the newest mine is hosted mainly in granitic rocks that yield clearer water (Shanyengana et al., 2020; Ram et al., 2021; Samper et al., 2022). These contrasts underscore significant differences in water clarity and particulate load between the two sites.

Electrical conductivity (EC) and total dissolved solids (TDS) showed a strong positive relationship across all groundwater samples, consistent with established hydrogeochemical patterns. In the oldest mine, EC values ranged from 6,882 µS/cm to 37,332.7 µS/cm (mean = 20,616.2µS/cm), while TDS concentrations varied between 4,327 mg/L and 32,105 mg/L (mean = 14,027.2 mg/L). At the newest mine, EC ranged from 4,730.7 µS/cm to 38,282 µS/cm (mean = 17,998 µS/cm), and TDS from 4,108 mg/L to 26,673 mg/L (mean = 13,356.5 mg/L). These results indicate high salinity levels characteristic of arid-zone aquifers (Hamutoko et al., 2014; Marusia et al., 2021; Pandit et al., 2022).

The slightly higher mean EC and TDS values in the oldest mine likely reflect cumulative effects of historical mining, legacy waste practices, and deeper groundwater circulation through mineralised zones. Long-term seepage from TSFs, waste-rock dumps, and evaporation ponds introduces soluble salts into aquifers (Newman et al., 2020; Bilibio et al., 2021; Elkhoumsi et al., 2022). Furthermore,

oxidation of sulphate-bearing waste and dissolution of secondary minerals in poorly contained stockpiles generate saline leachates that migrate into groundwater (Liu et al., 2019; Grantcharova & Fernández-Caliani, 2021; Guo et al., 2024). The strong correlation between EC and TDS across both sites highlights the dominance of dissolved ions in solution and demonstrates EC's reliability as a rapid proxy for assessing salinity and groundwater quality in mining-affected environments.

Redox potential (Eh) in the oldest mine ranged from −215.8 mV at X21 to 112.33 mV at N01A (mean = 21.16 mV), indicating predominantly reducing to mildly oxidising conditions. Uranium mobility in groundwater is closely linked to redox state, with higher solubility and radium prevalence occurring under reducing conditions (Vengosh et al., 2022; Choi et al., 2023). The newest mine exhibited higher Eh values, ranging from 19.8 mV at GW31 to 135.0 mV at GW30 (mean = 84.90 mV), reflecting a more oxidising environment that favours the mobility of redox-sensitive species such as uranium and arsenic. Under oxidising conditions, uranium predominantly occurs as U(VI), which is both more soluble and mobile (Skierszkan et al., 2021; Baják et al., 2022).

Dissolved oxygen (DO) levels were relatively similar between sites. The oldest mine recorded DO values ranging from 3 mg/L at N09 to 6.7 mg/L at X02 (mean = 4.7 mg/L), while the newest mine ranged from 2.3 mg/L at GW31 to 6.5 mg/L at GW16 (mean = 4.7 mg/L). These moderately oxidising conditions suggest that both aquifers can sustain the transport of uranium in its hexavalent form.

4.3.2 Major Ions

Major ions are widely used to characterise groundwater chemistry, identify contamination sources, and assess processes such as salinisation or water-rock interaction (Sudaryanto & Naily, 2018; Ch et al., 2022; Segaran et al., 2022). Table 4.4 summarises the observed concentrations of major ions in groundwater samples from the two uranium mines.

Table 4.4 Summary of descriptive statistics of the major ions.

Parameter	oldest uranium mine (n=8)			newest uranium mine (n=8)		
	Minimum (mg/L)	Maximum (mg/L)	Mean (mg/L)	Minimum (mg/L)	Maximum (mg/L)	Mean (mg/L)

Chloride (Cl^-)	1406	16378	7442	830	16378	6115.29
Fluoride (F^-)	0.2	3.2	1.7625	0.5	2.5	1.895833
Sulphate (SO_4^{2-})	1121	4238	2180.38	1308	3913	2258.13
Nitrate (NO_3^-)	0.2	1051	122.27083	0.6	577	120.7917
Nitrite (NO_2^-)	0	0.44	0.06125	0.01	0.76	0.0775
Bicarbonate (HCO3$^-$)	23.33	600	162.04	68.33	825.67	234.83
Sodium (Na^+)	857	8107	3812.71	912	8176	3463.29
Potassium (K^+)	74	215	128.28792	32	524	162.8333
Magnesium (Mg^{2+})	60	745	317.70833	35	610	243.1667
Calcium (Ca^{2+})	319	2456	1249.125	337	2044	947.7917

Sulphate $(SO_4^{2})^-$ is a key indicator of groundwater contamination from uranium processing, as sulfuric acid is extensively used in uranium extraction (Pandey et al., 2022; Sahoo et al., 2022; Guillon et al., 2024). Sulphate concentrations are relatively high at both mines, with the newer uranium mine showing a marginally higher mean (2 258.13 mg/L) than the older mine 2 133.72 mg/L. The aesthetic guideline of sulphate by WHO is 250ml, and for the Namibian Water Quality Guidelines for Potable water acceptable standard is <300ml (Ministry of Agriculture, 2013; World Health Organisation, 2022). The elevated sulphate levels are primarily attributed to the use of sulfuric acid in processing and subsequent leaching from tailings and waste rock (Cheng et al., 2022; Li et al., 2023; Liu et al., 2023). Monitoring records at the oldest mine consistently demonstrate a correlation between sulphate increases in groundwater boreholes and sulfuric acid inputs from ore processing at the plant, while hydrogeological variables such as redox conditions and flow paths further influence sulphate distribution (Abiriga et al., 2021; Daniel Chukwuemeka & Innocent Onyebuchi, 2021; Liu et al., 2023). Collectively, these factors explain the persistently high sulphate concentrations observed.

Both sites also present elevated chloride (Cl^-) levels; the older mine recorded a mean of 7 134.25 mg/L, slightly higher than the new mine's mean of 6 115.29 mg/L. These values likely result from prolonged evaporation and possible saltwater intrusion (Pandit et al., 2022). The wide range of chloride concentrations in the older mine (1 141-16 378 mg/L) indicates pronounced heterogeneity, potentially driven by complex lithology (De la Torre et al., 2020; Mohuba et al., 2020). In addition, limited recharge under arid conditions and legacy impacts, such as seepage from TSFs and waste dumps, contribute to spatially variable chloride enrichment (Edraki et al., 2019; Destouni et al., 2021; Adadzi et al., 2022).

Sodium concentrations are relatively high at both mines, reflecting significant water–rock interaction, ion exchange, and possible anthropogenic influence. In the oldest mine, sodium ranged from 857 mg/L to 8 107 mg/L (mean= 3 868.90), while the newest mine showed a comparable range (912 to 8 176 mg/L) with a slightly lower mean 3 463.29 mg/L. The predominance of Na-Cl water types and sodium concentrations above 500 mg/L across both sites underscores the role of evaporation and mineral dissolution in this arid environment (Kringel et al., 2010; Hamutoko et al., 2014; Abiye & Shaduka, 2017; Amwele et al., 2021).

Fluoride (F^-) concentrations showed comparable ranges between the two mines. In the oldest uranium mine, fluoride levels ranged from 0.2 mg/L to 3.2 mg/L, with a mean of 1.76 mg/L, while in the newest uranium mine, concentrations varied from 0.5 mg/L to 2.5 mg/L, averaging 1.90 mg/L. These relatively similar values suggest that fluoride enrichment is influenced more by localised geochemical conditions such as dissolution of apatite and minor fluorite in the Damara granites than by mining age (Makubalo & Diamond, 2020).

Nitrate ($N0_3^-$) and nitrite ($N0_2$) concentrations are also elevated at the oldest uranium mine than the newest uranium mine. Higher means were recorded at the older mine (122.27mg/L; 0.06mg/L) than at the newer mine (120.8 mg/L; 0.08 mg/L). Extremely high nitrite in the older mine (up to 1051 mg/L) may indicate prolonged nitrogen cycling, linked to past anthropogenic inputs, organic matter decay, or incomplete denitrification under semi-oxic conditions (Liu et al., 2021).

Bicarbonate ($HCO3^-$) levels highlight further contrast: the oldest mine ranged from 23.33 mg/L to 600 mg/L (mean 162.04 mg/L), while the newest mine displayed higher values (68.33 – 825.67 mg/L, mean 234.83 mg/L). Elevated bicarbonate in the newest mine may reflect enhanced dissolution of carbonate minerals such as calcite and dolomite, fostered by more sustained water-rock interactions or longer residence times (Kim et al., 2024; Oberhelman et al., 2024). Both sites overlie carbonate-bearing units, which contribute to uranium mineralisation and buffering capacity. Elevated HCO_3^- may thus promote alkaline conditions and influence trace metal transport and speciation.

Potassium concentrations differed most: the oldest mine had a mean of 128.29 mg/L (range 74 – 215 mg/L), versus the newest mine's mean of 162.83 mg/L (range 32-524 mg/L). High potassium in the

older mine likely reflects greater feldspar dissolution and legacy tailings input, coupled with naturally less mobile behaviour of K^+ in groundwater (Banerjee & Prasad, 2020; Ji et al., 2024).

Both magnesium (mean = 314.75 mg/L) and calcium (1,207.50 mg/L) are elevated in the older uranium mine relative to the newer mine (Mg: 243.17 mg/L; Ca: 947.79 mg/L). While both carbonate and silicate weathering may contribute to these concentrations (Huang et al., 2024), carbonate dissolution is likely the dominant process in the present study area. This interpretation is supported by the elevated total alkalinity and the presence of calc-silicate lithologies within the host formation, which promote enhanced calcite and dolomite dissolution under prolonged water-rock interaction. The longer operational history of the older mine further increases groundwater residence time, favouring intensified carbonate weathering compared to the newer site.

4.3.3 Geochemical Processes

Piper diagrams are commonly used to classify groundwater types and interpret hydrogeochemical evolution (Piper, 1944; Appelo & Postma, 2013; Hamutoko et al., 2017). Since TDS (a proxy for overall ionic strength and salinity) showed little variation across boreholes at each mine (see Table 4.3), we used average values for the Piper diagram analysis.

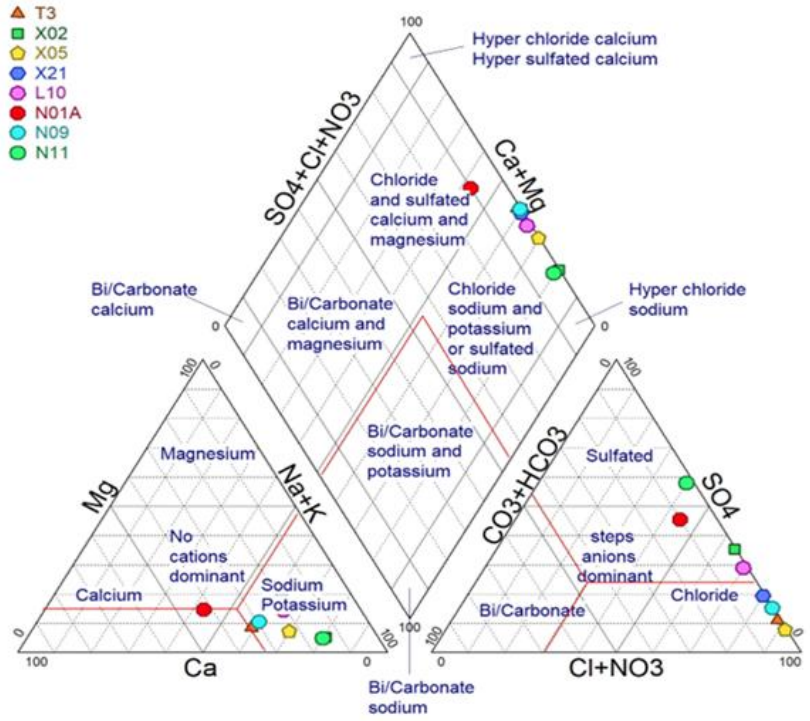


Figure 4-7 Piper diagram for the boreholes from the oldest uranium mine in meq/L

Groundwater samples from the oldest uranium mine plot predominantly within the chloride-sulphate-calcium-magnesium facies, suggesting consistent hydrochemical characteristics, as shown in Figure 4-

7. The dominance of divalent cations (Ca^{2+}, Mg^{2+}) and strong acid anions (Cl^{-}, SO_4^{2-}) indicates that these waters have undergone extensive rock-water interaction and the usage of sulphuric acid in the processing of uranium. This can be attributed to leachate from TSFs. These samples also fall within the "hyperchloride calcium" and "hyper sulphated calcium" fields in the central diamond, indicating elevated salinity and ion-exchange processes typical of long-term mining influence (Krishan et al., 2021; Obasi et al., 2021; Adamovic et al., 2022).

