Geohydrological modelling to determine cumulative impact on groundwater at the Letšeng Diamond Mine, Lesotho

Thato Theko

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Bloemfontein

DECLARATION

I, Thato Theko, hereby declare that this dissertation submitted for the Master of Science Degree to the Institute for Groundwater Studies, Faculty of Science, University of the Free State, Bloemfontein, South Africa, is my own independent work. This thesis has not been submitted to any other institution of higher education. I further declare that all sources cited have been acknowledged by means of a list of references.

Thato Theko

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ABSTRACT

Letšeng diamond mine (LDM) uses the split-shell open-pit mining method. The method includes excavation fromthe surface to access the ore at depth. Material from excavation and that separated during diamond extraction form primary mine waste. Approximately 20 million tonnes of waste is produced as fine-grained waste deposited into Tailings Storage Facilities (TSF) and coarse-grained waste deposited onto Waste Rock Dumps (WRDs). The waste can contain toxic chemical substances that can seep into groundwater or flow into surface water, contaminating it. For this reason, the study aims to determine the cumulative impacts of mining on groundwater quality. To achieve this, groundwater modelling techniques were employed to simulate groundwater flow and groundwater travel times and travel paths for contaminant transport.

Geological, hydrological, hydrogeological and hydrochemical data were collected, analysed, and integrated to conceptualise the hydrogeology of LDM to provide a better understanding of the hydrogeological system. The conceptual model also indicated possible sources of contamination and their possible receptors incorporating the Source Pathway Receptor concept. This was achieved by collecting and analysing the water quality data. Mine water sampling results show that most constituents are within the acceptable limits, while nitrates and sulphates were elevated above limits at locations down gradient from the Old Slimes Dam, WRDs and Patiseng TSF suggesting these areas are potential on-site sources of contamination.

The conceptual model formed the basis of the groundwater model. Based on the prevailing hydrogeological conditions in the mining area, a groundwater flow model was developed using MODFLOW 6. Due to data limitations, instead of simulating the contaminant from the source to the receptor using transport modelling, particle tracking with MODPATH was used to simulate the pathway and travel time of contaminants in groundwater. Particle tracking results show that the simulated extent of contaminant movement is generally in line with the water quality sampling results, where sampling points beyond the mine lease areas show acceptable water quality as opposed to samples closer to potential sources which show elevated levels of contamination, suggesting contamination is mostly contained within the mine lease area. Similarly, MODPATH results indicate that most particles do not exceed the lease area, also indicating that contamination from potential sources is mostly limited within the mine lease area.

Over a five-year simulation period, there is very limited movement of contaminants, although some particles from the Old Slimes Dam are released into the Mothusi Dam, thus posing a risk on its quality. Based on these findings, the Dam was identified as the most sensitive receptor. Over a 10-year

period, there is further movement of particles, and some start to move beyond the lease area as some boreholes startshowing increased nitrate concentrations such as borehole L_WE_010 down-gradient from the WRD east, suggesting groundwater contamination from the WRD. Over 20 years, a maximum travel distance of 5 km from the eastern WRD is observed, however no sensitive receptor was reached. While the calculated extent of the cumulative migration from the Old Slimes Dam is contained on- site over the 20 years, there is potential impact on the quality of groundwater as some particles intercept the boreholes downstream of the Mothusi Dam, borehole L_WE_015 and borehole L_WE_016. More boreholes are also intercepted over the 20 years.

Over time, contaminants will migrate off-site into the weathered shallow layer through the streams therefore reaching some of the receptors in the surrounding environment, either by percolation or conveyed as surface contaminants into the weathered layer. Due to low hydraulic conductivity in the types of rocks in the area, the migration of contaminates is very slow and is mostlylimited within the first layer. The results show that there is some seepage of contaminants from potential sources, mostly affecting surface water compared to groundwater. However, the groundwater modelling results also indicate that over long-term evaluations, mining activities at LDM have significant impacts on the groundwater quality, where contaminant particles from different sources are observed at monitoring boreholes suggesting groundwater contamination.

This study clarifies the slow but significant effects of mining operations on groundwater and surface water resources over time at Letšeng diamond mine. The results highlight the need for ongoing monitoring and mitigation measures to reduce cumulative effects on vulnerable receptors including the Khubelu, Qaqa Rivers and Mothusi Dam. The conclusion of this assessment emphasizes the critical need for ongoing environmental management within mining practices to protect the quality of nearby water resources. This is achieved by addressing the sources and pathways of contamination that have been identified, putting in place rigorous monitoring, and strengthening mitigation measures.

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1 INTRODUCTION

Water is a valuable natural resource supporting human life and the environment. However, due to climatic variability and human activities, global water resources are at risk. For instance, the increasing exploitation of water resources has resulted in water scarcity, where water resources are insufficient to meet basic human and environmental needs. To minimize the risk, it is important to manage water resources, by ensuring that they are well protected and are utilized sustainably.

1.1 MINING AND WATER RESOURCES

The mining industry is a major contributor to economic growth. However, mining activities have enormous impacts on the environment. Pollution of water resources is one of the major impacts of mining on the environment. In mining, water is used for several operations, for example, the crushing of rock at a large scale during mineral extraction in the diamond mining process requires a large supply of water. The water from such operations is usually contaminated and if not treated the water has the potential to affect the quality of surface water and groundwater (Goussard, 2017). The South African mining industry for instance does not consume as much water as other industries, although the industry is highly responsible for the deterioration of water quality in the country (Haggard et. al., 2015).

In most cases the impacts on water resources are due to tailing, acid mine drainage, lowering of the water table, subsidence and disturbance in the hydrological cycle. These factors can affect both the quantity and quality of water (Jhariya, 2016). The extent to which the water resources will be impacted depends on the location of the mine and/or the mining method. During open-pit mining in particular, extraction of the mineral at depth involves the removal of large quantities of waste rock, usually disposed of as Waste Rock Dumps (WRD). Water flowing through a WRD can react with present chemicals thus producing toxins that can seep into fresh water, thus contaminating it. Similarly, waste produced from mineral processing is usually discharged into Tailings Storage Facilities (TSF), and seepage from the waste, can also lead to contamination of groundwater and surface water resources. To minimize the impacts of mining on water resources, mines need to ensure that they protect water resources and utilize them sustainably to achieve sustainable water management.

1.2 MANAGEMENT OF WATER RESOURCES IN MINING

The effects of mining activities on water quality are significant. Hence, it is mandatory for the mining industry to satisfactorily manage the impacts on water resources throughout the life of the mine and post-closure by adopting optimal water management measures (DWAF, 2008). According to the Groundwater Management Framework Report to the Water Resource Commission (2011), the management of groundwater includes the protection and sustainable utilization of aquifers. Aquifer protection involves, amongst others, preventing water quality deterioration and aquifer rehabilitation; through pollution prevention and remediation processes. Aquifer utilisation involves all activities undertaken to ensure groundwater is used sustainably, securing its availability (Riemann et al., 2011).

In some instances, the scope of water management is limited to the periphery of the mine site and does not include interaction with the surrounding catchment. This tends to limit the sustainability of water management. Therefore, as a measure to assist mines in achieving sustainable water resources management, governments have put in place legislation and policies for the regulation of water resources. The Government of Lesotho has also put in place laws that guide the mining industry regarding protecting the environment. These include the Mines and Minerals Act of 2005, which regulates the establishment and governing of mines in Lesotho. According to the regulations, the leaseholder is expected not to engage in wasteful mining and compensate disturbance of damaged land, vegetation, or buildings. The Environmental Act of 2008 also gives a right to every person living in Lesotho the fundamental right to a scenic, clean, and healthy environment (Matandare, 2019). Mines therefore must ensure the protection of the environment, which includes the protection of water resources in compliance with set regulations.

For mines to achieve sustainable management of water resources, it is important not to limit management to current operations but to rather manage the impacts throughout the life of mine. It is therefore essential to adopt the Cumulative Impact Assessment (CIA) principle, a process of systematically analysing and assessing cumulative environmental change (DEAT, 2004). The process evaluates the consequences, sources and pathways of cumulative impacts of multiple activities. Cumulative impacts are environmental changes that are caused by an action in combination with other past, present and future human actions (DEAT, 2004). The predictive nature of models allows for the assessment of cumulative impacts. When simulation models are used, all relevant knowledge of the system can be incorporated, therefore predictions become more objective to the decision maker for effective management of groundwater resources. For this reason, groundwater modelling has become a powerful tool in the management of groundwater resources. As explained in the next section, this study therefore acknowledges the important role of groundwater modelling in groundwater management. Modelling tools will be utilised to assess the cumulative impacts of mining on the groundwater quality, thus assisting in control and mitigation measures towards sustainable groundwater management.

1.3 RESEARCH OVERVIEW: LETŠENG DIAMOND MINE

Letšeng Diamond Mine uses a split-shell open-pit mining method to mine its two twin pipes. The mining technique includes excavation from the surface to access the ore at depth. Benches of ore are drilled, blasted, loaded on trucks and transported for processing of the ore at the plant and thereafter diamond extraction (Shor, 2015). Material from excavation and that separated from diamond extraction forms primary mine waste. The mine produces approximately seven million metric tons of ore and 20 million metric tons of waste from extraction and processing. The waste is disposed of in two ways depending on the size of the grains. Waste rock is deposited as spoil heaps, and fine-grained waste is deposited as slurry in tailings dams. Tailings dams may contain a variety of toxic chemical species, which can seep into groundwater or flow into surface water (Dennis et al., 2008). It is for this reason that mining activities tend to trigger fear of water quantity and quality issues within communities around the mine. The mine is therefore expected to introduce environmental risk assessments about regulations and guidelines (Foster and Tyson, 2008). Letšeng diamond mine currently collects water quantity and quality data regularly. This data is used to:

1) Prepare monitoring reports,
2) Prepare audit reports that are submitted to the regulatory authorities according to the prescripts of related laws such as the Lesotho Water Act (Act 15, 2008) and the Environmental Act of Lesotho (Act 10, 2008),
3) To calibrate and update the mine water management models.

These reports are mainly written to describe the status of the water quality and quantity. To enhance the strategies towards groundwater management at LDM, this study proposes to use numerical modelling to determine the cumulative impacts on the quality of groundwater at the mine. The groundwater model will allow the simulation of the natural groundwater environment and predict the current and future impacts on the groundwater quality.

1.4 RESEARCH AIMS AND OBJECTIVES

The research aims to determine the cumulative impacts of mining on groundwater quality at the Letšeng Diamond Mine using groundwater modelling. The goal is to stimulate and enhance appropriate levels of regulatory effort needed or currently underway to mitigate or minimise the impact on water resources and work towards strengthening current practice to ensure minimal or zero impact.

