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School of Geosciences

Research Report (Geol7028)

In Partial fulfilment of the Master of Science Degree in Hydrogeology

Investigation of the groundwater evolution, interaction and potential radionuclide pollution from the unlined uranium tailings at Langerheinrich mine, Namibia.

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SUBMISSION DATE: 31 MAY 2016

Declaration

I **IGNATIUS SHIKONDJELENI SHADUKA** declare that this research report work is my own and ideas from other sources have been acknowledged accordingly. This work is submitted in partial fulfilment of Master of Science degree in Hydrogeology at the University of the Witwatersrand, Johannesburg in South Africa and has never been submitted before in any university for any examination or degree as far as my knowledge is concerned.

Name: Ignatius Shaduka

	31 May 2016	Johannesburg
Signature	Date	Place

Acknowledgements

Firstly I would like to thank God for the blessings to have given me the opportunity to further my studies.

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Dedication

This work is dedicated to my Son “Gerrard Namoloh Tuyambeka Shaduka”.

Abstract

Groundwater is a very scarce and sensitive resource in many parts of the World especially in Africa and in arid areas such as Western Namibia. The Western Namibia hosts the Erongo region which named the Uranium Province world class deposits of uranium and high exploration and mining in the area. The majority of the Erongo region in Namibia depends on groundwater from the Swakop River compartment, hence, is important to understand the mining effects to this precious resource. The safe guarding of groundwater pollution from various sources including mining is vital.

The extensive exploration and mining activities in the area raised environmental concerns especially threat to the huge ground water resources and the Aquatic systems in the proximity and hydraulically connected to the Swakopmund and Khan catchments. The study looked the impact of uranium mining in the area specifically focusing on the impact of the unlined uranium tailing dams at Langerheinrich uranium mine on the Gawib River a tributary of the Swakop River. The study reviewed the previous work on the Langerheinrich Uranium Mine that is related to groundwater pollution including the Environmental Impact Assessments carried out by the consultants for the mine. Ten water samples were obtained for the purpose of this study, the samples consists of the groundwater samples, recycled water and the fresh water supply to the mine.

The hydrochemistry, stable isotopes and tritium results show that there is contamination from the unlined uranium tailings into the Gawib shallow aquifer system. This could spread to deeper aquifer systems mainly through major structures such as fractures and faults in the area. The contamination plume will also spread downstream to the Gawib River towards the Swakop River unless serious mitigation measures are put in place. There is also a very high risk of the plume to reach the Atlantic Ocean by seasonal flash floods that occurs in the area approximately every after few years.

Keywords: Uranium Province, Langerheinrich uranium mine, Groundwater, Pollution, unlined tailings and Gawib River

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List of Abbreviations

°C – Degree Celsius
EC – Electrical Conductivity
Eh – Redox Potential
GMWL – Global Meteoric Water Line
^{2}H – Hydrogen-2/ Deuterium (Isotope of hydrogen)
^{3}H – Hydrogen-3 (Isotope of hydrogen)
ICP-MS – Inductively Coupled Plasma Mass Spectrometry
mg/l – Milligrams per litre
mS/cm – MilliSiemens per centimetre
^{16}O – Oxygen-16 (Isotope of oxygen)
^{18}O – Oxygen-18 (Isotope of oxygen)
SMOW – Standard Mean Oceanic Water
TDS – Total Dissolved Solids
TU – Tritium Unit
U – Uranium
WLMWL – Windhoek Local Meteoric Water Line
µg – Micrograms
δ^{18}O – Oxygen Isotope value (‰)
δ^{2}H – Hydrogen Isotope value (‰)
‰ – Per Mil
BIWAC – Bittner Water Consulting
CCD –counter-current decantation
SEA –Strategic Environmental Assessment
GSN – Geological Survey of Namibia
BGR – Bundesanstalt für Geowissenschaften und Rohstoffe
LHU –Langerheinrich Uranium Mine
TSF –Tailings Facility
MME – Ministry of Mines and Energy
ERI –Electrical Resistivity Imaging
NAMWATER –Namibia Water Corporation

Chapter 1. Introduction

1.1 Background

The study area is located within the Langerheinrich uranium mine Namibia. The mining activities are fairly new but yet a concern environmentally. Mining activities started in 2005 with first shipment in 2006. The deposit being mined at Langerheinrich mine is secondary calcrete hosted uranium extracted through alkaline leaching method.

Technically the study will point out the connectivity of the tailing seepage water to the groundwater if any and recommend any possible mitigation measures to be employed by the Langerheinrich Mine to prevent further groundwater pollution if any is identified. The findings and recommendations of previous researchers in the area on the similar subjects are closely evaluated.

The study reviewed the Langerheinrich mine "**Biannual Environmental Report January to** June 2011" groundwater monitoring findings. The report is hereby quoted stating that "The uranium concentrations in the area upstream of the plant are the highest. The source for this pollution is the tailings deposited at the Temporary Tailing storage facility (TSF1 and TSF 1 Extension)". The report further stated that TM46 reports the highest concentration in this period ranging from 452 ppm to as high as 540 ppm in February 2011. The boreholes in the Plant Area are reported to contain high Vanadium and Uranium, with the source of pollution identified as processing plant and barren stockpile, Langerheinrich mine (2011). The Study will compare the recent (2015) groundwater analysis of the monitoring boreholes to the historical analysis carried out in 2005, exactly ten year interval.

It is reported that the water level has risen in boreholes TM12, DW24 by 3.52m and 1.65m, respectively, which is understood to be seepage from the barren stockpile and the Leach/CCD area and the flooding episodes throughout the observation period, Langerheinrich mine (2011).

1.2 Research aim and objectives

The aim of the study is to build knowledge on the assessment and protection of groundwater resources in the Uranium mining areas of Namibia. The study aims to add value to the monitoring activities of the Radiation Protections Authority. The study also aims at strengthening the reviewing of the Environmental Impact Assessment’s (EIA’s) submitted to the regulators or generally to the licensing authorities in Namibia in order to protect the groundwater and other natural resources form radioactive pollution as well other forms of pollutions.

Although (MME, 2010) and (Schubert & Knöller, 2010) concluded that there is no possibility of pollution of groundwater with radionuclides from the tailings at Langerheinrich mine, it’s difficult to accept the conclusion without estimating the time it will take for the pollution plume to reach the groundwater through the thick unconsolidated sediments underneath the tailings. The study will, therefore, attempt to determine the seepage velocity in the study area and estimate how long it would take for the contamination plume to reach the groundwater and also to establish the status at the moment.

The Langerheinrich mine started production in 2006, hence, it is too early to expect that the seepage has travelled through unconsolidated sediments of about 40 m thickness in that short time as it would mean that the seepage will need to travel at the velocity of the 10 m/yr, in the period of 4 years considering the time in 2010. At some point in 2008, seepage from the tailings was found in some roads to the pit in the mine site downstream of the tailings and the important questions to ask are: how much of this water had infiltrated? What are the radionuclides content of the seepage water? The fact cannot be ignored here to mean that all the water has been pumped back to tailings with no infiltration, after all not all the water seeped out of sediments to pond as shown by the picture (Figure 1).

Figure 1. The seepage from the tailings dump at Langerheinrich in 2008 (Source: www.iaea.org/OurWork/ST/NE/NEFW/documents)

It also important to note the location of the tailings (Figure 2) that is directly on top of the paleo channel (Gawib River). The tailings are not lined to prevent the processing water ponding on the tailings to seep into the groundwater. How much of this water is recovered and recycled back into the processing system? This would scientifically need to be established.

Figure 2.The aerial view of the Langerheinrich tailings on top of the Gawib River (Source: MME, 2010)

1.3 Description of the study area

1.3.1 Location

Langerheinrich uranium mine is located in Erongo Region at the coastal area of Namibia, 80 km east of the coastal town of Swakopmund (Figure 3). The mine is developed in the tributary of the Swakop River called Gawib River.

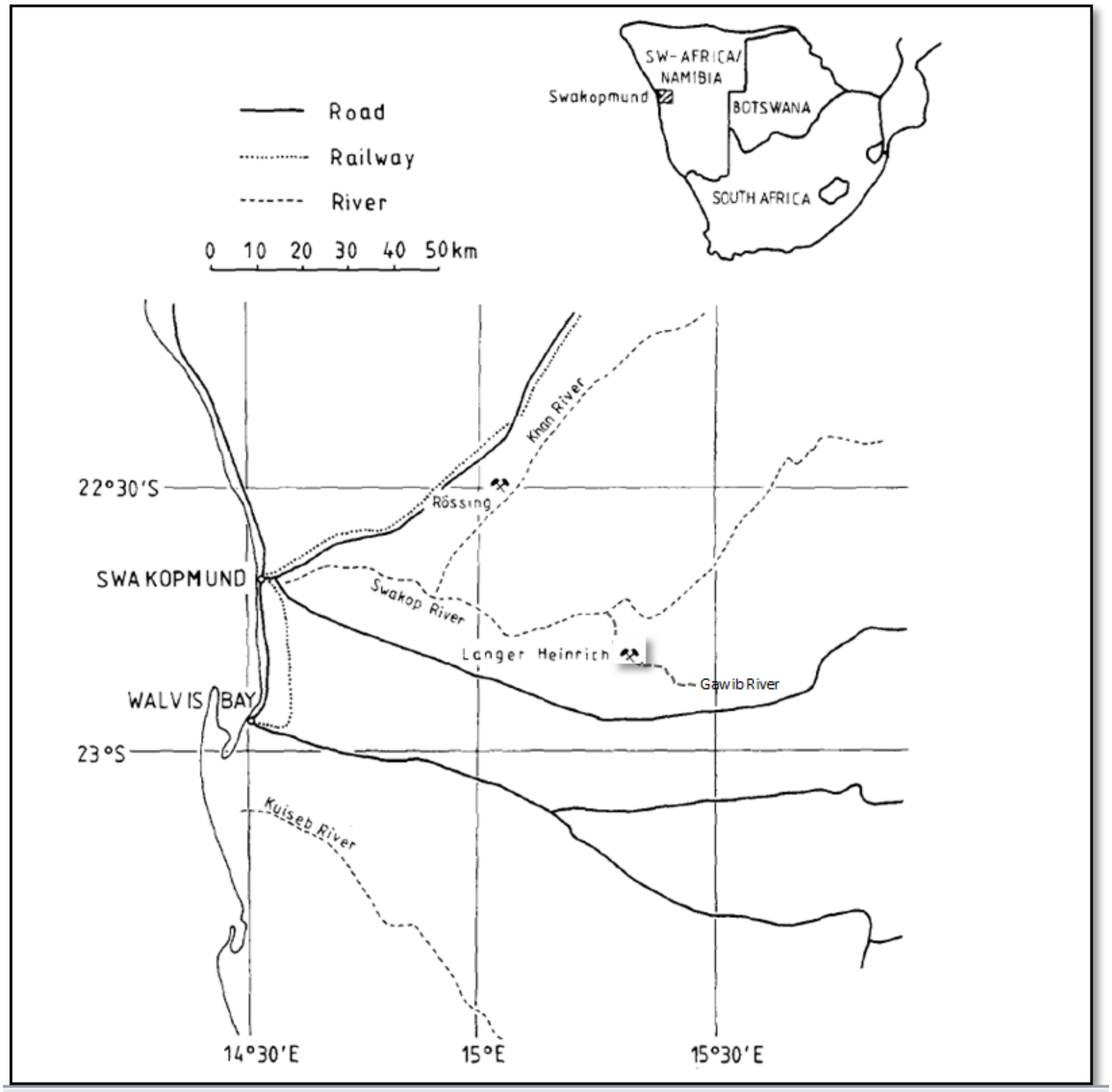


Figure 3.The locality map of the study area/ Langerheinrich mine (Source: Hartleb, 1987)

The Swakop River basin supplies water for agricultural and mining activities in the area and occasionally flows directly into Atlantic Ocean. The Swakop River is an ephemeral river that occasionally floods into the ocean (Figure 4), therefore, posing pollution hazards to the ocean from inland solutes.

Figure 4. Flooded Swakop River as it flows into the Atlantic Ocean in April 2011 (Picture by Monika Emvula)

Langerheinrich mine is located in the arid Namib Desert with minimal vegetation and average rainfall of less than 150 mm per annum (MME, 2010). The water is allowed to pond on the tailings and most of it evaporates and the remaining infiltrates downward through the tailings (Figure 5).

Figure 5. The author collecting soil samples on the unlined tailing facility at Langerheinrich mine in 2011, in the background are ponds of polluted water allowed to seep through the tailings

1.3.2 Drainage

The study area is located in the Gawib river, a paleo-channel and main tributary to the Swakop River (Figure 6). The Swakop River is an ephemeral River system. The flow through Gawib River enters the Swakop River system that flows during rainy seasons flowing from the eastern part of the study area. The catchment of the Swakop River extends as far as Khomas Hochland highlands and they are one of the major sources of water flowing during the rainy seasons.

The study area forms part of the Swakop River Basin and is located on the southern fringe of the Swakop River Basin and it is located within the Gawib sub-basin (Figure13). The Gawib sub basin has a size of 131 km² from the watershed to the inflow to the Swakop River (BIWAC, 2009).

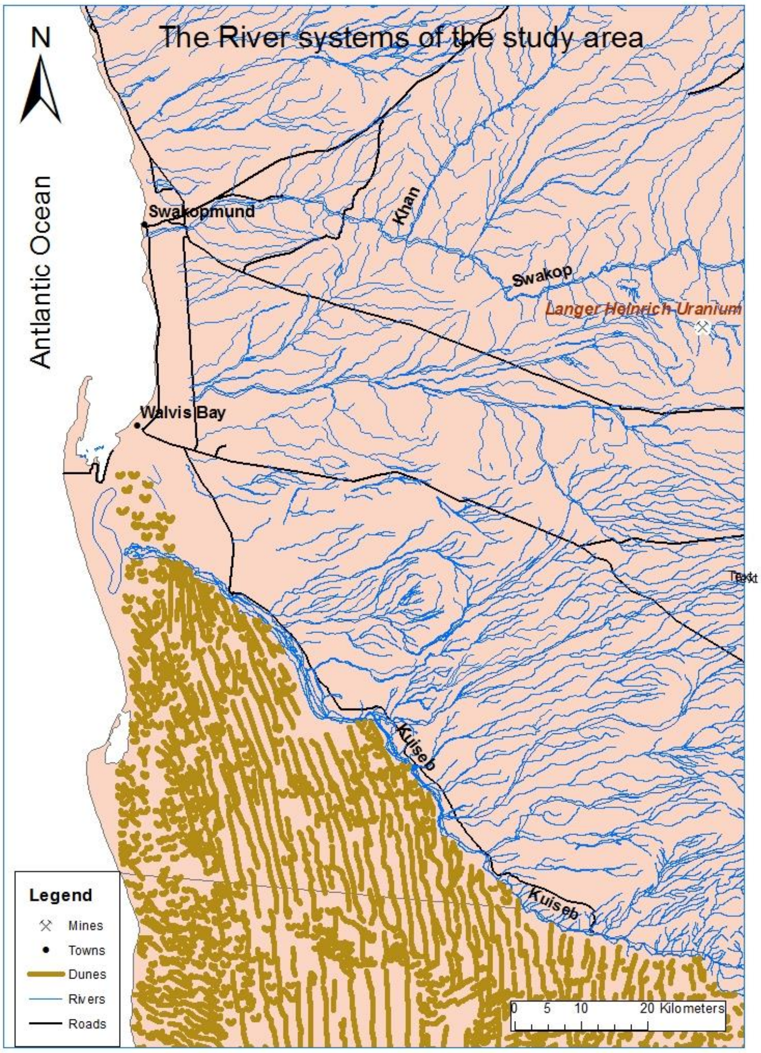


Figure 6.The drainage system of the study area and the related features

The Swakop River basin has approximately mean annual runoffs of about 40 million cubic metres per annum (MME, 2010). The main water quantity of the Swakop River mainly depends on the alluvial aquifers underneath.

1.3.3 Physiography

The Langerheinrich mine area is characterised by streams draining alluvial covers such as the Gawib River, which hosts the uranium mine. The mine is located between the Langerheinrich mountain that border the mine on the right (North East) and Schieferberge mountain immediately to the south (Figure 7). Upstream of the Gawib River is bound by hills of hard rocks on the eastern side and relatively gentle sloping hills on the western side of the stream.

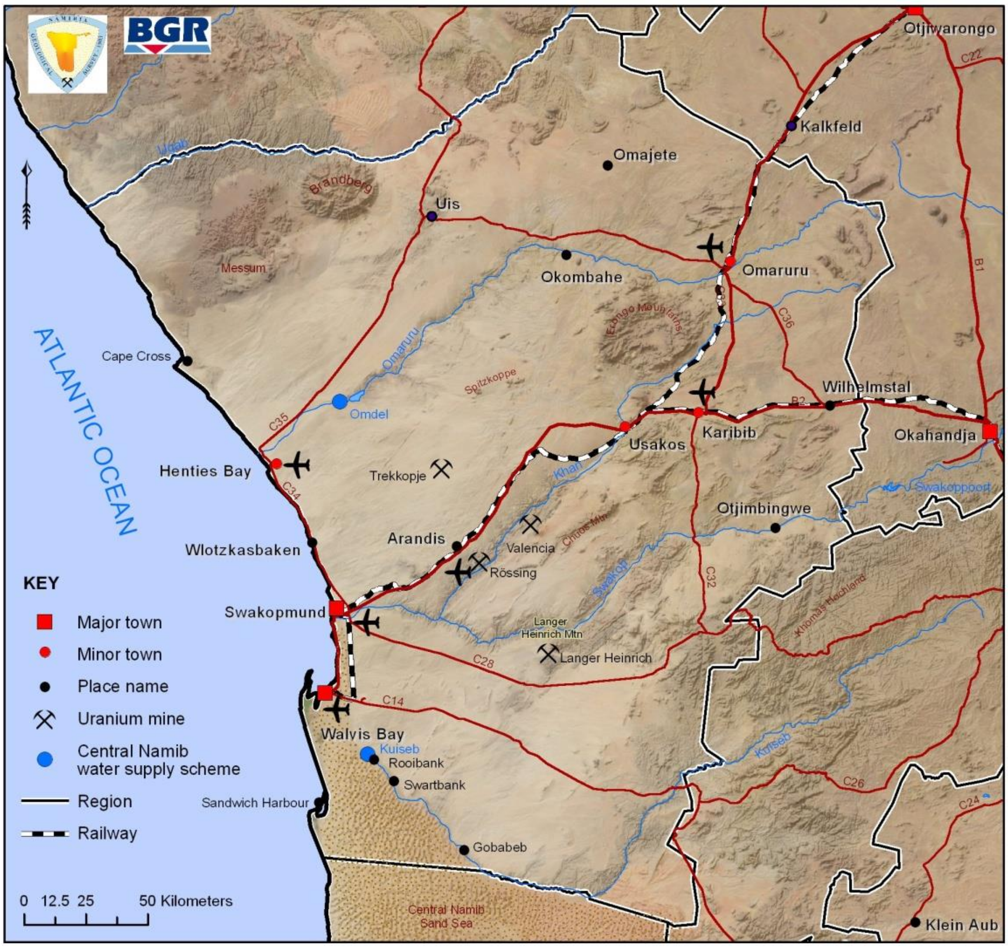


Figure 7. The main physical features and uranium Mining centres (after MME, 2010)

The Khomas Hochland highlands/mountains on the South East of the Langerheinrich, they are very crucial in the hydrogeology of the study area as they are the source of recharge for the Gawib River and eventually the Swakop River.

1.4 Methodology

1.4.1 Desktop study

The first literature reviewed were text books and hydrogeology course reference materials to understand the basics of hydrogeology as well the techniques to approach the research problem. The desktop study reviewed the published and unpublished literature with similar environmental concerns especially related to groundwater pollution and protection as well as remedial measures in the case of contamination. The literature from various journals were reviewed to look at similar case studies on the subject of uranium mining set up and tailing management. There was special focus to understand modern techniques in geophysical methods to determine the structures and wetness of the tailings, hence, techniques such as electrical resistivity imaging (ERI). The Namibian Government conducted a study to build knowledge on the assessment and protection of groundwater resources in the uranium mining environments.The study aimed to add value to the monitoring activities of the radiation monitoring as well as point out factors to be considered during the Environmental Impact Assessment (EIA) submitted to the regulators or generally to the licensing authorities in Namibia. This study has a specialist reports in various aspects including groundwater of the Erongo region, which include the Langerheinrich uranium mine. The Langerheinrich uranium mine reports to the regulators on the bi annual basis and the environmental reports proved handy in describing the activities of the mine and basic understanding of the study area in depth detail.

Chapter 2. Literature review

2.1 General

There have been many studies conducted related to the uranium mining environmental concerns, tailings and/or mining waste disposal, management and rehabilitation. It is very important for the mining companies and mining industry regulators to conduct comprehensive studies to ensure environmental protection. Tailing facilities at the uranium mines are often situated at wrong sites, therefore, pollution to water resources can be a consequence. The tailing site identification is vital in uranium and other commodities mining hence scientists have employed geophysical techniques such as electrical resistivity to understand and model the underlying geology and do the vulnerability assessment. This study reviewed some case studies related to the assessment of siting of tailings dams and environmental pollution related aspects from tailings as well as water seepage migration. If uranium mining is not handled professionally it could result in adverse effect of radiological environmental effects. In some cases the lithology plays a major role in controlling the pollution of groundwater resources from mining activities. Case studies discussed below have similar mine set up, or similar environmental pollution problem as well as investigations using techniques that this study have or wish to have employed.

2.1.1Case study: Application of electrical resistivity imaging (ERI) to a tailings dam project for artisanal and small-scale gold mining in Zaruma-Portovelo, Ecuador

The set of the mining activities in Zaruma-Portovelo Mining District in Ecuador, relates to the study area in a sense that; the mining activities in Ecuador are set up on top of the Amarillo River and (Figure 8) and this is the same set up at Langerheinrich uranium mine in Namibia, (Figure 2). There are well developed tools in Geophysics to be able to site the mining waste sites or tailing dams in an environmental safe manner. The case study showed the capability of electrical resistivity imaging (ERI) to identify key subsoil features that might affect a future tailings dam slated for construction at the Zaruma-Portovelo Mining District, Ecuador (Zarroca et al., 2015). Using the electrical resistivity imaging, it was discovered that the rock massif was composed of weathering horizons of different rock qualities, slopes that are affected by sliding surfaces and these features exert a control on the groundwater flow, hence, the original selected site to construct a dam was susceptible to land slide, therefore, alternative site was recommended in a layered granitic mountain. The tailings dams at Langerheinrich mine should have been sited using same methods and taking into account the hydrogeological sensitivity and vulnerability of the Gawib River.

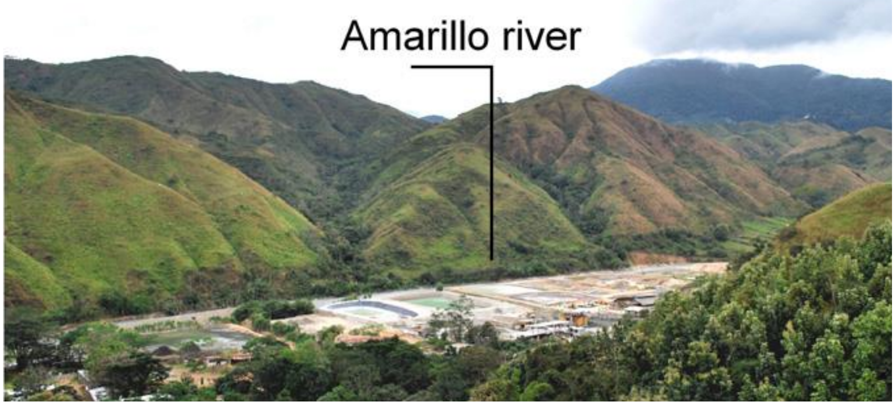


Figure 8. Detail of the mineral-treatment plants and tailings ponds on the alluvial plain of the Yellow River (Source: Zarroca et al., 2015)

2.2 Regional geology

The Langerheinrich Uranium mine is located in the central zone (CZ) of Damara belt, which was formed as result of the Damara Orogen. The well documented, hence, popular in the geological history of Namibia, belongs to the late-Precambrian (2.75 Ga), to early–Palaeozoic (2.5 Ga). The Damara Orogeny is part of Pan-African collisional belts in Southern Africa that record the amalgamation of the Gondwana supercontinent (Figure 9). In Namibia the Damara Orogeny has given birth to three distinct belts, which are Damara, Kaoko and Gariep belts. The Damara mobile belt is a result of the collision between the two continental crusts of the Congo and Kalahari cratons.