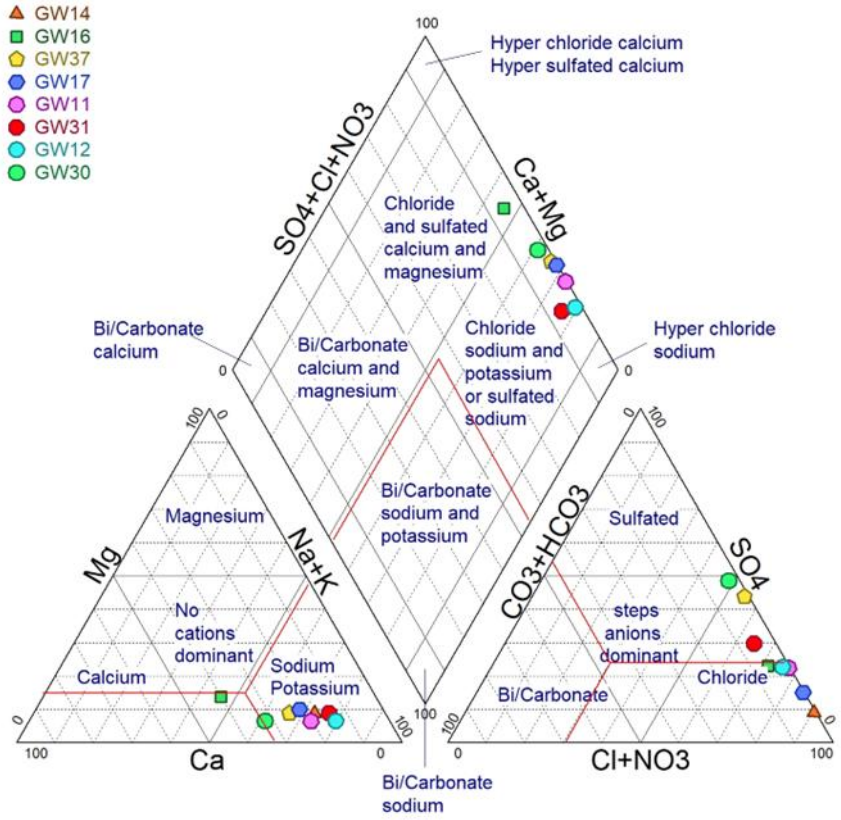


Figure 4-8 Piper diagram for the boreholes from the newest uranium mine in meq/L

In contrast, groundwater samples from the newest uranium mine also plot within the chloride-sulphate field but display a slightly greater spread toward the sodium-potassium facies, particularly for anions, as illustrated in Figure 4-8. This pattern suggests more variable geochemical processes, likely influenced by differences in geology, hydrodynamics, or the mine's shorter operational history. Geologically, the presence of alkali-bearing minerals such as feldspars and micas can release Na^{+} and K^{+} through silicate weathering, particularly under sulphate-rich conditions generated by the oxidation of sulphide minerals (Swoboda et al., 2022; Czerewko & Cripps, 2023). Hydrodynamically, disturbed

flow regimes, shorter groundwater residence times, and enhanced mixing between shallow and deeper aquifers during the early stages of mine development contribute to water-chemistry variability.

Furthermore, the use of sulphuric acid in ore processing introduces an additional source of sulphate and acidity, which accelerates mineral dissolution, mobilises Na^+ and K^+ from silicates and clays, and intensifies the observed chemical heterogeneity (Newman et al., 2019; Prates et al., 2020).

Although both mines are dominated by chloride-sulphate waters, the newest uranium mine exhibits a tighter clustering toward sodium/potassium-dominated facies, indicating a more uniform hydrochemical signature that may reflect the effects of recent mining activities. In contrast, the oldest uranium mine displays a greater diversity of water types, reflecting long-term geochemical evolution, a broader range of water-rock interactions, and potentially variable contaminant migration pathways developed over several decades, as indicated in other studies as well (Antunes et al., 2021; Cardenas et al., 2023; De Windt et al., 2025). The broader spread in the oldest mine may also result from cumulative impacts of historical operations, changes in mine-water management practices, and inherent hydrogeological heterogeneity.

Overall, the Piper diagrams reveal that the dominant hydrochemical facies (water types) at both sites are similar, indicating comparable underlying geochemical processes. However, the degree of hydrochemical variability reflected in the differences in significant ion concentrations is notably greater at the oldest uranium mine site. This increased variability, particularly in sulphate levels, is likely due to the longer operational history of the mine and the more complex mixing of natural groundwater with mining-impacted water from the TSF. These findings align with observed evidence of progressive downstream migration of sulphate from the TSF, highlighting the evolving impact of mining activities on groundwater chemistry over time (Abdelaal et al., 2021; Cheng et al., 2022; Chandekar et al., 2024).

4.3.4 Composition of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$) isotopes

Groundwater samples for $\delta^{18}O$ and $\delta^{2}H$ were analysed and compared with the Global Meteoric Water Line (GMWL; $\delta^{2}H = 8 \times \delta^{18}O + 10$) and the Local Meteoric Water Line (LMWL; $\delta^{2}H = 7.2 \times \delta^{18}O + 4.1$) for the Kuiseb basin in Namibia. The LMWL equation was derived by Turewicz in 2013 (Kgabi et al., 2018). The Kuiseb Basin is located in the vicinity of the study area and is more representative of the regional climatic and hydrological conditions, and is herein used for reference. While sources provide extensive isotopic rainfall data for other Namibian regions, such as the Cuvelai-Etosha Basin (Hamutoko et al., 2017; Mpofu et al., 2025; Wanke et al., 2025), none specifically address the study

area. This can be because the study area receives extremely low annual rainfall of about 0-50mm (Lohe et al. 2021, Atlas of Namibia Team 2022, Coetzee 2023).

The δ^2H and $\delta^{18}O$ values of groundwater samples from the oldest uranium mine plot are significantly below both the Global Meteoric Water Line (GMWL: $\delta^2H = 8 \times \delta^{18}O + 10$) and the Local Meteoric Water Line (LMWL: $\delta^2H = 7.2 \times \delta^{18}O + 4.1$), as shown in Figure 4-9. The regression line derived from the sampled data is described by the equation $\delta^2H = 1.93 \times \delta^{18}O - 22.22$, with a much shallower slope than both the GMWL and LMWL. This substantial deviation indicates that the groundwater has undergone significant evaporative enrichment, likely during or prior to recharge, leading to enrichment in heavier isotopes (higher $\delta^{18}O$ and δ^2H values)

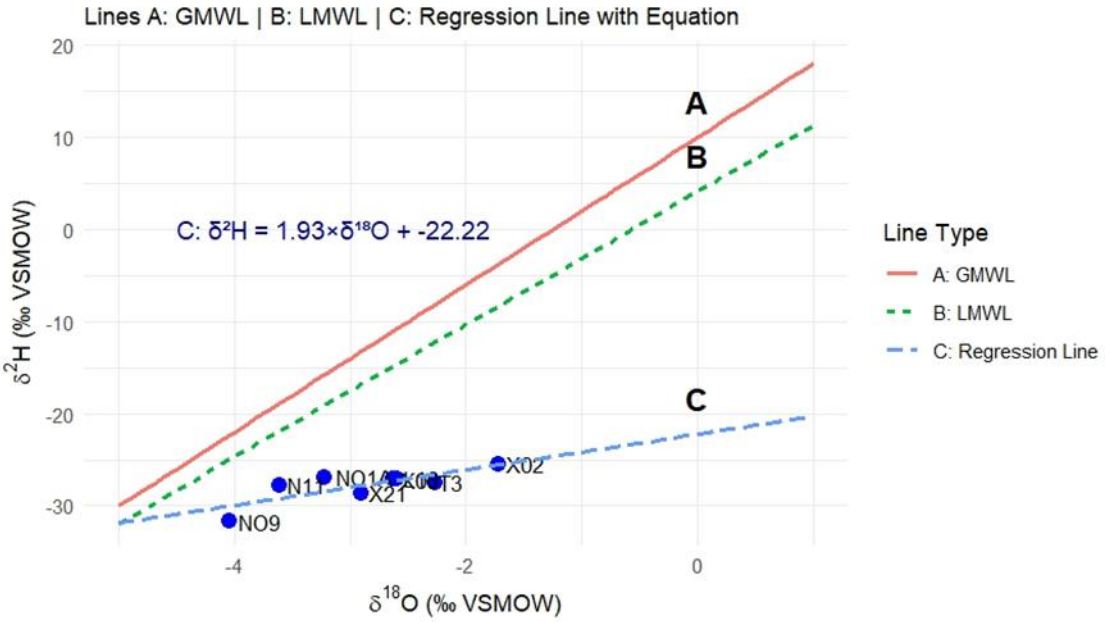


Figure 4-9 GMWL and LMWL lines on the δ^2H against $\delta^{18}O$ plot, including regression lines for the oldest uranium mine.

The d-excess values further support this interpretation. While typical meteoric waters have a d-excess of ~10‰, the groundwater samples exhibit consistently low and even negative d-excess values, ranging from –11.91‰ to 1.90‰, with a mean of –5.41‰. The lowest d-excess values (e.g., X02: –11.73‰; T3: –9.31‰) suggest recharge under low humidity conditions, characteristic of arid to semi-arid environments. These negative values are diagnostic of non-equilibrium evaporation, where the water has been subject to substantial evaporation either at the land surface (before infiltration) or within shallow unsaturated zones (Sreedevi et al., 2021; Xia et al., 2022).

The isotopic composition of samples such as NO9, N11, and NO1A (with $\delta^{18}O$ values below –3.5‰ and $\delta^{2}H$ more depleted than –30‰) indicates recharge from older or more distal precipitation sources, potentially linked to palaeo waters or episodic recharge events under different climatic regimes (Xia et al., 2022; García-López et al., 2023; Ram et al., 2024)

Overall, the isotopic signatures suggest that groundwater in the oldest uranium mine area is predominantly recharged from evaporated local precipitation, with limited modern recharge. The shallow slope of the regression line and depleted isotopic values underscore the influence of arid climate, long residence times, and possibly interactions with mine infrastructure or legacy waste that may contribute to isotopic fractionation.

The stable isotope composition of groundwater from the newest uranium mine provides important insights into recharge dynamics and evaporative processes within the hydrogeological setting impacted by mining. When evaluated against both the GMWL and the LMWL, the isotopic signatures reveal evidence for both meteoric recharge and varying degrees of evaporation before infiltration (Figure 4-10).

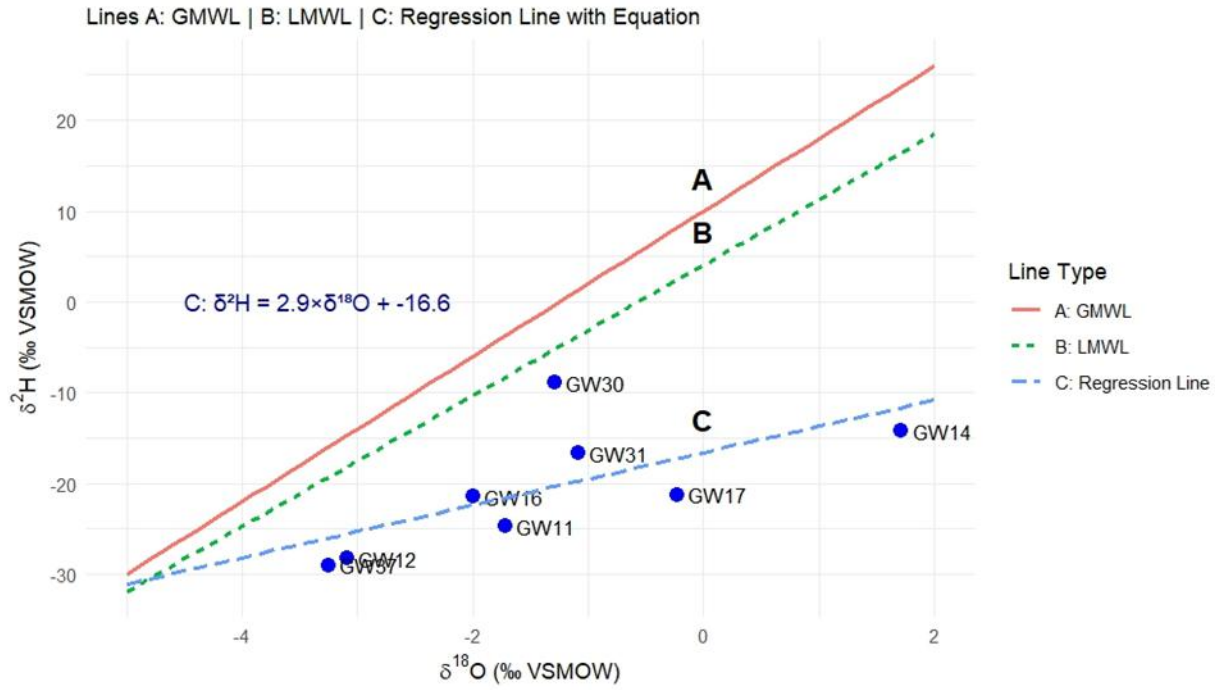


Figure 4-10 GMWL and LMWL lines on the $\delta^{2}H$ against $\delta^{18}O$ plot, including regression lines for the newest uranium mine.