The objectives of the research include:

- Develop a conceptual model to identify the impacts of mining on groundwater quality, incorporating a source-pathway-receptor model,
- Construct a numerical model to determine the flow of groundwater and conduct particle tracking on the model to determine contaminant fate,
- Based on the flow path model, conduct a cumulative impact assessment of mining on groundwater quality.
- Provide recommendations on sustainable groundwater management to minimize the impacts.

1.5 METHODOLOGY AND DATA AQUISITION

The following procedure was followed for data collection, analysis, and interpretation in the study:

Conceptual model

- The development of the conceptual model was mainly based on literature review and data collected from the mine. This includes data that defined the physical and hydrological framework of the area. The data was mainly deduced from borehole logs, structural maps, meteorological data, topographical data provided by the mine as well as some field observations.
- The hydrogeological properties were defined based on literature review and previous reports on aquifer test performed when the monitoring boreholes were drilled. The same reports were also used to inform the hydrocensus of the area.
- The groundwater flow directions for conceptual modelling were estimated from contoured groundwater elevation data using QGIS.
- Groundwater monitoring data was collected from the mine`s groundwater monitoring database. A hydrochemical distribution map was used to identify parameters of concern, which were then monitored over time against recommended standards. Both groundwater quality and surface water quality were monitored.
- The water quality analysis was carried out by use of time-series graphs, where areas with higher concentrations were identified as either sources of contamination or receptors in respect of the Source-Pathway-Receptor model.

Groundwater flow model

- The conceptual model was then used as the basis for the development of the groundwater flow model. The model was developed using MODFLOW code on Model Muse software. Where the model design included defining the model geometry, model discretisation and model boundaries. These were based on shapefiles created in GIS and imported into the modelling software.
- The hydraulic properties of the area were used to inform the model input parameters.
- The model was then calibrated by adjusting the hydraulic conductivities such that a correspondence between the observed and simulated head distribution was obtained. A sensitivity analysis was also performed using the same parameters.
- Following all the modelling steps, the model was developed for simulation of hydraulic heads, thus the groundwater flow model.
- Post-processing tool MODFLOW was then used to determine the travel paths and travel times for advective transport of particles in groundwater flow from identified sources of contamination.

Cumulative Impact Assessment

- The particle tracking results were used to assess the cumulative impacts of mining on the groundwater quality. This was also guided by the cumulative impact assessment criteria.
- Recommendations for sustainable groundwater management were then made based on the findings of the study.

1.6 THESIS STRUCTURE

The thesis is divided into the following seven chapters:

- Chapter one introduces the research, by providing an overview of groundwater management within mining as well as the aims and objective of the study,
- Chapter two provides a literature review, which focuses on the impacts of mining on groundwater, an overview of the principle of cumulative impacts and how they are assessed. Numerical modelling as a tool for groundwater management is also discussed.
- Chapter three presents the description of the study area, the location, mine layout, climate, geology, and geohydrology of the area.

- Chapter four is an outline of the data review and development of the conceptual model by incorporating all relevant data.
- Chapter five presents the construction of the numerical model based on the conceptual model. Including simulation of the groundwater flow.
- Chapter six the application of modelling in cumulative impact assessment is discussed, based on the flow path model.
- Chapter seven is discussion, where the results are interpreted and analysed.
- Chapter eight, conclusions are stated in response to the study objectives and recommendations on how to ensure sustainable groundwater management are made.

2 LITERATURE REVIEW

Mining activities disturb the hydrological cycle of a region within which they are located. It is therefore important for mines to monitor the impacts they pose on water resources throughout all the mining stages. Cumulative impact assessment (CIA) represents an emerging process within the broader field of integrated environmental management. The complicating factor is that the projects that need to be considered are from past, present, and reasonably foreseeable future developments. This complicating factor can effectively be handled by numerical modelling, a process of simulating real-life situations with mathematical equations to forecast or predict future hydrologic conditions related to quantity problems or quality problems (Anderson et al., 2015). This chapter aims to present the baseline concepts and fundamentals of groundwater numerical modelling and cumulative impact assessment, wherein the specific objective is to highlight the interactions and/or subsets between numerical modelling and the CIA.

2.1 CUMULATIVE IMPACTS

Human activities are associated with various environmental impacts. Land degradation, loss of biodiversity, air and water pollution are some of the major environmental impacts. According to Kruidenier (2016), an impact can be defined as any change caused by human activities on the physical, chemical, biological, and socio-economical environmental system. Environmental impacts can be divided into different types, that is direct, indirect, and cumulative impacts. Direct impacts are caused directly by an activity usually occurring at the same time and the same place as the activity. Indirect impacts are induced changes occurring after some time and usually at a different time and place of the activity (DEAT, 2006). Cumulative impacts are changes to the environment due to a combination of past, present and future human actions (Hegmann et.al., 1999).

2.1.1 Defining cumulative impacts

When individually assessed, direct and indirect impacts can be insignificant, however, when assessed in combination, the impacts can be substantial to the environment (DEAT, 2004). There has been a global effort to consider long-term changes on the environment by adopting the concept of cumulative impacts which were not assessed until the early 1970s (Blakley and Franks, 2021). According to Duinker et al. (2013), different scientists, practitioners and theorists of cumulative impacts have defined cumulative impacts in different ways. Hyder (1999) defined cumulative impacts as impacts resulting from incremental changes to the environment as a result of past, present or foreseeable activities. Franks et al. (2013) define cumulative impacts as successive, incremental, and combined impacts produced from one or more activities on the environment. The cumulative impacts may result from the aggregation and interaction of impacts on the receptor due to past, present or future activities. The same phenomenon is captured in the definition given by Gunn and Noble (2011) where cumulative impacts are defined as changes in the environment resulting from multiple interactions of human activities and natural processes that accumulate over time and space.

Although the most common understanding of cumulative impacts is that they result from multiple activities, definitions such as that given by Franks et al. (2013) suggest that cumulative impacts can result from the aggregation and interaction of impacts of single activities. Such contrast in definitions has led to many debates concerning the conceptualising of cumulative impacts. However, Weiland (2010) states that, there is still no legal definition of cumulative impacts or a uniform understanding of the approach to date. Another concern in the definition of cumulativeimpacts is the different units of analysis that are incorporated, that is, the actor, the activity, the impact, or the receiving entity (Franks et al., 2013). This poses a problem when analysing cumulativeimpacts for a specific study, where determining the appropriate unit of analysis may be a challenge. The different perspectives in defining cumulative impacts have made it difficult to determine a standard approach that works for all cumulative impacts Weiland (2010).

2.1.2 Cumulative impacts assessment and management

An environment management plan requires an efficient impact assessment. An impact assessment is a planning tool that assists in predicting potential future impacts of different positive and negative activities. The main objective of impact assessment is to identify and assess potential impacts of the activity by predicting the nature, magnitude, extent and duration of the impact, identification of mitigation measures and evaluating the significance of residual impacts (SEF, 2007). Commonly used impact assessment methods do not take into consideration that impacts from individual actions are not mutually exclusive and that they may accumulate and interact producing more significance (Roudgarmi, 2018). Cumulative impact assessments therefore differ from conventional assessments in that they assess environmental effects over a larger area, over a longer period and also consider the effect of the activity in combination with other actions (Hegmann, 1999). To this account, cumulative impact assessments have become more useful tools in the assessment of environmental impacts.

Judd et al. (2015) define cumulative impact assessment as a systematic process used to identify and evaluate the significance of impacts from multiple activities and to estimate the overall expected impact to inform management measures. The CIA process is also defined by Cardinale and Greig,

(2013) as a two-phased procedure where the first phase involves analysing the potential impacts and risks of proposed developments on Valued Ecosystem Components (VECs) over time, and the second phase where concrete measures to avoid and/or mitigate the cumulative impacts are proposed. VEC was defined as any environmental component which is regarded as important by different parties involved in the evaluation process (Duinker and Lorne, 2007). Valued ecosystem components have been implemented in cumulative impact assessments to describe valuable elements of the bio-physical environment which are prone to impacts from different activities (Stiff, 2001). This concept was by introduced by Duinker (1986) to help understand the core issue of environmental impact assessments.

Definitions of CIA stated by Judd et al. (2015) and Cardinale and Greig (2013) include in them an aspect of management of impacts. Management of cumulative impacts involves identifying and implementing measures to control, minimize, or prevent their adverse consequences (Kaveney et al., 2015). In early practice, the focus was mainly on CIA, whereas, in recent studies, there has been an effort to include management and mitigation of cumulative impacts within the assessment which Canter and Ross (2010) refer to as Cumulative Impact Assessment and Management (CIAM). Typically, a cumulative impact assessment and management is conducted when there is concern that an activity may contribute to cumulative impacts on one or more VECs. It can also be appropriate when a specific activity is expected to significantly impact future conditions of one or more VECs which may also be affected by other activities (Cardinale and Greig, 2013).

However, some practitioners tend to limit the assessment of cumulative impacts to the same type of activities. Cardinale and Greig (2013) argue that this is not a good CIA practice and suggest that a CIA can still be appropriate for a single new development, (with similar or different activities) where cumulative impacts concern already exists. This statement supports the narrative that cumulative impacts can also occur from a single development, where repeated actions may result in the build-up of impacts that accumulate and/or interact to produce cumulative impacts (DEAT, 2004). For instance, within a mining development, repeated mining activities can cause impacts which may individually be insignificant but may accumulate and produce cumulative impacts, and the assessment of such impacts can also be carried out by CIAs.

2.1.3 Approaches to CIA

Cumulative impact assessment is one of the tools for environmental risk management which have been developed to inform decision-making. The assessment of cumulative impacts can be carried out in two ways, 1) the application of CIA as a stand-alone process, and 2) CIA can also be incorporated into existing environmental assessments, for example, as part of Environmental Impact Assessments (EIA) or Strategic Environmental Assessments (SEA) (DEAT, 2004). The second approach has become the preferred approach as it is supported by already existing tools. However, there are different perspectives regarding the incorporation of cumulative impacts in EIA and SEA.

According to Roudgarmi (2018), the global perspective is that the assessment of cumulative impacts should be an integral part of the EIA process. In several countries such as Canada, USA, UK and others, the consideration of cumulative impacts in the EIAs is a legal requirement. Hegmann (1999) in Canadian guidelines for cumulative impacts assessments, argues that both assessments (CIA and EIA) are similar and often the CIA relies upon an established EIA stating that while most EIAs focus on a local scale, some do consider the combination of impacts, which is the purpose of CIA. The same perspective is shared by Roudgarmi (2018), stating that the CIA is considered a subdiscipline of EIA as it derives from the principles, methods and tools of EIAs. Despite these views, DEAT (2004) argue that it may be inadequate to incorporate cumulative impacts in EIAs for reasons such as, data deficiencies, the difficulty of conceptualizing cause-and-effect relationships and unclear criteria for identifying and assessing cumulative impacts.