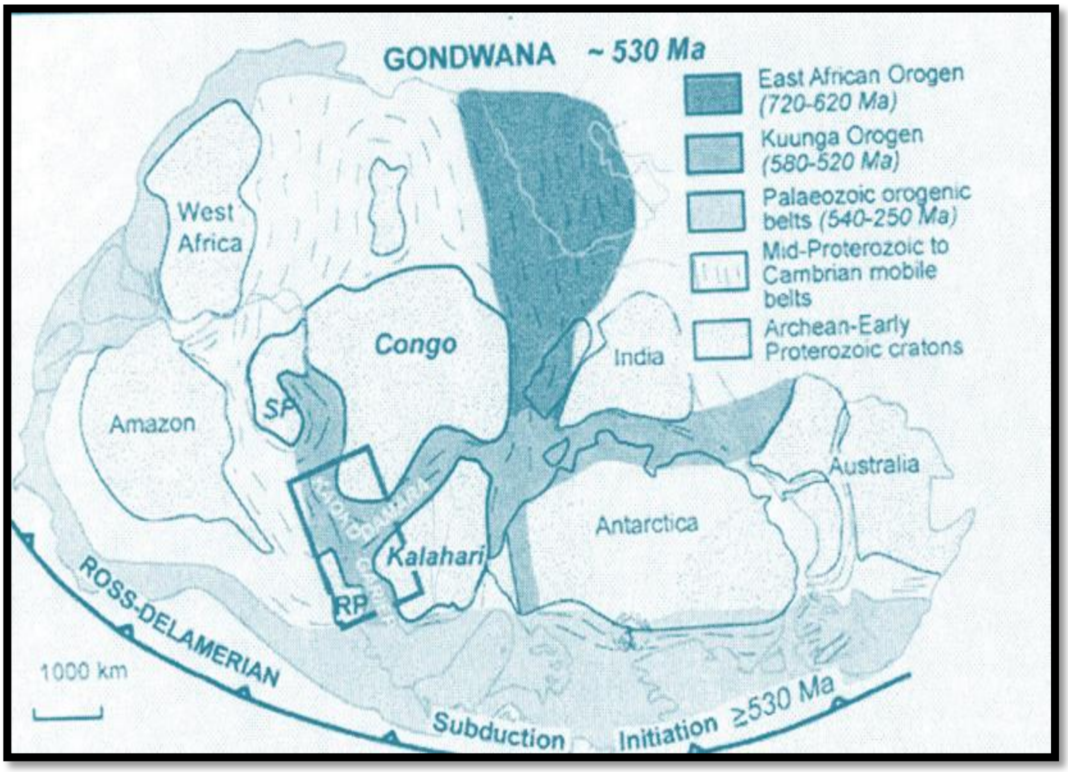
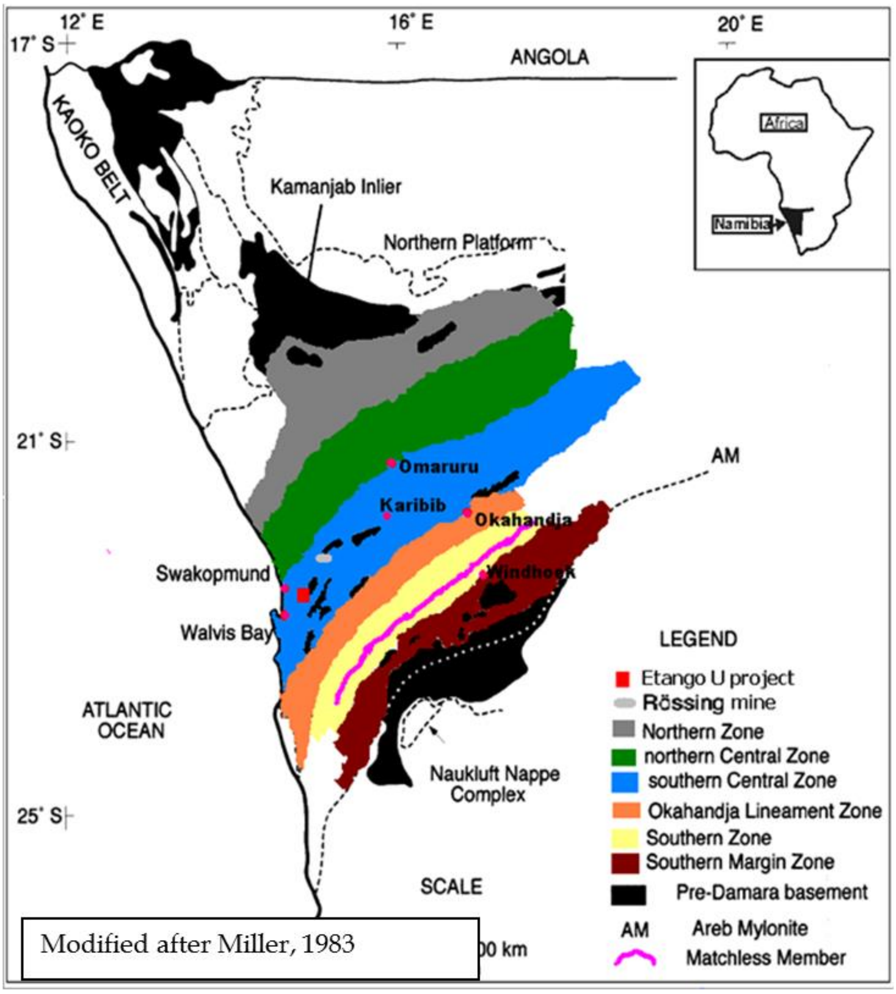


Figure 9. The Pan-Africans belts of the Gondwana Supercontinent (Source: Gray et al. 2006).

The Damara belt is divided into several tectono-stratigraphical units (Figure 10), (Miller and Hoffmann 1981), which can be distinguished on the basis of stratigraphy, structure and grade of metamorphism. From North to South, these zones are referred to as the Northern Zone (NZ), Central Zone (CZ), Okahandja Lineament Zone (OLZ), Southern Zone (SZ) and Southern Margin Zone (SMZ). The margins between the zones are faults (NZ-CZ), major lineaments (CZ-OLZ), or approximate stratigraphic boundaries (SZ-SMZ). The Northern platform consists of weakly folded, mainly carbonate rocks and is followed southwards by a transition zone where folding and metamorphism increase in intensity. The Central Zone is characterized by medium to high grades of metamorphism and voluminous granitic intrusions. The Southern Zone is about 100km wide and contains the Khomas trough, which consists of flysch like sequence of mica schists, quartzites and mafic Meta volcanic rocks such as Matchless member (Figure 10). This zone is separated from the Central Zone by a pronounced change in structural style, namely the Okahandja lineament (Miller and Hoffmann 1981).



Modified after Miller, 1983

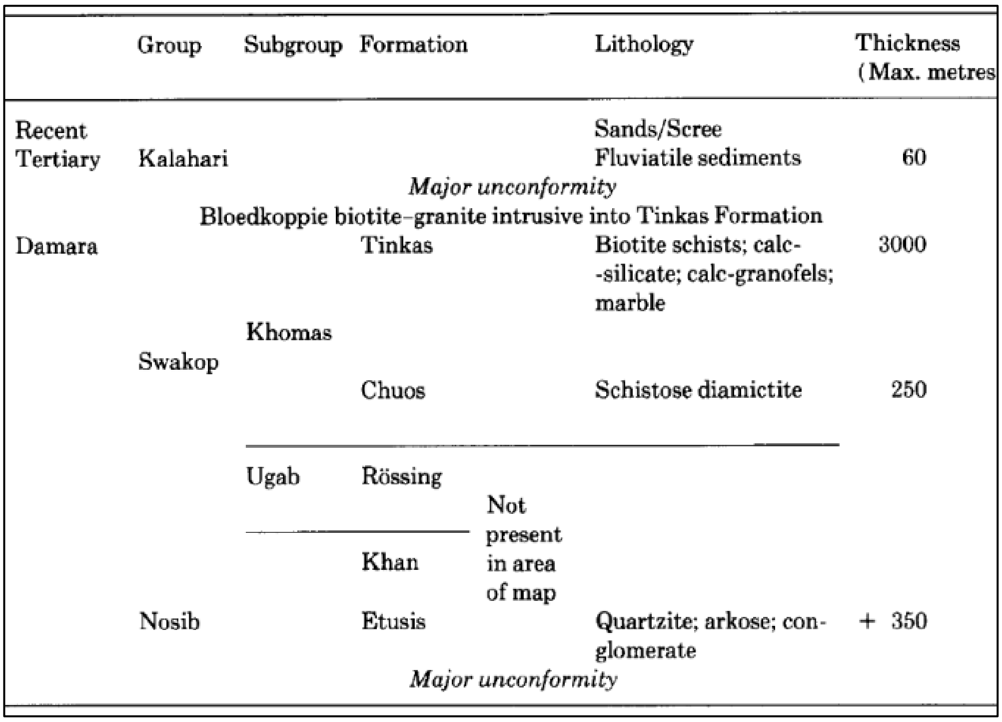
Figure 10. Regional Geology of the study area

2.3 Local geology

The Langerheinrich deposit is hosted geographically in the Namib Desert. Geologically, the Namib Desert lies within the Late Proterozoic Damara orogenic belt consisting of metamorphic sedimentary and volcanic rocks (Becker & Kärner, 2009). Becker & Karner (2009) described the different stages of syn- to post-tectonic granites and alaskites to have intruded into the Damara rocks, some of them containing naturally high amounts of uranium, e.g. Rössing and Ida Dome alaskites.

Further the breakup of Gondwana led to the rifting of the continental cratons of the Congo and the Kalahari during the Late Jurassic and related surface denudation of Proterozoic rock units were accompanied by the retreat of the Great Escarpment, which is one of the most prominent morphological features in Namibia and divides e.g. the Namib Desert from the Khomas Hochland plateau (Becker & Kärner, 2009). Continuous erosion of the high elevated plateaus and the resulting eastern movement of the Great Escarpment during the Cenozoic led to the deposition of fluvial and alluvial deposits west of the Escarpment (Becker & Kärner, 2009). These Cenozoic sediments are host to surficial uranium mineralization throughout the Namib Desert including the Langer Heinrich ore body (Becker & Kärner, 2009).

The stratigraphy of the Langerheinrich comprises of tertiary sands /scree fluviatile sediments of the Kalahari group that is about 60 m thick and underlain by the older Damara super group metasediments (Hartleb, 1987), (Figure 11).



	Group	Subgroup	Formation		Lithology	Thickness (Max. metres
Recent Tertiary	Kalahari				Sands/Scree Fluviatile sediments	60
			Major unconformity			
		Bloedkoppie biotite-granite intrusive into Tinkas Formation				
Damara			Tinkas		Biotite schists; calc--silicate; calc-granofels; marble	3000
		Khomas				
	Swakop					
			Chuos		Schistose diamictite	250
		Ugab	Rössing	Not present in area of map		
			Khan			
	Nosib		Etusis		Quartzite; arkose; conglomerate	+ 350
			Major unconformity			

Figure 11. The stratigraphic units at the Langerheinrich mine area (Source: Hartleb, 1987)

The Langerheinrich uranium deposit is hosted in the tertiary age alluvium deposits (Figure 11). The tertiary alluvial deposits in the form of gravels are locally referred to as the Langerheinrich Conglomerate. North of the study area is the Langerheinrich mountain composed of the quartzites and arkoses and belongs to the Etusis formation of the Nossib group (Figure 11) deposited between 650-900 Ma. The Gawib paleo-channel hosting the study area cross cut the Tinkas formation, which is composed of schists and greywackes and forms the Schieferberge mountain that is well known in this area. The map in Figure 12 clearly shows the extensive coverage of the western area by the granites of the Damara group.

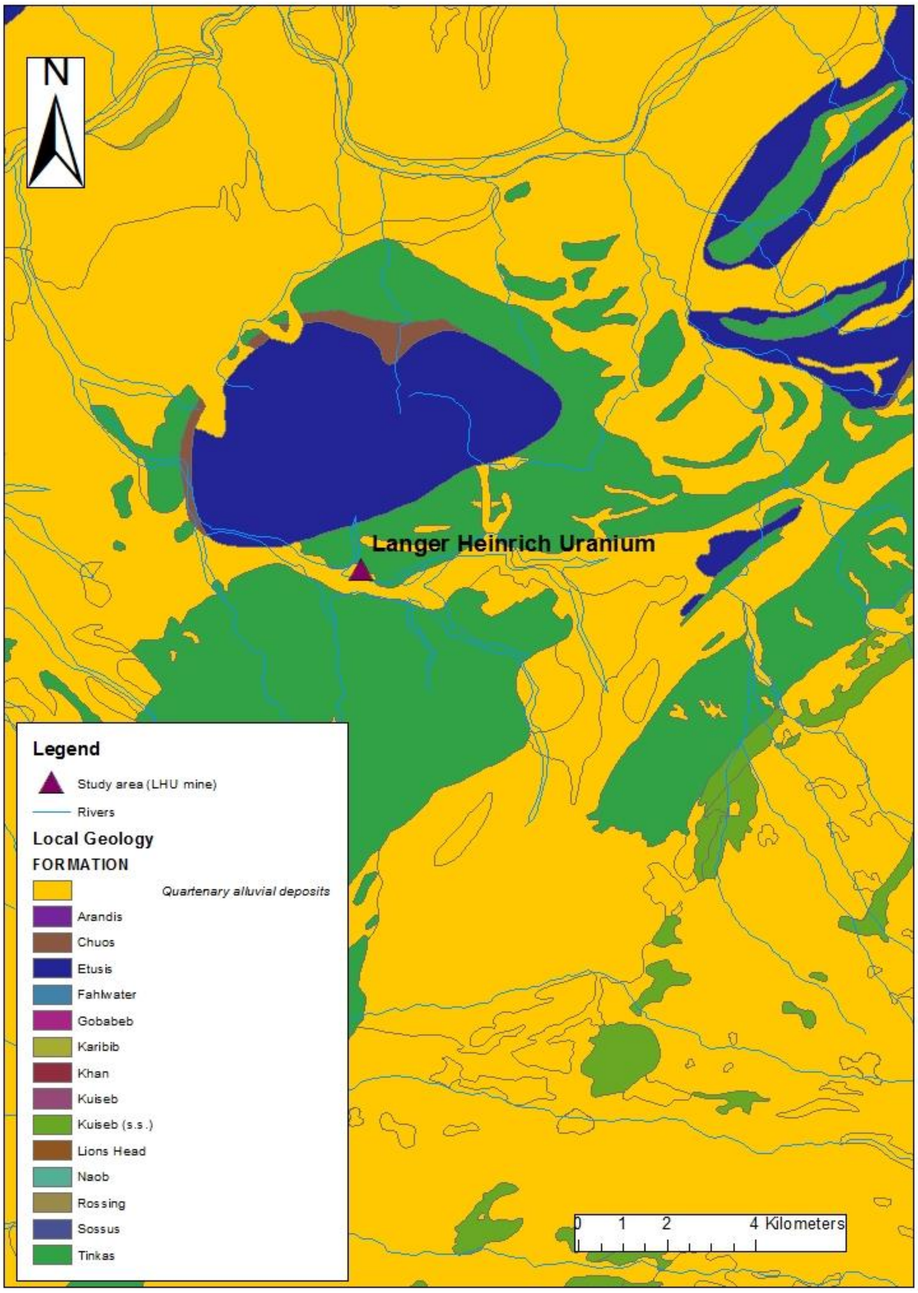


Figure 12. The local geology of the Langerheinrich uranium mine (Study area)

The lithological units at the Langerheinrich are composed of various lithologies as per the cross section below (Figure 13).

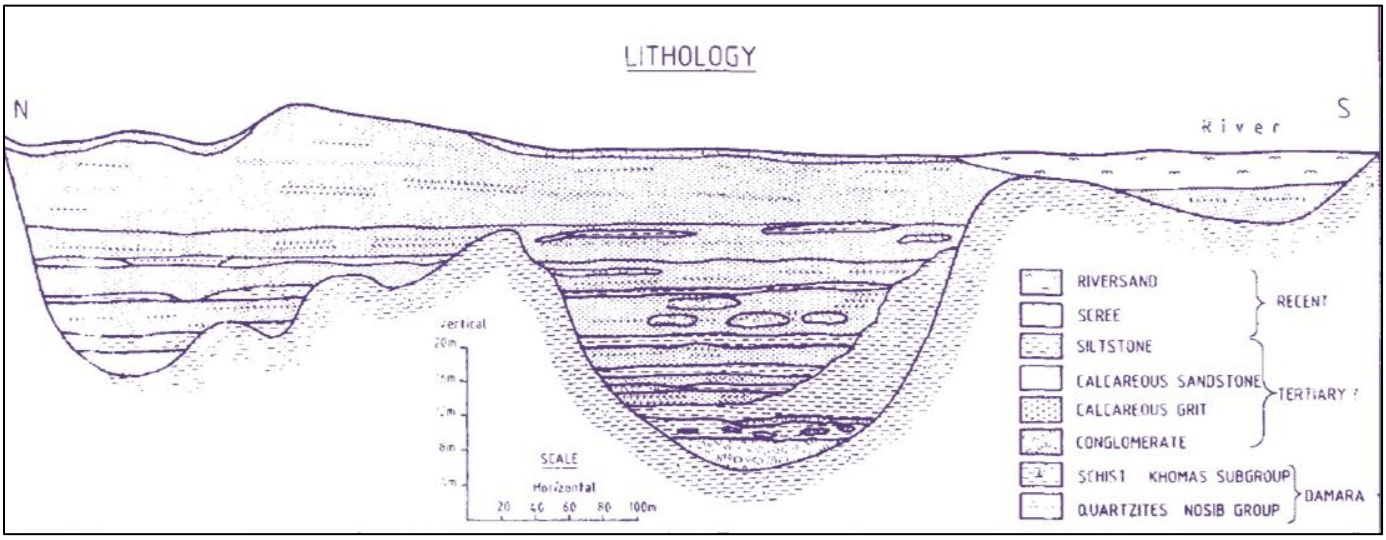


Figure 13. Lithological cross section of the local geology at Langerheinrich uranium mine (Source: Hartleb, 1987)

2.4 Hydrogeological setting

The study area is geographically located in the Namib Desert; it's a sandy coastal area underlain by crystalline rocks (United Nations, 1989). The sand or alluvial deposits are thickest at the foot of the central mountainous zone and in a wedge in the coastal zone in the west with mainly evaporate deposits such as gypsum and halite. The evaporates indicate the end of the groundwater flow, hence, virtually no chance of finding groundwater in the coastal zone, except in the sandy beds of the watercourses close to their mouths (United Nations, 1989). The westward-flowing Rivers (figure 14) such as Swakop River are life-sustaining oases in the Namib Desert and sand, gravel and silt deposits in the Riverbeds are usually 10-30m thick and have moderate to high yields. As the Swakop River enters the Namib Desert, its groundwater becomes gradually more saline and generally unsuitable for human consumption (Christelis & Struckmeier 2011).

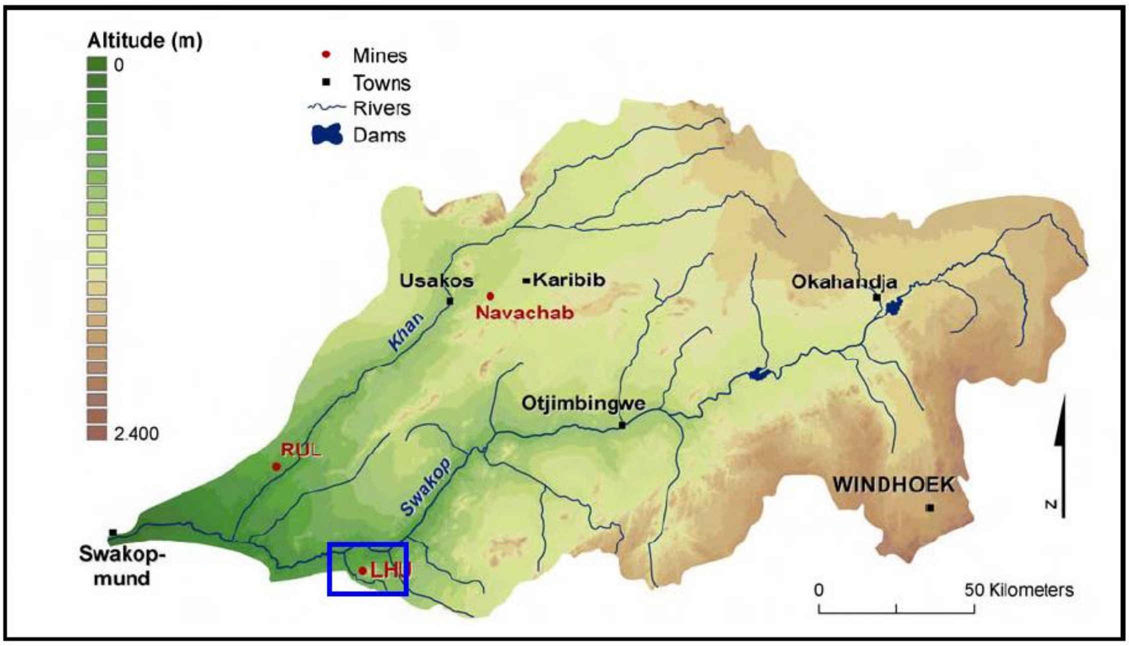
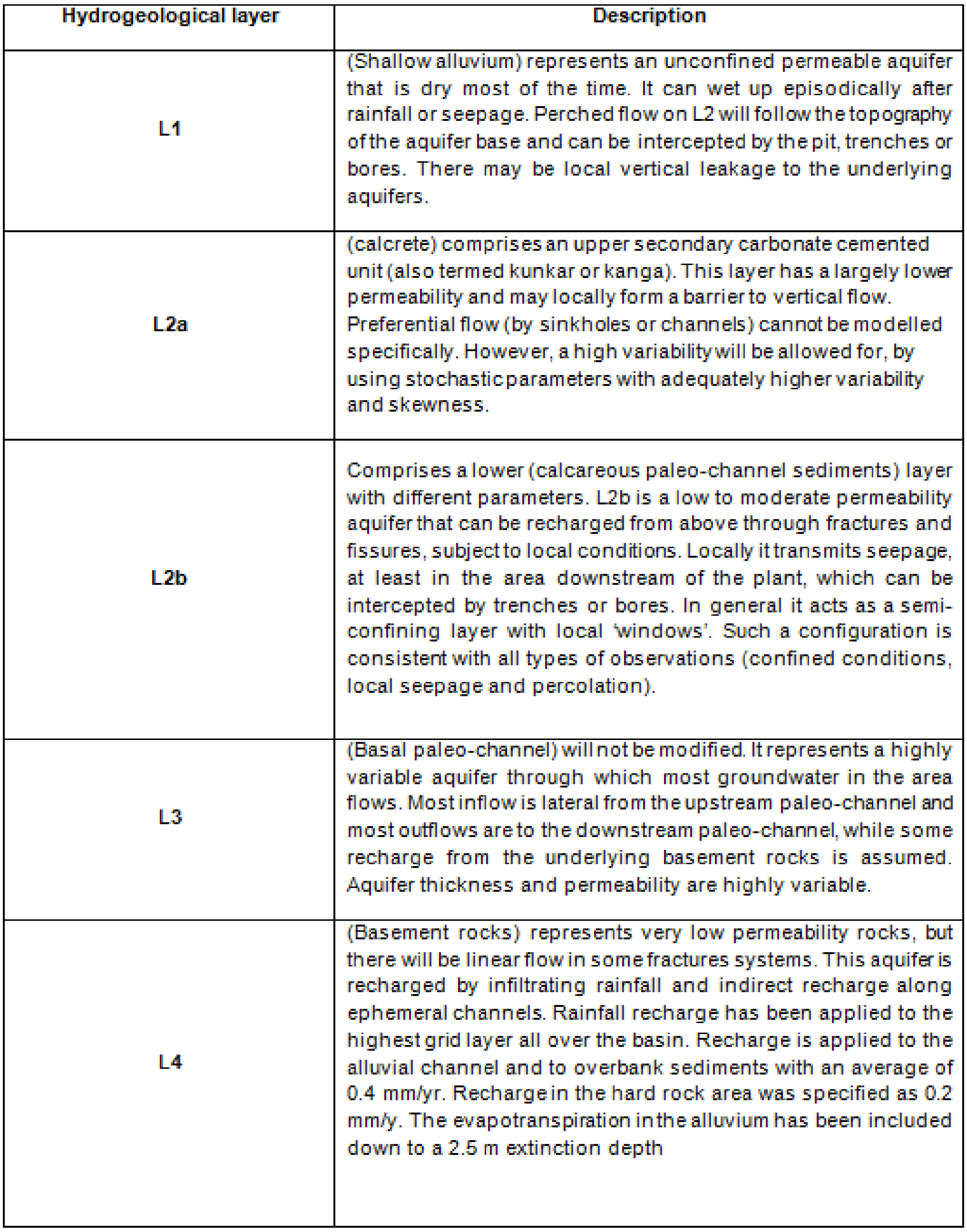


Figure 14. Location of the Langerheinrich uranium mine within the Swakop catchment (Source: BIWAC, 2009)

Five hydrogeological layers have been identified according to the geophysical, borehole logging and mapping work in the area. BIWAC (2009) has documented them very well and herein adopted and modified into Table 1. Therefore, the hydrogeological cross-sections used in this study will be clearly explained by the descriptions in table 1. The map in Figure 16 shows the study area and the cross-sections points.

Table 1. Five distinct hydrogeological layers identified at Langerheinrich (Source: BIWAC, 2009)



Hydrogeological layer	Description
L1	(Shallow alluvium) represents an unconfined permeable aquifer that is dry most of the time. It can wet up episodically after rainfall or seepage. Perched flow on L2 will follow the topography of the aquifer base and can be intercepted by the pit, trenches or bores. There may be local vertical leakage to the underlying aquifers.
L2a	(calcrete) comprises an upper secondary carbonate cemented unit (also termed kunkar or kanga). This layer has a largely lower permeability and may locally form a barrier to vertical flow. Preferential flow (by sinkholes or channels) cannot be modelled specifically. However, a high variability will be allowed for, by using stochastic parameters with adequately higher variability and skewness.
L2b	Comprises a lower (calcareous paleo-channel sediments) layer with different parameters. L2b is a low to moderate permeability aquifer that can be recharged from above through fractures and fissures, subject to local conditions. Locally it transmits seepage, at least in the area downstream of the plant, which can be intercepted by trenches or bores. In general it acts as a semi-confining layer with local 'windows'. Such a configuration is consistent with all types of observations (confined conditions, local seepage and percolation).
L3	(Basal paleo-channel) will not be modified. It represents a highly variable aquifer through which most groundwater in the area flows. Most inflow is lateral from the upstream paleo-channel and most outflows are to the downstream paleo-channel, while some recharge from the underlying basement rocks is assumed. Aquifer thickness and permeability are highly variable.
L4	(Basement rocks) represents very low permeability rocks, but there will be linear flow in some fractures systems. This aquifer is recharged by infiltrating rainfall and indirect recharge along ephemeral channels. Rainfall recharge has been applied to the highest grid layer all over the basin. Recharge is applied to the alluvial channel and to overbank sediments with an average of 0.4 mm/yr. Recharge in the hard rock area was specified as 0.2 mm/y. The evapotranspiration in the alluvium has been included down to a 2.5 m extinction depth

Detailed investigation of the study area by Hore &Luppnow, 2015 shows that Langerheinrich has three distinct aquifer systems namely; (1) Gawib shallow alluvium aquifers, above the orebody zone (2) Deeper Paleochannel aquifers, and (3) the Basement aquifers, fractured older Damara basement rocks (Figure 15).