Boreholes such as GW12 and GW37 exhibit depleted δ^2H and $\delta^{18}O$ values (δ^2H=-28.28 to -28.99‰; $\delta^{18}O$=-3.09 to -3.25‰) that plot near the LMWL and are accompanied by relatively high d-excess values (> +2‰). The elevated d-excess indicates that these waters likely originated from local precipitation with minimal isotopic modification. This is consistent with direct meteoric recharge, occurring rapidly through fractures or coarse sediment layers, typical of ephemeral recharge events in arid climates.

Conversely, GW30 is characterised by enriched δ^2H and $\delta^{18}O$ signatures (δ^2H = -11.13 to +1.40‰; $\delta^{18}O$ = -1.54 to +1.40‰) and exhibits markedly negative d-excess values, in some cases below -5‰. Such negative d-excess is a clear indicator of non-equilibrium evaporation, where water experiences substantial evaporative enrichment under low humidity and high temperature conditions before recharge (Mathuthu et al., 2025). This likely reflects infiltration from surface water bodies exposed to prolonged evaporation, such as ponds, tailings storage facilities, or runoff accumulation areas, highlighting the anthropogenic modification of the recharge process in certain zones of the mine. A wastewater treatment system is located north of the mine's borehole GW 30.

Intermediate boreholes (GW11, GW16, GW17 and GW31) plot slightly below the LMWL and show moderately negative d-excess values (-3‰ to -10‰), suggesting partial evaporative enrichment (Zhu et al., 2021; Letshele et al., 2023; Mathuthu et al., 2025). These signatures are indicative of recharge from water that underwent limited evaporation likely via soil moisture or shallow surface pools, before percolating into the aquifer.

The d-excess values when considered alongside δ^2H and $\delta^{18}O$ data, thus serve as an important diagnostic tool in distinguishing between groundwater derived from unmodified meteoric input versus that influenced by evaporation (Gibrilla et al. 2022, Mathuthu et al. 2025). The combined isotopic evidence reveals a dual recharge regime within the newest mine area: (1) infiltration of regionally derived meteoric water during episodic rainfall events and (2) recharge from locally evaporated sources, potentially exacerbated by mining infrastructure and land use.

For the oldest mine, the relationship between δ^2H and $\delta^{18}O$ was $\delta^2H = 1.93\ \delta^{18}O - 22.22$ ($R^2 = 0.18$, $p = 0.19$), while for the newest mine it was $\delta^2H = 2.90\ \delta^{18}O - 16.60$ ($R^2 = 0.33$, $p = 0.11$). Both slopes are below the typical evaporation range (4 - 6) but have wide confidence intervals, reflecting limited sample size and $\delta^{18}O$ variability. Diagnostic tests (residuals, Cook's D, and leverage) show no outliers or normalisation errors. The low apparent slopes, therefore, likely reflect partial mixing between depleted recharge and isotopically enriched groundwater rather than analytical bias. These findings

underscore the complex interplay between natural hydrological processes and mine-induced alterations in arid environments. The strong evaporative signals and negative d-excess values in specific boreholes also highlight potential zones of increased vulnerability to solute concentration and contamination, warranting targeted hydrogeochemical monitoring and groundwater protection strategies.

4.3.5 Comparison of groundwater quality between the Oldest and Newest Uranium Mines

Two-sample t-tests revealed that, of the 16 parameters analysed, only redox potential, turbidity, and pH showed statistically significant differences between sites at the 95% confidence level ($p < 0.05$). These results are summarised in Table 4.5

Table 4.5 Summary of t-test results comparing groundwater parameters

Parameter	p-value	oldest uranium mine mean	newest uranium mine mean	Sample Size (n)	Effect Size (Mean Difference)	Significant (α =0.05)
Calcium	0.29	1249.12	933.97	8	315.15	No
Chloride	0.53	7442.00	5890.53	8	1551.47	No
DO	0.93	4.72	4.68	8	0.04	No
Electrical Conductivity	0.87	2328.29	2224.75	8	103.54	No
Fluoride	0.86	1.76	1.83	8	0.07	No
Magnesium	0.38	317.71	240.03	8	77.68	No
Nitrate	0.69	122.27	152.07	8	29.8	No
Nitrite	0.11	0.09	0.22	8	0.13	No
Potassium	0.53	128.29	165.03	8	36,74	No
Redox	0.01	21.16	84.90	8	63.74	Yes
Sodium	0.68	3812.71	3338.19	8	474.52	No
Sulphate	0.89	2180.38	2224.81	8	44.43	No
Bicarbonate	0.45	162.04	254.83	8	92.79	No

Total Dissolved Solids	0.78	16665.04	15413.25	8	1251.79	No
Turbidity	0.01	342.36	14.10	8	328.26	Yes
pH	0.02	6.55	7.00	8	0.45	Yes

The oldest uranium mine exhibited a lower mean redox potential (21.16 mV), higher turbidity (mean = 342.36 NTU), and slightly acidic conditions (mean pH = 6.55), indicative of reducing environments that can enhance uranium mobility (Filter et al., 2024). Although direct uranium concentrations or U-series isotopic ratios were not measured in this study, these redox and pH conditions suggest potential for increased uranium solubility and transport, consistent with established geochemical behaviour under reducing conditions (Alvarez Salas et al., 2020; Smedley & Kinniburgh, 2022). Leaching from waste rock dumps and TSFs introduces both chemical contaminants and suspended particulates into groundwater, especially when containment structures are inadequately engineered or degraded. Such legacy impacts promote elevated turbidity and trace metal enrichment in groundwater.

In contrast, the newest uranium mine showed more oxidising conditions (mean redox = 84.90 mV), lower turbidity (mean = 14.10 NTU), and near-neutral pH (mean = 7.0), reflecting limited geochemical alteration, effective containment systems, and improved environmental management. These differences highlight the role of mine age, design, and operational standards in shaping hydrogeochemical characteristics within uranium-mining environments.

Comparative analysis of groundwater quality between the two mines reveals greater variability and contamination at the oldest site, characterised by extreme pH, high turbidity, elevated fluoride levels, and redox behaviour consistent with legacy contamination. The newest mine, by contrast, exhibits more stable, near neutral, and oxidising conditions, suggesting more mature aquifer management and reduced geochemical disturbance. Isotopic evidence at this site shows more variable $\delta^{18}O$ and $\delta^{2}H$ signatures (e.g., wider scatter in d-excess), consistent with ongoing mixing between mine waters and local aquifers reflecting active recharge in a less evaporated system. In comparison, the oldest site displays isotopic enrichment indicative of prolonged evaporation as the dominant process. Statistically, only redox potential, turbidity, and pH differed significantly between the two sites, while other parameters showed no meaningful variation.

4.4 Conclusion

This study demonstrates prominent spatial variability in groundwater quality across uranium-mining zones in Namibia, revealing distinct hydrogeochemical and isotopic signatures between older and newer operations. The oldest uranium mine exhibits greater variability in water chemistry, manifested by extreme pH, elevated turbidity, high fluoride concentrations, and complex redox dynamics, reflecting legacy contamination and prolonged geochemical evolution. In contrast, the newer mine shows more stable, near-neutral, and oxidising conditions, attributable to improved containment design and shorter operational history.

Stable isotope analysis reveals that groundwater at the oldest mine is largely influenced by long-term evaporative processes, whereas the newest mine exhibits more heterogeneous isotopic compositions, indicating interaction between mine-affected water and regional aquifers. Together, hydrogeochemical and isotopic data provide a coherent understanding of groundwater recharge processes, contaminant migration, and aquifer geochemical evolution in uranium-mining settings.

These findings form a robust foundation for groundwater protection, environmental monitoring, and sustainable resource management in uranium-rich arid regions. Future research should integrate long-term monitoring with predictive hydrogeochemical and isotopic modelling to better assess contaminant transport dynamics, aquifer vulnerability, and the interactions between isotopic composition and uranium mobility. This integrated approach will deepen understanding of mining impacts on groundwater systems and support proactive groundwater protection and adaptive, evidence-based water management strategies in semi-arid, uranium-affected environments.

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CHAPTER 5: ASSESSING TRACE ELEMENTS AND RADIOLOGICAL RISKS AROUND URANIUM MINE TAILINGS: INSIGHTS FROM NAMIBIA

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Abstract

Groundwater contamination by trace metals and radionuclides near uranium mining sites poses significant environmental and public health risks. This study assessed groundwater quality at two uranium mines in Namibia, a legacy operation active since 1976, and a recently developed mine commissioned in 2016, to evaluate spatial variations in trace element concentrations and radiological hazards. Sixteen boreholes (eight per mine) located near tailings storage facilities were sampled for arsenic, cadmium, lead, uranium, and naturally occurring radionuclides (^{226}Ra, ^{232}Th, ^{40}K). Descriptive statistics, two-sample t-tests, and radiological hazard indices were applied to compare contamination

levels against the World Health Organisation (2017) and Namibian potable water quality standards. Groundwater from the oldest mine exhibited consistently elevated arsenic, cadmium, lead, and uranium concentrations, with all boreholes exceeding national and international guideline values. The newest mine showed more heterogeneous contamination patterns, with certain hotspots, most notably borehole GW31, recording extremely high uranium concentrations (6700 µg/L). Statistical comparisons revealed significant differences in cadmium concentrations between the two sites ($p = 0.01$), while arsenic, lead, and uranium did not differ significantly. Radionuclide activity was dominated by ^{40}K, and all calculated radiological hazard indices remained below the recommended safety threshold of 370 Bq/L, indicating limited radiological risk from groundwater ingestion. Overall, the findings demonstrate persistent groundwater contamination associated with both legacy and modern uranium mining operations. The study underscores the necessity for enhanced site-specific monitoring, stringent regulatory oversight, and targeted remediation interventions to safeguard groundwater resources and mitigate risks to surrounding communities.

Keywords: Uranium mining, groundwater pollution, groundwater monitoring, uranium radionuclides, spatiotemporal distribution.

5.1 Introduction

Groundwater contamination by toxic metals and radionuclides represents a major global threat to environmental sustainability and public health (Li et al., 2021; Karunanidhi et al., 2022; Taloor et al., 2024; Umeh et al., 2025). Nearly one-third of the global population depends on groundwater as a primary source of drinking water, yet this critical resource faces escalating pressures from urbanisation, agricultural intensification, and industrial activities (Famiglietti & Ferguson, 2021; Karunanidhi et al., 2022; Pattison & Cooke, 2024; Cooper & Hiscock, 2025). While some metals are essential for biological functions, others, particularly those mobilised by mining operations, can persist in the environment at hazardous concentrations (Shah, 2021; Bibi, 2023; Devi, 2024). Trace elements such as arsenic, cadmium, lead, and uranium are of particular concern, as their presence in groundwater poses significant health risks worldwide (Boumaza et al., 2021; Muhaya et al., 2021; Asim et al., 2024; Sultan et al., 2025). Although recent site-specific studies (2020-2025) for the Erongo Region do not explicitly document As, Cd, or Pb-bearing minerals in primary ore bodies, their geochemical association with uranium mineralisation is well-established globally via substitution in U-minerals or accessory sulphides, mobilised during mining (Luo et al., 2020; Kaczowka et al., 2021; Rodríguez-Hernández et al., 2021; Chen et al., 2022). These elements amplify toxicity, As carcinogenic, Cd nephrotoxic, Pb neurotoxic, often exceeding WHO guidelines in mine-impacted aquifers (Enyigwe et al., 2022; Baah et al., 2024; Silva-Gigante et al., 2024).

Radionuclides, including uranium and thorium, occur naturally but may also be released through anthropogenic activities (Adebiyi et al., 2021; Ram et al., 2021; Severinenko et al., 2023; Vengosh et al., 2022). Their mobility and toxicity are strongly governed by geochemical speciation and surrounding environmental conditions (Beccia et al., 2022; Vengosh et al., 2022; Williamson et al., 2024). Uranium is of particular concern due to its widespread occurrence, high environmental mobility, and decay into radiotoxic progeny such as radium-226, which is highly persistent and presents substantial health hazards (Makubalo & Diamond, 2020; Bala et al., 2022; Mathuthu et al., 2021; Faqir et al., 2025). Understanding contaminant pathways is therefore essential for effective radiological risk assessment and long-term groundwater management. However, comprehensive investigations are often constrained by safety considerations and regulatory limitations (Deblonde et al., 2020; Chen et al., 2022; Vengosh et al., 2022; Maes et al., 2024; Kim et al., 2025).