Gunn and Noble (2011) also add that there are constraints to assessing and managing cumulative environmental impacts in project-based environmental assessments such as EIAs. They continue to state that a more regional and strategic approach to the CIA provides a suitable impact assessment framework for addressing cumulative impacts. A strategic approach to the CIA as provided by the SEA can be more effective in identifying and minimizing potential cumulative impacts, allowing them to be addressed early in the planning process (Cooper and Sheate, 2004). Compared to the project-based approach, the scopeof the SEA considers time and space scales which are the context of cumulative impacts (DEAT, 2004). Although SEA is considered to best address cumulative impacts, its approach carries some challenges. In their paper on “Conceptual and methodological challenges to integrating SEA and cumulative effects assessment”, Gunn and Noble (2011) identify the challenges of addressingcumulative impacts within SEAs. By interviewing international SEA and CEA academics and practitioners, the challenges identified related to the weak conceptualization of CEA, varyingmethods of effects aggregation and lack of consensus relating to the scope and methodology of SEA(Gunn and Noble, 2011).

2.1.4 Management of cumulative impacts

Mitigation and management are critical aspects of the CIA. An effective management plan considers ecological boundaries, establishes management objectives and response triggers, employs an adaptive management approach, involves affected interests in management plans and activities, and establishes roles and responsibilities for long-term implementation, monitoring and feedback (Blakley, 2021). Adaptive management is a developing subject with increasing relevance to cumulative impact management, either locally or regionally (Canter and Atkinson, 2008). Adaptive management is intended to be a follow-up method to conventional impact studies, especially when there are uncertainties. A thoroughly thought-out monitoring program is a fundamental component of adaptive management, and the findings are utilized to guide future operational procedures and decision-making (Canter and Ross, 2010).

Because cumulative impacts frequently come about as a consequence of several developments which have successive, incremental, and/or combined effects, responsibility for their management and prevention is shared by the various contributing developments. Collaboration is usually necessary because it is typically impossible for any one party to adopt all the strategies required to mitigate or eliminate cumulative consequences (Cardinale and Greig, 2013). Therefore, to effectively manage and assess cumulative impacts, a holistic understanding, coordination, integration and cooperation across the industry, government and community sectors is usually required (Franks et al., 2013). Governments may significantly contribute to achieving social and environmental sustainability by establishing and implementing regulatory frameworks that direct and promote the appropriate identifying and managing of cumulative impacts (Cardinale and Greig, 2013)

Within the Australian resource context, Porter et al. (2013) state that the use of collaboration is believed to present opportunities for addressing cumulative impacts. The opportunities include the creation of more efficient resource allocation across parties, fostering innovation and creativity through the diversity of participants and identification and implementation of long-term solutions. Despite challenges to the collaboration approach, such as time, effort and creativity required to address cumulative impacts, significant benefits to the approach were identified. For a successful resolution of cumulative impacts, Porter et al. (2013) therefore suggest that the right people should be involved in the process, the consideration process must be adaptive, and there should be enough learning and sharing of knowledge. On that note, Franks et al. (2013) also identify strategies for managing cumulative impacts. These include information exchange, networking, partnership for program implementation, coordinated community engagement, multi-stakeholder monitoring and collective management of data. Although similar to the basis of collaboration, these strategies are said to require a higher degree of maturity.

2.2 METHODS AND TOOLS FOR CIA

Different sources have mentioned conducting the CIA as a challenging process. Some of the challenges for conducting the CIA include the complexity and difficulty of implementing CIA, the lack of systematic approaches for doing so, the difficulty of clearly defining CIA boundaries, the lack of skilled CIA practitioners and managers, and the uncertainty surrounding the outcomes of CIA (Roudgarmi, 2018). However, several frameworks have been designed to guide the CIA process. The frameworks outline step-by-step procedures for conducting CIAs such as those given by DEAT (2004), Cardinale and Greig (2013) and Hegmann et al. (2004). Based on different guidelines, the procedure for conducting CIA can be summarized in the following six steps in Figure 2-1 (Judd et al., 2015).

With growing research on cumulative impacts, numerous methods and tools have been adopted to assess cumulative impacts. Work such as that of Canter and Ross (2010) and the Council on Environmental Quality (1997) increased awareness of innovative concepts, tools, and approaches to promote the development of the best methods for effective CIA. According to Roudgarmi (2018), the use of questionnaires and interviews with knowledgeable individuals, baseline data can be collected to assist with understanding the environmental impacts resulting from physical activities, affected VECs and possible mitigation measures (Roudgarmi, 2018). Checklists of common likely impacts can assist in identifying potential cumulative impacts. Using Network analysis, cause-effect relationships can be delineated. Spatial analysis such as GIS tools can be used for capturing and analysing spatial data (DEAT, 2004). Within the wide spectrum of tools available for the CIA, risk-based approaches and modelling are considered the most innovative methods for the enhancement of the CIA in recent years (Roudgarmi, 2018).

For this study, a brief review on the aspects of the two vastly used methods or tools for CIA, risk-based approach and modelling is carried out.

2.2.1 Risk-based approach for CIA

For every CIA, the linkage between multiple activities, multiple effects and multiple ecosystem components needs to be established and evaluated. This has become a challenge for CIAs, making it impractical to assess all potential combinations of activities, pressures, and ecosystem components. To overcome this challenge, a method that filters parameters to be included in the assessment needs to be adopted. According to Judd et al. (2015), environmental risk assessment concepts have commonly been used to provide a clear structure for CIAs. Stelzenmüller et al. (2018), share the same sentiments of applying risk assessment concepts in CIA by emphasizing more on risk management, where cumulative pressures are managed to ensure that they do not exceed the accepted threshold. The risk management process comprises risk identification, risk analysis and risk evaluation. Although the approach carries some challenges, Stelzenmüller et al. (2018) argue that the risk-based approach has helped standardize the CIA procedure as it considers uncertainties in cause-effect relationships and accounts for management measures.

STEP 1 Defining the scope

- What is the purpose and the scope of the cumulative impacts assessment?
- Is it to provide planning or management options?
- To assess and predict total/subset of multiple pressures?

STEP 2: For the purpose and scope defined in Step 1

- What are the pressures/effects and how they interact?
- What are the sources of these effects?
- What are the environmental responses to these effects?

STEP 3: For the purpose and scope defined in Steps 1 and 2

- Describe the Source - Pressure - Pathway - Receptor relationships

STEP 4: For the purpose, scope and relationships defined in Steps 1 and 2

- What are the spatial and temporal scale of the effects?
- What is the likelihood of exposure?
- What are the assumptions?
- What uncertainity is there in the assessment?

STEP 5 Significance evaluation

- What is the significance of cumulative impacts identified, whats are the casual factors, what mitigation measures are available and who is responsible for managing the situation?

STEP 6 Conclusion

- What are the conclusions of the CIA? How can the outputs be applied and who is responsible for applying them?

Figure 2-1 A step-by-step procedure for conducting a CIA (Judd et al., 2015).

When it comes to environmental risk assessment, it is critical to have a structure that will help in accurately identifying the potential environmental effects of a certain activity and where it is appropriate to implement control measures. As stated by Judd et al. (2015), an essential and integral part of the CIA process is the analysis of causes or sources, pathways, and consequences of the effects on the receptors. To this effect, the Source-Pathway-Receptor (SPR) model has proven to assist in effective environmental risk assessment. Horrillo-Caraballo et al., (2013) define the SPR model as a basic conceptual model for illustrating systems and processes that result in particular consequences.

Figure 2-2 summarizes the concepts of the SPR model. Waldschläger et al. (2020) add that the SPR model is a simple, flexible model that can identify relations in complex systems, providing environmental management professionals with a standardised approach to determining and controlling risks.

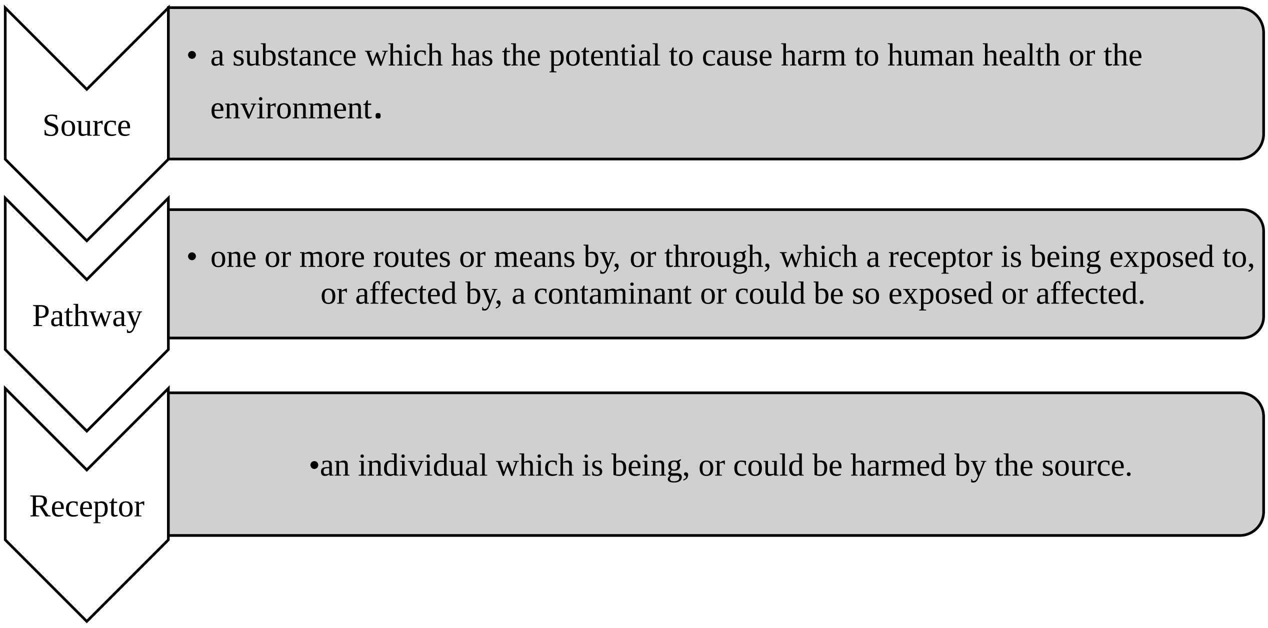

Figure 2-2 Source-Pathway- Receptor model defined.

2.2.2 Modelling as a tool for CIA

DEAT (2004) and Roudgarmi (2018) provide details on the effectiveness of modelling as a tool for the CIA. Highlighting that the most important aspect of modelling as an analytical tool for CIA is the ability to determine the behaviour of environmental systems using mathematical simulation as a mode of analysis. A review of Methods for Cumulative Effects Assessment by Smit and Spaling (1995) is one of the works of literature that evaluate the role of modelling in CIA, stating that simulation modelling meets most of the requirements of the assessment criteria of cumulative impacts. Simulation models emphasize cause-and-effect relationships and can typically distinguish between additive and interacting processes, offering one of the best opportunities for examining specific pathways of cumulative environmental change. Simulation models can detect cumulative environmental changes including time lags, thresholds, spatial crowding, and fragmentation effects because they concentrate on functional change, structural change, or both (Smit and Spaling, 1995).