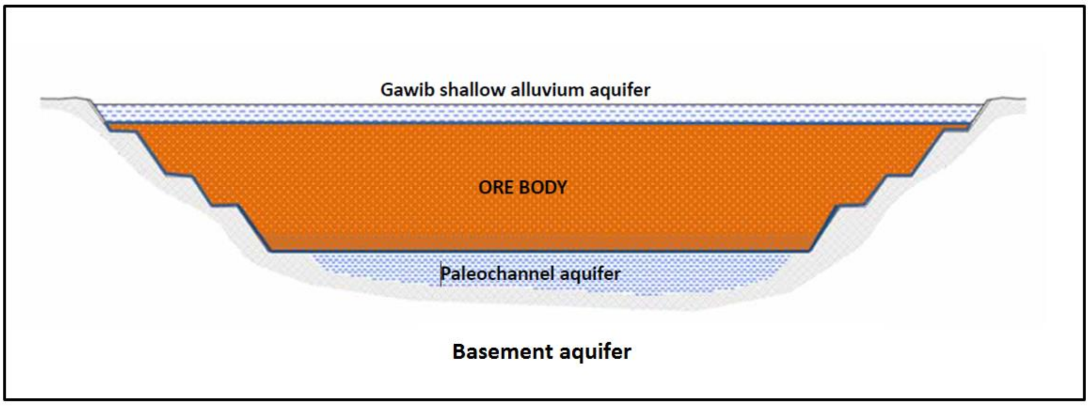


Figure 15.The principal aquifer systems at Langerheinrich (Source: Hore & Luppnow, 2015)

The study area falls in the area of poor/saline groundwater quality. The lithologies in the area have little groundwater potential, even though the aquifers are composed of unconsolidated sediments.

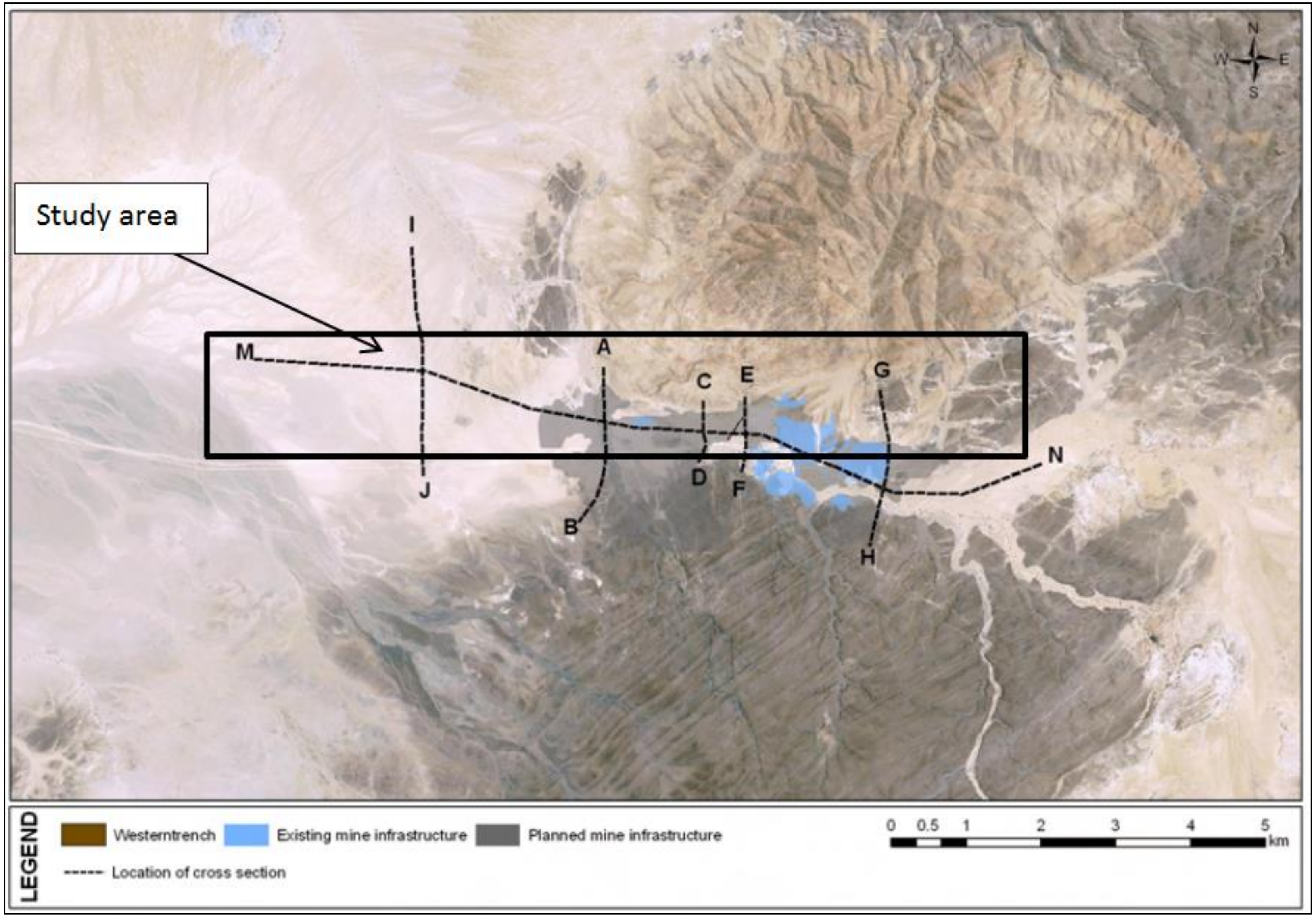


Figure 16. Map showing the five cross-sections and one longitudinal section of the Gawib paleo-channel (Source: BIWAC, 2009).

The hydrogeological cross section indicates that the alluvium deposits or units of the Gawib River dips and, hence, deepening towards the west, clearly shows that the water flowing direction is from the east to the west (Figure 17).

The hydrogeological cross section C-D (Figure 18) shows that the groundwater flows from the south and from the north towards the centre of the paleo-channel and then proceeds to flow westward as per the cross section M-N (Figure 17)

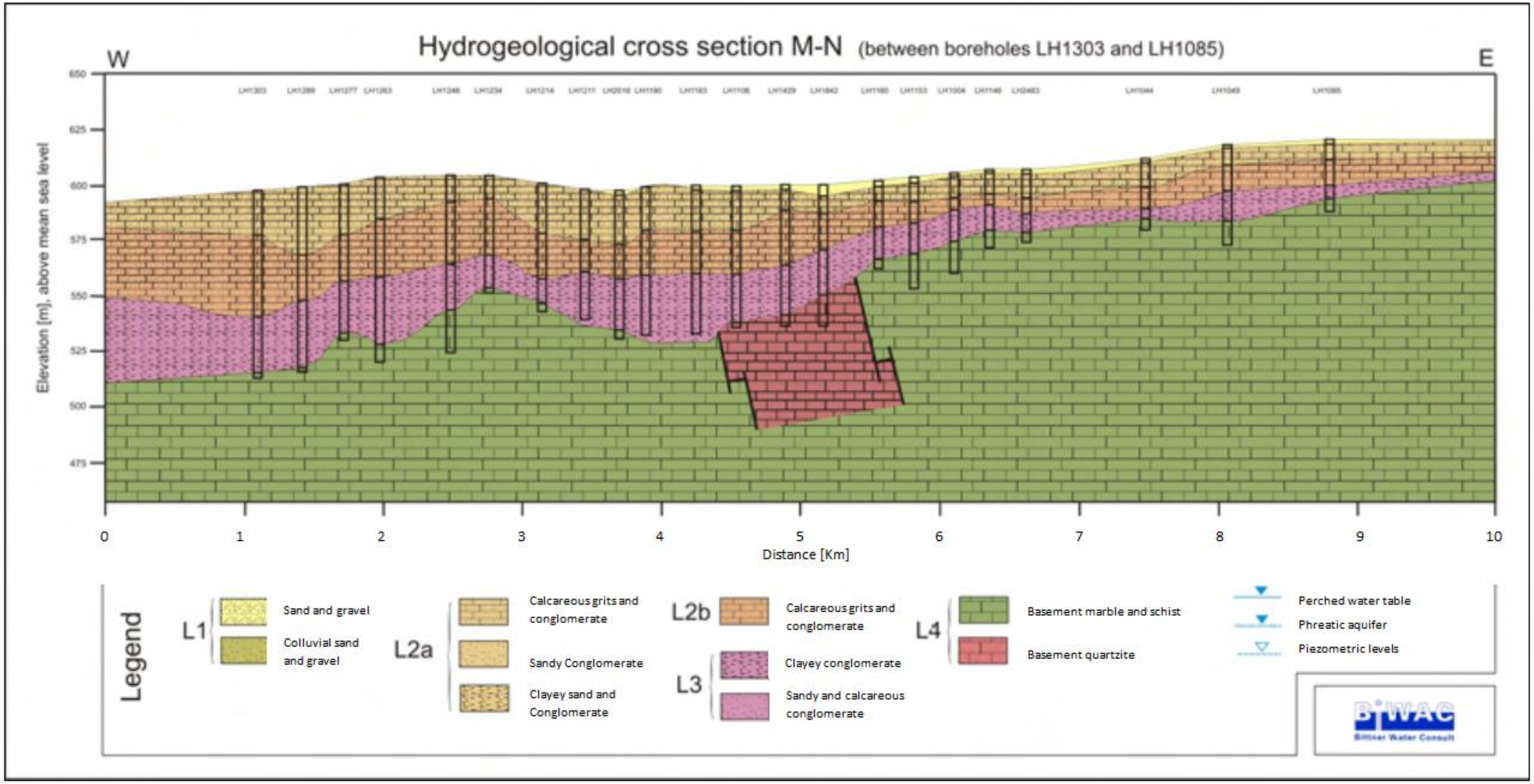


Figure 17. Hydrogeological cross section M-N (source: BIWAC, 2009)

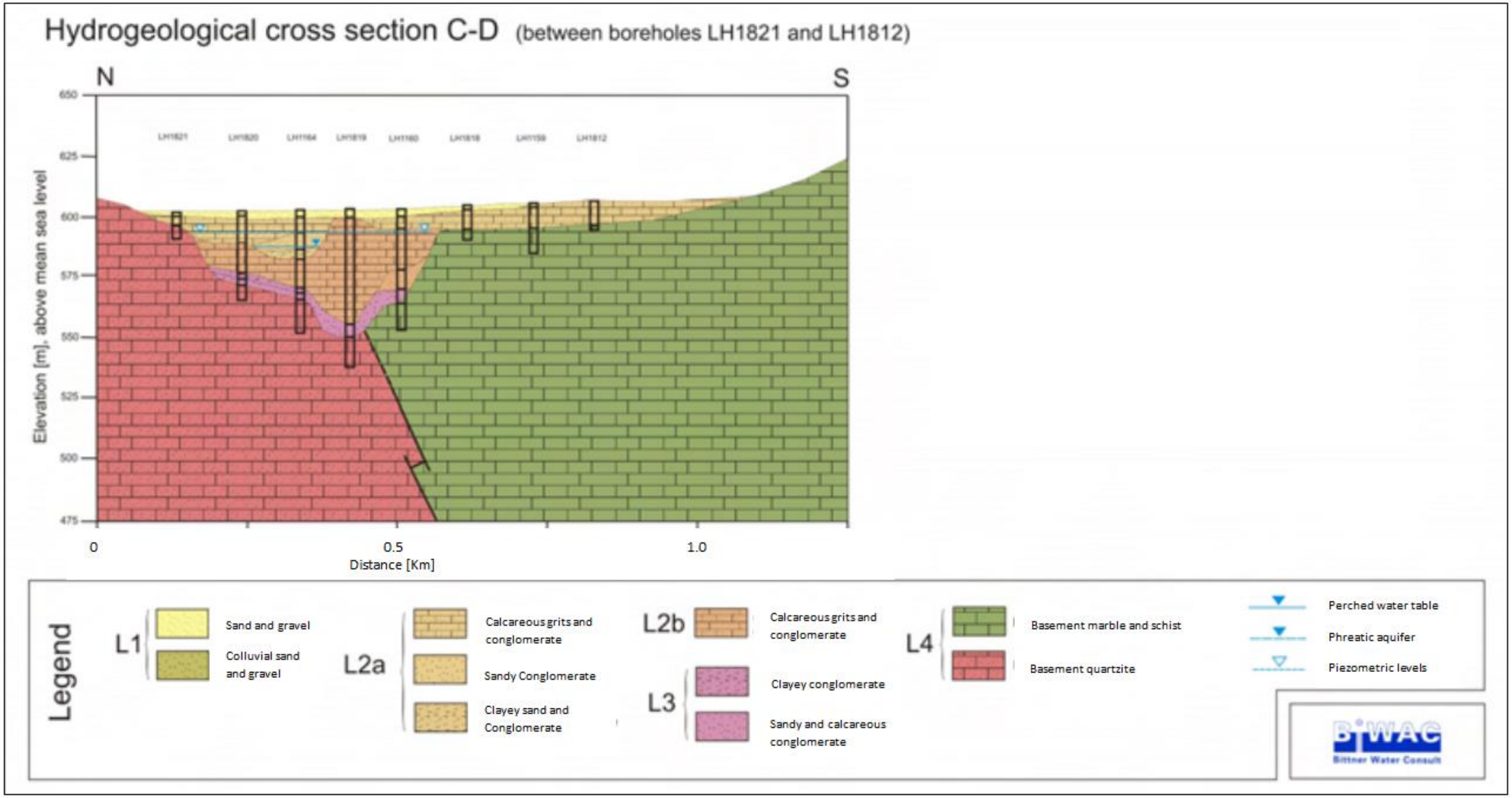


Figure 18. Hydrogeological cross section C-D (Source: BIWAC, 2009)

2.5 Mineralisation of the Langerheinrich deposit

The Langer Heinrich ore body occurs over 15 km length and strikes east-west along a paleo-channel, located between the Langer Heinrich Mountain in the north and the Schieferberge to the south (Becker & Kärner, 2009). The host rocks are composed of calcretized conglomerates, grits, and minor sands and silts. The bedding is lenticular with meter-thick fining upward sequences being common. Vertical as well as lateral facies changes are rapid (Becker & Kärner, 2009).

The uranium deposit is a result of secondary mineralisation. MME, (2010) has described it as Cenozoic uranium mineralisation that occurred as carnotite. The uranium mineralisation occurs as carnotite, an oxidised uranium and vanadium secondary mineral (Becker & Kärner, 2009). Carnotite is evenly disseminated throughout the rocks as well as being completely irregular forming tiny powdery specks within the matrix of the calcareous rock types (Hartleb, 1987). The deposit occurs over a 15km length in seven higher grade pods within a lower grade mineralised envelope. After calcretisation and uranium deposition, parts of the host sediments were eroded as a result of uplift and rejuvenated River flows (Becker & Kärner, 2009).

The present day Gawib River has dissected and modified both the calcrete and associated mineralisation. The carnotite occurs as thin films lining cavities and fracture planes and as grain coatings and disseminations in the calcretized sediments. Carnotite is the main ore mineral and has been precipitated from groundwater, with uranium being derived from Damaran granites and pegmatites exposed in the vicinity of the Langer Heinrich paleo-channel (Miller, 2008). The mineralisation at Langerheinrich is hosted by the deep incised channel franked by the Damaran basement and at Langerheinrich Karpfenkliff is eroded (Figure19)

The near-surface mineralisation is between 1m to 30m thick and 50m to 1,100m wide depending on the width of the paleo-valley (Figure 18). At a 250 ppm of the U_3O_8 cut-off grade the current resource contains 127.1 Mt@0.06% U_3O_8 containing 74 415 t U_3O_8 (164 Mlb U_3O_8) including an ore reserve of 50.6 Mt@0.06% U_3O_8 (65.84 Mlb U_3O_8). Mining operations started in August 2006 (Miller, 2008).

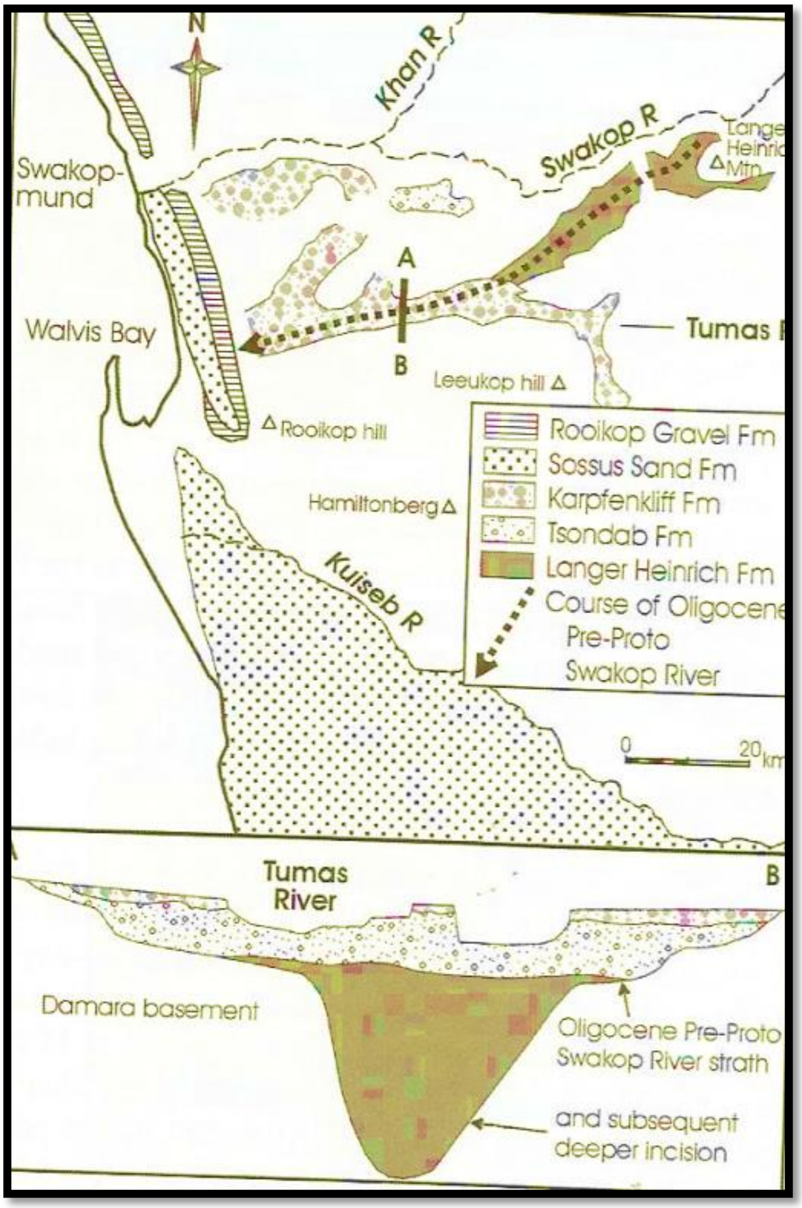


Figure 19. The location of the Langerheinrich Conglomerate formation filling the deeply incised course of the Oligocene and its Langerheinrich tributary "the Gawib River" (Source: Miller, 2008)

The mineralisation zone is controlled by depth and structural factors. The mineralisation is randomly distributed making envelopes of the high grade in the middle of medium and low grades (Figure 19). The most mineralization occurs at the middle of the paleo-channel (Figure 20).

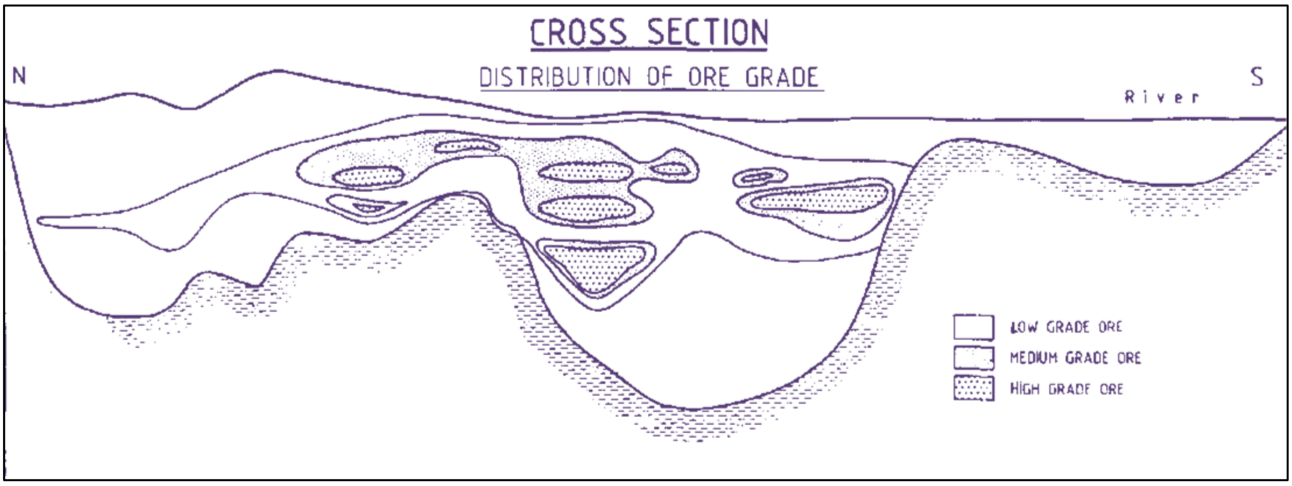


Figure 20. The cross section of the mineralisation in at Langerheinrich uranium mine

2.6 Uranium processing at Langerheinrich

The extraction method at Langerheinrich mine is alkaline leaching and according to Citect Professional Services, the uranium extraction (Figure 21) starts with the supply of ore to the crusher. This is followed by scrubbing, attritioning, leaching/heating, and counter-current decantation (CCD). The discharge slurry circuit is then balanced, providing pregnant liquors to the uranium oxide extraction 14 circuit. This circuit consists of ion exchange, precipitation, elution and product preparation to produce uranium oxide (Case study on LHU by Citect Professional Services).

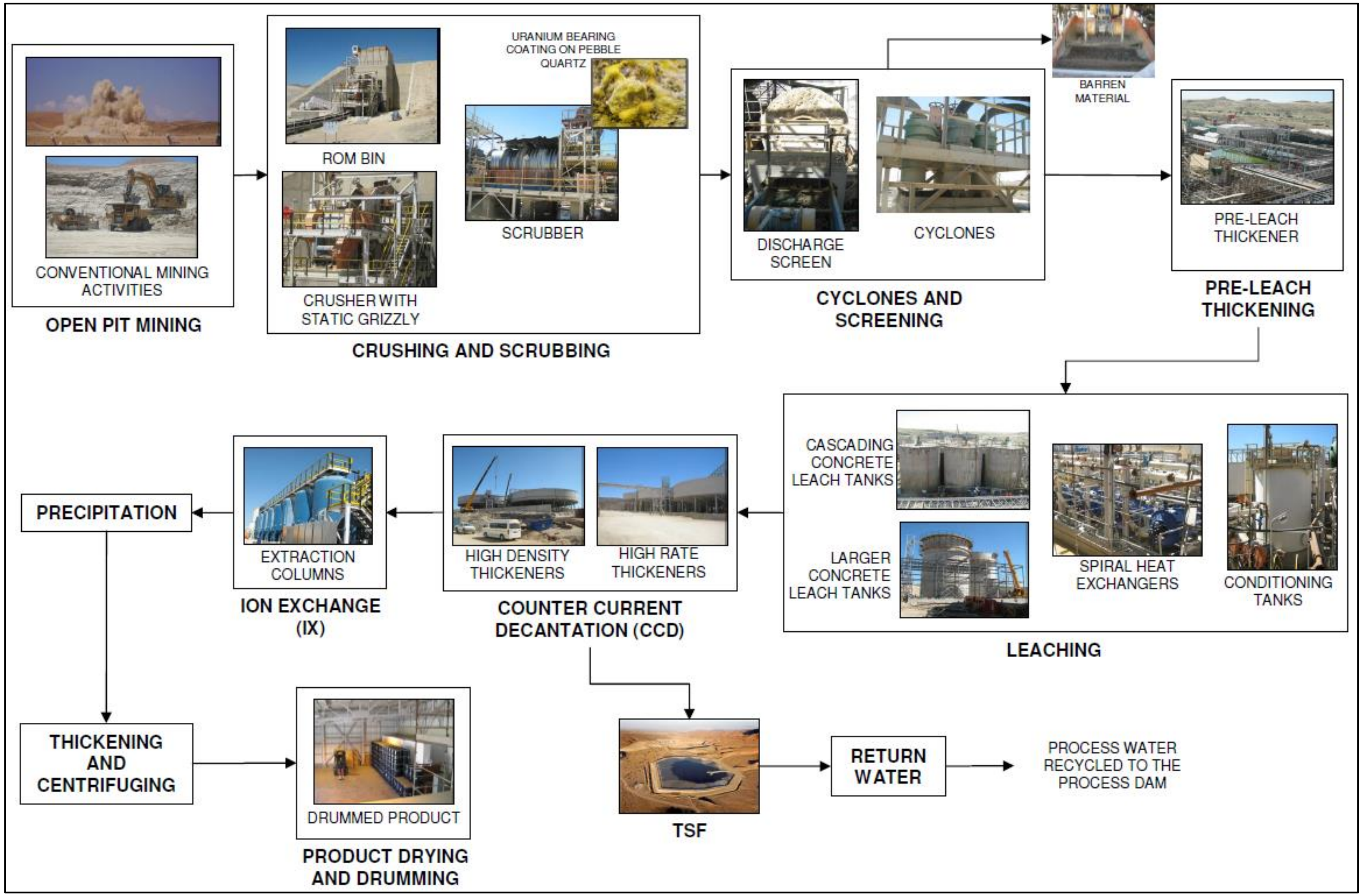


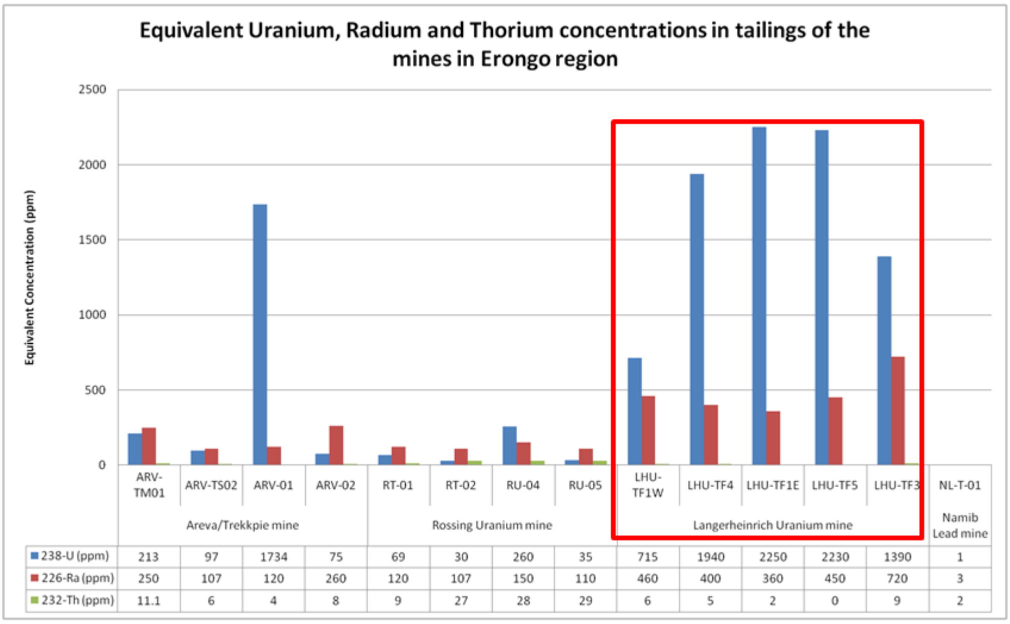
Figure 21. Process flow diagram at Langerheinrich showing main process components (Source: Case study on LHU by Citect Professional Services, 2007).