Mining-induced groundwater contamination is particularly acute in arid environments, where aquifers constitute the primary source of water for domestic, agricultural, and industrial use. In such settings, contaminants tend to accumulate due to limited dilution and recharge capacity, entering groundwater

systems gradually through leaching or abruptly during operational failures, thus contributing to significant deterioration of water quality (Mathuthu et al., 2021; Kandjou et al., 2022; Pandey et al., 2023; Ali & Negm, 2024).

Namibia, one of the world's leading uranium producers (Namibian Chamber of mines, 2023), has reported instances of groundwater pollution associated with unlined tailings storage facilities, underscoring the vulnerability of its limited water reserves (Abiye & Shaduka, 2017; Mathuthu et al., 2021). Monitoring data from the Namibian Uranium Province not only supports national water management strategies but also provides a valuable basis for comparative studies in other uranium-producing regions (Mathuthu et al., 2021). These insights advance global discourse on aquifer protection, radiological hazard evaluation, and the sustainable development of mineral resources under water-scarce conditions.

This study evaluates both trace element and radiological risks associated with uranium mine tailings in Namibia's Uranium Province, which is in the Swakop Upper Omatako basin (Figure 5-1). It delivers critical evidence to guide groundwater management, mitigate mining-related impacts, and safeguard limited water resources in arid environments.

5.2 Methods

5.2.1 Study Area

Namibia is divided into twelve groundwater management basins established to advance the principles of Integrated Water Resources Management (IWRM) (Ministry of Agriculture, 2013). This study focuses on the Swakop-Upper Omatako Basin (Figure 5-1), which covers approximately 30,100 km² across the Khomas, Erongo, and Otjozondjupa regions in central-western Namibia.

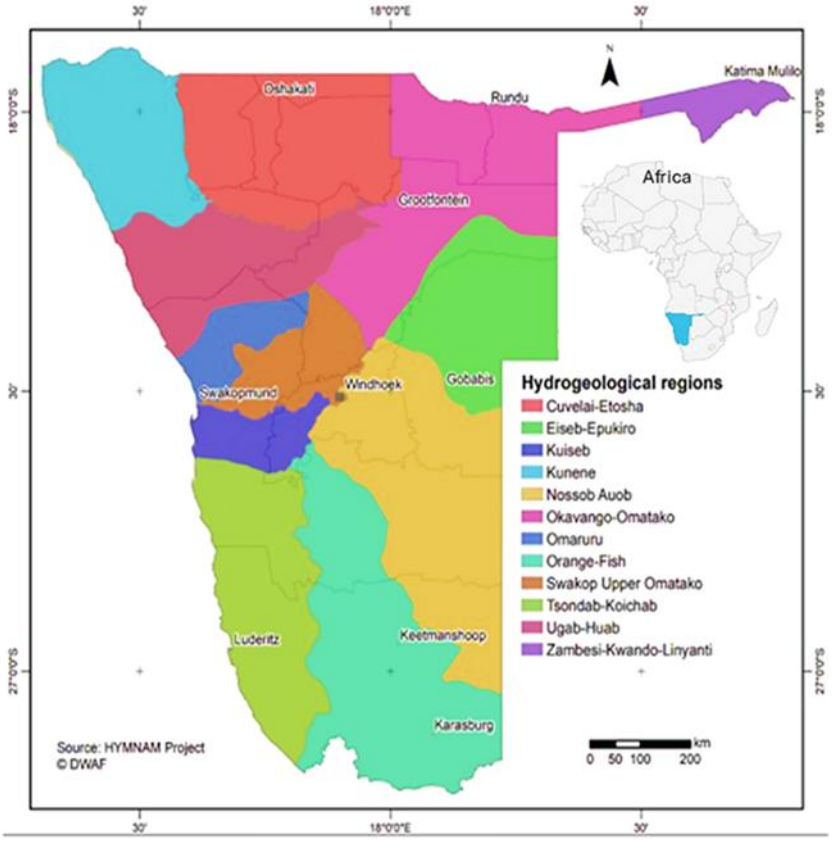


Figure 5-1 Groundwater management basin of Namibia. *Note*: Adapted from Lohe et al. (2021).

The basin is characterised by an arid climate with high evaporation rates, low humidity, and mean annual rainfall of less than 20 mm, concentrated primarily between October and April (Lohe et al., 2021; Atlas of Namibia Team, 2022; Coetzee, 2023). Geologically, the basin is characterised by primary alaskite-hosted uranium and secondary calcrete uranium deposits (Chudasama et al., 2019; Shanyengana et al., 2020; Mathuthu et al., 2021; Wilde, 2023). Hydrogeologically, the area hosts crystalline carbonate, granite and schist-type aquifers, with several ephemeral streams that host deep alluvial aquifers in the Khan, Swakop and Kuiseb rivers (Lohe et al., 2021; Wilde, 2023) (Figure 5-2).

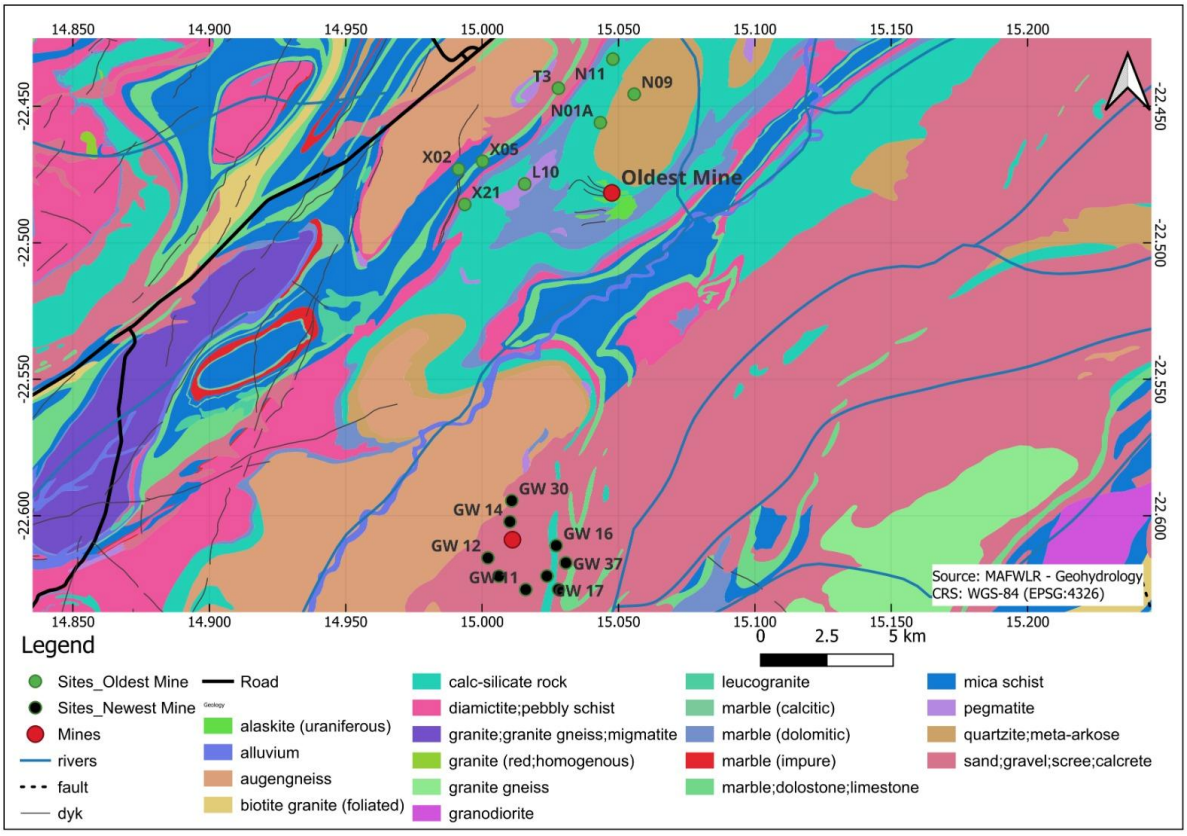


Figure 5-2: Local geology in the study area in the Erongo region of Namibia (QGIS version 3.40.5 2025)

Groundwater recharge within the area is sporadic, with water table depths typically ranging from 20 to 30 m below the surface during peak dry seasons (Hamutoko et al., 2014). Groundwater flow generally follows topographic gradients from the elevated eastern highlands toward the west, as reported in the Strategic Environmental Assessment of the Erongo Region conducted by the Ministry of Mines and Energy (MME) (Mathuthu et al., 2021). The basin encompasses the Namibian Uranium Province in the Erongo Region, where groundwater serves as the primary water source for local communities and agricultural activities, particularly in rural areas lacking surface water infrastructure (Hamutoko et al., 2014; Mathuthu et al., 2021; Coetzee, 2023).

The region's oldest uranium mine, commissioned in 1976, is the longest-operating open-pit uranium mine in Namibia (Namibian Chamber of Mines, 2023). In 2023, it produced 2,920 tonnes of uranium oxide, a 10% increase from the previous year (Namibian Chamber of Mines, 2023). In contrast, the newest mine, which commenced export production in 2016, has rapidly emerged as the world's second-largest uranium producer, with output of 5,318 tonnes of uranium oxide in 2023 (Namibian Chamber of Mines, 2023).

5.2.2 Sample Collection

Groundwater samples were collected from 16 boreholes, comprising eight located near the oldest uranium mine and another eight near the newer mine within the study area (Figures 5-3 and 5-4). The characteristics of these boreholes are summarised in Tables 5.1 and 5.2. Borehole selection prioritised sites based on their proximity to tailings storage facilities, alignment with dominant groundwater flow pathways (westward along ephemeral river alluvium) to achieve representative spatial coverage of radiological contamination risks. This approach captures both near-field impacts and downgradient dispersion potential, as informed by regional hydrogeological assessments. Borehole coordinates were recorded using QGIS version 3.40.5.

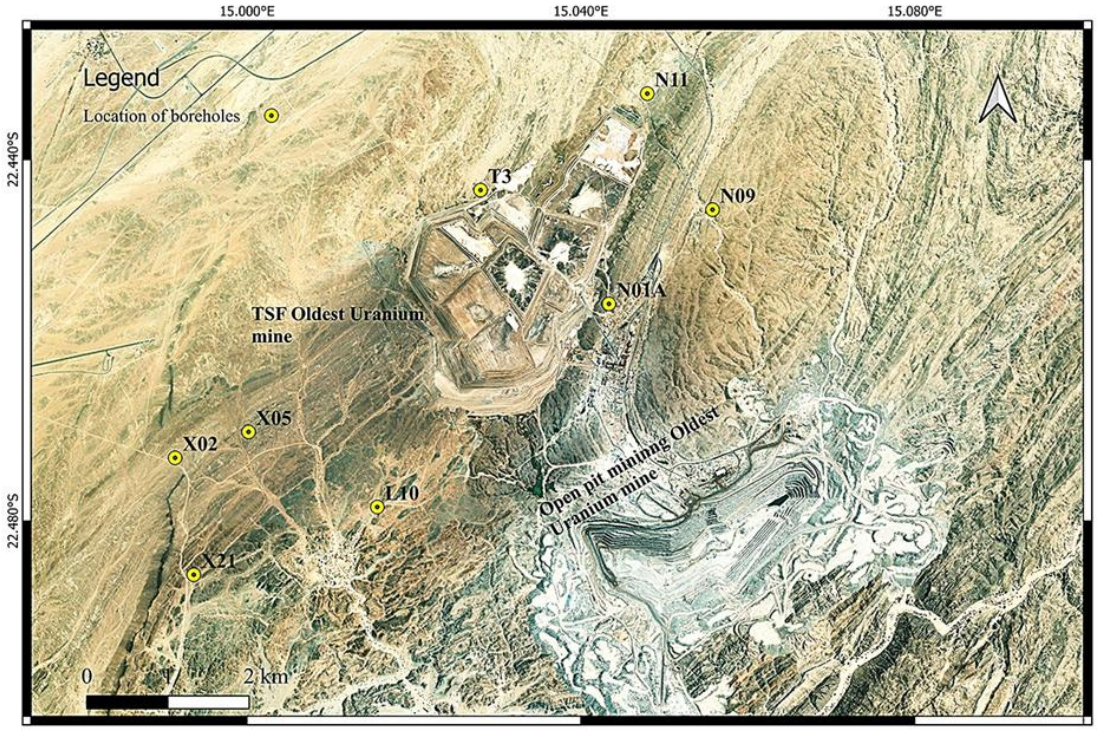


Figure 5 3 Borehole location at the oldest uranium mine in Namibia (QGIS version 3.40.5 2025)