Modelling as a management tool has advantages that include, providing conceptualized representation of systems, allowing for the development and investigation of scenarios, and identifying indirect pathways and connections between components of a system (Scharler and Fath, 2012). Although there are merits to the utilization of models in CIA, there are some challenges that the method possesses. For instance, the accuracy of the simulation depends on the quality of data, the validity of the method and available resources. Scharler and Fath (2012) also state that despite a significant increase in processing data available to simulate ecological systems, several fundamental concepts remain unresolved therefore further progress is still required in such areas to realize the full potential of modelling in environmental management.

The modelling analysis relevant to this study is groundwater modelling. To understand the role of groundwater modelling in CIA, the concepts of groundwater modelling are evaluated in the next section.

2.3 GROUNDWATER MODELLING

Management of groundwater resources requires hydrogeological knowledge and analysis of hydrogeological information. With groundwater modelling, a quantitative framework for analysing field information and conceptualising hydrogeological processes is provided (Anderson et al., 2015). A groundwater model consists of multiple physically and mathematically based components which add to the general understanding of processes at work within a groundwater system (Wels and Jacek, 2012). This definition includes the classification of groundwater models into two types, physical and mathematical models as described by (Essink, 2000). Physical models also known as scale models physically replicate the groundwater flow system, typically for simple aquifers within a laboratory setting. With the advancement of digital computers, the use of physical models has decreased, and mathematical models have gained ground (Wels and Jacek, 2012).

A mathematical model is a series of equations that, under the assumption of specific premises, quantifies the physical processes occurring in the studied aquifer system(s) (Middlemis, 2001). Further details on the definition of mathematical models are provided by (Essink, 2000), adding that mathematic models are formed by solutions to partial differential equations together with the specification of system geometry, boundary conditions and initial conditions for transient processes. Depending on the modelling problem, the mode of analysis for mathematical modelling will differ.

According to (Essink, 2000), the application of groundwater models can be described in terms of modelling quantity problems or quality problems. For quantity problems, modelling groundwater flow through the mathematical interconnection of the equation of motion and the equation of continuity is carried out (Essink, 2000). Application of groundwater flow models as defined by (Sikdar, 2019) includes the interpretation of observed heads, comprehension of a groundwater system's reaction to variations in natural and anthropogenic recharge and discharge, prediction of drawdown, determination of water balances, and delineation of well catchment regions. For quality problems, the advection-dispersion-reaction equation is added to the groundwater flow equation to simulate solute transport. Transport models can be used for the analysis of concentration data, the mass balance of pollutants, forecasting of pollutant plumes, the organization of a monitoring plan and risk assessment in the event of waste disposal (Sikdar, 2019). These applications can be achieved by applying either analytical or numerical methods for analysing mathematical models.

Analytical models obtain solutions based primarily on numerical techniques (Essink, 2000). Although solutions are effectively obtained, the assumptions set by analytical models limit their application to simple systems (Anderson et al., 2015). Despite the limitations of analytical models being acknowledged by several studies, some literature argues that analytical methods have a significant role in modelling. Bear (1992) states that analytical models allow researchers to undertake sensitivity analysis and rapid preliminary study of groundwater contamination and therefore they should be regarded as complementary to numerical models. This concept is applied by Locatelli (2019) who uses analytical modelling as a simple tool to model contaminant fate and transport for management and risk assessment of groundwater pollution from contaminated sites. Arguing that the tool uses a simplified method for estimating the contamination levels of aquifers in a preliminary, conservative, quick, and affordable manner compared to numerical models (Locatelli, 2019).

The development of computers and digital technology, has brought about the ability of numerical models to simulate more complex systems. Numerical modelling, has allowed hydrogeologists to estimate the solutions of the system's complex differential equations by translating them into discrete equations and modifying the domain into meshes or grids (Saatsaz and Eslamian, 2020). The most widely used numerical methods are the Finite Difference (FD) and Finite Element (FE) methods. According to Viney et al. (2021) both methods are suitable for modelling groundwater, however, finite element methods provide the opportunity to describe irregularly shaped geological features and structures more accurately, while finite differences represent more regular geometries. The ability of these methods to handle complicated systems has influenced the use of numerical models in simulating the status of aquifers by gathering information about the inputs and outputs of the groundwater systems and therefore using the information to investigate the impact of existing and future activities on groundwater resources (Ostad-Ali-Askari, and Shayannejad, 2021).

Model development process

Despite various applications of models, the model development process is similar. Several modelling guidelines provide steps for developing groundwater models such as the methodology outlined in

Figure **2-3**. Middlemis, (2001) states that the modelling development procedure follows a 3-stage approach, conceptualisation, calibration, and prediction, which summarises the steps of modelling. Groundwater modelling procedures adhere to the scientific method. In a scientific method, a question is posed, a hypothesis is developed and investigated, and then it is decided whether to accept or reject it. If the test is unsuccessful, the procedure is repeated using a new hypothesis (Anderson et al., 2015). It is important to note that the modelling process is iterative, where results from one step serve as input for previous steps. The modelling methodology is therefore flexibly designed such that it allows adaptive management suiting the specifics of any project.

For every modelling problem, the objectives of the model need to be defined appropriately, such that they meet the general objectives of the project. According to (Wels and Jacek, 2012), the objectives and the intended outcome of the study determine the selection of the model approach and the data requirements suitable to address the problem (Baalousha, 2008). For instance, objectives for models developed to assess environmental effects must define the environmental receptors, as well as the nature and the scale of the effect significance (Wels and Jacek, 2012). Once the objectives have been set, the next step is data collection, classification and preparation (Saatsaz and Eslamian, 2020). Baalousha (2008), defines the data collection and processing step as a key step in the process of modelling. The process entails two steps, a compilation of existing data and analysis to enhance the understanding of the fundamental dynamics of the system (Wels and Jacek, 2012). Data compilation and review form the basis of model conceptualization.

The conceptual model captures all physical aspects of the real system. It is constructed based on a set of assumptions that describe the composition of the system, transport processes and their governing mechanisms (Bear, 1992). Baalousha (2008) describes a conceptual model as a descriptive representation of a groundwater system which provides an interpretation of the geological and hydrological condition.

Model conceptualization can be divided into two modules, 1) schematisation of the hydrological model and 2) concept of the mathematical model. Schematizations of groundwater problems typically concentrate on the subsoil composition, the type of groundwater flow, the characteristics of groundwater, the study area boundaries, and the use of averaged values such as piezometric head, the thickness of layers and groundwater discharge (Baalousha, 2008). The mathematical model concept is developed based on the schematization of the hydrologic problem. The goal of developing a concept is to simplify the field problem so that the schematization is appropriate for numerical modelling (Anderson et al., 2015).

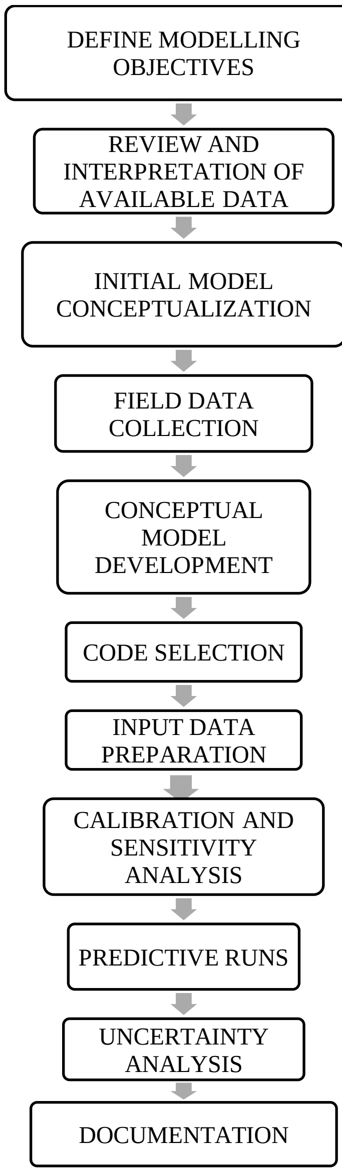

Figure 2-3 Stepwise methodology for developing a model (Wels and Jacek, 2012).

The concept of the hydrologic problem must be converted into a model which can be implemented into a selected computer code. When designing the model simulation, the process involves the design of the domain partition, selection of the length of time steps, and setting of boundary conditions and initial conditions (Anderson et al., 2015). The equations generated from the mathematical model are programmed into a computer code. A modelling code is a computer software that solves the groundwater flow equations (Wels and Jacek, 2012). The most common code used for groundwater flow problems is the FD code MODFLOW created by the US Geological Survey (USGS). While the FEFLOW code has been widely used for FE models. According to Baalousha (2008), selecting a code depends on the hydrogeological problem, the available options in the code and user preference. Wels and Jacek (2012) also add that the level of assessment required, dimensionality and the required outputs are some of the factors that will determine the code selection process.

The most important step in modelling is model calibration. The calibration process involves adjustments to the system parameters such that the model output matches the measured data. The parameters are adjusted within a range of uncertainty until the model results are approximate to the calibration target (Essink, 2000). To improve the confidence in the model calibration a second independent set of data is used to test the model. This is referred to as model verification. According to Baalousha (2008), the process determines if the model applies to any dataset. A model is verified when the set targets are matched without adjusting the calibrated parameters. Essink (2000) defines the next step in the modelling process, sensitivity analysis as a process that determines parameters that have a greater influence on the model output, thus reducing the uncertainty in the calibrated model. This is done by changing the value of one parameter at a time and analysing the influence the change has on the model results. A well-calibrated and verified model can then be simulated to predict the response of the groundwater systems to different conditions as per the modelling objectives. For instances, for this study, the model can be used over long periods of simulation to predict the cumulative impacts of mining on groundwater quality or to determine the impacts of a combination of sources as per the objectives of a CIA. The last step is the modelling report, where results in response to the problem are presented (Bear and Cheng, 2010).

2.4 ROLE OF MODELLING IN GROUNDWATER MANAGEMENT WITHIN THE MINING ENVIRONMENT

Martinez and Ugorets (2010) state three major issues that relate to groundwater in mining, 1) mine dewatering; 2) pit wall stability; and 3) environmental impacts on groundwater quality and quantity during and post-mining. Further stating that groundwater modelling is an effective tool for analysing, estimating and predicting these impacts. Similarly Essink (2000) outlines the main applications of groundwater modelling in mining as predicting and simulating activities, planning and evaluating different scenarios and strategies, and optimizing the use of water resources. Results of groundwater modelling usually include a prediction of mine water inflow, the input of parameters into an EIA and water management as well as providing data that can assist in decision making.