2.7 Previous studies on the Langerheinrich uranium mine

In 2010 a study was completed by the Namibian Government in partnership with the German Government through the German-Namibian Technical Cooperation Project of the Geological Surveys of Germany (BGR) and Namibia (GSN). The study was referred to as "**Strategic Environmental Assessment (SEA) for the central Namib Uranium Rush**" (**MME, 2010**). This study was carried out through several experts including water quality assessments in the shallow, alluvial aquifers (primary aquifers) of the Khan and Swakop Rivers. The findings indicated that groundwater quality in the two Rivers is acceptable for drinking water as per the water act of 1956 (MME, 2010). The assessments done on the groundwater upstream and downstream showed that the uranium mines do not have influence on the water in the main streams (MME, 2010). It's a fair conclusion; however, one need to understand that at the time of this study being conducted the Langerheinrich mine has only been operational for less than 5 years; hence, the plume will not have reached the groundwater yet. Hence, further assessments could have been done to assess the potential of the radionuclides contamination to the main Rivers from the uranium mines especially with emphasis on the potential sources of pollution at the mine sites.

Other independent researchers that have carried out work in the same or similar subject are Schubert & Knöeller, (2010) and Shaduka, (2012). In the study entitled " **Application of naturally occurring radionuclides and stable isotopes as environmental tracers as part of the SEA - Uranium Rush" (**Schubert & Knöeller, 2010) concluded that there are no seepages of tailings water into the aquifer, which could be true, but doesn't rule out the possibility or the potential for the leakage and eventual contamination. However, Schubert & Knöller, (2010) made a very valid observation that stable isotopes results show that the groundwater in the River valleys is extremely vulnerable to diffuse and point source contamination.

A study carried out by Shaduka (2012) observed that the radium series nuclides are very much lower than the uranium nuclide series in the tailings (Figure 22), which suggest a possible migration of radium with infiltrating water from the tailings. Hence, further investigation needs to be done at Langerheinrich mine to assess the possibility of radionuclides escape from the tailings.



	ARV-TM01	ARV-TS02	ARV-01	ARV-02	RT-01	RT-02	RU-04	RU-05	LHU-TF1W	LHU-TF4	LHU-TF1E	LHU-TF5	LHU-TF3	NL-T-01
	Areva/Trekkpie mine				Rossing Uranium mine				Langerheinrich Uranium mine					Namib Lead mine
🟦 238-U (ppm)	213	97	1734	75	69	30	260	35	715	1940	2250	2230	1390	1
🟥 226-Ra (ppm)	250	107	120	260	120	107	150	110	460	400	360	450	720	3
🟩 232-Th (ppm)	11.1	6	4	8	9	27	28	29	6	5	2	0	9	2

Figure 22. The activity concentration of the uranium and its decay products in the tailings of the uranium mines in Erongo region (Source: Shaduka, 2012)

Chapter 3. Field work

3.1 General

The field work mainly involved water sampling at the Langerheinrich uranium mine. The field work was supported by the directorate of Atomic Energy and Radiation Protection Authority, a directorate of the Ministry of Health and Social Services in Namibia. The directorate provided funding for travel expenses as well as the basic materials needed for the water sampling campaign. The Langerheinrich mine provided the water sampling pump (Figure 23 (a)), off road vehicle (Figure 23 (a)), water bailing equipment (Figure 23 (b)), dip meter (Figure 24), multi meter (Figure 25) for measuring the onsite parameters as well as the man power to carry out the sampling campaign.

Figure 23. (a) The MP1 water sampling pump mounted on trailer (b) The water bailer, being used by the mine staff member (c) The filtering set used to filter water samples

The static water levels and depths of boreholes were measured and recorded at each borehole (Figure 24).

Figure 24. The dip meter used in the measurement

Using the Multimeter all the onsite parameters (pH, EC, Redox and temperature) were recorded and logged in the meter (Figure 25)

Figure 25. The Multi-parameter probe used to measure the onsite parameters in the field

3.2 Sampling

The boreholes samples were selected according to their position in relation to the tailings dam being investigated i.e. TSF1 temporary shaded pink (Figure 26). Some borehole were selected from the upstream of the tailing facility in the paleo-channel and some downstream of the tailings facility.

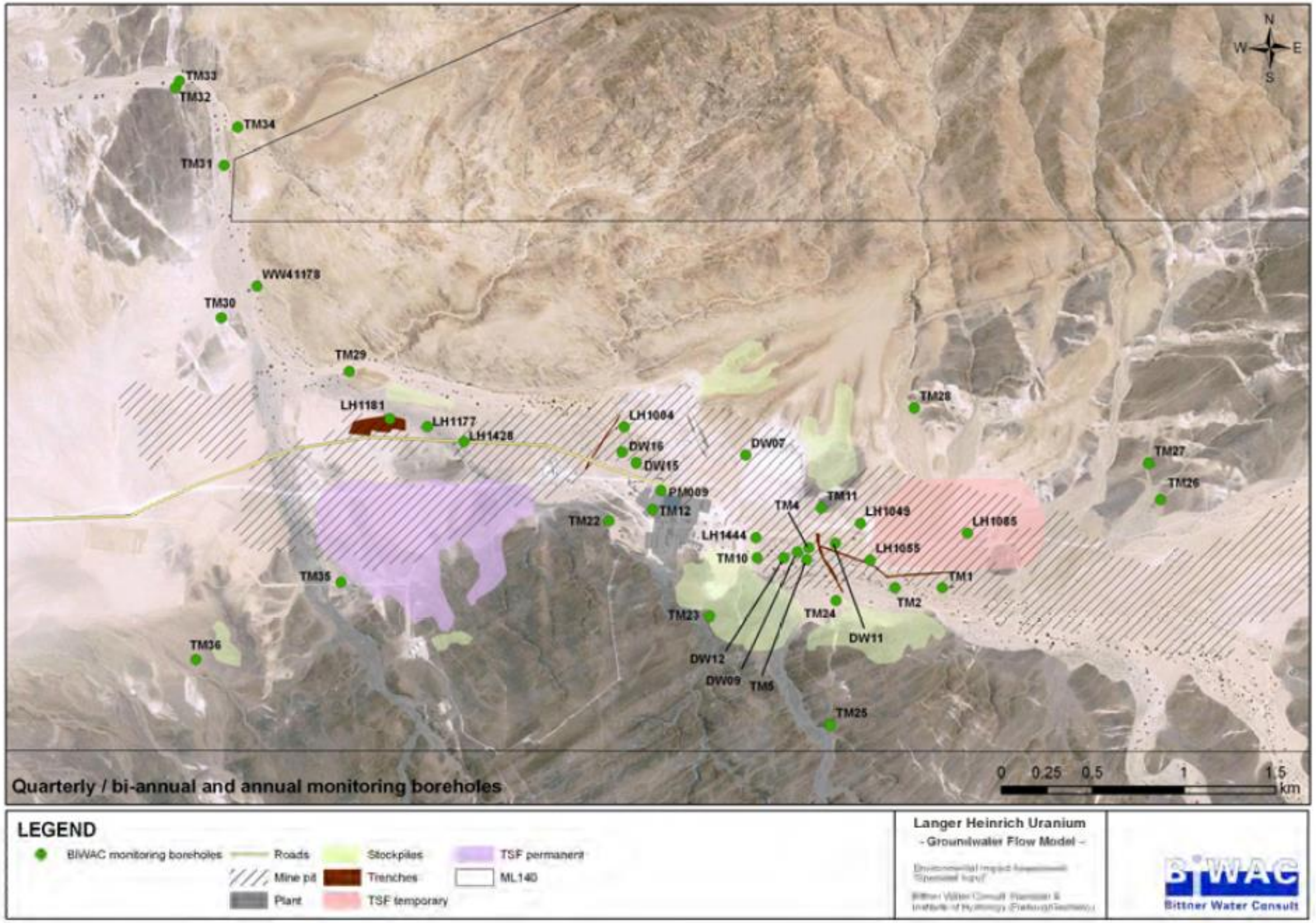


Figure 26. The borehole map including the eight sampled boreholes (TM26, TM28, TM29, TM31, TM46, XB34, XB32 and LH1049) in relation to the tailing facilities at Langerheinrich uranium mine (source: BIWAC, 2009)

The water samples were limited to ten samples and this included the fresh water sample (water supplied to the mine by NAMWATER) and processing water sample, which is the water being recycled and deposited on the tailings dumps. The eight samples are from the boreholes; see the boreholes identities, locations, elevations and depths that are given Table 2.

Table 2. The properties of the sampled monitoring boreholes at Langerheinrich

	UTM Coordinates				
Boreholes ID	EASTING	NORTHING	Datum/ Elevation (m a.s.l)	Boreholes depth (m)	Water Level (m)
TM 26	36111.19	-90046.49	666.52	50.54	24.10
TM 28	34764.19	-89543.43	661.63	47.1	13.59
TM 29	31674.21	-89340.23	593.77	60.67	30.74
TM 31	30988.00	-88212.00	567.14	50	25.99
TM46	35098.05	-90483.45	645.30	16.5	6.86
XB34	42664.88	-90636.11	722.20	43.63	28.35
XB32	39738.58	-90686.17	717.80	43.75	33.19
LH1049	34468.88	-90173.70	641.18	61	17.15

3.3 Sample Analysis

3.3.1 Stable Isotopes

The 100 ml samples were collected and analyzed using the spectro-laser analyser (Figure 27) for stable isotopes (δ^{18}O and δ^{2}H) at two laboratories of two different Universities, namely University of the Witwatersrand (South Africa) and the University of Namibia. Both results correlates well hence an average/mean was used as final isotopic compositions (Table 3)

Figure 27. Liquid Water Isotope Analyser used for the analysis of oxygen-18 and deuterium

Table 3. The Stable isotopes results

Sample Name	d^{2}H‰	^{2}H StDev	d^{18}O‰	^{18}O StDev
TM26	-31.00	0.26	-5.06	0.10
XB34	-20.7	0.00	-2.80	0.00
TM31	-39.26	0.06	-7.86	0.08
TM29	-38.02	0.09	-7.97	0.07
CHLI FW	-30.30	0.12	-6.96	0.09
XB32	-40.54	0.11	-7.92	0.11
LHU PW	-13.50	0.29	-3.27	0.03
TM 46	-27.48	0.24	-4.82	0.05
TM28	-39.22	0.05	-7.25	0.05
LHU1049	-38.97	0.06	-7.10	0.04

3.3.2 Tritium

This set of 10 samples was taken in 1 litre sampling bottles and were neither filtered nor preserved. They were sent for tritium analysis to the Environmental Isotope Laboratory of iThemba Laboratories, Gauteng, South Africa.

As per the laboratory procedure, the samples were distilled and subsequently enriched by electrolysis. Some 500 ml of the water sample, having first been distilled and containing sodium hydroxide, was introduced into the cell. A direct current of some 10–20 ampere was then passed through the cell, than cooled because of the heat generation. After a week, the electrolyte volume was reduced to 20 ml. The volume reduction of some 25 times produced a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) was run in one cell of each batch to check on the enrichment attained. For liquid scintillation counting samples are prepared by directly distilling the enriched water sample from the highly concentrated electrolyte. 10 ml of the distilled water sample was mixed with 11 ml Ultima Gold and placed in a vial in the analyser and counted 2 to 3 cycles of 4 hours. Detection limits are 0.2 TU for enriched samples.

3.3.3 Water Chemistry

The standard water test was performed on the samples by the Analytical Laboratory services and the major and minor elements were analysed as well as the physical parameters such as pH, Electrical Conductivity, Eh and temperature were measured in the field. The samples were additionally analysed for trace elements such as uranium, vanadium, cobalt, nickel, lithium and rubidium using the Inductively Couple Plasma (ICP).

The results were scrutinized for the correctness using the ion balance method as tabulated below (Table 4). The ion balance method shows that the results are very reliable as the error percentage for all 8 samples falls within the acceptable limit of 5 % error with only two samples TM46 and LHU-PW exceeding 5% error with 5.57 % and 6.00 % respectively. This is due to the matrix interference, which could not be compensated for since the samples were highly polluted or contaminated. The TM46 borehole is located downstream of the tailings (Figure 28) and LHU-PW is the sample obtained from the processing water, it is also an unfiltered sample hence the little error.

Figure 28. The TM46 Borehole with the unlined tailings in the background

Table 4. Error analysis using Ion Balance method, using the conversion factors (after Hem 23)

Sample	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{-}	NO_3^{-}	Total Alkalinity $CaC0_3$			
	Mg/l										
TM29	**617**	**127**	**1205**	**89**	**2658**	**657**	**3.4**	**264**			
TM 26	**1406**	**166**	**5442**	**229**	**10400**	**1940**	**2.8**	**62**			
TM 28	**981**	**251**	**2803**	**98**	**5732**	**1027**	**60**	**201**			
TM 31	**412**	**83**	**1461**	**83**	**2557**	**674**	**12**	**189**			
TM46	**7**	**3**	**19020**	**406**	**5134**	**10915**	**56**	**28215**			
XB34	**381**	**46**	**1284**	**48**	**2440**	**414**	**8.1**	**148**			
XB32	**631**	**73**	**671**	**32**	**1869**	**225**	**20**	**234**			
LH1049	**1339**	**362**	**2654**	**129**	**5732**	**2475**	**59**	**345**			
LHU-PW	**16**	**18**	**14020**	**244**	**2916**	**3933**	**21**	**26648**			
LHU-FW	**66**	**16**	**195**	**9.4**	**319**	**62**	**2.7**	**121**			
Conversion factors	**0.0499**	**0.08226**	**0.0435**	**0.025557**	**0.02821**	**0.02082**	**0.01613**	**0.019996**			
	Meq/L								Total Cations	Total Anions	ION BALANCE (% error)
TM29	30.7883	10.44702	52.4175	2.274573	74.98218	13.67874	0.054842	5.278944	95.927393	93.994706	**1.02**
TM 26	70.1594	13.65516	236.727	5.852553	293.384	40.3908	0.045164	1.239752	326.394113	335.059716	**-1.31**
TM 28	48.9519	20.64726	121.9305	2.504586	161.69972	21.38214	0.9678	4.019196	194.034246	188.068856	**1.56**
TM 31	20.5588	6.82758	63.5535	2.121231	72.13297	14.03268	0.19356	3.779244	93.061111	90.138454	**1.60**
TM46	0.3493	0.24678	827.37	10.376142	144.83014	227.2503	0.90328	564.18714	838.342222	937.17086	**-5.57**
XB34	19.0119	3.78396	55.854	1.226736	68.8324	8.61948	0.130653	2.959408	79.876596	80.541941	**-0.41**
XB32	31.4869	6.00498	29.1885	0.817824	52.72449	4.6845	0.3226	4.679064	67.498204	62.410654	**3.92**
LH1049	66.8161	29.77812	115.449	3.296853	161.69972	51.5295	0.95167	6.89862	215.340073	221.07951	**-1.32**
LHU-PW	0.7984	1.48068	609.87	6.235908	82.26036	81.88506	0.33873	532.853408	618.384988	697.337558	**-6.00**
LHU-FW	3.2934	1.31616	8.4825	0.2402358	8.99899	1.29084	0.043551	2.419516	13.3322958	12.752897	**2.22**

Chapter 4. Results and Discussion

4.1 Field parameters

The onsite parameters such as the pH, electrical conductivity, Redox Potential (Eh) and temperature were recorded using the HD40d Multimeter; the data is summarized in Table 5.

Table 5. Field measured parameters

Sample	Sample type	Date of sampling	Water Level	PH	Eelectrical Conductivity (mS/cm)	Redox (Mv)	Temperature (°C)
TM 26	Groundwater	2015/10/06	24.1	7.3	28.3	-24.9	28.9
TM 28	Groundwater	2015/10/06	13.59	6.93	15.76	-3.2	30.0
TM 29	Groundwater	2015/10/07	30.74	6.48	8.66	21.5	29.0
TM 31	Groundwater	2015/10/07	25.99	0.9	8.52	11.6	29.6
TM46	Groundwater	2015/10/07	6.86	10.03	54.1	-182.6	28.9
XB34	Groundwater	2015/10/06	28.35	6.63	7.66	14.1	27.6
XB32	Groundwater	2015/10/06	33.19	6.88	6.2	-0.7	27.7
LH1049	Groundwater	2015/10/06	17.15	6.84	17.57	1.6	27.2
LHU-PW	Pond water	2015/10/07	NA	8.11	1.33	-71.7	27.8
LHU- FW	Freshwater pipeline sample	2015/10/07	NA	10.5	40		25.7

The pH values recorded at the time of sampling for the majority of the water samples falls between 6.48 and 7.3 which maybe be regarded as environmentally acceptable.

However, pH for three samples fall in an alkaline range, 8.11 for the LHU-PW (Processing water), while for LHU-FW and TM46 samples, pH values are 10.5 and 10.0, respectively. The water samples have Electrical Conductivity values ranging between 1.33 mS/cm -28.3 mS/cm for eight samples except LHU-FW and TM46 samples with 40 mS/cm and 54.1 mS/cm, respectively. The redox values falls between -207.4 mv and +21.5 mv and LHU-PW has relatively lower value of -71.7 mv whereas the LHU-FW and TM46 again being outliers with -207.4 and -182.6 mv.

The field observations prove that there is a seepage problem at Langerheinrich that cannot only be proved through scientific investigations but even with naked eyes one can able to identify the seepage as currently happening with the badly designed new tailings dump that are lined (Figure 29).

Figure 29. The currently ongoing seepage at Langerheinrich mine from the lined new tailing dumps

The new tailings dump that are currently being used are only lined underneath the dumps but on the sides is not lined hence the continuous lateral seepage from the tailings. Figure 30 below is one of the active tailing dumps with ponding water on top and unlined on the walls of the dumps.

Figure 30. The ponding of water on the new tailings dumps

The TM46 borehole immediately downstream of the unlined tailings produced yellowish sample (Figure 31). This is a clear evidence of the seepage from the tailings dams.

Figure 31. The yellowish colour of groundwater water from borehole TM46

4.2 Laboratory Parameters

4.2.1 Major Ion Chemistry

The analytical results for the selected metals have been presented in Table 6 and with the original analysis reports annexed in Appendix13.3.

Table 6. Results of major ions and trace elements in water samples from the Langer-heinrich mine area

Parameters & elements	units	TM29	TM 26	TM 28	TM 31	TM46	XB34	XB32	LH1049	LHU-PW	LHU-FW
p H		6.7	7.1	7.2	6.8	10.0	6.8	7.1	7.1	10.5	8.00
Electrical Conductivity	mS/m	931	3040	1737	932	5580	813	667	1923	4310	142.40
Turbidity	NTU	2.0	4.2	7.9	0.70	10	0.80	1.0	21	40	0.25
Total Dissolved Solids (calc.)	mg/l	5983	19960	11432	5808	51009	4632	4193	13844	36967	720.77
P-Alkalinity as $CaCO_3$	mg/l	0	0	0	0	12018	0	0	0	13063	0.00
Total Alkalinity as $CaCO_3$	mg/l	264	62	201	189	28215	148	234	345	26648	121.00
Total Hardness as $CaCO_3$	mg/l	2064	4194	3483	1371	30	1141	1876	4834	114	230.69
Ca-Hardness as $CaCO_3$	mg/l	1541	3511	2450	1029	17	951	1576	3343	40	164.80
Mg-Hardness as $CaCO_3$	mg/l	523	684	1034	342	12	189	301	1491	74	65.89
Chloride as Cl^-	mg/l	2658	10400	5732	2557	5134	2440	1869	5732	2916	319.00
Fluoride as F^-	mg/l	1.2	1.6	1.4	2.0	131	2.2	1.9	1.6	62	0.30
Sulphate as SO_4^{2-}	mg/l	657	1940	1027	674	10915	414	225	2475	3933	62.00
Nitrate as N	mg/l	3.4	2.8	60	12	56	8.1	20	59	21	2.70
Nitrite as N	mg/l	<0.1	<0.1	<0.1	<0.1	2.4	<0.1	0.72	<0.1	7.6	<0.1
Sodium as Na	mg/l	1205	5442	2803	1461	19020	1284	671	2654	14020	195.00
Potassium as K	mg/l	89	229	98	83	406	48	32	129	244	9.40
Magnesium as Mg	mg/l	127	166	251	83	3	46	73	362	18	16.00
Calcium as Ca	mg/l	617	1406	981	412	7	381	631	1339	16	66.00
Manganese as Mn	mg/l	0.29	0.12	<0.1	0.08	<0.1	0.01	0.12	<0.02	<0.1	0.05
Iron as Fe	mg/l	1.4	0.56	2.9	0.33	0.22	0.01	0.03	0.04	0.38	0.96
Stability pH, at 25°C		6.4	6.7	6.3	6.7	6.4	6.8	6.4	6.0	6.0	7.59
Langelier Index		0.3	0.4	0.9	0.1	3.6	0.0	0.7	1.1	4.5	0.41
Ryznar Index		6.0	6.3	5.4	6.6	2.8	6.8	5.7	4.8	1.6	7.17
Corrosivity ratio		16.8	269.4	45.6	22.8	0.7	26.2	12.3	30.9	0.3	4.26
Trace elements											
Uranium as U	mg/l	0.19	0.12	0.14	0.15	369	0.16	0.18	8.9	91	0.08
Vanadium as V	mg/l	0.08	<0.1	<0.1	0.08	73	0.04	0.03	0.07	118	0.02
Cobalt as Co	mg/l	<0.01	<0.1	<0.1	<0.01	<0.1	<0.01	<0.01	<0.02	<0.1	<0.01
Nickel as Ni	mg/l	<0.01	<0.1	<0.1	<0.01	<0.1	<0.01	<0.01	<0.02	<0.1	<0.01
Lithium as Li	mg/l	0.23	0.41	0.18	0.28	0.17	0.17	0.09	0.10	0.25	0.04
Rubidium as Rb	mg/l	0.06	0.16	0.10	0.05	<0.1	0.02	0.03	0.04	<0.1	<0.01

The results were plotted on the piper diagram (Figure 32) to determine the hydrogeochemical facies of water samples. Most water samples fall in the region of sodium/potassium type with XB32 plotting on Ca, Mg and Na dominant field. It is, however, important to observe the position of LHU-PW (processing water) and TM46 (borehole water downstream the tailings) both plot at same place on the cations field. On the anion plot, the samples LHU-PW and TM46 were plotted on bicarbonate type, whereas all other samples plot on the chloride type field. On the combined cations and anions field all the water samples plots on the Cl and SO_4 region except LHU-1049, which plots on the Na+K, Ca+Mg and Cl+SO_4 , HCO_3-CO_3 (Figure 32).