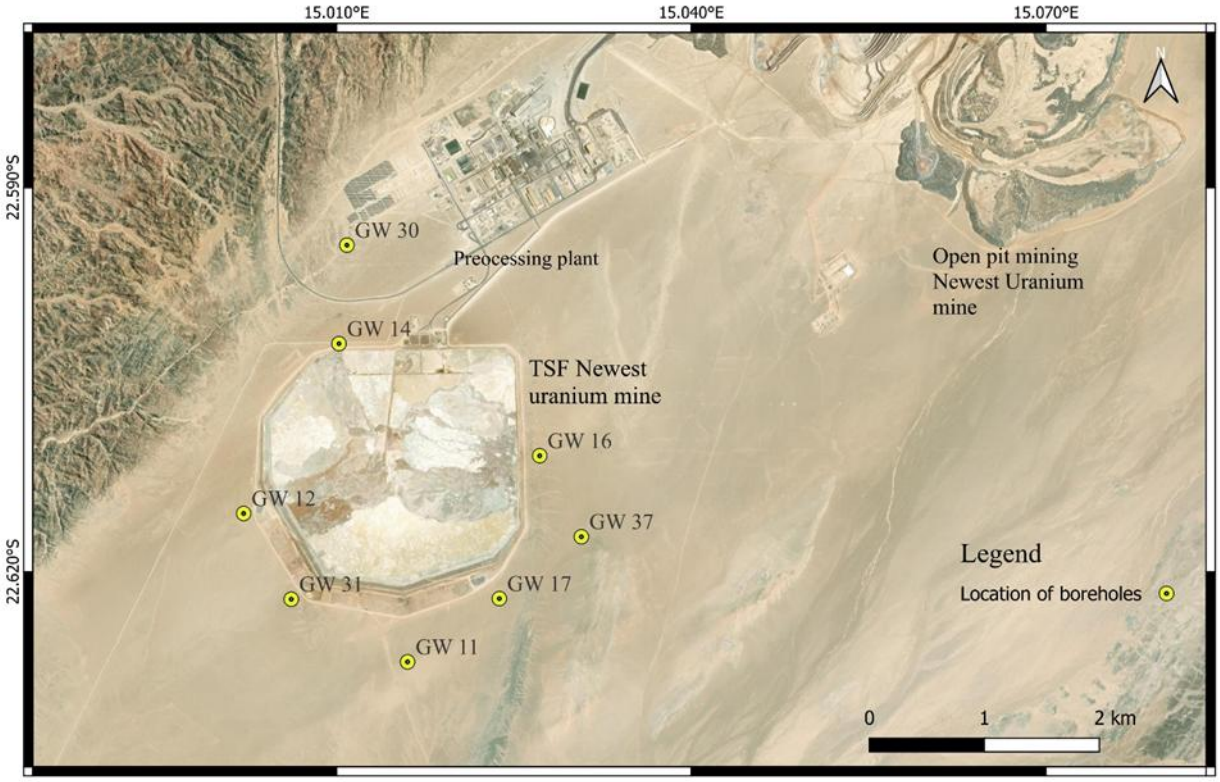


Figure 5-3 Borehole location at the newest uranium mine in Namibia (QGIS version 3.40.5 2025)

Table 5.1 Locations and characteristics of boreholes at the oldest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	Jun-24			Oct-24			Mar-25		
								Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)
T3	22°26′36.13″	15°1′40.73″	9.41	612	0.59	7	612.59	7.16	2.25	605.43	7.36	2.05	605.23	7.34	2.07	605.25
X02	22°28′22.80″	14°59′28.97″	53.44	564	0.56	30	564.56	13.39	40.05	551.17	13.39	40.05	551.17	13.42	40.02	551.14
X05	22°28′12.47″	15°0′0.68″	49.45	561	0.55	25	561.55	4.95	44.5	556.6	5.05	44.4	556.5	4.95	44.5	556.6
X21	22°29′9.35″	14°59′37.03″	49.57	544	0.53	30	544.53	21.47	28.1	523.06	21.77	27.8	522.76	20.74	28.83	523.79
L10	22°28′42.38″	15°0′56.20″	49.48	540	0.52	25	540.52	11.98	37.5	528.54	10.88	38.6	529.64	11.96	37.52	528.56
N01A	22°27′21.46″	15°2′36.13″	52.11	603	0.59	25	603.59	0.1	52.01	603.49	0.1	52.01	603.49	0	52.11	603.59
N09	22°26′43.94″	15°3′20.81″	10.43	591	0.57	8	591.57	3.83	6.6	587.74	3.08	7.35	588.49	3.41	7.02	588.16
N11	22°25′57.68″	15°2′52.66″	49.38	619	0.62	25	619.62	4.83	44.55	614.79	4.68	44.7	614.94	4.77	44.61	614.85

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - rest water level (m)

Table 5.2 Borehole locations and characteristics of the newest uranium mine

Borehole	Latitude (S)	Longitude (E)	Borehole depth(m)	Ground elevation (m asl)	Collar height (m)	Sampling depth (m)	Collar elevation (m asl)	Jun-24			Oct-24			Mar-25		
								*Rest water level (m)	∴Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (masl)	Rest water level (m)	Height of water column (m)	Static water level (m asl)
GW 14	22°36′7.87″	15°0′36.74″	99.49	496	0.51	40	496.51	34.4	96.05	462.11	35.79	63.7	460.72	33.74	65.75	462.77
GW 16	22°36′39.38″	15°1′37.87″	119.93	491	0.35	80	491.35	54.4	65.53	436.95	53.55	66.38	437.8	52.19	67.74	439.16
GW 37	22°37′2.17″	15°1′50.56″	100.05	478	0.51	70	478.51	47.41	52.64	434.1	46.68	53.82	431.83	45.48	54.57	433.03
GW 17	22°37′19.54″	15°1′25.58″	99.87	469	0.48	80	469.48	60.5	39.37	408.98	58.02	41.85	411.46	54.14	45.73	415.34
GW 11	22°37′37.34″	15°0′57.63″	98.9	464	0.51	70	464.51	43.41	55.49	426.1	41.19	57.71	423.32	40.29	58.61	424.22
GW 31	22°37′19.71″	15°0′22.21″	106.42	466	0.54	80	466.54	31.91	74.48	434.63	32.56	73.86	433.98	81.09	24.91	385.45
GW 12	22°36′55.61″	15°0′7.71″	120.48	472	0.52	90	472.52	80.9	39.58	391.62	79.88	40.6	392.64	33.03	87.45	439.49
GW 30	22° 35' 40.16″	15° 0' 39.16"	101.8	498	0.52	80	498.52	33.24	68.56	465.28	32.55	69.25	465.97	23.46	78.34	475.06

Rest water level (m)= water level (m)- collar height (m)

Height of water column (m) = borehole depth (m) - rest water level (m)

Collar elevation (masl) = ground elevation (masl) + collar height (m)

Static water level (masl) = collar elevation (masl) - rest water level (m)

Before sampling, all boreholes were purged to remove stagnant water. Sampling campaigns were conducted in June 2024, October 2024, and March 2025 to capture seasonal variability. Standard protocols were strictly followed to prevent cross-contamination, minimise the loss of trace metals and radionuclides, and maintain sample integrity.

From each borehole, two water samples were collected after filtration through a 0.45 µm cellulose membrane and immediately preserved with dilute nitric acid. One set, comprising a 1 L sample, was designated for trace element analysis, including uranium (U), arsenic (As), cadmium (Cd), and lead (Pb). For radionuclide analysis, a 500 mL sample was collected, tightly sealed, and secured with duct tape to prevent leakage during transport. Duplicate samples were taken from each borehole to ensure data reliability. All samples were stored at 4 °C in a portable refrigerator until laboratory analysis.

5.2.3 Laboratory Analysis

Trace element analyses were performed at the Analytical Laboratory in Windhoek using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The instrument was calibrated by a certified PerkinElmer technician during scheduled service intervals. Quality control procedures included the use of blanks, replicates, and certified reference materials. Each analyte was measured in accordance with the laboratory's Standard Operating Procedures (SOPs) and the Standard Methods for the Examination of Water and Wastewater manual (AWWA, latest edition).

Analytical accuracy for the 48 groundwater samples collected during the study period was evaluated using the ion charge balance error method. Of these, 38 samples (79%) fell within the acceptable ±5% margin of error, indicating reliable analytical results. The remaining 10 samples slightly exceeded this threshold; however, the deviations were not considered significant enough to affect the overall hydrogeochemical interpretation. Given the minimal error and consistent trace element trends, all samples were included in the data treatment and interpretation.

Radionuclide measurements were carried out at the Centre for Applied Radiation Science and Technology (CARST), North-West University, South Africa. The Broad Energy Germanium (BEGe) detector was employed to determine activity concentrations of radium-226 (^{226}Ra), thorium-232 (^{232}Th), and potassium-40 (^{40}K) after the samples had reached secular equilibrium. The BEGe detector (model BE6530, Canberra Industries) offers a relative efficiency of 60% and an energy resolution of 2.0 keV at the 1332 keV gamma-ray line of Co-60 (Agostini et al., 2019). Prior to measurement, both energy and dual-efficiency calibration curves were performed to ensure accuracy and precision.

5.2.4 Radiation Hazard Indices

Radiation hazard indices are quantitative parameters used to evaluate the overall radiological impact of naturally occurring radionuclides (Erzin, 2024; Rilwan et al., 2020; Sabbarese et al., 2021). The key indices considered in this study include the Radium Equivalent Activity (Ra_{eq}), External Hazard Index (H_{ex}), and Internal Hazard Index (H_{in}) (Rilwan et al., 2020; Mathuthu et al., 2021; Eke et al., 2024).

Radium Equivalent Activity (Raeq) is a combined radiological parameter used to assess the potential radiological risk posed by ^{238}U, ^{232}Th, and ^{40}K decay series (Mathuthu et al., 2021; Rahim et al., 2023; Eke et al., 2024). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) recommends a maximum limit of 370 Bq/L for Raeq (Mathuthu et al., 2021). Ra_{eq} is derived from the activity concentrations of these radionuclides using Equation (1).

$$Ra_{eq}(Bq^{-1}) = C_{Ra} + 1.43C_{Th} + 0.077C_K \quad (1)$$

where C_{Ra}, C_{Th}, and C_K are the activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K, respectively, in Bq/L.

The external and internal hazard indices are key parameters used to evaluate the radiological risks associated with environmental samples. The External Hazard Index (H_{ex}) (Equation 2) quantifies the potential risk of radiation exposure from external gamma radiation, whereas the Internal Hazard Index (H_{in}) (Equation 3) estimates the risk of internal exposure through ingestion or inhalation of radionuclides (Ahmed, 2020; Purnama & Damayanti, 2020). According to international safety standards, particularly the recommendations of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), both indices should not exceed one (≤ 1) to remain within acceptable radiological safety limits (Ahmed, 2020; Purnama & Damayanti, 2020; Mathuthu et al., 2021).

$$H_{ex}= \frac{C_{Ra}}{370} + \frac{C_{Th}}{370} + \frac{C_K}{4810} \quad (2)$$

$$H_{in} = \frac{CRa}{185} + \frac{CTh}{259} + \frac{CK}{4810} \quad (3)$$

5.2.5 Data Analysis

Data were processed using R (version 4.3.0) and Microsoft Excel (version 2502) for descriptive and quantitative statistical analyses. A two-sample t-test was used to assess whether there were statistically significant differences in groundwater quality parameters between the oldest and newest uranium mines. The spatial distribution of borehole locations was visualised using QGIS (version 3.28).

5.3 Results

5.3.1 Trace Elements

In both mines, values frequently exceeded international and national drinking water guideline limits. Groundwater quality at the oldest uranium mine showed persistently elevated trace-metal concentrations (Figure 5-5).

Arsenic (As) concentrations in all boreholes exceeded the WHO standard of 10 µg/L, and seven exceeded the Namibian limit of 50 µg/L (Figure 5-5). Borehole L10 at the oldest uranium mine recorded the maximum value (96.67 µg/L) (Figure 5-5) as concentrations at the oldest uranium mine varied between 46.67µg/L and 96.67 µg/L.

Cadmium (Cd) concentrations ranged from 7.67µg/L to 40 µg/L (Figure 5-5). All boreholes exceeded the WHO guideline of 3 µg/L, with only N01A (7.67 µg/L) remaining below the Namibian standard of 10 µg/L (Figure 5-5). The highest concentration was recorded at borehole X05 (40 µg/L).