According to Rapantova et al. (2007) objectives of a modelling study differ depending on the stage of mining, whether during active mining operations or mine closure. During operations, groundwater modelling can be used to evaluate groundwater management strategies or as part of the monitoring of environmental effects. Where impacts are observed, mitigation measures may also be designed using groundwater models. In some cases, regulators may also request models or model updates to address permit non-compliance issues where impacts are observed (Wels and Jacek, 2012). Some of the reasons for modelling in active mining operations as stated by Rapantova et al. (2007) include measures for efficient mine dewatering, such as the development of procedures for regulating site discharge and adhering to discharge standards, specifically the monitoring of quantity and quality of contaminants discharged from the site into water resources.

Although there are different applications of modelling in mining environments, several studies have shown the modelling of mine dewatering as the most common application. Martinez and Ugorets (2010) draw attention to the benefits of employing numerical groundwater modelling for mine dewatering projects with complicated hydrogeological conditions. Providing actual cases describing how a 3D groundwater numerical model is used as a predictive tool in mine dewatering projects in both opencast and underground mining. Another example is provided by Rapantova et al. (2007) where groundwater flow modelling becomes a crucial tool in updating mine safety regulations on the protection of underground mines against water inrushes. According to the study, the main portion of the Upper Silesian Coal Basin is separated into three sub-basins; two of them are flooded, and groundwater is maintained at a specific level to prevent overflow into the third sub-basin, which is currently being exploited. Using MODFLOW, they were able to produce a model prediction of dewatering drainage of water into active and abandoned mines thus assisting in the management of groundwater resources (Rapantova et al., 2007).

During mine decommissioning, plans are required for permit processes, therefore modelling can play a significant role in this aspect, by forecasting qualitative and quantitative environmental changes (Wels and Jacek, 2012). With specific attention to opencast mines, Szczepiński (2019) adds that a rational plan for flooding and managing the post-mining void, estimation of the time required to fill an excavation with water, estimation of the final level of water in the post-mining reservoir, and projection of changes in quantity and quality in the reservoir and its surroundings before, during, and after flooding can be achieved through modelling.

Despite being an effective tool for groundwater management in mining, modelling is limited to some extent. The limitations and uncertainties are related to stresses and parameters assumed in the model, including boundary conditions shortcomings and variabilities, hydrogeological and spatial parameters, recharge, and mining plans to mention a few Szczepiński (2019). In an overview of features and problems of groundwater modelling applications in mines, Rapantova et al. (2007) also indicate that commonly used groundwater flow simulation models, such as MODFLOW, do not accurately simulate dual-porosity flow with preferential flow through fractures. Because of the complexity of the models and the lack of suitable input data, the use of fracture flow and transport models (e.g. FEFLOW) in mining projects has been extremely limited.

Despite the limitations, both authors Szczepiński (2019) and Rapantova et al. (2007) agree that modelling is the most practical method for evaluating the effects of hydraulic stresses placed on aquifers and providing the most thorough details regarding the mine dewatering system and its effects on the environment. Szczepiński (2019) added that for their effective application in mining, models need to be periodically verified based on new data on how the aquifer system responds to mine drainage, the actual climate conditions, and updated mine schedules.

2.5 CASE STUDIES ON ASSESSING CUMULATIVE IMPACTS IN MINES USING GROUNDWATER MODELLING.

As mentioned earlier, modelling is an effective and innovative method for addressing cumulative impacts. With the basic concepts of modelling described, it is also important to highlight some of the applications of groundwater modelling in assessing cumulative impacts in mining to form the basis for the approach to be considered in this study.

The use of modelling to assess cumulative impacts dates to the late 1970s. However, based on the available literature, the application of modelling cumulative impacts of mining has only started increasing recently. These recent applications related to the assessment of cumulative impacts of coal mines. An earlier example is that outlined by Peacock (1997), where cumulative impacts of surface mining and coal bed methane development on shallow aquifers are assessed. MODFLOW was used to construct a regional groundwater model to simulate the impacts of three surface coal mines and coal bed methane developments. The modelling objectives included modelling aquifer stresses to two coal Formations. Another objective was to provide a dynamic tool for regulatory bodies for the assessment of impacts from current and future energy developments (Peacock, 1997). The model output presented the predicted impacts of coal bed methane development and surface coal mining through the anticipated life of mining.

Sreekanth et al. (2019) applied modelling to assess the cumulative groundwater impacts from coal seam gas to coal mining developments. These developments involve the extraction of large quantities of groundwater; hence it is important to carry out assessments to predict the cumulative impacts of such development. Propagation of depressurization of overlying aquifers was one of the major potential cumulative impacts. A regional-scale numerical groundwater model was developed to assess potential groundwater impacts due to additional coal resource development from a deep sedimentary basin underlying the Great Artesian Basin (Australia). Using MODFLOW-USG code, the model simplified the hydrogeology and flow processes of the region. Allowing it to be tenable for probabilistic predictive analysis of cumulative impacts of coal mining and coal seam gas development from a stratigraphically complex sedimentary basin (Sreekanth et al., 2019). Based on model simulations of 1983 – 2102, results showed that the water-table drawdown from individual mining developments was not significant, the drawdown difference reached a maximum of less than 0.2 m with the probability of exceeding the threshold decreasing rapidly with increasing distance from the mine site (Sreekanth et al., 2019).

Naja et al. (2011) determined the hydrochemical impacts of Limestone rock mining. Rock mining is said to have a long-term and cumulative impact on surface water quality, based on new data focusing on surface-groundwater interactions. In this study, a steady-state groundwater flow and transient solute transport model along a cross-section of an unconfined aquifer was conducted. The model was used to estimate surface-groundwater interactions, to assist the understanding of solute transport from rock mining into the water resources. The modelling analysis showed that the consequence of surface mining in the area is the increase in direct groundwater-surface water interactions which continually alter the groundwater quality and the surface quality (Naja et al., 2011).

Gresswell et al. (2019) present the application of hydrogeological modelling to inform closure planning for Hazelwood Mine, Australia. The mine closure procedure signifies the change from the mining's operational phase, which involves significantly depressurizing constrained aquifers to provide safe mining conditions, to the phase of closure, during which the mine will be filled to create a lake, therefore impacting the hydrogeological system. Hydrogeological modelling is a crucial part of the closure planning process since it contributes to other technical studies that resource managers are obliged to conduct to inform groundwater and surface water licencing components of the mine closure. In this case, the confined aquifer depressurization during operation caused a significant cone-shaped depression in the piezometric surface, with drawdowns of up to 130 m. The extending cone of depression merged with the cone of depression emanating from the nearby Loy Yang Mine, having a significant cumulative effect within the confined aquifers. Therefore, a numerical groundwater model was contracted to simulate the cumulative impacts of three coal mines within the region where three pit lakes were simulated over 100 years. The results were then used to inform water needs for closure and measures for the management of water resources (Gresswell et al., 2019).

Another common application of modelling in cumulative impact assessment of mining is the hydrogeological assessment of proposed mining projects or developments. These are carried out to determine the potential impacts of new developments on the environment as well as to obtain approval to carry out such projects. Post et al. (2020) present an assessment of the hydrological impacts of proposed coal mines and coal seam gas in subregions of eastern Australia. The study included carrying out surface water and groundwater modelling to assess the cumulative regional-scale hydrological impacts of multiple mine developments.

According to Post et al. (2020), the results showed that under the best-case scenario, the impact of the proposed coal development on groundwater levels and surface water characteristics was quite small. However, in the worst-case scenario, groundwater drawdown was likely for up to 5 km from the development, but not beyond 20 km. Where there are multiple developments nearby, the cumulative hydrological impacts would be higher. The information was then used to inform the approval process for coal resource developments in the areas (Post et al., 2020).

A similar application is given by Sheppard et al. (2009) where modelling is used to predict the cumulative impacts of multiple iron-ore projects at Cape Preston. Due to their proximity, the proposed pits create some difficult project approvals and environmental management problems regarding the effects of individual project dewatering and the cumulative impact of continuing development on local and regional groundwater resources. A groundwater model was developed to assess the potential cumulative impacts of the iron-ore projects on the surrounding hydrogeological system, in particular, the cumulative impacts of dewatering. The modelling results showed that the cumulative impacts of dewatering at the four projects on the groundwater system were only marginally more than the individual impacts and the impact on the local aquifer was negligible.

Based on the case studies provided, one can deduce that indeed the predictive nature of modelling plays a crucial role in the assessment of cumulative impacts. Providing decision-makers with not only a conceptual understanding of hydrogeological systems under study but also providing qualitative and quantitative information to guide decision-making related to effective management of groundwater resources. This can either occur during any stage of mining, be it during the exploration where there is a need to acquire mining permits, during the operational phase where cumulative impacts of active mining such as dewatering are assessed or during post-closure, where future consequences of mining can be assessed. However, based on the literature review, the use of groundwater modelling to assess cumulative impacts in mining seems to be limited and still needs further attention, considering the capability of models.

2.6 SUMMARY

Mining activities affect the environment. The impact is also seen in groundwater quality and quality in mining areas. It is, therefore, necessary to assess the impacts of mining on these resources to aid the management, protection, and sustainability of water resources. Modelling is a method of simulating real-life situations with mathematical equations to forecast or predict their future behaviour, enabling the quantification of impacts that can affect the environment by simulating environmental conditions. Groundwater models can forecast the outcome of future groundwater behaviour, support decision-making and allow the exploration of alternative management approaches. Consequently, groundwater models can be used to assess the impacts of past, current and future mining activities on groundwater resources. Reviewing the literature on how groundwater models have been used to determine different types of impacts (including cumulative impacts) on groundwater in various mining environments, can provide a basis for this study. Providing background information on the subject as well as providing guidance on the procedure to follow. Based on this review, the study will therefore adopt the modelling approach to assess the cumulative impacts of mining at LDM on groundwater quality, in terms of modelling impacts from combined sources as well as over cumulative periods.

The next chapter is the description of the study area, including the location of the study area, and the geological and hydrogeological setting. This provides a better understanding of the area which will assist in developing the conceptual model.

3 SITE CHARACTERISATION

The chapter gives a detailed description of the study area. It outlines a brief historical background of the mine, its location, the climate of the area and a description of the physical environment. This includes characterisation of the topography, drainage, geology, and geohydrology of the area.

3.1 BACKGROUND OF LETŠENG DIAMOND MINE

The first discovery of diamondiferous kimberlite pipes at Letšeng-la-Terae was in 1957 by Peter Nixon of the Research Institute of African Geology at the University of Leeds. Later in 1967, a digger, Ernestine Ramaboa, unearthed a brown coloured diamond weighing 601.26 ct in Letšeng-la-Terae (Balfour, 1981). Following a series of formal explorations by the then Rio Tinto Zinc (RTZ), De Beers officially opened the Letšeng diamond mine in 1977, but the mine was closed in 1982 due to untenable running (Blauer, 2010). In May 2004, the mine operations were resumed by the Letšeng Holdings consortium; however, in 2005, the Letšeng Holdings consortium fell short of the funds needed to develop the mine to full operation (Telfer and McKenna, 2011). This led to the mine being sold to Gem Diamonds and the mine operated under the name Letšeng Diamonds Ltd. Currently Gem Diamonds owns 70% of the shares while 30% of the shares are owned by the government of Lesotho. Letšeng diamond mine is well known for its large, quality diamonds. It produces the highest percentage of large kimberlite diamonds and has therefore been regarded as the world`s highest dollar value per carat kimberlite diamond mine (Madowe, 2013).