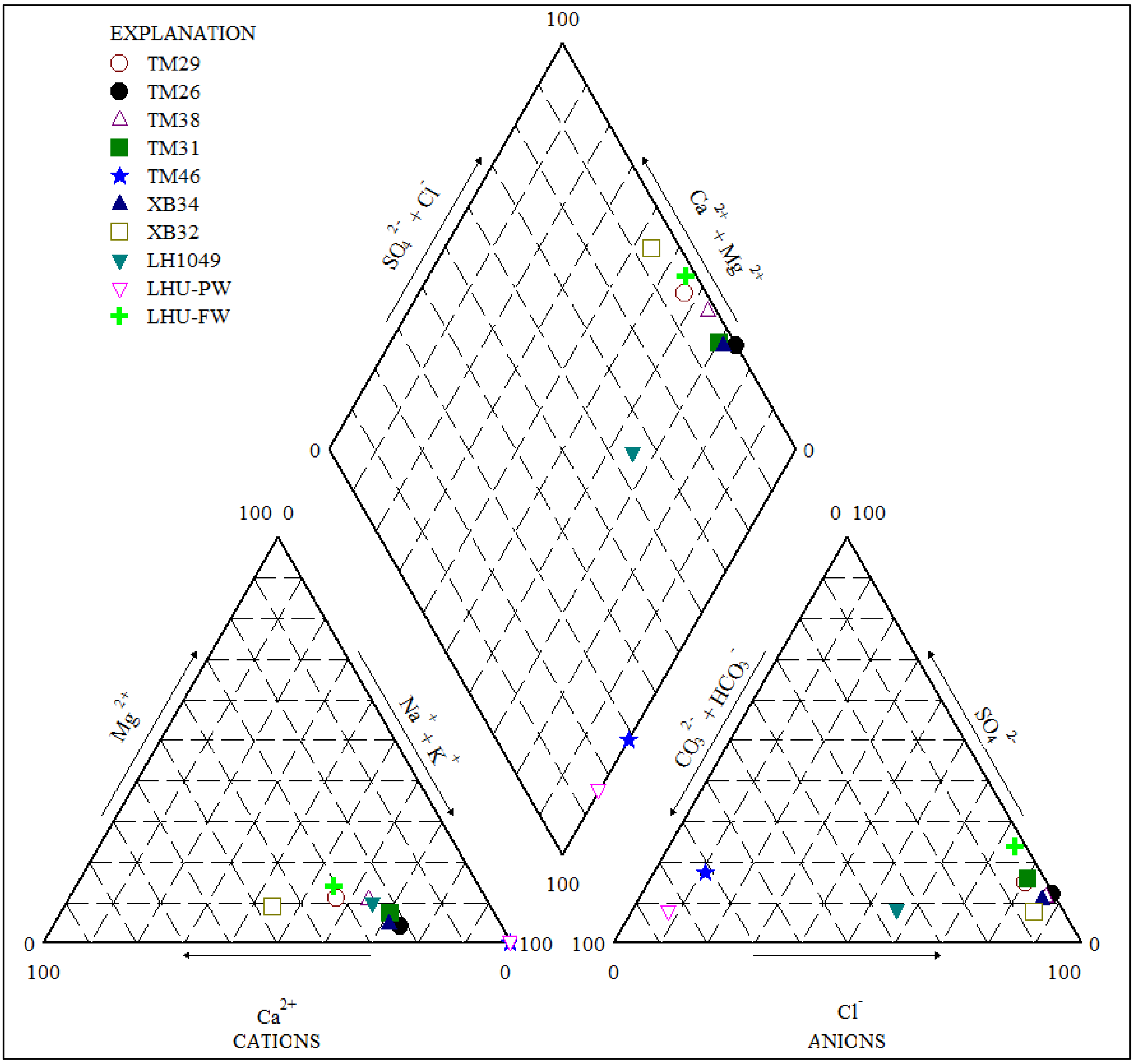


Figure 32. The water samples results plotted on the piper diagram

Most of the water samples have plotted on the zone of 30- 50 % of the Ca^{2+} and Mg^{2+}, with TM46 & LHU-PW plotting on the region of freshening while LHU-1049 plots on the Mixing zone. This shows that TM46 is directly contaminated by the seepage from the tailing (due to mixing) with similar chemical composition as LHU-PW since they show similar chemical behaviour. TM46 and LHU-PW were plotted on the freshening region of the piper since “LHU-PW” processing water is continuously mixed with the clean water supplied to the mine. The same effect is passed on to the polluted borehole. The LHU-1049 has plotted on the mixing region suggesting the end members similar to the typical groundwater and the processing water.

The borehole LHU-1049 (figure 33) is the only borehole that was sampled in the baseline water sampling campaigns in 2005 this was before the mining activities started in the area. Most of the baseline boreholes were destroyed due to mine development. The historical data of other boreholes could not be obtained from the mine. The results of the 2015 water analysis of the LHU-1049 and of 2005 was compared to determine if there is an impact of pollution to this particular borehole for the past ten years (Table 7).

Table 7. The change in the water quality over the ten year period of the borehole LHU-1049

Comparison of water chemistry for ten year period for Borehole: LHU-1049			
Parameter /element	units	Year 2005	Year 2015
pH		7.0	7.1
Electrical Conductivity	mS/m	1149.0	1923.0
TDS (det.)	mg/l	7208.1	13844.0
P-Alkalinity as $CaCO_3$	mg/l	0.0	0.0
T-Hardness as $CaCO_3$	mg/l	181.0	4834.0
Ca-Hardness as $CaCO_3$	mg/l	1446.0	3343.0
Mg-Hardness as $CaCO_3$	mg/l	667.0	1491.0
Chloride as Cl^-	mg/l	3468.0	5732.0
Fluoride as F^-	mg/l	1.8	1.6
Sulphate as SO_4^{2-}	mg/l	628.0	2475.0
Nitrate as N	mg/l	8.5	59.0
Nitrite as N	mg/l	0.0	0.1
Calcium as Ca	mg/l	579.0	1339.0
Magnesium as Mg	mg/l	162.0	362.0
Sodium as Na	mg/l	1462.0	2654.0
Potassium as K	mg/l	109.0	129.0
Uranium as U	mg/l	0.1	8.9
Vanadium as Va	mg/l	0.2	0.1

The 2015 water analysis of this borehole shows that the water quality has deteriorated enormously due to the mining activities specifically contamination from the tailings facility upstream of this borehole. All parameters and elements concentrations show that they have increased with huge values in the past ten years. The uranium concentration has increased with 8.8 mg/l in the past ten years. Vanadium has decreased from 0.2 mg/l to 0.1 mg/l perhaps due to dilution of the tailings seepage. Electrical Conductivity has increased with huge amount (Table 7 and Figure 34).

Figure 33. The LHU-1049 borehole directly below the unlined tailings

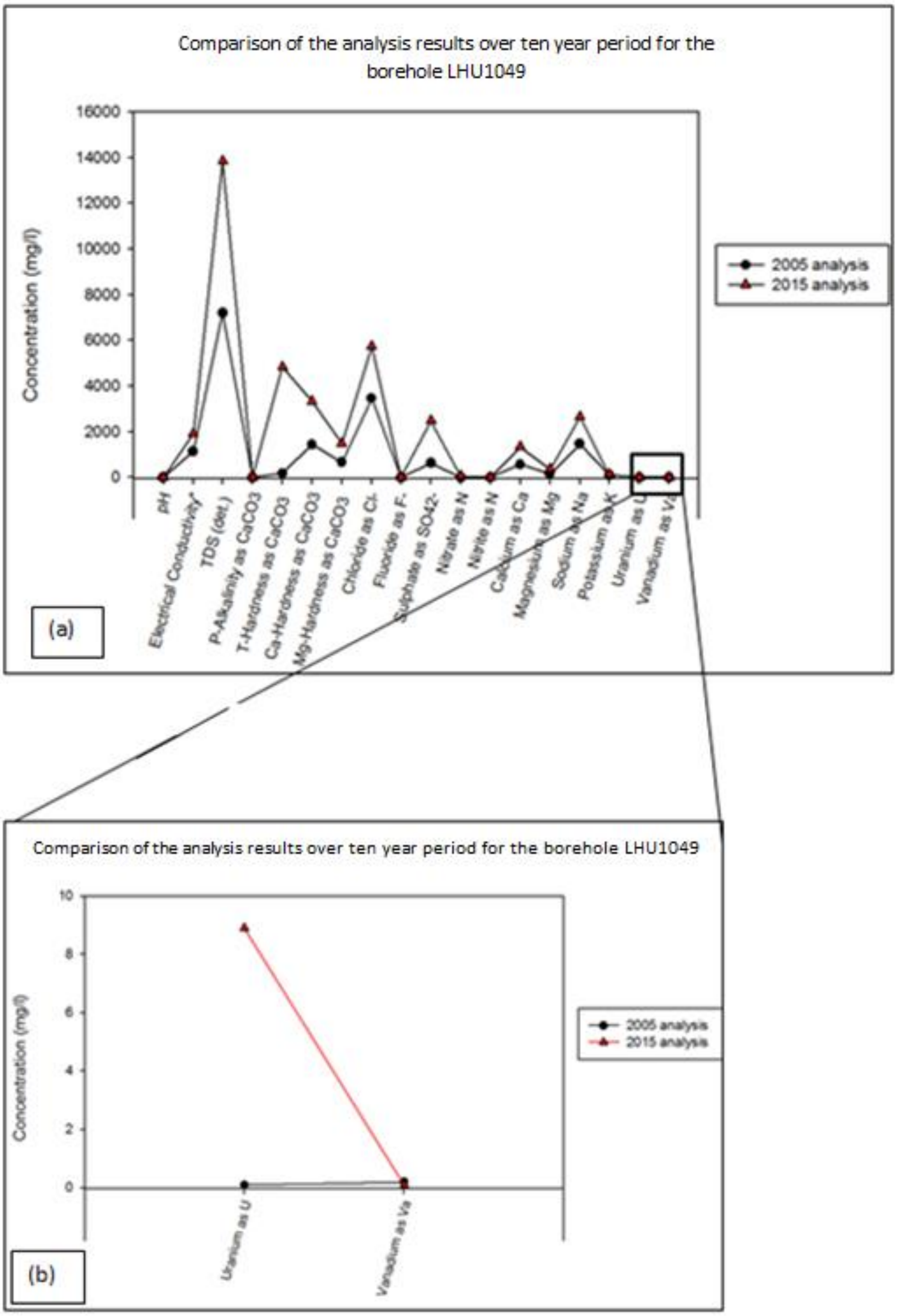


Figure 34. (a) Temporal chemical change in the LHU-1049 borehole and (b) in the specific change in U and V.

4.2.2 Environmental Isotopes

4.2.2.1 Stable isotopes

The isotopic results (figure 35) plot off the GMWL ($\delta^2H=8\delta^{18}O + 10‰$) and the MWL ($\delta^2H=7.1\delta^{18}O + 8.01‰$) for Windhoek (Christelis et al.(undated)) plots to the right hand of the Meteoric Water lines (Figure 35). The LHU-PW sample plots in the enriched zone reasonably due to recycling, hence, repetitive enrichment of the isotope. The samples upstream of the mining area i.e. XB34 and XB32 and samples from far downstream do not seem to be affected by seepage as they plot between the signature of the groundwater and the LHU-PW (Processing water sample) which is the seepage contaminant, they have pure groundwater isotopic signature. However the samples in the mining area i.e. TM46, TM26, LHU1049 and TM28 isotopic signatures seems to be affected by the seepage signature (LHU-PW) hence other tools will need to be employed to support the stable isotope study.

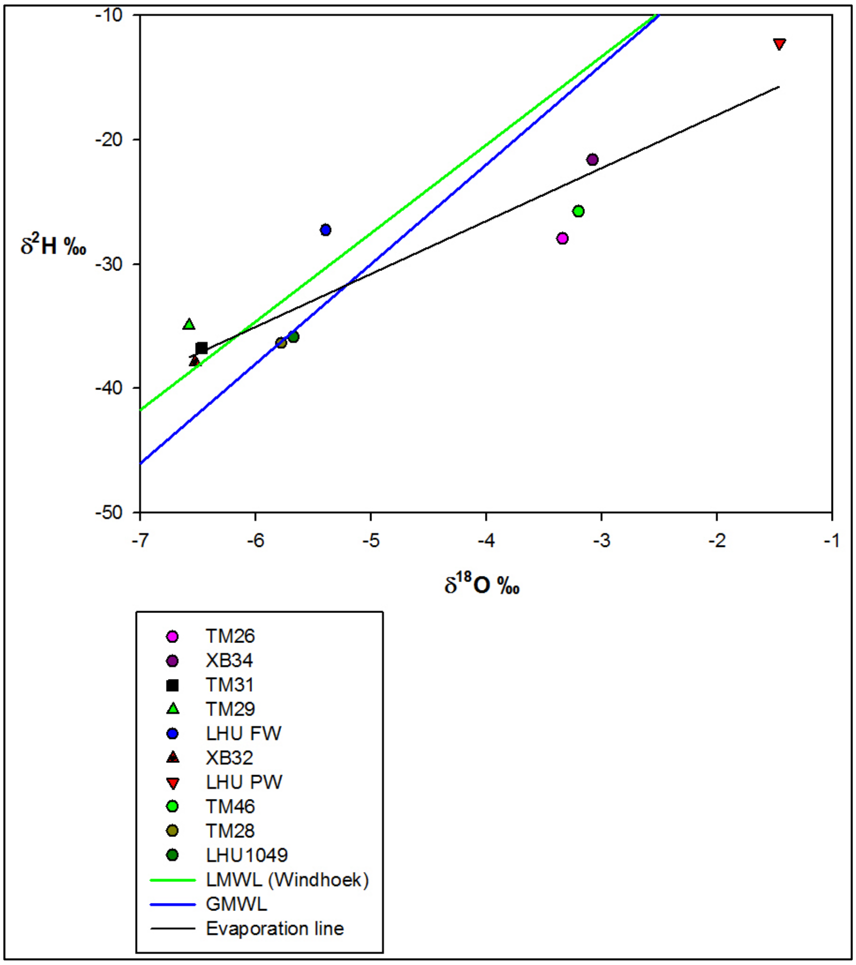


Figure 35. Plots of the stable isotopes for the water samples at Langerheinrich Uranium Mine.

TM46 is a mixture between groundwater similar to TM26 and the contaminant LHU-PW. The stable isotopes of ^{18}O and ^{2}H also confirm that the aquifer in the area is an open system, which is supported by the enrichment of ^{18}O, hence, its vulnerability to seepage and extra caution is required to protect the precious groundwater resource from pollution.

Coastal precipitations are isotopically enriched while the colder inner continental regions receive isotopically depleted. Precipitation at lower altitudes where the average temperature is higher, precipitation will be isotopically enriched (Abiye, 2015) and slight enrichment of samples from the GMWL, (Figure 35).

4.2.2.2 Tritium

Stable isotopes do not provide an ‘age’ of the groundwater sampled, instead, they provide a tool by which to distinguish between modern recharge and recharge from some other time in the past or from some other source (Kendall et al., 2010). Tritium is an excellent tracer for determining time scales for the mixing and flow of waters because it is considered to be relatively conservative geochemically and is ideally suited for studying processes that occur on a time scale of less than 100 years (Kendall et al., 2010).

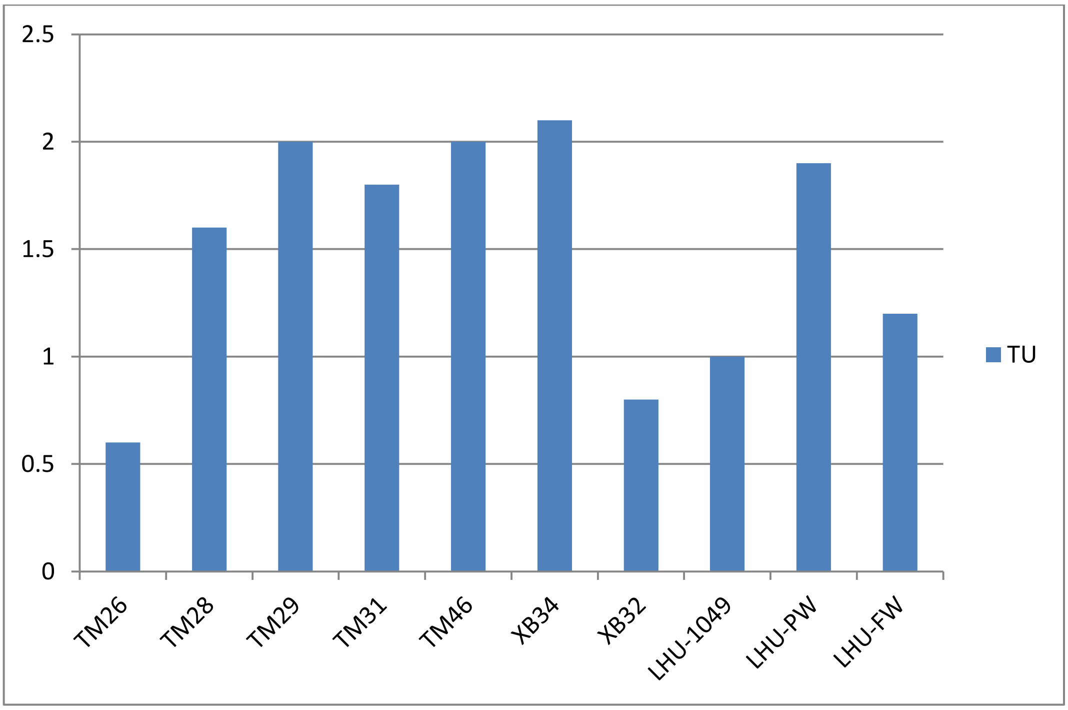
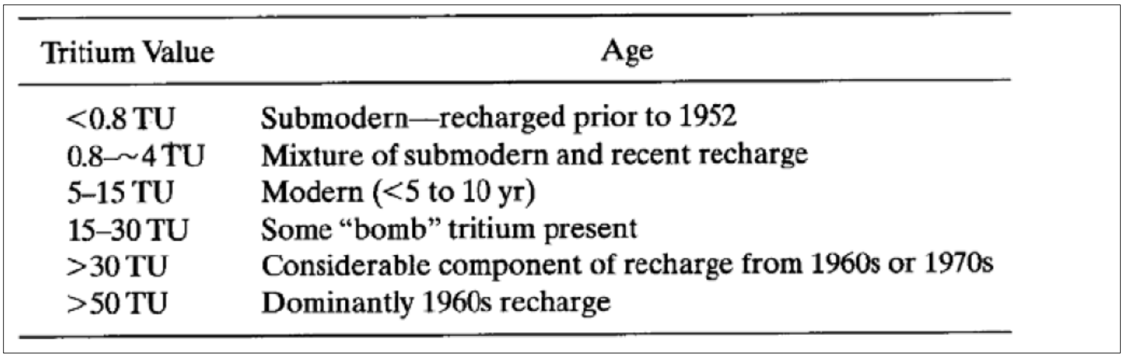


Figure 36. Tritium content of the water samples

The tritium results (figure 36) show the two water samples (borehole/underground water) has values less than 0.8 TU i.e. TM26 (0.6TU) and XB34 (0.8 TU). The rest of the samples have tritium values ranging between 1 and 2.1 TU, (Figure36). The Tritium content of the precipitation at Windhoek is 2.6 TU and 3.6 TU for January and February 2000 according to the Global Network of Isotopes in Precipitation data by the IAEA. Hence this signature does not reflect in any of the samples, evidence that there is no recharge from precipitation in this area.

Tritium can be used as a rough indicator of groundwater recharge time, (Figure 37), TM6 and XB34 samples have less than 0.8 TU, hence referred to as Sub modern – recharged prior to 1952 (Clark and Fritz, 1997). The other six borehole samples and the two samples obtained from the pipeline and water pond (processing water) have tritium units falling in the bracket of 0.8-4 TU, hence, referred to as mixture of sub modern and recent recharge (Clark and Fritz, 1997). The tritium result again shows that there is an open hydrological system at Langerheinrich mine and there is a recent recharge to the groundwater in the mining area, hence suggesting the possibility for pollutants to enter the underlying aquifer from the mining activities.



Tritium Value	Age
<0.8 TU	Submodern—recharged prior to 1952
0.8–~4 TU	Mixture of submodern and recent recharge
5–15 TU	Modern (<5 to 10 yr)
15–30 TU	Some "bomb" tritium present
>30 TU	Considerable component of recharge from 1960s or 1970s
>50 TU	Dominantly 1960s recharge

Figure 37. Approximate groundwater recharge age for continental areas based on tritium values (Source:Clark and Fritz, 1997).

4.3 Contaminant Migration

BIWAC, (2009) has described the contaminant migration to principally being governed by (1) the flow of groundwater, (2) dispersion and (3) water-rock interaction and chemical reactions. However, there are other major factors including the lithologies and structural factors that would affect contaminant migration, while major structures such as faults and fractures as outline in the structural geophysical survey section above. The faults especially on the edge of the unlined tailing facility (TSF1), (Figure 38) may influence the downward movement of the contamination plume or seepage from the tailings.

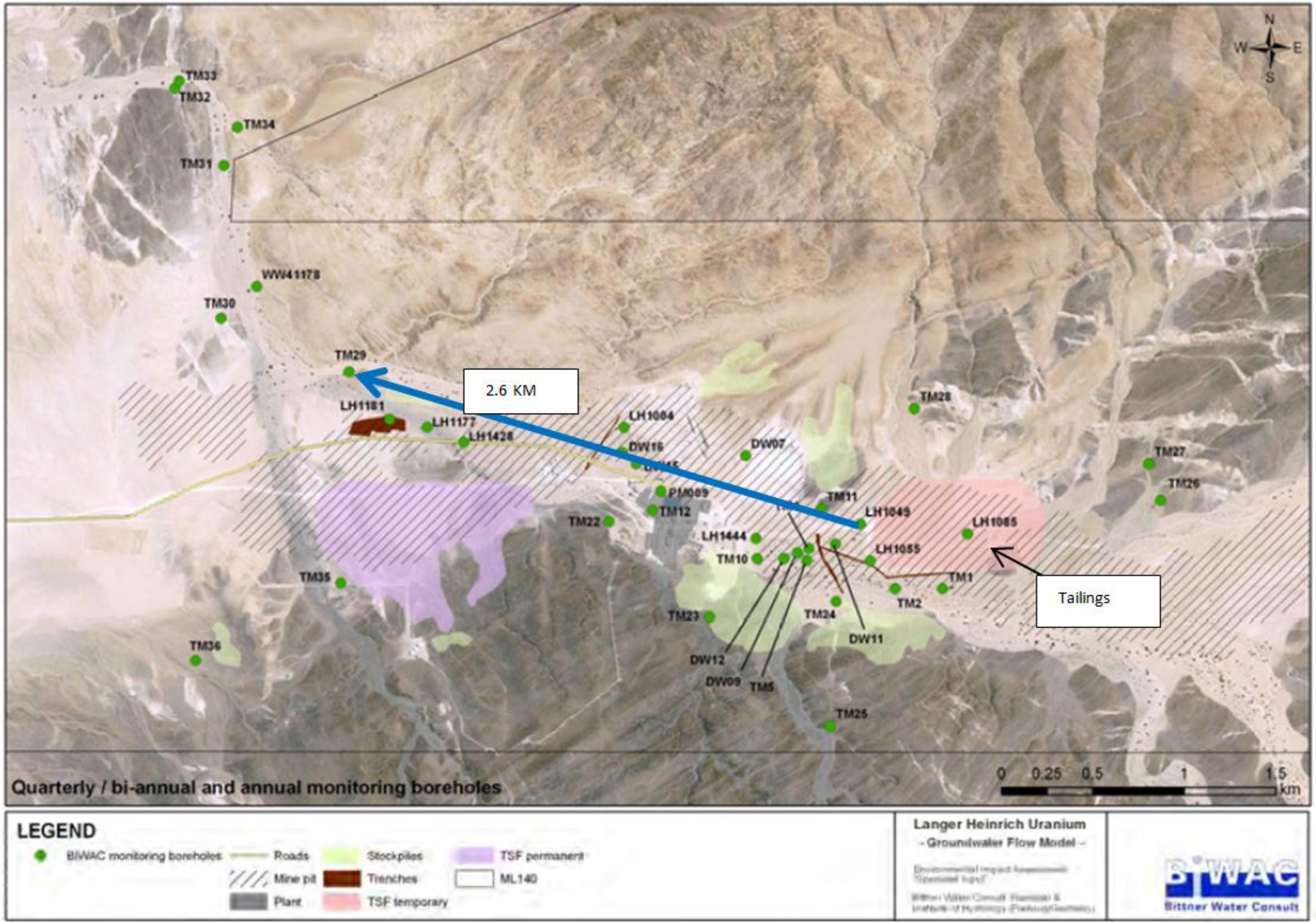


Figure 38. The spatial location of the LHU-1049 and TM29 boreholes

The groundwater table lies in layer L1 about 0-8 m within the shallow aquifer (BIWAC, 2009), hence, the hydrogeological properties such as hydraulic conductivity (k) and effective porosity ($ŋ_e$) are directly adopted from the expert studies conducted in the same area by BIWAC in 2009. The horizontal distance between the two boreholes is also identified using the GIS maps as 2.6 km (Figure 38). The groundwater head between the two boreholes is calculated from the field data as shown in the parameters below;

Parameters

- Hydraulic conductivity (K) = 10 m/d=365 m/yr
- Effective porosity ($ŋ_e$) = 0.25
- Change in groundwater head (ΔH) = LHU-1049 (30.74 m) & TM29 (17.15) = 13.59 m
- Hydraulic gradient (i) = 13.59/2600 m=0.00523
- True Velocity (Vt)= to be calculated, all parameters given above

Hence; the True velocity (Vt) between LHU-1049 and TM29

Assumption: the contaminant is non-reactive and its dispersion velocity component is Zero hence only adjective velocity Component is governing the migration

$$\mathrm{Vt}=\frac{\mathrm{K}\times \mathrm{i}}{\mathrm{n_e}} = \frac{365\mathrm{m/yr}\times 0.00523}{0.25} = 76.4\ \mathrm{m/yr}$$

The study has estimated the travel time of 76.4 m/yr for the contamination plume from the contaminated borehole LHU-1049 to the non-contaminated borehole TM29 which is 2.6 km downstream towards the Swakop River (Figure 38).

Therefore, the seepage is estimated to take approximately 34 years to reach the borehole TM29. This is the seepage from the old tailings, however given the situation that the current active tailings next to the TM29 borehole are also having a seepage problem, the seepage may reach this borehole in a very short time as compared to seepage of the old tailings as estimated above. It is also important to note that the estimated velocity does not take into account the fractures and faults in the area that may boost the seepage velocity.

BIWAC,(2009) also estimated the seepage contamination using Modflow particle tracking software and the results correlates well with the outcome of this study. In the BIWAC (2009) output, it's estimated that the seepage will travel about 75 m/year downstream simillar to the estimation done in this study (Figure 39). However, as one moves downstream the Modflow estimated even higher velocities taking into account the structures such faults and fractures. Therefore, using Modflow the seepage is estimated to reach the borehole area of TM29 in less than 6 years (Figure 38).