Lead (Pb) concentrations ranged from 26.67 to 180 µg/L (Figure 5-5). Every measured borehole exceeded the WHO guideline of 10 µg/L, and six others exceeded the Namibian threshold of 50 µg/L. The highest concentration observed was at borehole N11 (180 µg/L).

In all boreholes, the values of uranium (U) exceeded both the Namibian guideline of 15 µg/L and the WHO guideline of 30 µg/L except borehole X21, with the highest concentration recorded at borehole N01A (520.67 µg/L) (Figure 5-5). U concentrations ranged from 23.33 to 520.67 µg/L (Figure 5-5).

Overall, groundwater in the oldest uranium mine showed consistently elevated concentrations of Cd, Pb, As, and U across the network.

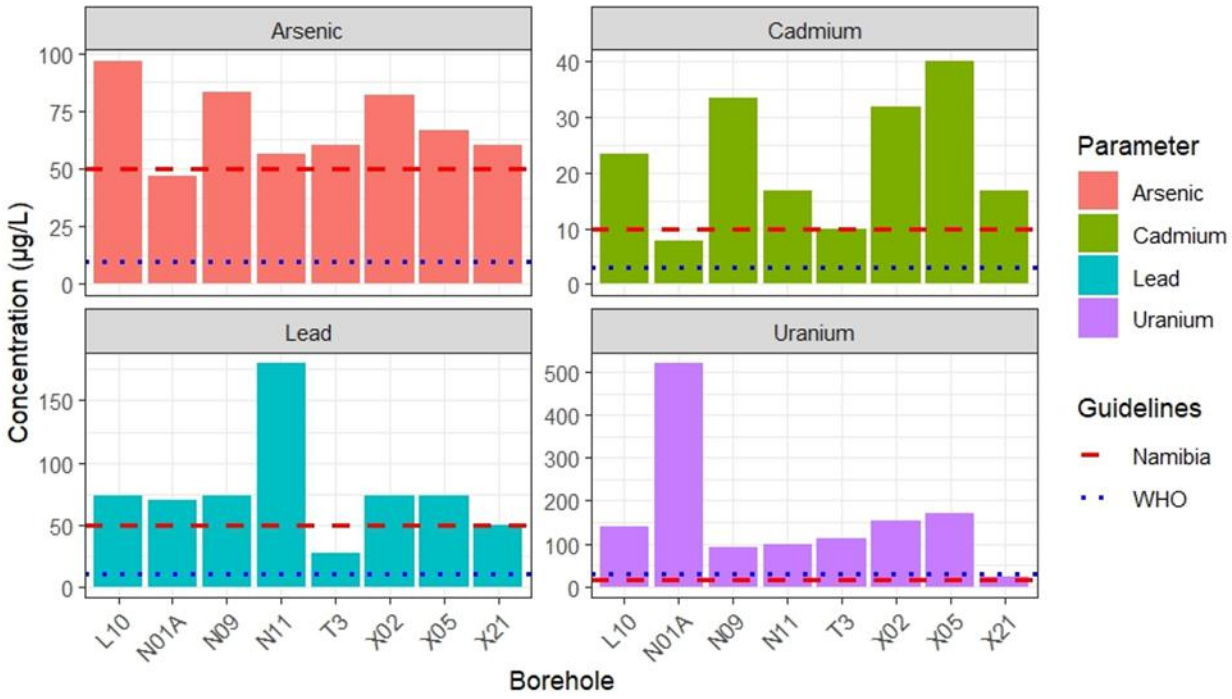


Figure 5-4 Mean trace element levels compared to international and national water quality guidelines (Ministry of Agriculture, 2013; World Health Organization, 2022) for the oldest uranium mine.

For the newest uranium mine, WHO guideline limits were exceeded in all instances, and most samples also surpassed Namibian guidelines. Groundwater quality assessment at the newest uranium mine revealed varied trace metal concentrations across the eight monitoring boreholes, as shown in Figure 5-6. Cd concentrations ranged from 0.095 to 15 µg/L (Figure 5-6). Only GW11 (0.105 µg/L) and GW14 (0.095 µg/L) remained below the WHO guideline of 3 µg/L (Figure 5-6). Three boreholes, GW31 (10 µg/L), GW37 (15 µg/L), and GW12 (10 µg/L) also exceeded the Namibian standard of 10 µg/L.

Pb levels varied widely, between 0.06 and 226.67 µg/L (Figure 5-6). Except for GW11 and GW14, all boreholes were above the WHO limit of 10 µg/L. Six boreholes (GW12, GW16, GW17, GW30, GW31, GW37) also surpassed the Namibian threshold of 50 µg/L, with GW31 recording the maximum concentration (226.67 µg/L).

As concentrations ranged from 0.004 to 75 µg/L (Figure 5-6). GW11 (0.004 µg/L) and GW14 (0.01 µg/L) were the only boreholes below the WHO guideline of 10 µg/L. Five boreholes (GW12, GW16, GW17, GW30, GW37) exceeded the Namibian limit of 50 µg/L, with GW30 showing the peak value (75 µg/L).

U concentrations showed the greatest variability, ranging from 16.67 to 6700 µg/L (Figure 5-6). All boreholes exceeded both the Namibian (15 µg/L) and WHO (30 µg/L) guidelines. GW31 presented an

extreme anomaly (6700 µg/L), likely reflecting localised enrichment associated with tailings storage or ore deposits.

Overall, groundwater in the newest mine showed frequent exceedances of both WHO and Namibian guideline values, particularly for uranium and lead. Unlike the more evenly distributed contamination observed in the oldest mine, the newest site exhibited a pronounced single-point anomaly at GW31, highlighting localised but severe contamination risk.

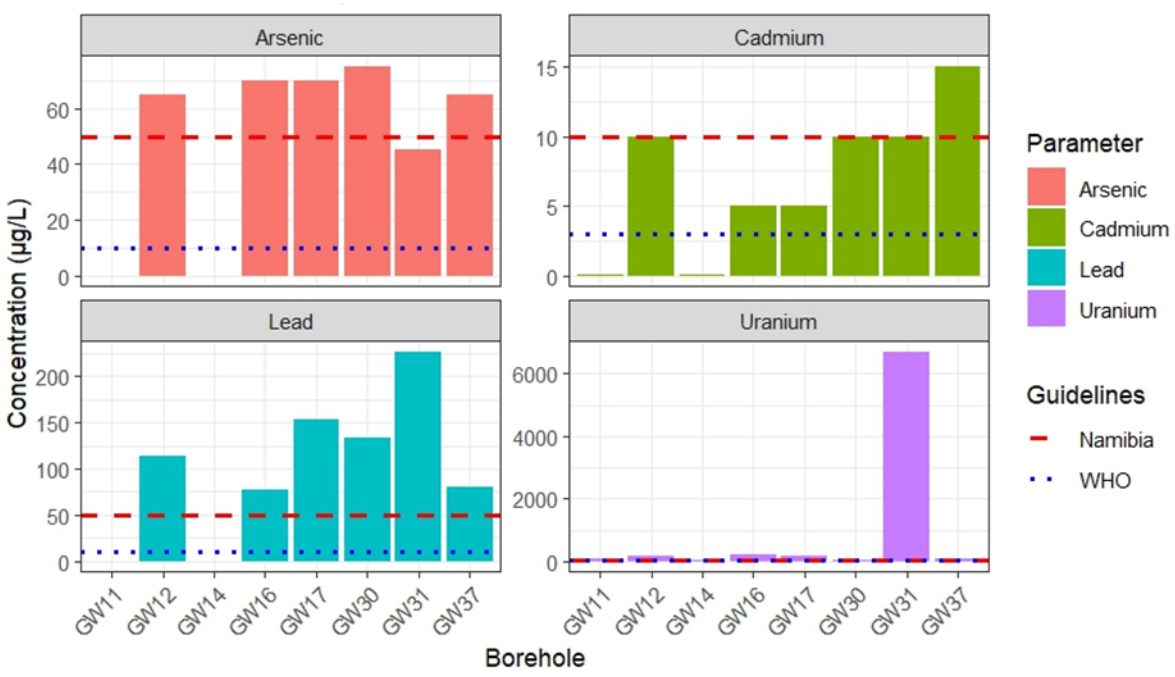


Figure 5-5 Mean trace element levels compared to international and national water quality guidelines (Ministry of Agriculture, 2013; World Health Organization, 2022) for the newest uranium mine

5.3.2 Statistical Analysis

Varying degrees of statistical significance were observed in the concentrations of trace metals between the oldest and newest uranium mines. Notably, cadmium concentrations differed significantly, with the oldest uranium mine recording a mean of 22.42 µg/L, compared with 6.90 µg/L in the newest mine. The two-sample t-test yielded a t-statistic of -3.43 with 9.74 degrees of freedom and a p-value of 0.01, indicating a statistically significant difference ($p < 0.05$) between the two sites. This result suggests that cadmium levels are significantly higher in groundwater samples from the oldest uranium mine.

In contrast, the statistical analysis revealed no significant differences in the concentrations of lead, arsenic, or uranium between the oldest and newest uranium mines (Table 5.3).

Table 5.3 Statistical analysis of the oldest and newest uranium mine, including the mean values

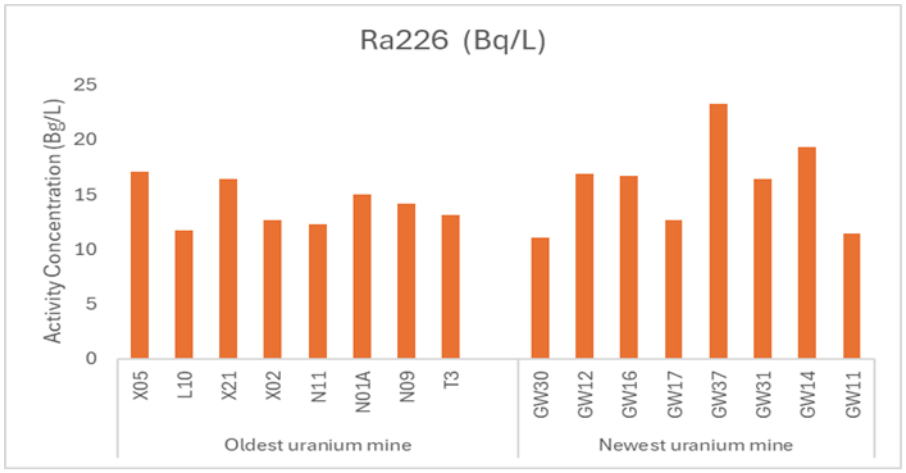
Parameter	t statistic	Degrees of freedom	p-value	Mean oldest uranium mine (µg/L) (n=8)	Mean newest uranium mine (µg/L) (n=8)
Cadmium	-3.43	9.74	0.01	22.42	6.90
Lead	0.65	11.27	0.53	77.50	97.93
Arsenic	-1.61	10.67	0.14	68.96	48.75
Uranium	0.93	7.06	0.38	164.46	930.04

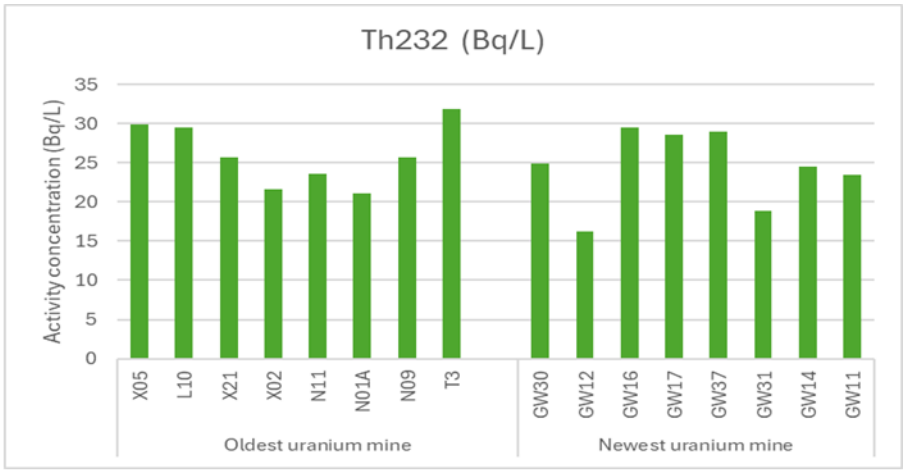
5.3.3 Radionuclide activity and concentrations

The activity concentrations of naturally occurring radionuclides in groundwater from the oldest and newest uranium mines are presented in Figure 5.6. For ^{226} Ra concentrations, the highest activity was recorded in sample X05 (17.10 Bq/L) and the lowest in L10 (11.68 Bq/L) for the oldest uranium mine. With T3, which is closest to the TSF (Figure 5-3) and shows the highest concentration, ^{232}Th levels ranged from 21.14 Bq/L (N01A) to 31.86 Bq/L. ^{40}K recorded the highest activity among the radionuclides at the oldest uranium mine, ranging from 1506 Bq/L (N11) to 1620.33 Bq/L (T3). Overall, ^{40}K, although recording the highest activity among the radionuclides, showed less variation across the boreholes when compared to ^{226}Ra and ^{232}Th.