3.2 LOCATION AND MINING

3.2.1 Locality

Letšeng Diamond Mine (LDM) is located at around 28.9888° S, 28.8631° E, in the north-eastern highlands of Lesotho, in the Mokhotlong district (Figure 3-1). Lesotho`s highlands are formed by the Drakensberg and Maluti mountain ranges. The elevation of the mountain ranges reaches the highest level of 3482 m, with a high alpine basalt plateau that is up to 3400 m in height. LDM being in this area, lies at an average elevation of 3100 mamsl, making it the highest mine in the world.

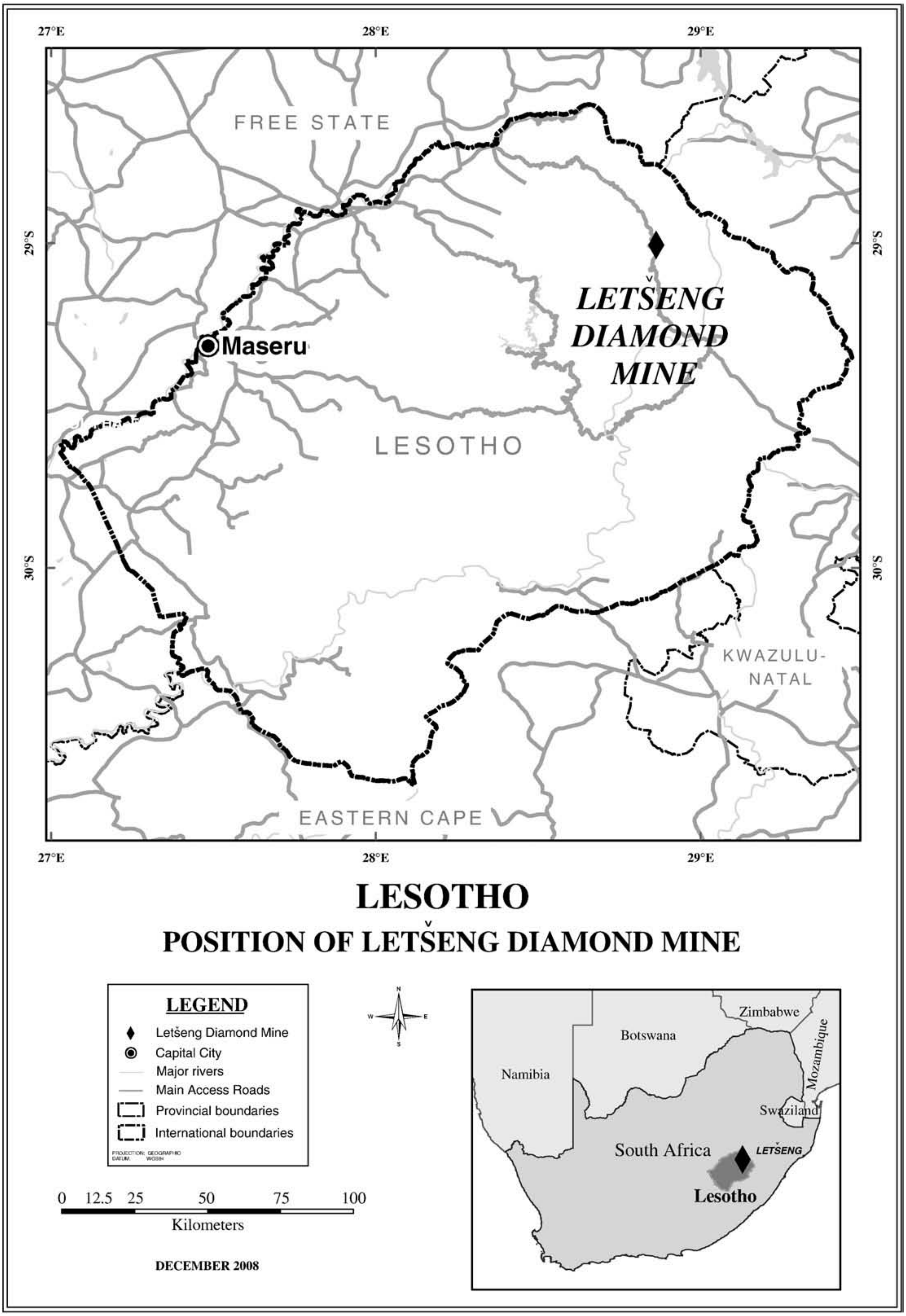

Figure 3-1 Locality Map of Letšeng Diamond Mine, Lesotho (Bloomer and Nixon, 1973)

3.2.2 Mine Layout

The layout of Letšeng Diamond Mine is shown in Figure 3-2. The mine comprises two approximately 91 Ma kimberlite pipes, the Main pipe, and the Satellite pipe. The main pipe is cone-shaped covering an area of 17 ha and consists of eight varieties of kimberlite, which have been grouped into four facies for mining purposes (Shor et al., 2015). The satellite pipe is elliptical and covers about 5.2 ha in size, including a basalt raft. It also comprises of at least two facies of kimberlite. Although it covers a smaller area, the satellite pipe has higher grade and higher content of larger diamonds than the main pipe. According to Shor et al. (2015) the main pipe accounts for 75% of the mine`s output with an average of 0.88 carats per hundred metric tons of material, while the satellite pipe yields 2.6 carats per hundred metric tons.

The mine layout also shows the two large waste rock dumps (WRD) located east and west of the satellite and main pit, respectively. Further east of the main pit is the Patiseng TSF, while north of the site is the Slimes Dam or Old TSF. The Old TSF is a standby facility and only used when Patiseng TSF is not available. Pond water from the Old TSF is pumped directly into the plant. Further north of the mine is the Mothusi dam, which the mine mainly uses for potable water, about 60% of the water is treated for domestic use for the camp while about 40% of the water is used at the plants. The dam is man-made and receives water from precipitation and streams that flow into it. The Process Control Dam (PCD) to the north of the main pit is used for mining purposes, particularly for treatment at the plants. The water in the PCD is pumped from the Patiseng TSF and seepage dam.

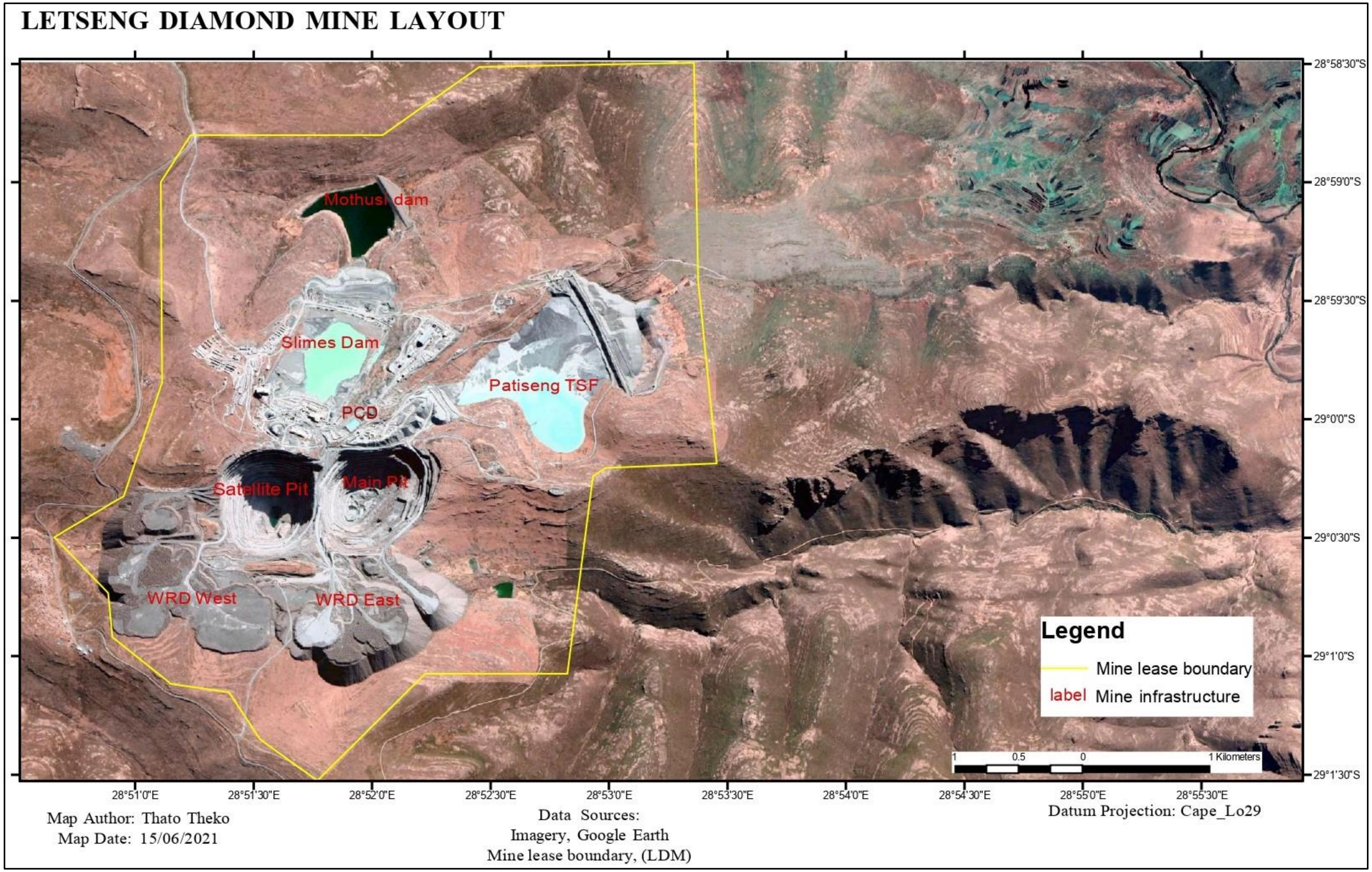

Figure 3-2 Mine Layout showing current mine infrastructure based on different mining activities around the mine.

3.2.3 Mining at LDM

Currently, the two pipes have mined over 150 mbgl using conventional open-pit mining techniques on a split shell design (Shor et. al., 2015). Mining activities at LDM include block clearing, pattern marking, drilling, charging, blasting, loading, and hauling and dumping. At deeper levels where there is groundwater presence, dewatering of the pit becomes the initial activity. During mining, waste (basalt) is deposited on WRD, while the ore (kimberlite) is fed into the two treatment plants for processing. In the plants ore is crushed and concentrated to separate heavy material from light material. The heavy material is then scanned for diamonds while the light material is disposed into the Patiseng TSF as fine tailings. Coarse tailings are transported through the conveyor-belt system to tailings dam walls. The tailings are one of the major by-product of ore processing, covering about 151.71 ha of the area.