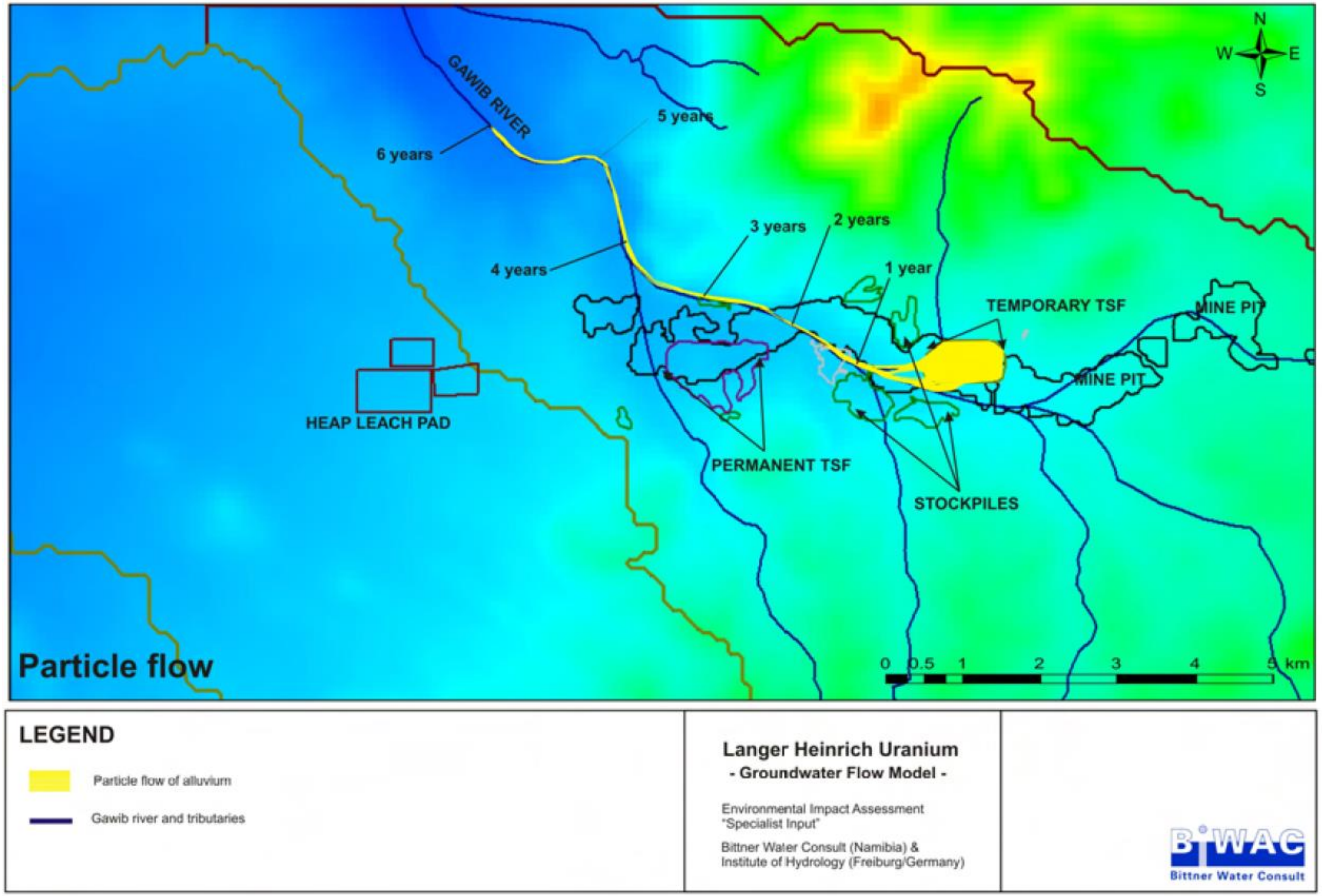


Figure 39. Results of the particle tracking for seepage from the temporary TSF into the shallow alluvium (source: BIWAC, 2009)

4.4 Geophysical Surveys to map important geologic structures

The geophysical survey was conducted in the study area by BIWAC in 2009 for the Environmental Impact Assessment for the Langerheinrich Uranium Mine. The aim of the survey was borehole siting. However, this study finds it useful in the results discussion especially in light of the current status of the seepage at the mine. The structures such as faults and fractures play a major role in the contaminant migration. The GEONICS survey identified major faults in the Tinkas and Etusis formations (Figure 37), (BIWAC, 2009).The positions of the faults are very crucial in tailings and borehole siting; this is discussed in detail in the section of contamination migration section.

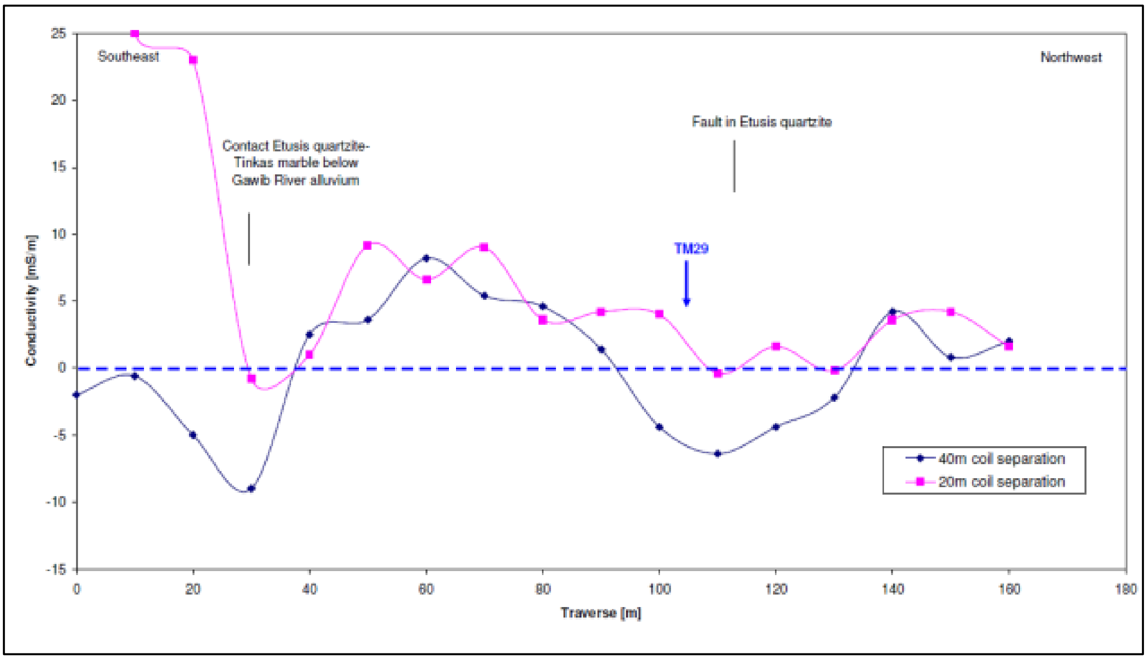


Figure 40. The 180 m traverse of the GEONICS EM34-3 survey (BIWAC, 2009)

Various boreholes are sited along the major faults; however the critical one is LHU-1049 and the position of the tailings facility (Figure 38). The LHU-1049 borehole is now heavily contaminated and this may allow the downward migration of the pollution in the deep aquifer and the basement aquifer systems.

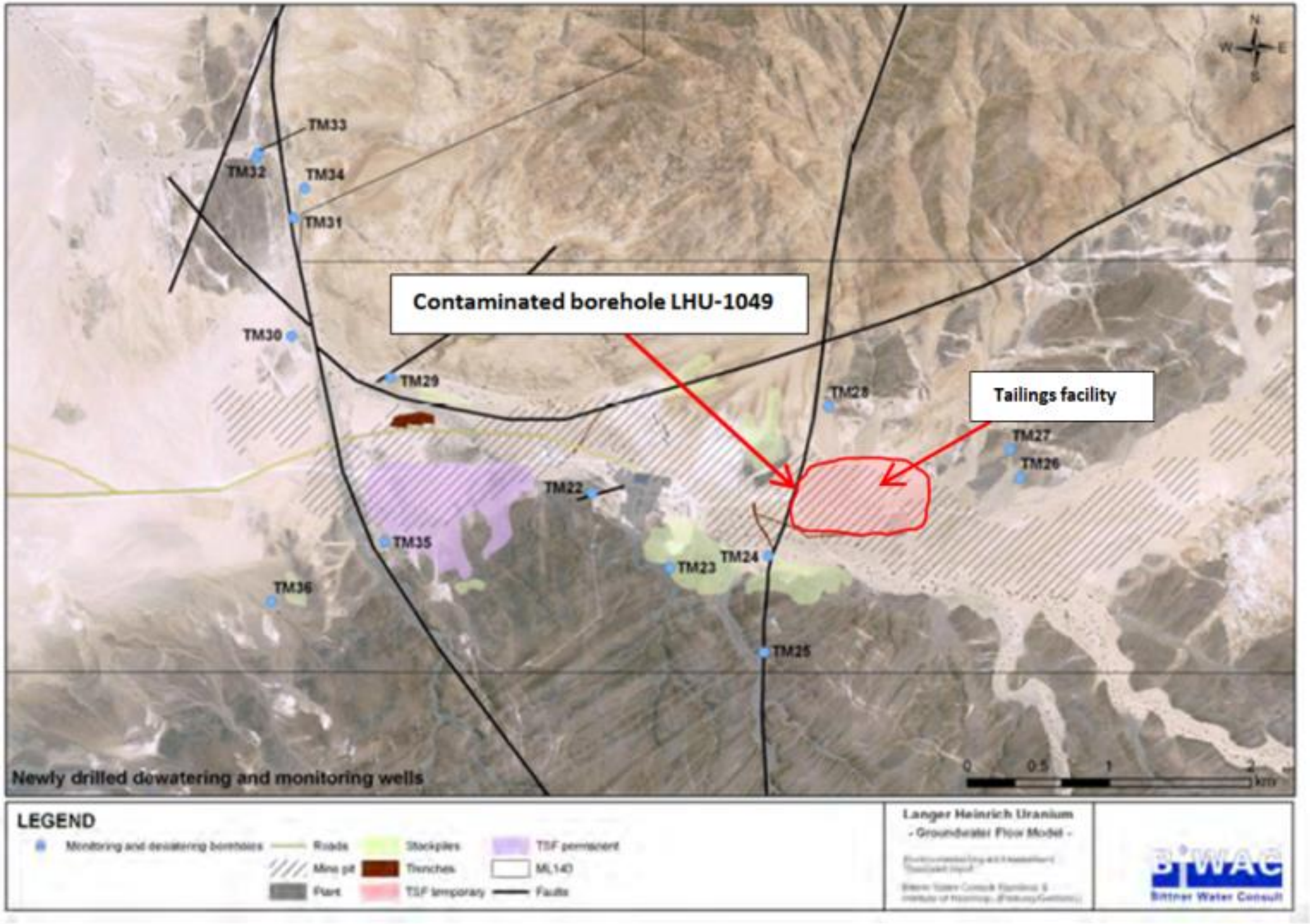


Figure 41. Faults and fractures inferred from geological and geophysical surveys (BIWAC, 2009)

4.5. Conceptual model

The study area has four main aquifer zones namely; the Gawib alluvium aquifer overlying the ore body zone sediments, which are instead underlain by the Paleo-channel aquifer. At the bottom is the basement aquifer, which is composed of fractured and faulted basement rocks. The unlined tailing lies exactly on top of the ephemeral Gawib River where most of the mine establishments are developed within the river channel.

Groundwater flows towards the west toward the Swakop River. The seepage from the unlined tailings migrates within the Gawib Shallow Aquifer downstream where it intersects the main fault systems and major faults. The seepage could migrate slowly towards the deep paleo-channel aquifer system and later joins the basement aquifer system.

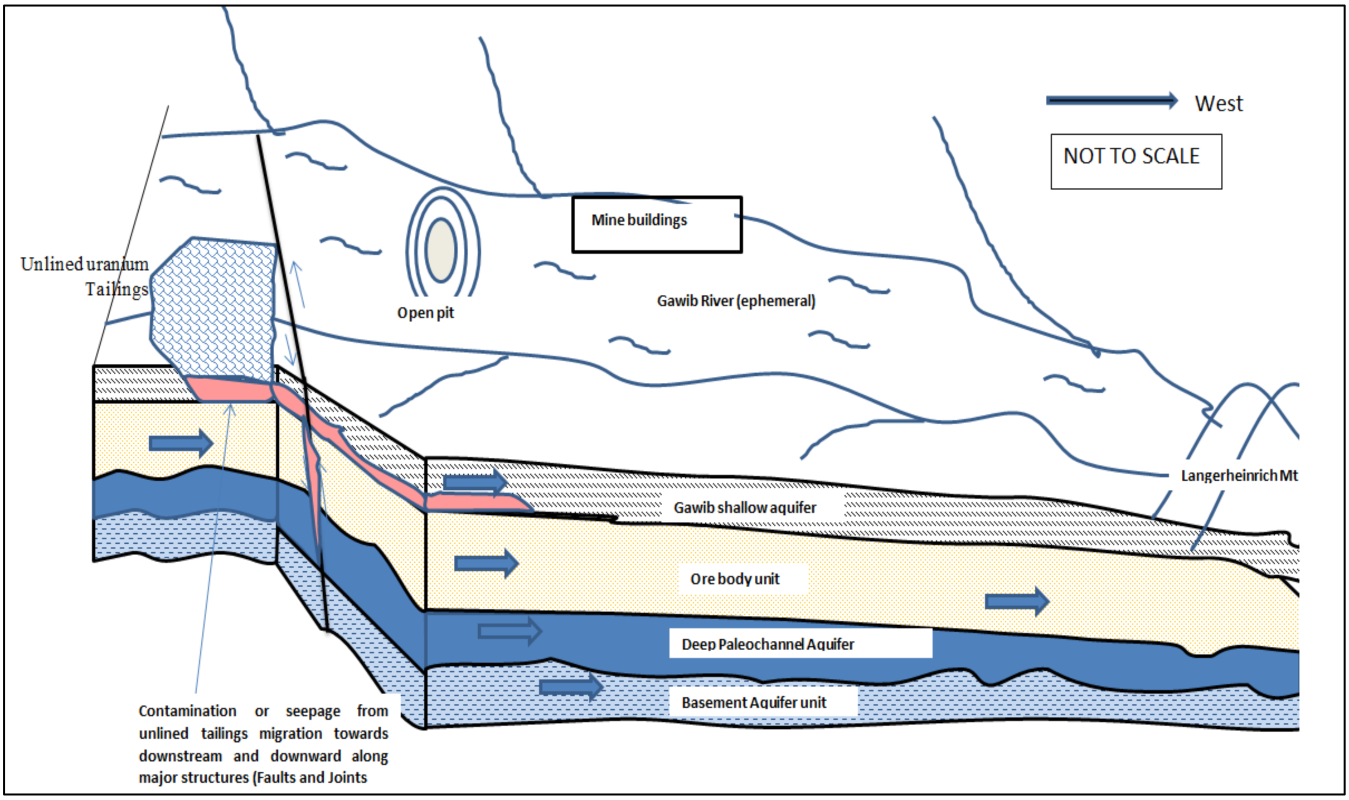


Figure 42. The conceptual model of the study area

5. Conclusion

The objectives of the study were attained based on the methodologies applied in the project. The study has managed to show that the shallow groundwater aquifer is affected by the seepage from the unlined tailing and the contamination plume, which is migrating downstream. The groundwater in the area is generally of poor quality, saline and with elevated metal concentration due to geological sources. However, uranium mining has affected the quality of the groundwater in Gawib shallow aquifer system by seepage contamination from the unlined tailings evident in some monitoring boreholes such as TM 46 and LHU-1049. The Gawib shallow aquifer system is polluted by the seepage and this is also documented in the Langerheinrich Uranium Mine Environmental Impact Assessment, a Groundwater Specialist input by BIWAC in 2009.

The major ions results show that borehole TM46 is directly contaminated by the source with similar chemical composition as LHU-PW since they show similar chemical behaviour, facilitating seepage from the tailings as a source of contamination for the boreholes in the Gawib Shallow aquifer system. The borehole LHU-1049 was plotted on the mixing region suggesting the end members similar to the typical groundwater and the processing water

The isotopic results shows that the processing water sample (LHU-PW) is isotopically enriched reasonably due to recycling of water, hence, repetitive enrichment of the isotopes. The groundwater samples upstream of the mining area and samples from far downstream are not affected by seepage and they have pure groundwater isotopic signature. The groundwater sample within the tailings and vicinity (LHU1049 and TM46) shows the mixing effect between the groundwater and the processing water samples.

The metal concentrations trend analysis in borehole (LHU-1049) indicates that there is a significant impact on the groundwater quality in the past ten years where uranium concentration has increased from 0.1 mg/l to 8.9 mg/l.

The two main affected boreholes are TM46 followed by LHU- 1049 at the moment. These boreholes are next to the tailing, hence, the immediate contamination effect was observed. The plume should be expected to reach other boreholes further downstream in the mining area and beyond with time. This contamination problem cannot be regarded as local as the Gawib River is hydraulically flows toward Swakop River which eventually is connected to the Atlantic Ocean.

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7. Appendix

7.1 LHU water analysis, 2005

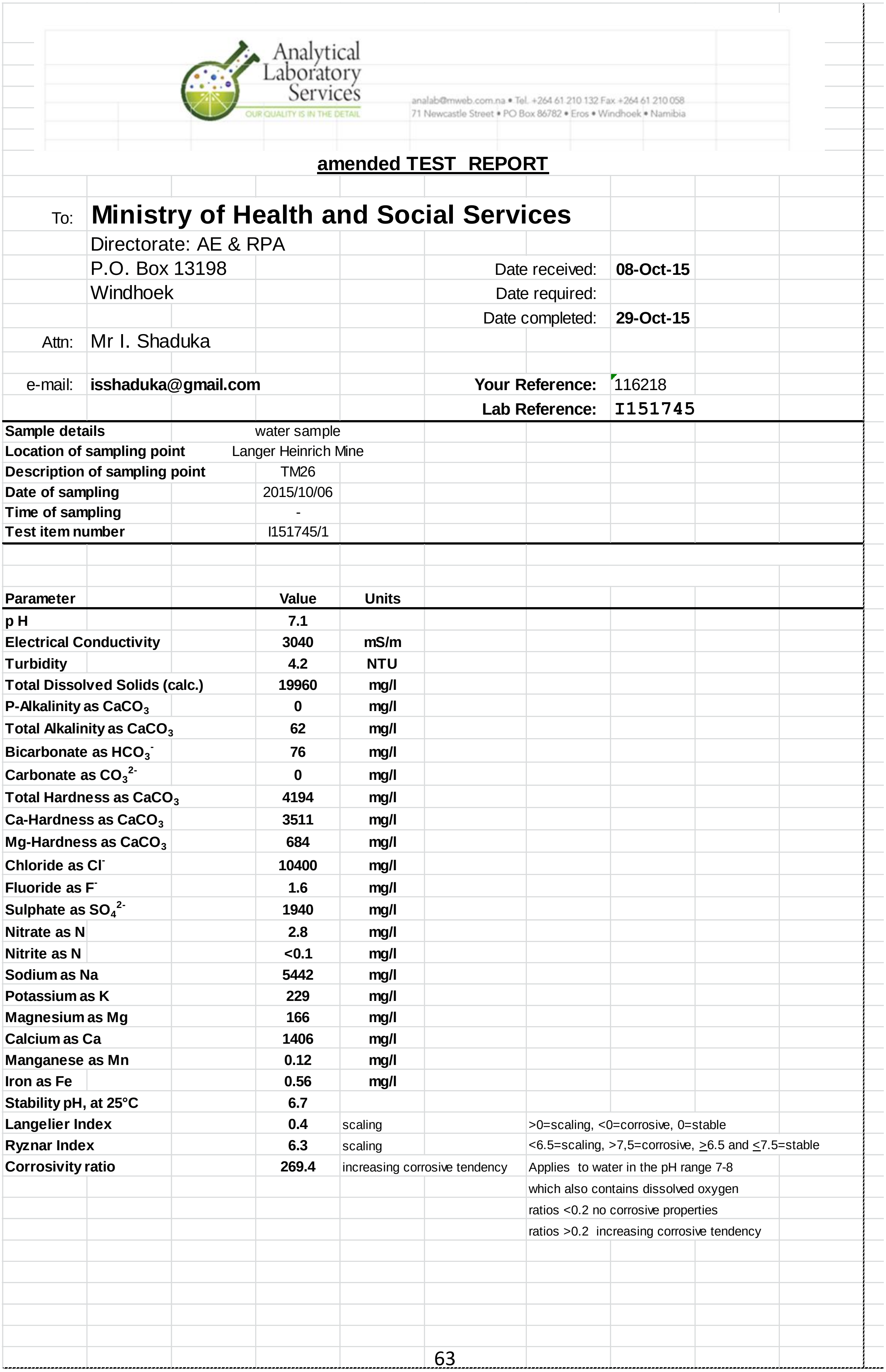
	Sampling date	2005/07/30	2005/07/26	2005/07/26	2005/07/22	2005/07/20	2005/07/28	2005/08/17	2005/08/18	2005/08/19	2005/08/24
	Your sample I.D.	LH 1008	LH 1020	LH 1049	LH 1074	LH 1077	LH 1146	LH 1004	LH 1097	LH 1160	LH 1177
Assay	Lab. #	I050441/1	I050441/2	I050441/3	I050441/4	I050441/5	I050441/6	I050441/7	I050441/8	I050441/9	I050441/10
Standard analysis:											
pH		7.0	7.1	7.0	7.1	7.0	7.0	6.9	7.0	7.0	6.9
Electrical Conductivity*	mS/cm	1817	1032	1149	1077	1436	1090	1953	1607	2481	1471
TDS (det.)	mg/l	11778	6292	7208	6603	9016	6671	12938	10277	16260	9345.4
P-Alkalinity as $CaCO_3$	mg/l	0	0	0	0	0	0	0	0	0	0
M-Alkalinity as $CaCO_3$	mg/l	148	194	181	165	160	186	158	158	129	155
T-Hardness as $CaCO_3$	mg/l	2744	1606	2113	1699	3045	1727	2951	2656	3645	2474
Ca-Hardness as $CaCO_3$	mg/l	2053	1141	1446	1139	2167	1278	2222	2005	2834	1943
Mg-Hardness as $CaCO_3$	mg/l	692	465	667	560	877	449	729	651	811	531
Chloride as Cl^-	mg/l	5605	2981	3468	3278	4560	3064	5582	4560	7577	4347
Fluoride as F^-	mg/l	2.4	2.0	1.8	2.2	2.0	1.8	3.0	2.9	2.8	2.3
Sulphate as SO_4^{2-}	mg/l	1119	604	628	417	574	686	1743	958	1389	780
Nitrate as N	mg/l	5.8	6.4	8.5	7.8	9.0	6.0	5.1	4.3	4.5	4.6
Nitrite as N	mg/l	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02
Calcium as Ca	mg/l	822	457	579	456	868	512	890	803	1135	778
Magnesium as Mg	mg/l	168	113	162	136	213	109	177	158	197	129
Sodium as Na	mg/l	2744	1408	1462	1409	1972	1462	2844	2305	3738	2395
Potassium as K	mg/l	208	103	109	109	143	110	249	196	284	152
Trace element analysis:											
Iron as Fe	µg/l	<10	<10	50	<10	<10	<10	<10	<10	<10	<10
Manganese as Mn	µg/l	20	<10	<10	<10	<10	<10	90	110	330	50
Arsenic as As	µg/l	60	30	30	40	50	40	70	60	100	60
Bismuth as Bi	µg/l	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Cadmuim as Cd	µg/l	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Copper as Cu	µg/l	590	510	550	610	840	540	520	490	580	460
Mercury as Hg	µg/l	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Antimony as Sb	µg/l	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Selenium as Se	µg/l	210	120	140	130	160	120	180	150	250	160
Tellurium as Te	µg/l	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Uranium as U	µg/l	90	150	120	160	160	130	180	140	60	110
Uranium as U_3O_8 calc.	µg/l	107	179	143	190	190	155	214	167	71	131
Vanadium as Va	µg/l	300	190	230	190	200	200	340	290	330	250
No Radionuclide analysis											