At the newest uranium mine, ^{226} Ra activity concentrations ranged from 11.02 Bq/L (GW30) to 23.21 Bq/L (GW37). Widely varying, ^{232}Th ranged from 16.28 Bq/L (GW12) to 29.50 Bq/L (GW16). With GW14 recording the highest activity concentration, ^{40}K levels were slightly higher than the oldest uranium mine and ranged between 1538 Bq/L to 1635.33 Bq/L (GW30) (Figures 5-3, 5-4 and 5-7).

Overall, the results indicate that ^{40}K activity concentrations dominate the radioactivity profile of groundwater samples in both mines, while ^{226}Ra and ^{232}Th showed spatial heterogeneity. All the measured radionuclides exceeded the WHO drinking water of 1 Bq/L (World Health Organization, 2022).





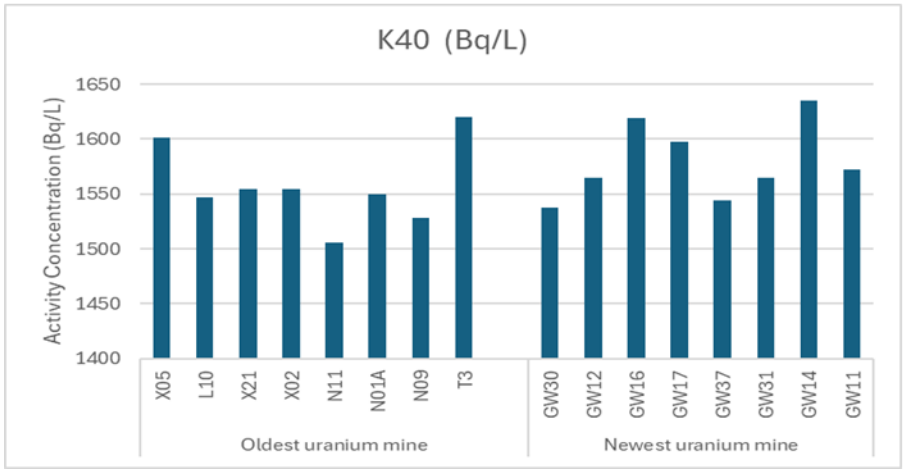


Figure 5-6 Activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K in groundwater samples from the Oldest and Newest Uranium Mine (Bq/L

5.3.4 Radiation hazard indices

To evaluate the potential health risks associated with radionuclides in groundwater, radiological hazard indices were calculated for all boreholes at both mining sites. The Radium Equivalent Activity (Ra_{eq}), External Hazard Index (H_{ex}), and Internal Hazard Index (H_{in}) were determined using the measured activity concentrations of ^{226}Ra, ^{232}Th, and ^{40}K. These indices were then compared with internationally recommended safety limits to assess radiological risk levels.

The calculated Ra_{eq} values for groundwater samples from the two uranium mines are shown in Figure 5-8. The range of Raeq in the oldest mine was from 162.02 Bq/L (N11) to 183.46 Bq/L (T3). While at the newest uranium mine, it ranged from 160.62 Bq/L (GW12) to 183.58 Bq/L (GW16). All the recorded values were below the UNSCEAR recommended limit of 370 Bq/L (Mathuthu et al., 2021).

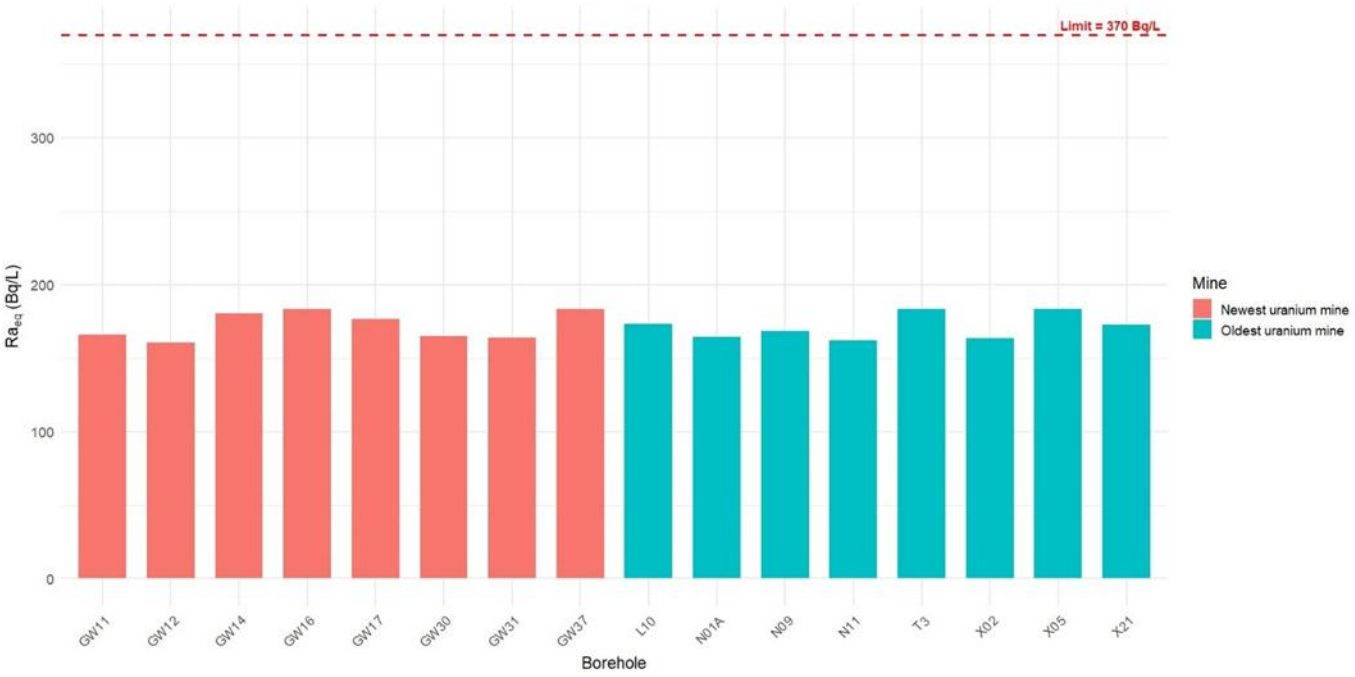


Figure 5-7 Ra_{eq} levels in groundwater from boreholes of the oldest and newest uranium mines

The H_{in} levels were all found to be below the recommended safe limit of 1 (Mathuthu et al., 2021) in all boreholes (Figure 5-9). For the oldest uranium mine, the H_{in} levels ranged from 0.47 Bq/L (N11) to 0.54 Bq/L (X05), and in the newest uranium mine, from 0.48 Bq/L (GW11, GW12, GW30) to 0.56 Bq/L (GW37).

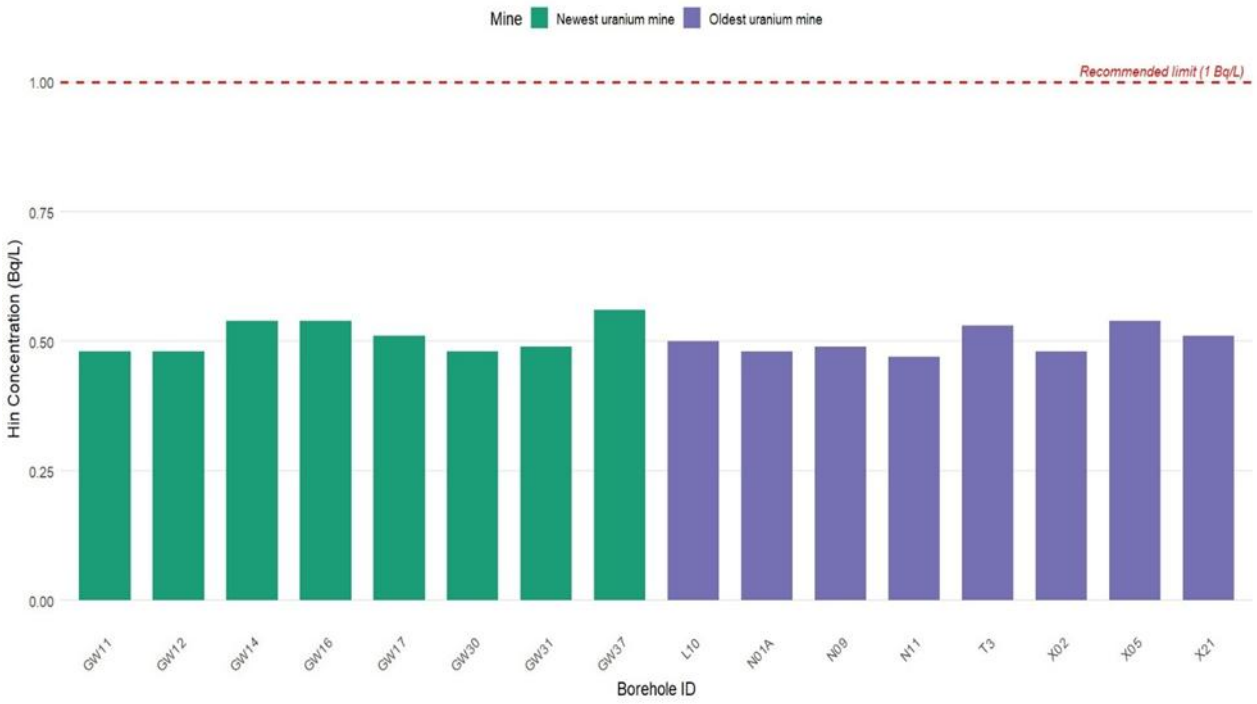


Figure 5-8 H_{in} levels in groundwater from the boreholes of the oldest and newest uranium mines

As shown in Figure 5-10, the H_{ex} values for all sampled boreholes were below unity (<1), indicating that the radiation hazard from external gamma exposure remains within safe limits (Mathuthu et al., 2021).

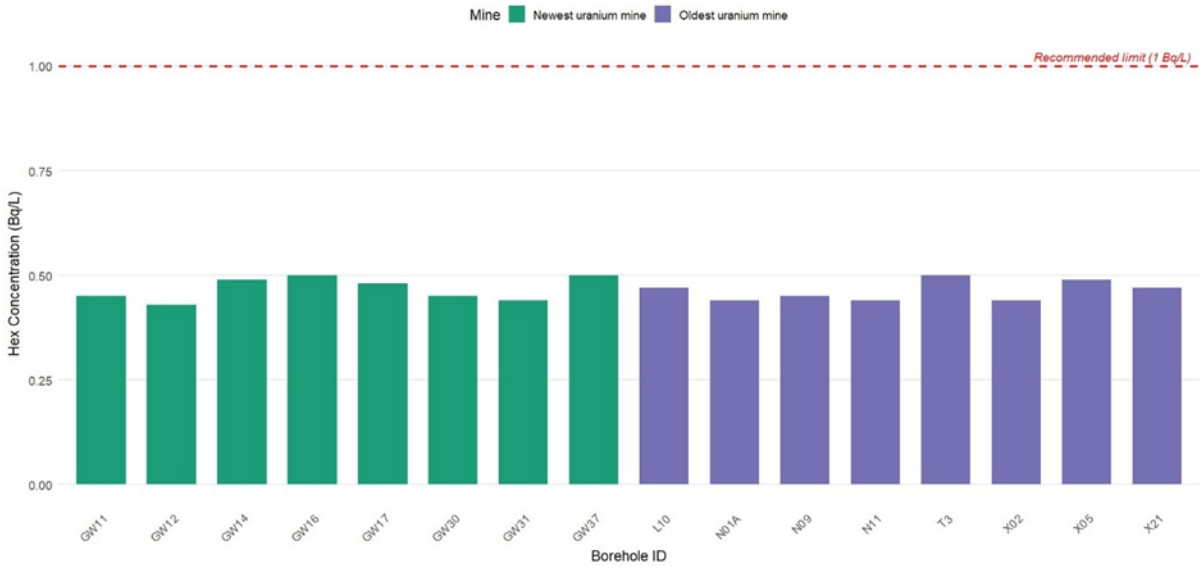


Figure 5-9 H_{ex} levels in groundwater from the boreholes of the oldest and newest uranium mines

5.4 Discussion

The groundwater quality assessment conducted in the vicinity of uranium mines revealed substantial contamination by trace elements, with pronounced spatial variability between the oldest and newest mining sites. The oldest uranium mine exhibited consistently elevated concentrations of arsenic, cadmium, lead, and uranium, all exceeding both the WHO (2022) and Namibian Water Quality Guidelines and Standards for Potable Water. This contamination pattern aligns with previous studies that have documented the long-term, cumulative effects of legacy uranium mining on groundwater systems, where continuous leaching from unlined or ageing tailings storage facilities sustains metal mobilisation into aquifers (Ballini et al., 2020; Byrne et al., 2021; Kent et al., 2024). The severe exceedance of arsenic concentrations across multiple boreholes is particularly concerning given its well-established toxicity and carcinogenicity, even at moderate levels (Fatoki & Badmus, 2022; Aralu et al., 2023; Mahlknecht et al., 2023).