On average, the mine produces about 6 million tons of ore per year and carat recoveries of 100 000 carats per year, while waste produced is estimated at 12.5 million tons per annum (LDM, 2021). Figure 3-3 shows the mid-term to long-term mine plan in terms of ore and waste mined currently until mine closure. The current mining operations are planned for 2035. On average 6 million tonnes of ore and 12 million tonnes of waste are produced annually. Mining of ore in the satellite pit is planned to continue up to 2024 while mining continues up to mine closure in the main pit. Throughout the life of mine, low-grade ore is stockpiled. According to the mine plan, tonnage of waste mined decreases over time and beyond 2031 mining continues only for ore, either from the pits or stockpile.

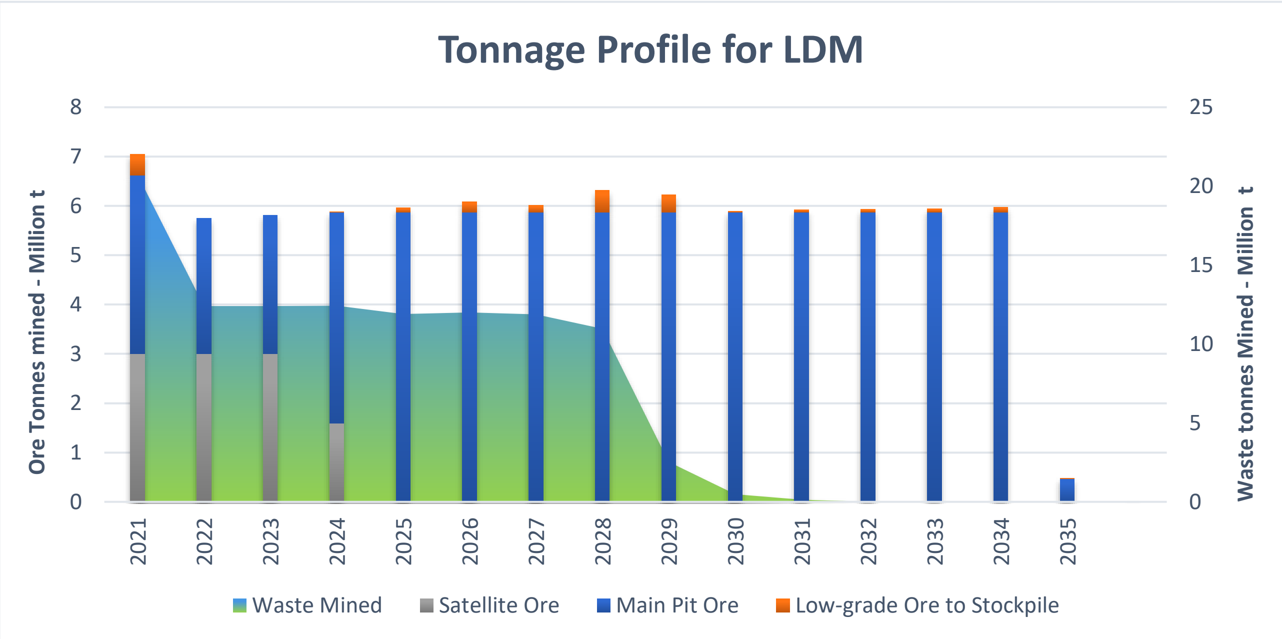

Figure 3-3 Tonnage profile for LDM, current to mine closure (LDM, 2021).

According to ITASCA (2021), the mine area is characterised by deep aquifers which could be the reason for the limited utilisation of groundwater resources. The main activity related to groundwater is monitoring of groundwater quality and quantity. Surface water monitoring on the other hand involves monitoring of streams in the mining area, to ensure that water flowing from the mine into rivers downstream is of good quality. In terms of stormwater management, the objective is to separate clean water and dirty water. The plan includes the channelling of clean water using existing streams within the mine. The water is allowed to flow downstream into the main rivers and some of the water is channelled into the Mothusi dam for domestic use. Unclean water from the plants is channelled to TSFs and some is channelled into the water treatment plant for purification.

3.3 SITE DESCRIPTION

3.3.1 Climate

According to Lesmet (2021), Lesotho`s climate is mainly influenced by high altitude and latitudinal position. The winters are generally dry and cold, while summers are hot and humid. However, due to its location, the study area records low temperatures all year round. Using data collected from the mine weather station, the average monthly temperature and rainfall from 2013 to 2020 are shown in

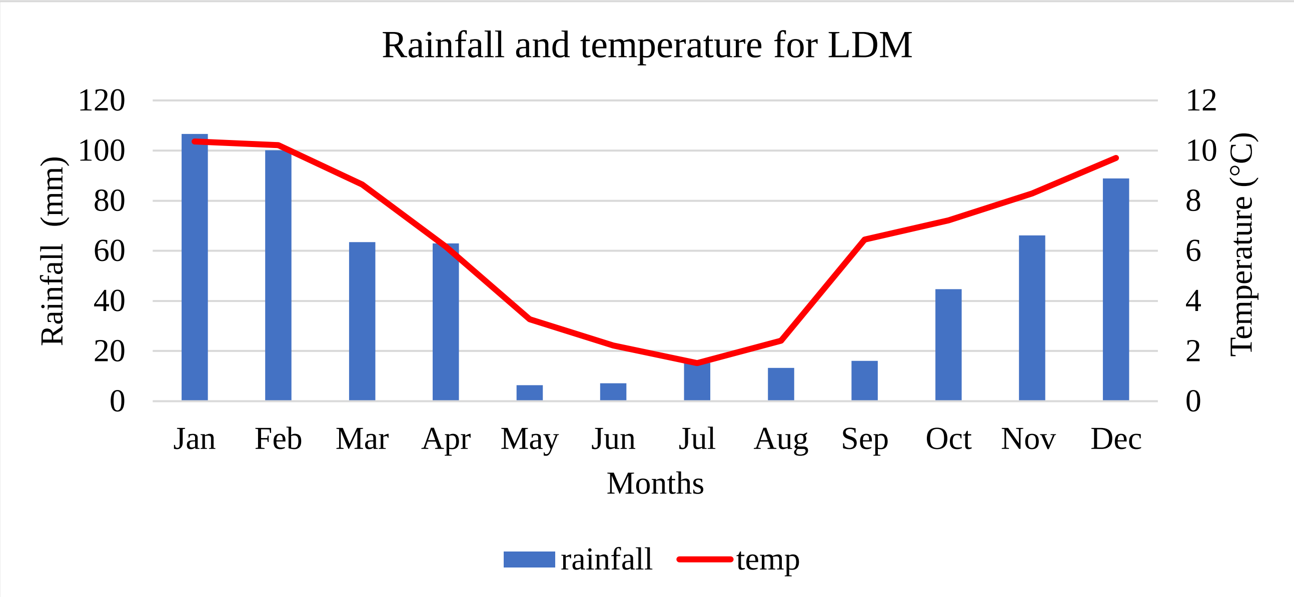

Figure 3-4. The minimum average temperature ranges between 1°C and 3°C during winter (May to August) while the maximum average summer temperature is approximately 10°C. The mine receives the lowest rainfall in winter with minimum average monthly rainfall of 6 mm. The highest rainfall was recorded in summer with maximum average rainfall ranging from 80 mm to 100 mm per month between December and February.

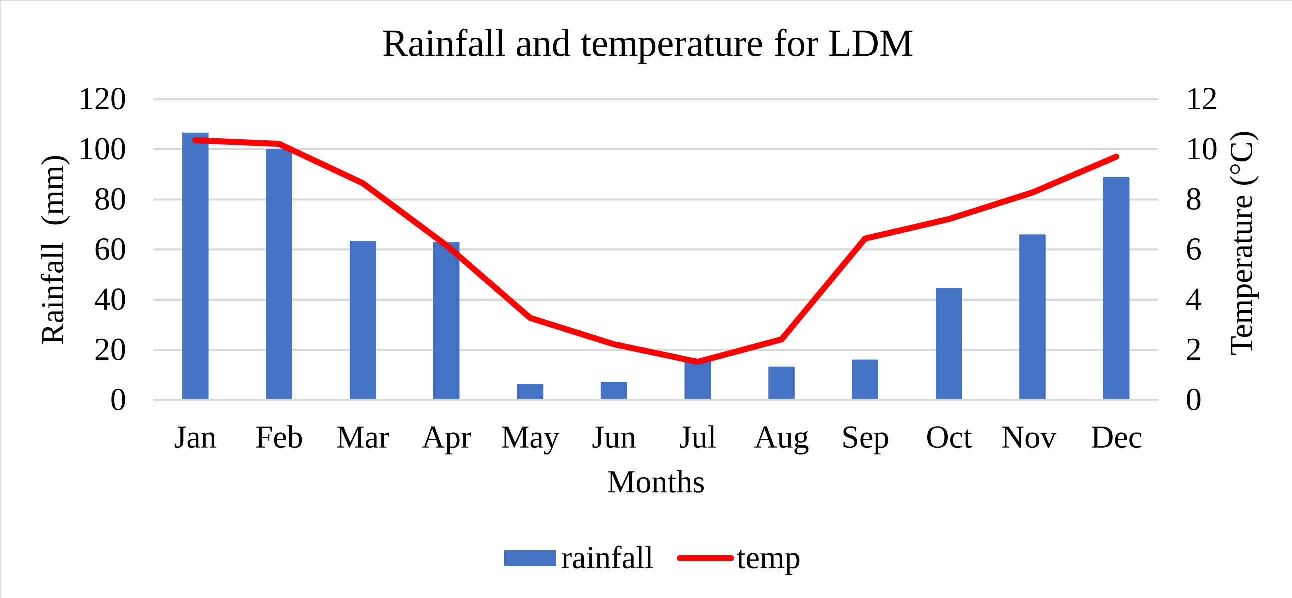

Figure 3-4 Rainfall and temperature graph for LDM.

3.3.2 Topography and drainage

Letšeng is located at a high elevation of 3 100 mamsl. The area around the pits has the highest elevation owing to the surrounding flood basalts of the highly elevated Drakensberg group. Due to mining ore down the pipes, the pits have become the lowest points within the area, at an elevation of 2 780 mamsl in the Satellite pit and 2 800 mamsl in the Main pit. Figure 3-5 shows the topographic profile of LDM along the N-S and the SW-NE, cutting through the pits. Moving towards the WRDs in the southern part of the area has a high elevation slightly above 3 100 mamsl. In the SW-NE direction, the elevation decreases from 3 100 mamsl to 2 950 mamsl, except for the pits which are at the lowest elevation. Further NE, the area lies at a lower topographical level, with valleys through which streams flow.