7.2 LHU water analysis, 2006

Analysis of groundwater samples taken from proposed monotoring boreholes

	Sampling date	2006/10/11	2006/10/11	2006/10/11	2006/10/11	2006/10/11	2006/10/11	2006/10/12	2006/10/12	2006/10/12
	Sample I.D.	LH 1444	LH 1049	LH 1085	LH 1177	DW 07	DW 09	WW 41180	WW41181	WW41182
	Location	Pchannel south	Tailings dnstream	Tailings upstream	Lower Pchannel	Upper Pchannel	Tailings dnstream	Gawib dnstream	Swakop dnstream	Swakop dnstream
Standard analysis:										
p H		6.9	6.8	6.8	6.8	7.5	6.8	7.2	7.1	7.1
Electrical Conductivity	mS/m	961	1133	1669	1458	1405	1026	666	1033	1342
Turbidity	NTU	17	6.4	285	1.3	150	17.00	0.2	7.1	1.1
Total Dissolved Solids (calc.)	mg/l	6108	7290	10729	9408	8687	6436	3975	7214	9210
P-Alkalinity as CaCO$_3$	mg/l	0	0	0	0	0	0	0	0	0
Total Alkalinity as CaCO$_3$	mg/l	207	184	204	170	152	193	161	290	348
Total Hardness as CaCO$_3$	mg/l	1487	2006	2951	2391	1104	1826	992	2186	2901
Ca-Hardness as CaCO$_3$	mg/l	1071	1363	1823	1765	704	1361	704	1536	2033
Mg-Hardness as CaCO$_3$	mg/l	416	642	1128	626	399	465	288	651	869
Chloride as Cl$^-$	mg/l	2652	3351	5159	4243	4194	2989	1856	2941	3905
Fluoride as F$^-$	mg/l	3.3	2.2	1.9	3.1	2.2	3.5	1.8	0.1	0.2
Sulphate as SO$_4^{2-}$	mg/l	759	1023	991	1059	1113	810	460	896	1151
Nitrate as N	mg/l	17.7	20	11.5	20.7	19.8	20.5	9.7	<0.1	<0.1
Nitrite as N	mg/l	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
Sodium as Na	mg/l	1362	1561	2483	2186	2320	1355	1039	1305	1654
Potassium as K	mg/l	95	98	99	116	112	95	61	77	90
Magnesium as Mg	mg/l	101	156	274	152	97	113	70	158	211
Calcium as Ca	mg/l	429	546	730	707	282	545	282	615	814
Manganese as Mn	mg/l	0.07	0.07	0.39	0.05	0.7	0.08	0.07	16	3.6
Iron as Fe	mg/l	0.08	0.4	1.42	0.6	0.3	0.2	0.2	2.9	0.9
Stability pH, at 25°C		6.6	6.6	6.4	6.5	7.0	6.6	6.9	6.3	6.1
Langelier Index	scaling	0.3	0.2	0.4	0.3	0.5	0.2	0.3	0.8	1.0
Ryznar Index	scaling	6.4	6.4	6.1	6.2	6.4	6.3	6.6	5.6	5.2
Corrosivity ratio	increasing corrosive te	21.9	31.5	40.8	41.7	46.6	26.2	19.2	17.5	19.3
Trace element analysis:										
Arsenic as As	mg/l	0.01	0.01	0.01	0.01	0.01	0.01	0.003	0.01	0.01
Bismuth as Bi	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium as Cd	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Copper as Cu	mg/l	<0.001	<0.001	0.01	<0.001	0.003	<0.001	<0.001	<0.001	<0.001
Mercury as Hg	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Antimony as Sb	mg/l	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Selenium as Se	mg/l	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.003	0.004
Tellurium as Te	mg/l	<0.001	<0.001	0.002	0.002	<0.001	<0.001	<0.001	<0.001	<0.001
Uranium as U	mg/l	0.18	0.18	0.26	0.10	0.17	0.30	0.06	0.06	0.11
Aluminium as Al	mg/l	0.80	0.23	2	0.03	5	0.76	<0.001	<0.001	<0.001
Cobalt as Co	mg/l	<0.001	<0.001	0.003	<0.001	0.005	<0.001	<0.001	<0.001	<0.001
Chromium as Cr	mg/l	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001	<0.001
Molybdenum as Mo	mg/l	0.03	0.03	0.02	0.06	0.03	0.04	0.02	0.01	0.01
Nickel as Ni	mg/l	<0.001	<0.001	0.003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Lead as Pb	mg/l	0.02	0.002	0.01	0.004	0.03	0.003	<0.001	<0.001	<0.001
Zinc as Zn	mg/l	0.0013	<0.001	0.01	0.001	0.004	<0.001	0.02	<0.001	<0.001
Total organic carbon	mg/l	3.2	1.4	1.5	<1	<1	<1	<1	5.3	4
Radionuclides										
Th-230	[Bq/L]	0.00	0.29	0.61	0.05	3.36	1.22	0.06	0.00	0.00
Ra-226	[Bq/L]	1.46		2.58	2.26	0.46	4.56	0.05		0.06
Pb-210	[Bq/L]	(results not obtained from NECSA)								
Po-210	[Bq/L]	0.55	1.94	0.86	1.13	0.06	3.32	0.01	0.01	0.00
Th-227	[Bq/L]	0.00	0.12	0.04	0.02	0.16	0.06	0.00	0.00	0.01
Ra-223	[Bq/L]	0.05		0.24	0.05	0.01	0.26	0.01		0.00
Th-232	[Bq/L]	0.00	0.00	0.01	0.00	0.01	0.02	0.00	0.00	0.00
Th-228	[Bq/L]	0.01	0.01	0.01	0.01	0.02	0.04	0.01	0.00	0.01
Ra-224	[Bq/L]	0.01		0.03	0.01	0.01	0.00	0.01		0.00

7.3 Water Chemistry analysis report, 2015



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amended TEST REPORT

To: **Ministry of Health and Social Services**
Directorate: AE & RPA
P.O. Box 13198
Windhoek

Date received: **08-Oct-15**
Date required:
Date completed: **29-Oct-15**

Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM26
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/1

Parameter	**Value**	**Units**	
p H	**7.1**		
Electrical Conductivity	**3040**	**mS/m**	
Turbidity	**4.2**	**NTU**	
Total Dissolved Solids (calc.)	**19960**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**62**	**mg/l**	
Bicarbonate as HCO_3^-	**76**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**4194**	**mg/l**	
Ca-Hardness as $CaCO_3$	**3511**	**mg/l**	
Mg-Hardness as $CaCO_3$	**684**	**mg/l**	
Chloride as Cl^-	**10400**	**mg/l**	
Fluoride as F^-	**1.6**	**mg/l**	
Sulphate as SO_4^{2-}	**1940**	**mg/l**	
Nitrate as N	**2.8**	**mg/l**	
Nitrite as N	**<0.1**	**mg/l**	
Sodium as Na	**5442**	**mg/l**	
Potassium as K	**229**	**mg/l**	
Magnesium as Mg	**166**	**mg/l**	
Calcium as Ca	**1406**	**mg/l**	
Manganese as Mn	**0.12**	**mg/l**	
Iron as Fe	**0.56**	**mg/l**	
Stability pH, at 25°C	**6.7**		
Langelier Index	**0.4**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**6.3**	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**269.4**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Your Reference: 116218
Lab Reference: `I151745`

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM28
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/2

Parameter	Value	Units	
p H	7.2		
Electrical Conductivity	1737	mS/m	
Turbidity	7.9	NTU	
Total Dissolved Solids (calc.)	11432	mg/l	
P-Alkalinity as $CaCO_3$	0	mg/l	
Total Alkalinity as $CaCO_3$	201	mg/l	
Bicarbonate as HCO_3^-	245	mg/l	
Carbonate as CO_3^{2-}	0	mg/l	
Total Hardness as $CaCO_3$	3483	mg/l	
Ca-Hardness as $CaCO_3$	2450	mg/l	
Mg-Hardness as $CaCO_3$	1034	mg/l	
Chloride as Cl^-	5732	mg/l	
Fluoride as F^-	1.4	mg/l	
Sulphate as SO_4^{2-}	1027	mg/l	
Nitrate as N	60	mg/l	
Nitrite as N	<0.1	mg/l	
Sodium as Na	2803	mg/l	
Potassium as K	98	mg/l	
Magnesium as Mg	251	mg/l	
Calcium as Ca	981	mg/l	
Manganese as Mn	<0.1	mg/l	
Iron as Fe	2.9	mg/l	
Stability pH, at 25°C	6.3		
Langelier Index	0.9	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	5.4	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	45.6	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM29
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/3

Parameter	Value	Units	
p H	6.7		
Electrical Conductivity	931	mS/m	
Turbidity	2.0	NTU	
Total Dissolved Solids (calc.)	5983	mg/l	
P-Alkalinity as $CaCO_3$	0	mg/l	
Total Alkalinity as $CaCO_3$	264	mg/l	
Bicarbonate as HCO_3^-	322	mg/l	
Carbonate as CO_3^{2-}	0	mg/l	
Total Hardness as $CaCO_3$	2064	mg/l	
Ca-Hardness as $CaCO_3$	1541	mg/l	
Mg-Hardness as $CaCO_3$	523	mg/l	
Chloride as Cl^-	2658	mg/l	
Fluoride as F^-	1.2	mg/l	
Sulphate as SO_4^{2-}	657	mg/l	
Nitrate as N	3.4	mg/l	
Nitrite as N	<0.1	mg/l	
Sodium as Na	1205	mg/l	
Potassium as K	89	mg/l	
Magnesium as Mg	127	mg/l	
Calcium as Ca	617	mg/l	
Manganese as Mn	0.29	mg/l	
Iron as Fe	1.4	mg/l	
Stability pH, at 25°C	6.4		
Langelier Index	0.3	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	6.0	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	16.8	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM31
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/4

Parameter	**Value**	**Units**	
p H	**6.8**		
Electrical Conductivity	**932**	**mS/m**	
Turbidity	**0.70**	**NTU**	
Total Dissolved Solids (calc.)	**5808**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**189**	**mg/l**	
Bicarbonate as HCO_3^-	**231**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**1371**	**mg/l**	
Ca-Hardness as $CaCO_3$	**1029**	**mg/l**	
Mg-Hardness as $CaCO_3$	**342**	**mg/l**	
Chloride as Cl^-	**2557**	**mg/l**	
Fluoride as F^-	**2.0**	**mg/l**	
Sulphate as SO_4^{2-}	**674**	**mg/l**	
Nitrate as N	**12**	**mg/l**	
Nitrite as N	**<0.1**	**mg/l**	
Sodium as Na	**1461**	**mg/l**	
Potassium as K	**83**	**mg/l**	
Magnesium as Mg	**83**	**mg/l**	
Calcium as Ca	**412**	**mg/l**	
Manganese as Mn	**0.08**	**mg/l**	
Iron as Fe	**0.33**	**mg/l**	
Stability pH, at 25°C	**6.7**		
Langelier Index	**0.1**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**6.6**	stable	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**22.8**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Your Reference: 116218
Lab Reference: `I151745`

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	XB32
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/5

Parameter	Value	Units	
p H	**7.1**		
Electrical Conductivity	**667**	**mS/m**	
Turbidity	**1.0**	**NTU**	
Total Dissolved Solids (calc.)	**4193**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**234**	**mg/l**	
Bicarbonate as HCO_3^-	**285**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**1876**	**mg/l**	
Ca-Hardness as $CaCO_3$	**1576**	**mg/l**	
Mg-Hardness as $CaCO_3$	**301**	**mg/l**	
Chloride as Cl^-	**1869**	**mg/l**	
Fluoride as F^-	**1.9**	**mg/l**	
Sulphate as SO_4^{2-}	**225**	**mg/l**	
Nitrate as N	**20**	**mg/l**	
Nitrite as N	**0.72**	**mg/l**	
Sodium as Na	**671**	**mg/l**	
Potassium as K	**32**	**mg/l**	
Magnesium as Mg	**73**	**mg/l**	
Calcium as Ca	**631**	**mg/l**	
Manganese as Mn	**0.12**	**mg/l**	
Iron as Fe	**0.03**	**mg/l**	
Stability pH, at 25°C	**6.4**		
Langelier Index	**0.7**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**5.7**	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**12.3**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	XB34
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/6

Parameter	Value	Units	
p H	**6.8**		
Electrical Conductivity	**813**	**mS/m**	
Turbidity	**0.80**	**NTU**	
Total Dissolved Solids (calc.)	**4632**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**148**	**mg/l**	
Bicarbonate as HCO_3^-	**181**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**1141**	**mg/l**	
Ca-Hardness as $CaCO_3$	**951**	**mg/l**	
Mg-Hardness as $CaCO_3$	**189**	**mg/l**	
Chloride as Cl^-	**2440**	**mg/l**	
Fluoride as F^-	**2.2**	**mg/l**	
Sulphate as SO_4^{2-}	**414**	**mg/l**	
Nitrate as N	**8.1**	**mg/l**	
Nitrite as N	**<0.1**	**mg/l**	
Sodium as Na	**1284**	**mg/l**	
Potassium as K	**48**	**mg/l**	
Magnesium as Mg	**46**	**mg/l**	
Calcium as Ca	**381**	**mg/l**	
Manganese as Mn	**0.01**	**mg/l**	
Iron as Fe	**0.01**	**mg/l**	
Stability pH, at 25°C	**6.8**		
Langelier Index	**0.0**	corrosive	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**6.8**	stable	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**26.2**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM46
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/7

Parameter	Value	Units	
p H	**10.0**		
Electrical Conductivity	**5580**	**mS/m**	
Turbidity	**10**	**NTU**	
Total Dissolved Solids (calc.)	**51009**	**mg/l**	
P-Alkalinity as $CaCO_3$	**12018**	**mg/l**	
Total Alkalinity as $CaCO_3$	**28215**	**mg/l**	
Bicarbonate as HCO_3^-	**5098**	**mg/l**	
Carbonate as CO_3^{2-}	**14412**	**mg/l**	
Total Hardness as $CaCO_3$	**30**	**mg/l**	
Ca-Hardness as $CaCO_3$	**17**	**mg/l**	
Mg-Hardness as $CaCO_3$	**12**	**mg/l**	
Chloride as Cl^-	**5134**	**mg/l**	
Fluoride as F^-	**131**	**mg/l**	
Sulphate as SO_4^{2-}	**10915**	**mg/l**	
Nitrate as N	**56**	**mg/l**	
Nitrite as N	**2.4**	**mg/l**	
Sodium as Na	**19020**	**mg/l**	
Potassium as K	**406**	**mg/l**	
Magnesium as Mg	**3**	**mg/l**	
Calcium as Ca	**7**	**mg/l**	
Manganese as Mn	**<0.1**	**mg/l**	
Iron as Fe	**0.22**	**mg/l**	
Stability pH, at 25°C	**6.4**		
Langelier Index	**3.6**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**2.8**	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**0.7**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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Lab Reference: `I151745`

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU PW
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/8

Parameter	**Value**	**Units**		
p H	**10.5**			
Electrical Conductivity	**4310**	**mS/m**		
Turbidity	**40**	**NTU**		
Total Dissolved Solids (calc.)	**36967**	**mg/l**		
P-Alkalinity as $CaCO_3$	**13063**	**mg/l**		
Total Alkalinity as $CaCO_3$	**26648**	**mg/l**		
Bicarbonate as HCO_3^-	**637**	**mg/l**		
Carbonate as CO_3^{2-}	**15665**	**mg/l**		
Total Hardness as $CaCO_3$	**114**	**mg/l**		
Ca-Hardness as $CaCO_3$	**40**	**mg/l**		
Mg-Hardness as $CaCO_3$	**74**	**mg/l**		
Chloride as Cl^-	**2916**	**mg/l**		
Fluoride as F^-	**62**	**mg/l**		
Sulphate as SO_4^{2-}	**3933**	**mg/l**		
Nitrate as N	**21**	**mg/l**		
Nitrite as N	**7.6**	**mg/l**		
Sodium as Na	**14020**	**mg/l**		
Potassium as K	**244**	**mg/l**		
Magnesium as Mg	**18**	**mg/l**		
Calcium as Ca	**16**	**mg/l**		
Manganese as Mn	**<0.1**	**mg/l**		
Iron as Fe	**0.38**	**mg/l**		
Stability pH, at 25°C	**6.0**			
Langelier Index	**4.5**	scaling		>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**1.6**	scaling		<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**0.3**	increasing corrosive tendency		Applies to water in the pH range 7-8
				which also contains dissolved oxygen
				ratios <0.2 no corrosive properties
				ratios >0.2 increasing corrosive tendency

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Date completed: **29-Oct-15**

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e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU 1049
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/9

Parameter	**Value**	**Units**	
p H	**7.1**		
Electrical Conductivity	**1923**	**mS/m**	
Turbidity	**21**	**NTU**	
Total Dissolved Solids (calc.)	**13844**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**345**	**mg/l**	
Bicarbonate as HCO_3^-	**421**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**4834**	**mg/l**	
Ca-Hardness as $CaCO_3$	**3343**	**mg/l**	
Mg-Hardness as $CaCO_3$	**1491**	**mg/l**	
Chloride as Cl^-	**5732**	**mg/l**	
Fluoride as F^-	**1.6**	**mg/l**	
Sulphate as SO_4^{2-}	**2475**	**mg/l**	
Nitrate as N	**59**	**mg/l**	
Nitrite as N	**<0.1**	**mg/l**	
Sodium as Na	**2654**	**mg/l**	
Potassium as K	**129**	**mg/l**	
Magnesium as Mg	**362**	**mg/l**	
Calcium as Ca	**1339**	**mg/l**	
Manganese as Mn	**<0.02**	**mg/l**	
Iron as Fe	**0.04**	**mg/l**	
Stability pH, at 25°C	**6.0**		
Langelier Index	**1.1**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**4.8**	scaling	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**30.9**	increasing corrosive tendency	Applies to water in the pH range 7-8
			which also contains dissolved oxygen
			ratios <0.2 no corrosive properties
			ratios >0.2 increasing corrosive tendency

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amended TEST REPORT

To: **Ministry of Health and Social Services**
Directorate: AE & RPA
P.O. Box 13198
Windhoek

Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

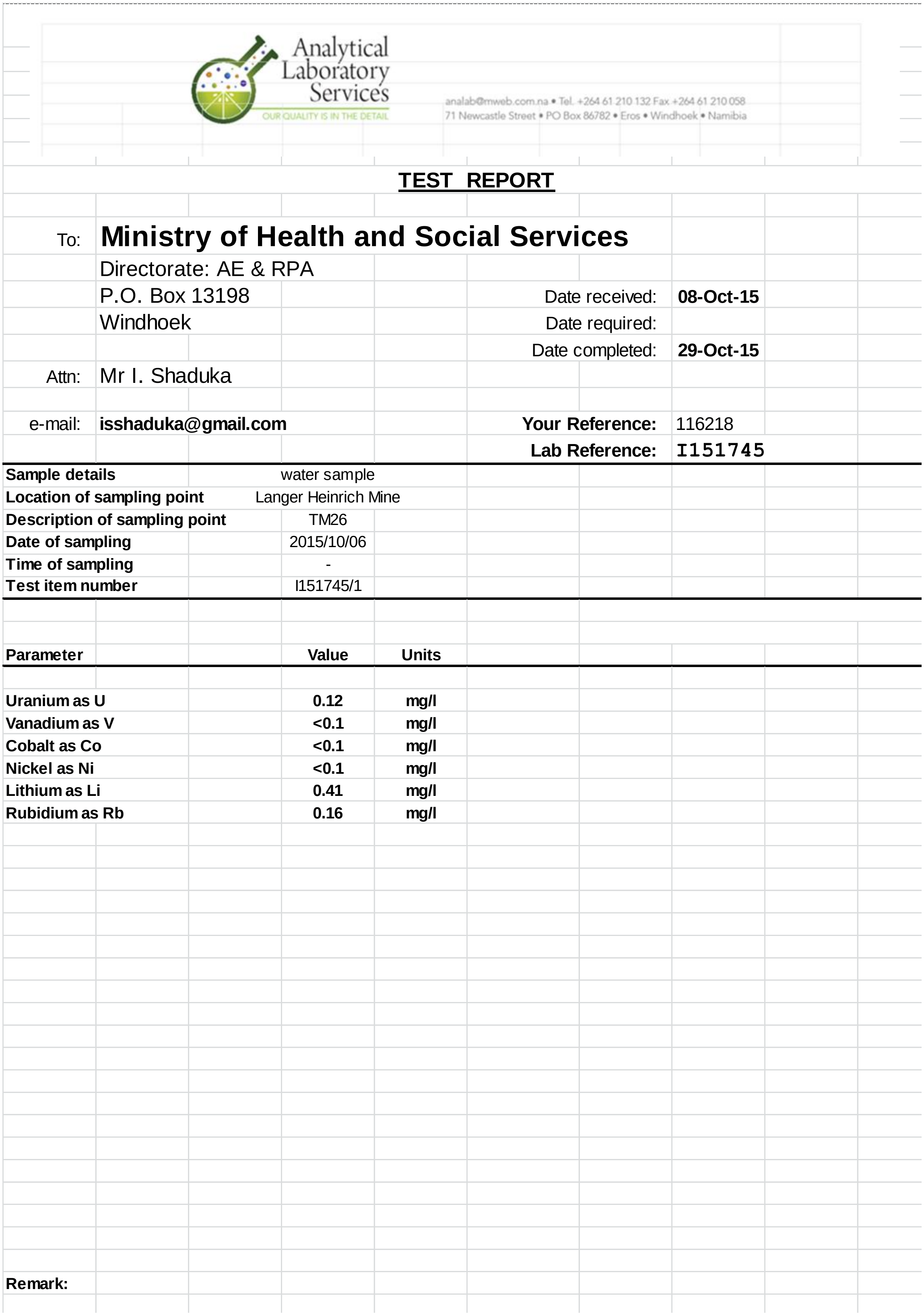
Date received: **08-Oct-15**
Date required:
Date completed: **29-Oct-15**

Your Reference: 116218
Lab Reference: **I151745**

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU-FW
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/10

Parameter	**Value**	**Units**	
p H	**8.0**		
Electrical Conductivity	**142.4**	**mS/m**	
Turbidity	**0.25**	**NTU**	
Total Dissolved Solids (calc.)	**721**	**mg/l**	
P-Alkalinity as $CaCO_3$	**0**	**mg/l**	
Total Alkalinity as $CaCO_3$	**121**	**mg/l**	
Bicarbonate as HCO_3^-	**148**	**mg/l**	
Carbonate as CO_3^{2-}	**0**	**mg/l**	
Total Hardness as $CaCO_3$	**231**	**mg/l**	
Ca-Hardness as $CaCO_3$	**165**	**mg/l**	
Mg-Hardness as $CaCO_3$	**66**	**mg/l**	
Chloride as Cl^-	**319**	**mg/l**	
Fluoride as F^-	**0.3**	**mg/l**	
Sulphate as SO_4^{2-}	**62**	**mg/l**	
Nitrate as N	**2.7**	**mg/l**	
Nitrite as N	**<0.1**	**mg/l**	
Sodium as Na	**195**	**mg/l**	
Potassium as K	**9.4**	**mg/l**	
Magnesium as Mg	**16**	**mg/l**	
Calcium as Ca	**66**	**mg/l**	
Manganese as Mn	**0.05**	**mg/l**	
Iron as Fe	**0.96**	**mg/l**	
Stability pH, at 25°C	**7.6**		
Langelier Index	**0.4**	scaling	>0=scaling, <0=corrosive, 0=stable
Ryznar Index	**7.2**	stable	<6.5=scaling, >7,5=corrosive, ≥6.5 and ≤7.5=stable
Corrosivity ratio	**4.3**	increasing corrosive tendency	Applies to water in the pH range 7-8 which also contains dissolved oxygen ratios <0.2 no corrosive properties ratios >0.2 increasing corrosive tendency

8.4 Trace Elements analysis reports



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P.O. Box 13198
Windhoek

Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

Date received: **08-Oct-15**
Date required:
Date completed: **29-Oct-15**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM26
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/1

Parameter	Value	Units
Uranium as U	**0.12**	**mg/l**
Vanadium as V	**<0.1**	**mg/l**
Cobalt as Co	**<0.1**	**mg/l**
Nickel as Ni	**<0.1**	**mg/l**
Lithium as Li	**0.41**	**mg/l**
Rubidium as Rb	**0.16**	**mg/l**

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e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM28
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/2

Parameter	**Value**	**Units**
Uranium as U	**0.14**	**mg/l**
Vanadium as V	**<0.1**	**mg/l**
Cobalt as Co	**<0.1**	**mg/l**
Nickel as Ni	**<0.1**	**mg/l**
Lithium as Li	**0.18**	**mg/l**
Rubidium as Rb	**0.10**	**mg/l**

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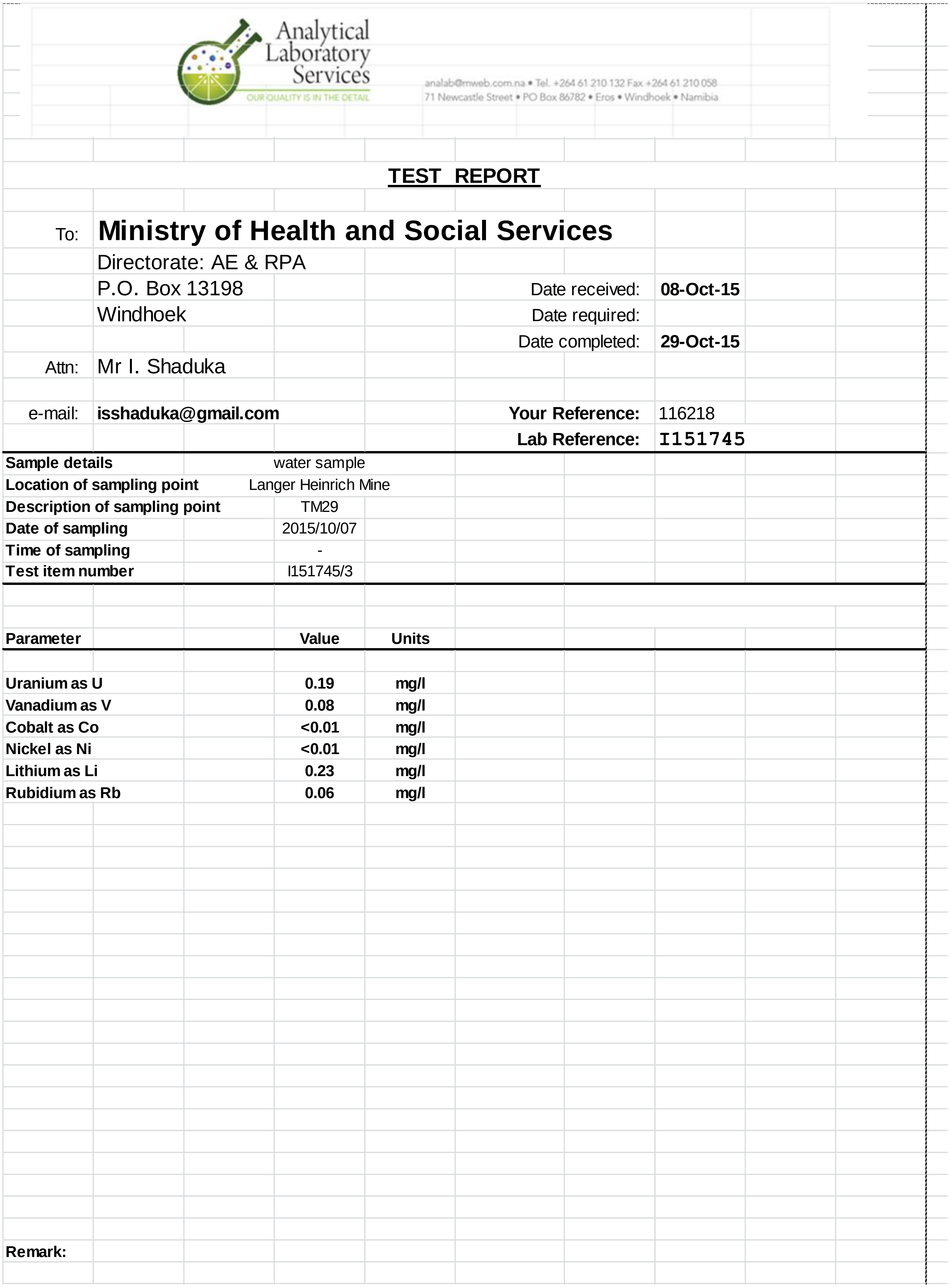

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e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM29
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/3