In contrast, the newest uranium mine displayed a more heterogeneous contamination pattern. Several boreholes recorded concentrations below established guideline limits, while others showed pronounced anomalies, most notably the exceptionally high uranium concentration observed at borehole GW31 (6700 µg/L). This localised hotspot likely reflects ongoing leaching processes associated with tailings or ore storage, emphasising the influence of site-specific hydrogeochemical factors and spatial heterogeneity in contaminant dispersion. Such variability is typical of newly developed uranium operations, where modern containment infrastructure and engineered barriers may reduce, but not entirely eliminate, groundwater infiltration and contaminant migration (Barbosa et al., 2021; Adadzi et al., 2022).

Statistical analysis corroborated these observations, identifying a significant difference only in cadmium concentrations between the two sites, with higher mean values recorded at the oldest mine. This finding suggests greater persistence or enhanced mobility of cadmium under the prevailing geochemical conditions of legacy tailings. The absence of significant differences in lead, arsenic, and uranium concentrations may indicate that similar geochemical processes, such as redox reactions, pH buffering, or adsorption-desorption dynamics, govern the behaviour of these elements in both mining environments. Additionally, the diffusion of contaminants beyond immediate tailings zones could contribute to comparable concentration ranges across the two sites. At the oldest uranium mine, only borehole N01A shows U-contamination, whereas at the newest uranium mine, it is borehole GW31. This paucity of U contamination confirms that most of the U is recovered in the process.

Radiological assessments indicated that, despite elevated activity concentrations of naturally occurring radionuclides (^{226}Ra, ^{232}Th, and ^{40}K), the calculated hazard indices (Ra_{eq}, H_{ex}, H_{in}) remained consistently below international safety thresholds. This trend suggests that while chemical contamination from trace metals presents substantial environmental and public health concerns, the radiological risk associated with these radionuclides is comparatively low. These results are consistent with UNSCEAR guidelines and previous studies demonstrating that chemical toxicity often poses a greater immediate risk to water quality than radiological exposure in mining-affected aquifers (Duggal et al., 2021; Mathuthu et al., 2021; Ramesh et al., 2021).

Collectively, these findings highlight the need for continued, site-specific groundwater monitoring, focusing particularly on areas exhibiting localised contamination spikes. Implementing robust tailings management practices and periodically evaluating containment system performance are essential to mitigate further groundwater deterioration. Integrating chemical and radiological monitoring frameworks will strengthen environmental risk assessments and support the development of targeted remediation and mitigation strategies.

5.5 Conclusion

This study demonstrates significant groundwater contamination by trace metals in both legacy and active uranium mining areas. The oldest mines exhibit widespread exceedances associated with long-term tailings degradation, while the newest mines show localised but severe contamination anomalies. Cadmium concentrations were statistically higher in groundwater from the older mining site, suggesting its persistence and potential for environmental accumulation. Elevated concentrations of arsenic, lead, and uranium across both sites pose potential health risks, underscoring the need for sustained monitoring and remediation efforts.

Despite these elevated trace metal levels, radiological hazard indices indicate that the activity concentrations of naturally occurring radionuclides currently remain below internationally accepted safety limits. Consequently, although no immediate radiological health risks are evident, the chemical toxicity associated with trace-metal contamination warrants continued attention.

Future work should prioritise enhanced spatial and temporal monitoring of groundwater quality, complemented by targeted remediation in identified hotspots. Identifying the sources of Cd, As, and Pb is of interest. These efforts are critical to preserving potable water resources in uranium mining regions and ensuring long-term compliance with both national and international water quality and safety standards.

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CHAPTER 6: SYNTHESIS

6.1 Introduction

This synthesis chapter integrates findings from the four primary objectives to build a unified understanding of groundwater contamination, hydrogeochemical evolution, isotopic behaviour, and radiological risk in uranium-mining environments. Using inductive reasoning, it progresses from specific empirical observations to broader conceptual insights concerning uranium mobility, groundwater-rock interactions, and contamination processes in semi-arid aquifers. The chapter also compares results across sites and chapters. This highlights trends in contamination and isotopic composition to frame an integrated assessment of aquifer vulnerability. Collectively, the results show that uranium mining in Namibia's arid region causes both localised and enduring effects on groundwater systems. Geological heterogeneity, historical mining legacies, and evolving management strategies shape these variations. When hydrochemical patterns are interpreted alongside isotopic evidence, they reveal overarching trends that define aquifer resilience, contamination persistence, and pathways of pollutant migration in mining-affected settings.

6.2 Integration of Key Findings

The review of global uranium-contamination studies (Objective i) demonstrates that groundwater pollution remains a substantial environmental and health challenge, though research coverage varies geographically. Developed regions such as the United States and Australia maintain structured monitoring frameworks, whereas much of Africa, South America, and Central Asia remain underrepresented (Ju et al., 2020; Wang et al., 2023; Liu et al., 2024). Namibia exemplifies this disparity: while technical monitoring systems are strong, peer-reviewed publications remain limited. The literature highlights that sustainable uranium mining requires integrated hydrochemical, isotopic, and health-based assessments to evaluate contamination risks and support credible remediation strategies (Lopez et al., 2021; Punia et al., 2021).

Field investigations at Namibian mine sites (Objectives ii-iv) show both spatial and temporal variability in groundwater quality near tailings storage facilities (TSFs). A direct quantitative comparison reveals that concentrations of key trace metals (As, Cd, Pb, U) at the newest uranium mine exceed both national and international water quality guidelines (Figure 5-6), with an anomaly at GW31. The oldest mine exhibits clear evidence of legacy contamination, marked by elevated salinity, ion accumulation, and persistent

radiological signals (Skierszkan et al., 2020; De Windt et al., 2025). By contrast, at the newest mine, the groundwater around the TSF displays moderate hydrochemical conditions, reflecting improved containment and shorter exposure histories (Sahu et al., 2023; Dolchinkov et al., 2024). Nonetheless, both sites are influenced by complex hydrogeochemical processes involving silicate weathering, carbonate buffering, and evaporative concentration as shown in other studies (Adamovic et al., 2022; Sikakwe et al., 2024).

Spatial data indicate stark contrasts between the two mines. The older site consistently reports elevated concentrations of arsenic, cadmium, lead, and uranium, with levels exceeding both the WHO (2022) and Namibian drinking-water standards. These findings suggest prolonged contamination resulting from unlined TSFs as well as natural geochemical processes. In contrast, the newer mine presents isolated anomalies, including uranium levels at borehole GW31 (6700 µg/L), which suggest early-stage leaching and restricted contaminant migration due to shorter residence times (Barbosa et al., 2021; Adadzi et al., 2022).

Isotopic analyses provide further clarity on recharge patterns and contaminant transport. Groundwater from the oldest mine shows enriched $\delta^{18}O$ and $\delta^{2}H$ values, evidence of strong evaporative influence and limited modern recharge. Meanwhile, isotopic variability in the newer mine suggests mixing between regional and mine-impacted waters (H. Li et al., 2023; Shi et al., 2023). Combined with hydrochemical data, these findings reveal distinct water sources and contamination dynamics between legacy and recent operations.

Radiological assessments indicate elevated ^{226}Ra, ^{232}Th, and ^{40}K activities, but hazard indices are below international safety limits (Duggal et al., 2021; Mathuthu et al., 2021). This suggests that chemical toxicity poses the greater immediate risk, even though radiological exposure remains within compliance limits. Persistent trace-metal accumulation, however, underscores the need for long-term monitoring frameworks that integrate both chemical and radiological parameters.

6.3 Emerging patterns and conceptual understandings

The synthesis illustrates a dual contamination pattern in uranium-mining environments: prolonged legacy effects versus emerging, localised risks. The oldest mine exemplifies cumulative impacts from decades of tailings leachate infiltration, while the newest shows the onset of hydrogeochemical alteration (Balaram et al., 2022; Bhavya et al., 2023). This temporal contrast provides insight into the progression of contamination under varying operational and environmental contexts.

Interactions among lithological composition, hydrodynamic conditions, and management practices collectively shape uranium and trace-metal mobility. Silicate weathering, carbonate buffering, and redox variations govern contaminant stability, while evaporative enrichment common in arid zones concentrates solutes and accelerates accumulation within shallow aquifers (Chen et al., 2022; Ji et al., 2024).

Isotopic evidence reinforces these patterns by linking geochemical diversity to recharge mechanisms. Enriched isotopic signatures at the legacy site reflect low recharge and high evaporation, whereas heterogeneous isotopic values at newer mines indicate infiltration of tailings-derived water through permeable or preferential pathways and meteoric water through episodic rainfall events.

6.4 Implications for groundwater management and sustainability

The integrated findings emphasise that legacy contamination persists long after mine closure, necessitating continuous monitoring and proactive remediation. Newer mines should employ adaptive containment and early-warning systems to avoid the recurrence of chronic contamination (Tillman et al., 2021).

Hydrochemical heterogeneity underscores the need for site-specific monitoring programs that reflect local geological and geochemical variability. Tailings seepage and leachate assessments should inform transport models that simulate contaminant behaviour under fluctuating climatic and operational conditions.

From a regulatory perspective, chemical toxicity should receive equal emphasis alongside radiological safety, given the chronic exposure risks to communities reliant on groundwater (Ramesh et al., 2021). Integrating isotopic tracers into routine assessments can substantially enhance understanding of contamination pathways and aquifer recovery. Broader governance efforts in Namibia would benefit from

greater transparency in data and cross-sector collaboration among industry, academia, and regulators (Lu et al., 2024).

6.5 Knowledge gaps and future perspectives

6.5.1 Limitations

Although this research advances understanding of uranium impacts on arid-zone aquifers, several gaps remain.

- Limited temporal resolution: The absence of long-term isotopic datasets limits the resolution of recharge cycles and temporal variability.
- Sparse spatial coverage: Sparse monitoring wells restrict accurate delineation of contamination plumes.
- Operational constraints: Data on containment efficiency and tailings composition are insufficient for predictive modelling

6.5.2 Future Research Directions

Future studies should:

- couple isotopic and hydrochemical data with predictive numerical models to simulate contaminant transport under evolving climate conditions.
- Investigate interactions among trace metal mobility, redox shifts, and microbial mediation. Advanced speciation and reactive-transport modelling are crucial for quantifying the behaviour of uranium and cadmium under variable redox regimes.
- Pilot innovative remediation strategies in low-resource environments, including permeable reactive barriers, phytoremediation, and sorptive filtration, should be piloted. Evaluations must consider long-term viability, cost efficiency, and community engagement to ensure social and technical sustainability.

6.5.3 Practical Recommendations for Groundwater Protection and Management in Uranium Mining Regions

The findings of this study provide a scientific basis for the practical management and protection of groundwater resources in uranium mining regions of Namibia's arid environment. The identified spatial and temporal variations in trace metals and radionuclides highlight the need for strengthened and continuous groundwater monitoring programs, particularly around tailings storage facilities and along potential groundwater flow pathways. The integration of hydrochemical, isotopic, and radiological assessments can be applied as a routine monitoring framework to distinguish between natural geogenic contributions and mining-related contamination. In addition, the results can inform risk-based groundwater management strategies by identifying areas that may require priority monitoring, mitigation measures, or remediation. From a social-ecological perspective, the findings contribute to protecting groundwater-dependent communities and ecosystems that rely on limited water resources in arid environments. By supporting evidence-based decision making, the study can help guide sustainable mining practices, improve environmental governance, and strengthen the long-term resilience of coupled human water systems in Namibia's mining landscapes.

6.6 Concluding Remarks

This synthesis underscores that uranium mining affects groundwater through both immediate and long-term processes. By integrating hydrochemical, isotopic, and radiological evidence, the study demonstrates that contamination evolves as a product of geological setting, climate, and operational management. The contrasting conditions at Namibia's oldest and newest uranium mines capture the transition from legacy accumulation to emerging risk, revealing the cyclical nature of aquifer vulnerability in arid regions. Ultimately, the findings contribute to a broader conceptual framework for understanding groundwater evolution under mining influence and call for transparent, interdisciplinary, and adaptive management to ensure long-term groundwater resilience.

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