Parameter	**Value**	**Units**
Uranium as U	**0.19**	**mg/l**
Vanadium as V	**0.08**	**mg/l**
Cobalt as Co	**<0.01**	**mg/l**
Nickel as Ni	**<0.01**	**mg/l**
Lithium as Li	**0.23**	**mg/l**
Rubidium as Rb	**0.06**	**mg/l**

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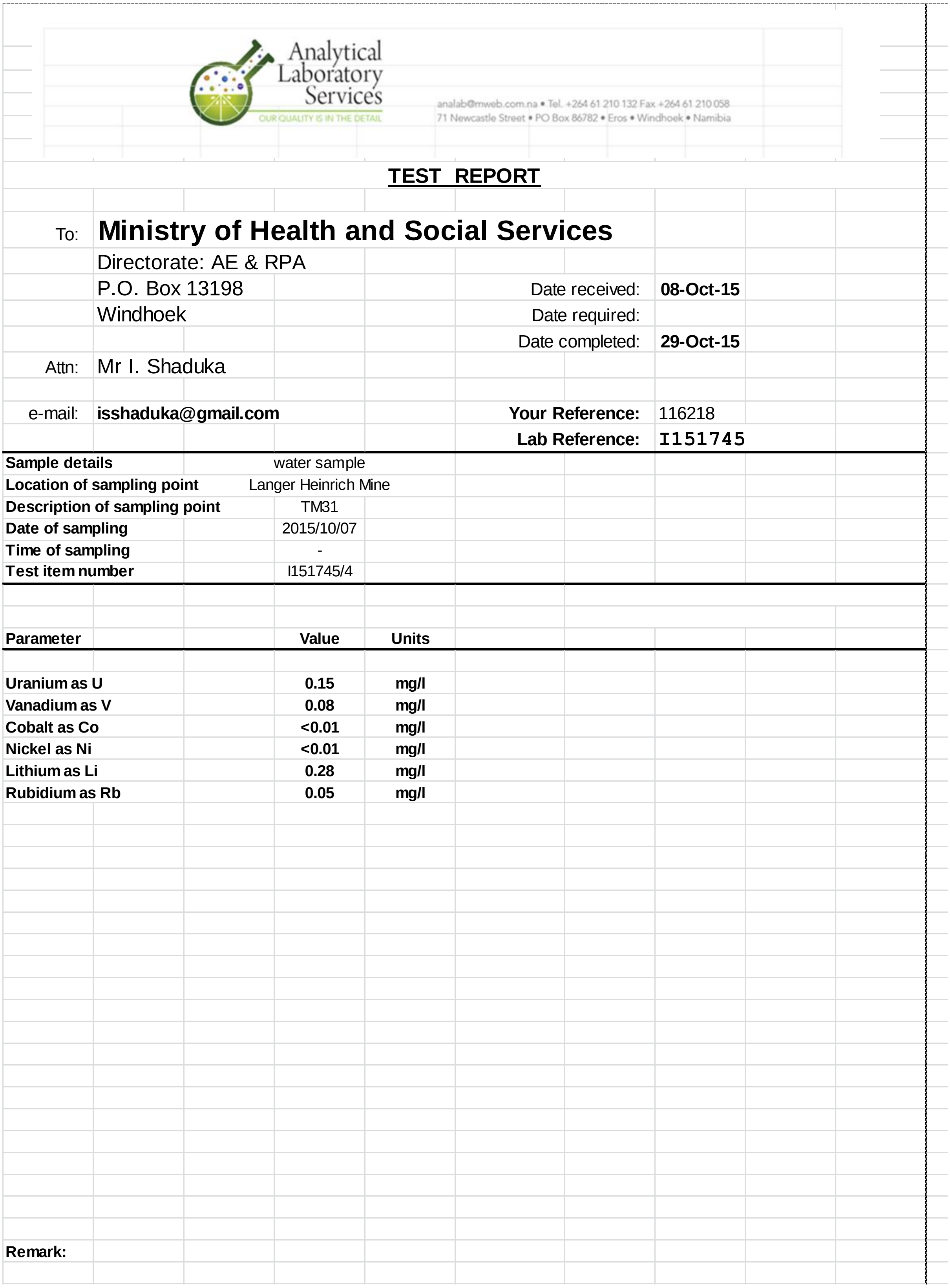

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Date required:
Date completed: **29-Oct-15**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM31
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/4

Parameter	**Value**	**Units**
Uranium as U	**0.15**	**mg/l**
Vanadium as V	**0.08**	**mg/l**
Cobalt as Co	**<0.01**	**mg/l**
Nickel as Ni	**<0.01**	**mg/l**
Lithium as Li	**0.28**	**mg/l**
Rubidium as Rb	**0.05**	**mg/l**

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Your Reference: 116218
Lab Reference: **I151745**

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	XB32
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/5

Parameter	**Value**	**Units**
Uranium as U	**0.18**	**mg/l**
Vanadium as V	**0.03**	**mg/l**
Cobalt as Co	**<0.01**	**mg/l**
Nickel as Ni	**<0.01**	**mg/l**
Lithium as Li	**0.09**	**mg/l**
Rubidium as Rb	**0.03**	**mg/l**

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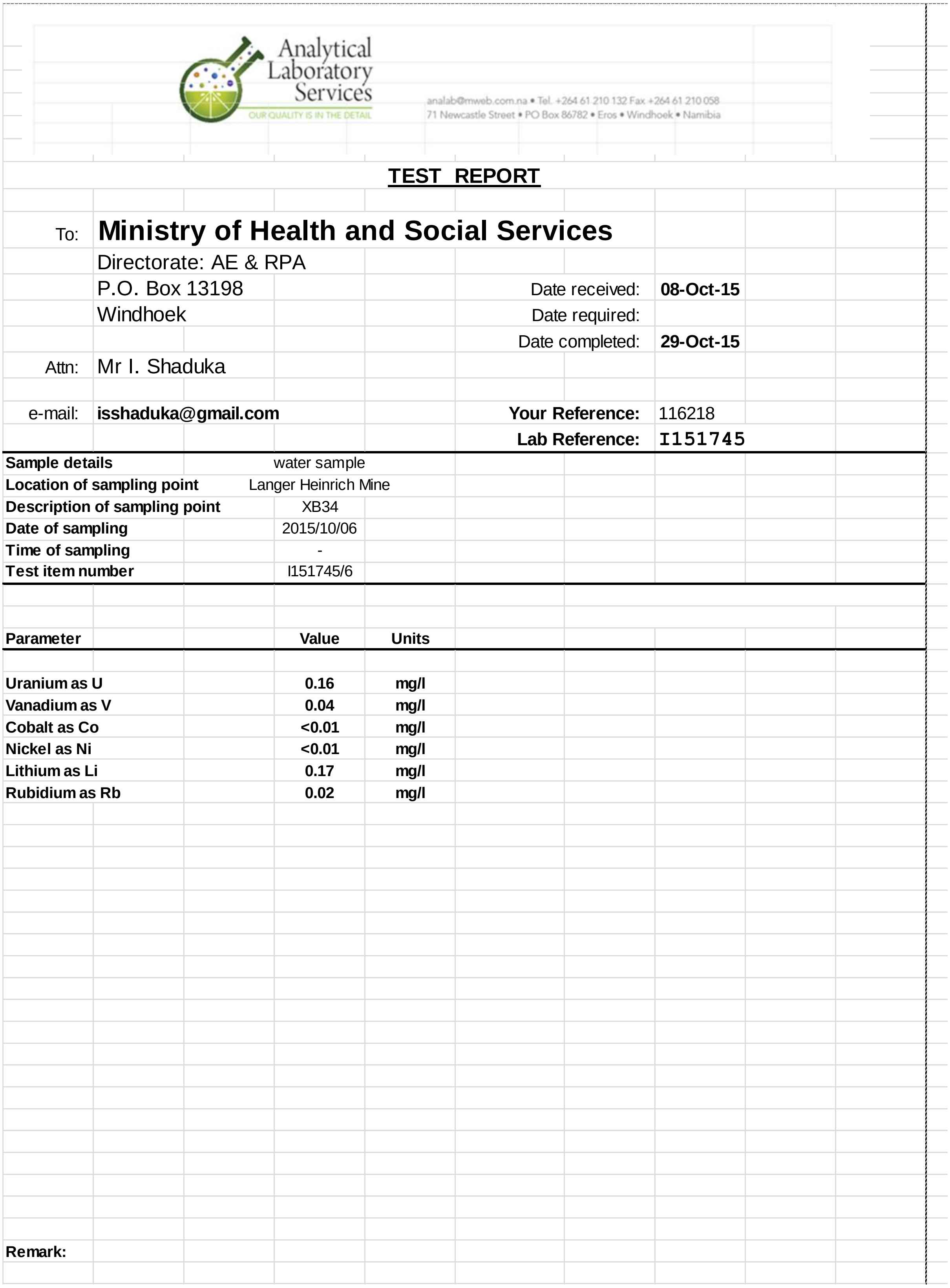

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Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	XB34
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/6

Parameter	**Value**	**Units**
Uranium as U	**0.16**	**mg/l**
Vanadium as V	**0.04**	**mg/l**
Cobalt as Co	**<0.01**	**mg/l**
Nickel as Ni	**<0.01**	**mg/l**
Lithium as Li	**0.17**	**mg/l**
Rubidium as Rb	**0.02**	**mg/l**

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Date required:
Date completed: **29-Oct-15**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	TM46
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/7

Parameter	**Value**	**Units**
Uranium as U	**369**	**mg/l**
Vanadium as V	**73**	**mg/l**
Cobalt as Co	**<0.1**	**mg/l**
Nickel as Ni	**<0.1**	**mg/l**
Lithium as Li	**0.17**	**mg/l**
Rubidium as Rb	**<0.1**	**mg/l**

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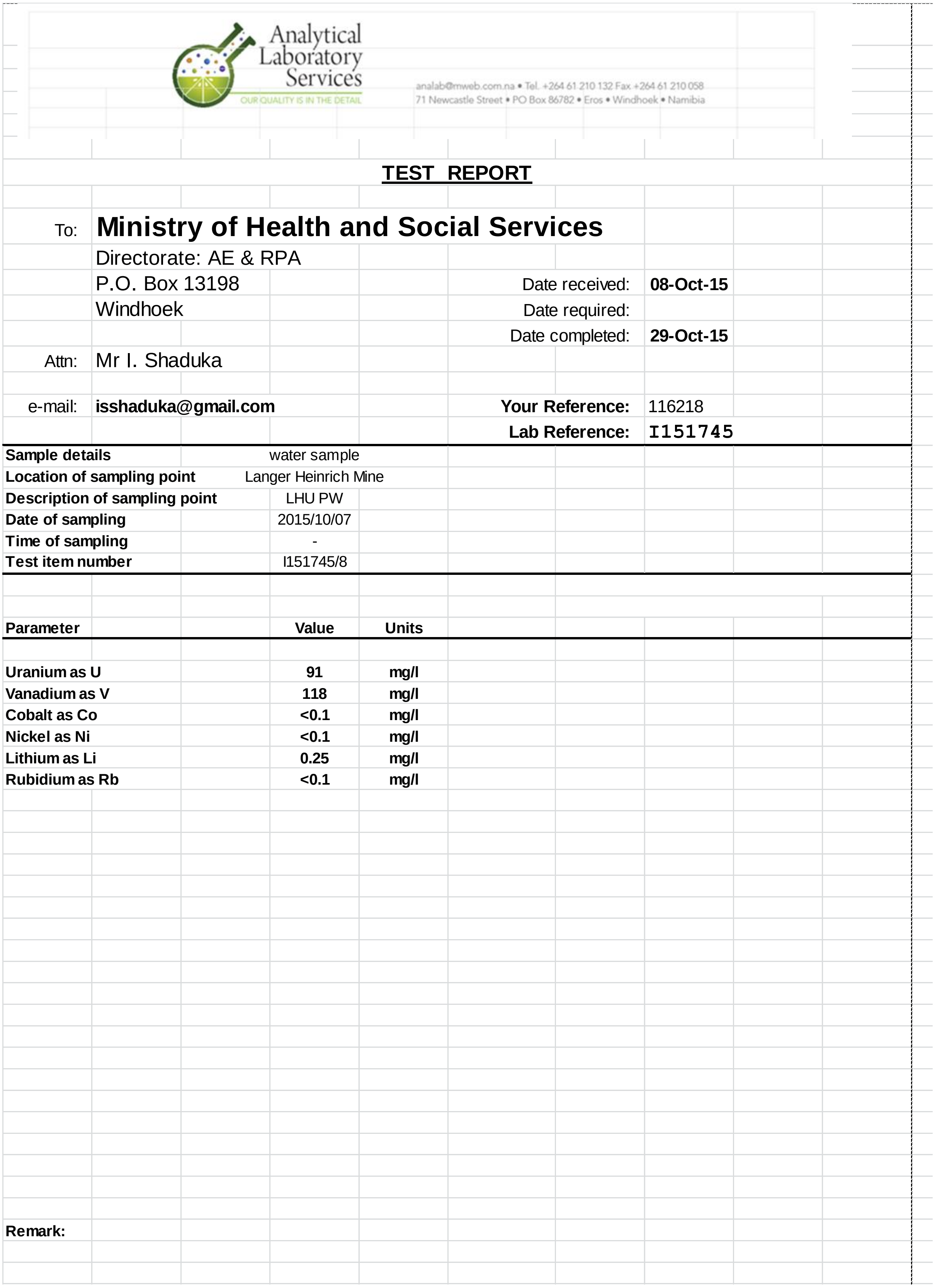

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Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU PW
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/8

Parameter	**Value**	**Units**
Uranium as U	**91**	**mg/l**
Vanadium as V	**118**	**mg/l**
Cobalt as Co	**<0.1**	**mg/l**
Nickel as Ni	**<0.1**	**mg/l**
Lithium as Li	**0.25**	**mg/l**
Rubidium as Rb	**<0.1**	**mg/l**

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e-mail: **isshaduka@gmail.com**

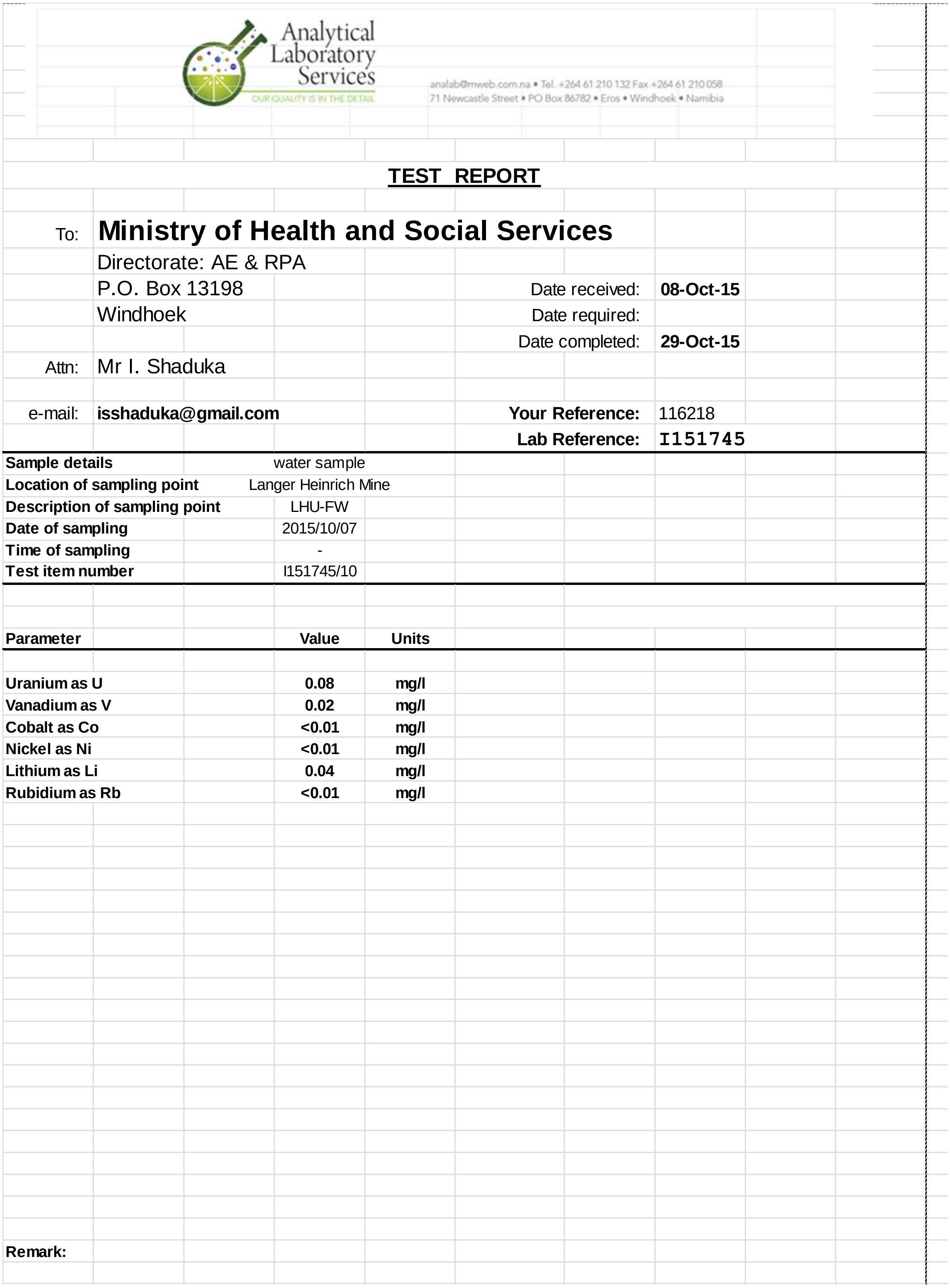
Date received: **08-Oct-15**
Date required:
Date completed: **29-Oct-15**

Your Reference: 116218
Lab Reference: `I151745`

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU 1049
Date of sampling	2015/10/06
Time of sampling	-
Test item number	I151745/9

Parameter	**Value**	**Units**
Uranium as U	**8.9**	**mg/l**
Vanadium as V	**0.07**	**mg/l**
Cobalt as Co	**<0.02**	**mg/l**
Nickel as Ni	**<0.02**	**mg/l**
Lithium as Li	**0.10**	**mg/l**
Rubidium as Rb	**0.04**	**mg/l**

Remark:



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Attn: Mr I. Shaduka

e-mail: **isshaduka@gmail.com**

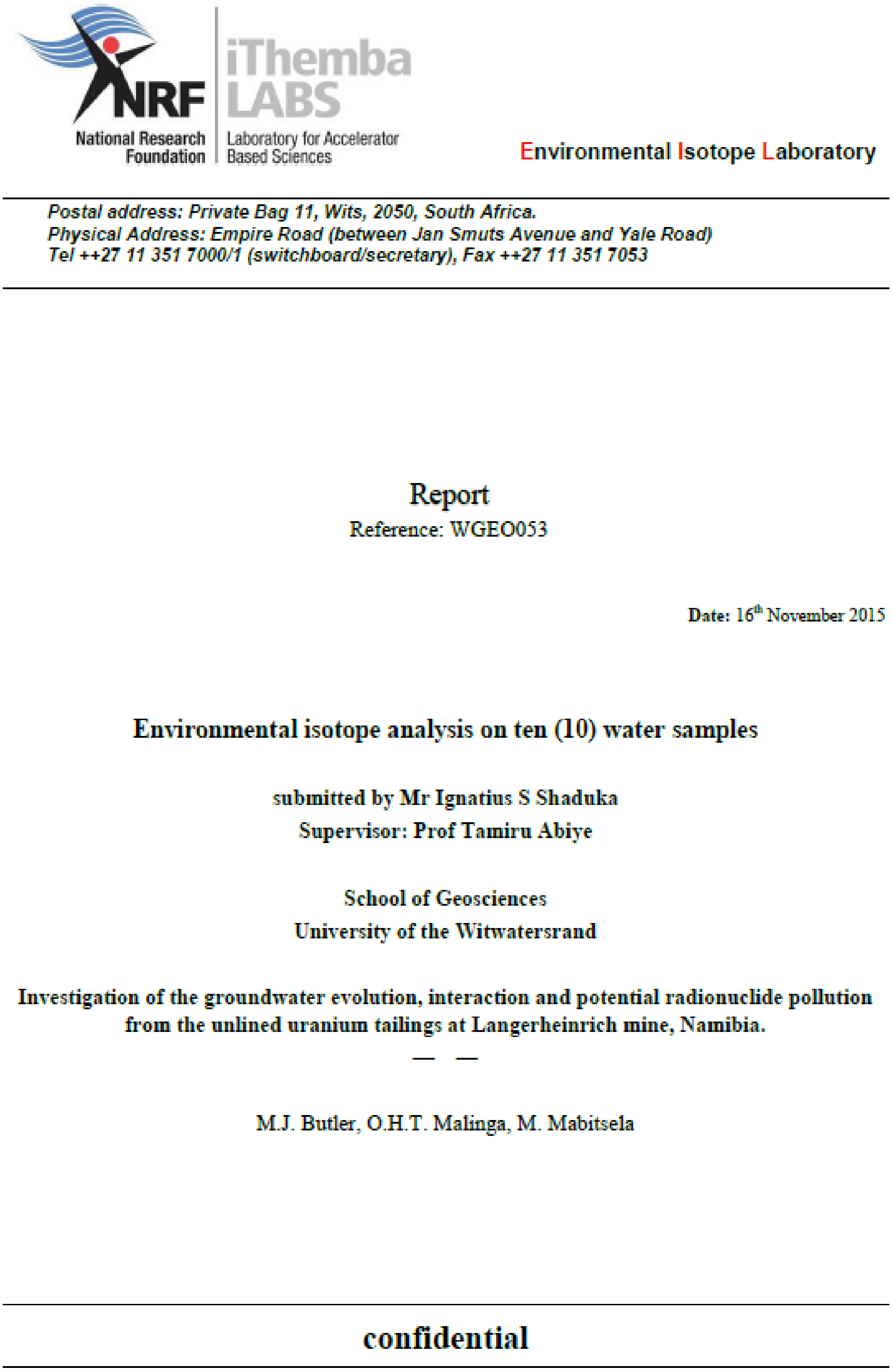
Your Reference: 116218
Lab Reference: I151745

Sample details	water sample
Location of sampling point	Langer Heinrich Mine
Description of sampling point	LHU-FW
Date of sampling	2015/10/07
Time of sampling	-
Test item number	I151745/10

Parameter	**Value**	**Units**
Uranium as U	**0.08**	**mg/l**
Vanadium as V	**0.02**	**mg/l**
Cobalt as Co	**<0.01**	**mg/l**
Nickel as Ni	**<0.01**	**mg/l**
Lithium as Li	**0.04**	**mg/l**
Rubidium as Rb	**<0.01**	**mg/l**

Remark:

7.5 Tritium analysis report



National Research Foundation

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Laboratory for Accelerator Based Sciences

Environmental Isotope Laboratory

Postal address: Private Bag 11, Wits, 2050, South Africa.
Physical Address: Empire Road (between Jan Smuts Avenue and Yale Road)
Tel ++27 11 351 7000/1 (switchboard/secretary), Fax ++27 11 351 7053

Report

Reference: WGEO053

Date: 16th November 2015

Environmental isotope analysis on ten (10) water samples

submitted by Mr Ignatius S Shaduka
Supervisor: Prof Tamiru Abiye

School of Geosciences
University of the Witwatersrand

Investigation of the groundwater evolution, interaction and potential radionuclide pollution from the unlined uranium tailings at Langerheinrich mine, Namibia.

M.J. Butler, O.H.T. Malinga, M. Mabitsela

confidential

1. General

Ten water samples were submitted by Mr I. Shaduka of the School of Geosciences, University of the Witwatersrand, for tritium analysis. The samples were received on the 12th of October 2015.

2. Tritium Analysis

The samples were distilled and subsequently enriched by electrolysis. The electrolysis cells consist of two concentric metal tubes, which are insulated from each other. The outer anode, which is also the container, is of stainless steel. The inner cathode is of mild steel with a special surface coating. Some 500 ml of the water sample, having first been distilled and containing sodium hydroxide, is introduced into the cell. A direct current of some 10–20 ampere is then passed through the cell, which is cooled because of the heat generation. After several days, the electrolyte volume is reduced to some 20 ml. The volume reduction of some 25 times produces a corresponding tritium enrichment factor of about 20. Samples of standard known tritium concentration (spikes) are run in one cell of each batch to check on the enrichment attained.

For liquid scintillation counting samples are prepared by directly distilling the enriched water sample from the now highly concentrated electrolyte. 10 ml of the distilled water sample is mixed with 11 ml Ultima Gold and placed in a vial in the analyser and counted 2 to 3 cycles of 4 hours. Detection limits are 0.2 TU for enriched samples.

3. Results

The analytical results are presented in Table 1.

Table 1: Analytical Results

			Tritium	
Lab No	Field Name	Description	TU	±
WITS 621	TM 26	2015/10/06	0.6	0.2
WITS 622	TM 28	2015/10/06	1.6	0.3
WITS 623	TM 29	2015/10/07	2.0	0.3
WITS 624	TM 31	2015/10/07	1.8	0.3
WITS 625	TM46	2015/10/07	2.0	0.3
WITS 626	XB34	2015/10/06	2.1	0.3
WITS 627	XB32	2015/10/06	0.8	0.2
WITS 628	LH1049	2015/10/06	1.0	0.3
WITS 629	LHU-PW	2015/10/07	1.9	0.3
WITS 630	LHU-FW	2015/10/07	1.2	0.3

7.6 Stable isotopes analysis results

a) University of Witwatersrand- Hydrogeology laboratory

Sample Name	δ2H‰	2H StDev	δ18O‰	18O StDev
TM26	-31.00	0.26	-5.06	0.10
XB34	-20.7	0.00	-2.80	0.00
TM31	-39.26	0.06	-7.86	0.08
TM29	-38.02	0.09	-7.97	0.07
CHLI FW	-30.30	0.12	-6.96	0.09
XB32	-40.54	0.11	-7.92	0.11
LHU PW	-13.50	0.29	-3.27	0.03
TM 46	-27.48	0.24	-4.82	0.05
TM28	-39.22	0.05	-7.25	0.05
LHU1049	-38.97	0.06	-7.10	0.04