Figure 3-6 shows the drainage system of the area which consists of four catchments as labelled on the map. The Mokoalibane catchment is in the north, the Patiseng catchment is in the northeast and the RTZ catchment is in the east. Streams flowing within these catchments flow into to the major perennial rivers, which support communities downstream with water. For this reason, the mine monitors the quality of water that flows into these rivers by taking quality samples downstream from the mine along streams within each catchment.

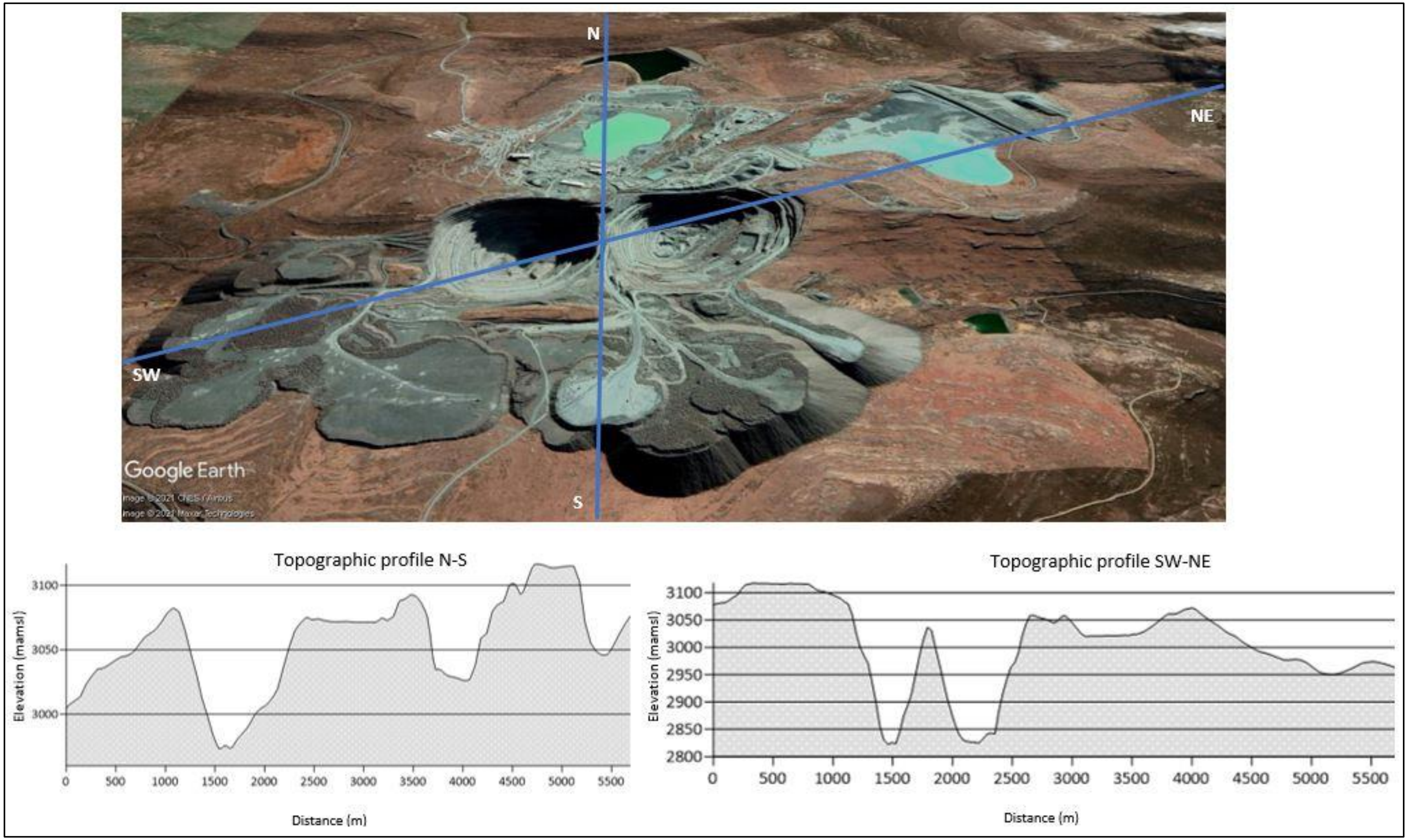

Figure 3-5 Topographic profile of LDM along the N-S and the SW-NE of both pits .

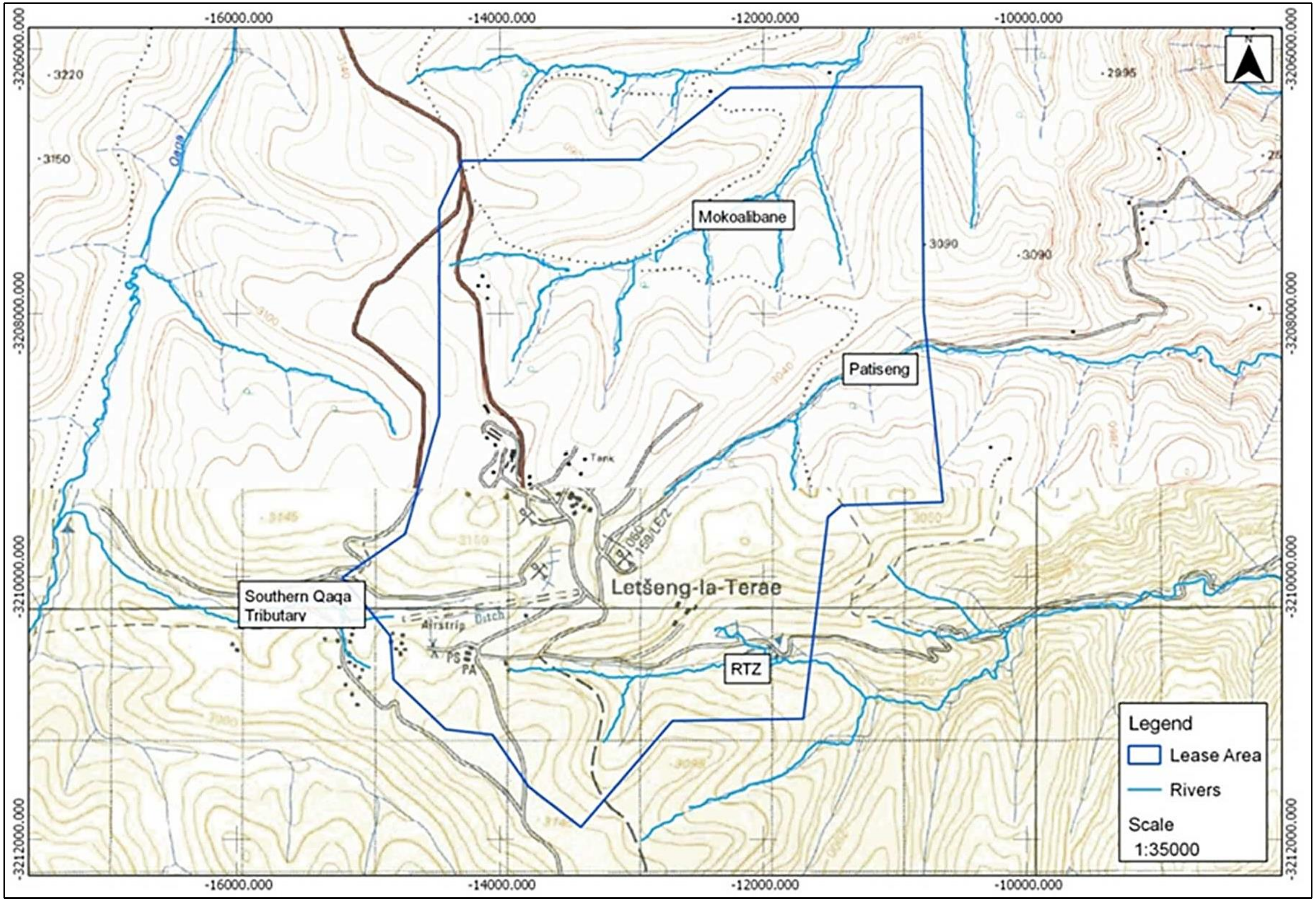

Figure 3-6 Map showing the drainage system of study area (adapted from Ross-Gillespie et al., 2018).

3.3.3 Soil and vegetation

Lesotho is generally covered in grassland. The study area is covered in Drakensberg Afro-alpine Heathland and a portion consisting of the Lesotho Highland Basalt Grassland. The soils are Mollisols, typical soils for grassland vegetation. The soils are composed of coarse sand, fine sand, clay, and organic matter (Mucina and Rutherford, 2006).

3.3.4 Regional geology and hydrogeology

The geology of Lesotho is dominated by volcanic massive basalts of the Drakensberg group and a horizontal bedding of sediments, which lies in the lowlands (Figure 3-7). Rapopo et al. (2018), states that the geology can be classified into three lithostratigraphic groups, the sedimentary Beaufort and Stormberg groups and the volcanic Drakensberg Group. The first unit consists of the Burgersdrop Formation of the Beaufort group with grey and purplish sandstones and shales of the Middle Triassic age. The overlying Stormberg group of the late Triassic to Early Jurassic age consists of fluvial sandstones and mudstones of the Molteno Formation. These rocks are overlain by fluvial sandstones, siltstones, and mudstones of the Elliot Formation and Clarens Formation. The Lesotho Formation overlies the Clarens Formation with a thick sequence of compact and amygdaloidal basalt flows. This Formation is characterised by intrusion of the Late Cretaceous diamondiferous kimberlite pipes, dykes and dolerite sills. This sequence of kimberlite intrusions lies in the northern parts of Lesotho and is referred to as the Northern Lesotho Kimberlite Field (NLKF) (Ntsolo et al., 2017). Letšeng diamond mine is located towards the north-eastern part of the NLKF with twin kimberlite pipes. The kimberlite pipes comprise volcanic-rich, potassic and ultrabasic igneous rock, however, like other kimberlite pipes, these pipes comprise several kimberlite magma pulses, which differ slightly in age, size, content, and the quality of diamonds (Shor, 2014).

Table A Summary of Lesotho`s Stratigraphy

Age	**Group**	**Formation**	**Lithology**
Quaternary and Tertiary		Alluvium, colluvium and residual deposits	Clays, silts, and gravels
Middle Jurassic to Permian	Drakensberg	Lesotho	Basaltic lava with subordinate tuff and lenses of sandstone near the base
	Stormberg	Clarens	Sandstone and siltstone
	Beaufort	Elliot	Mudstones and shales with subordinate feldspathic sandstone
		Molteno	Sandstones, grits, mudstones, shales, and coals

		Burgersdorp	Mudstones and siltstones, sandstone intercalation common
Early Tertiary to Late Cretaceous	Intrusive Rocks	Dykes and sills	Basalt, dolerite, and gabbro
		Clusters of pipes and dykes at depth	Kimberlite

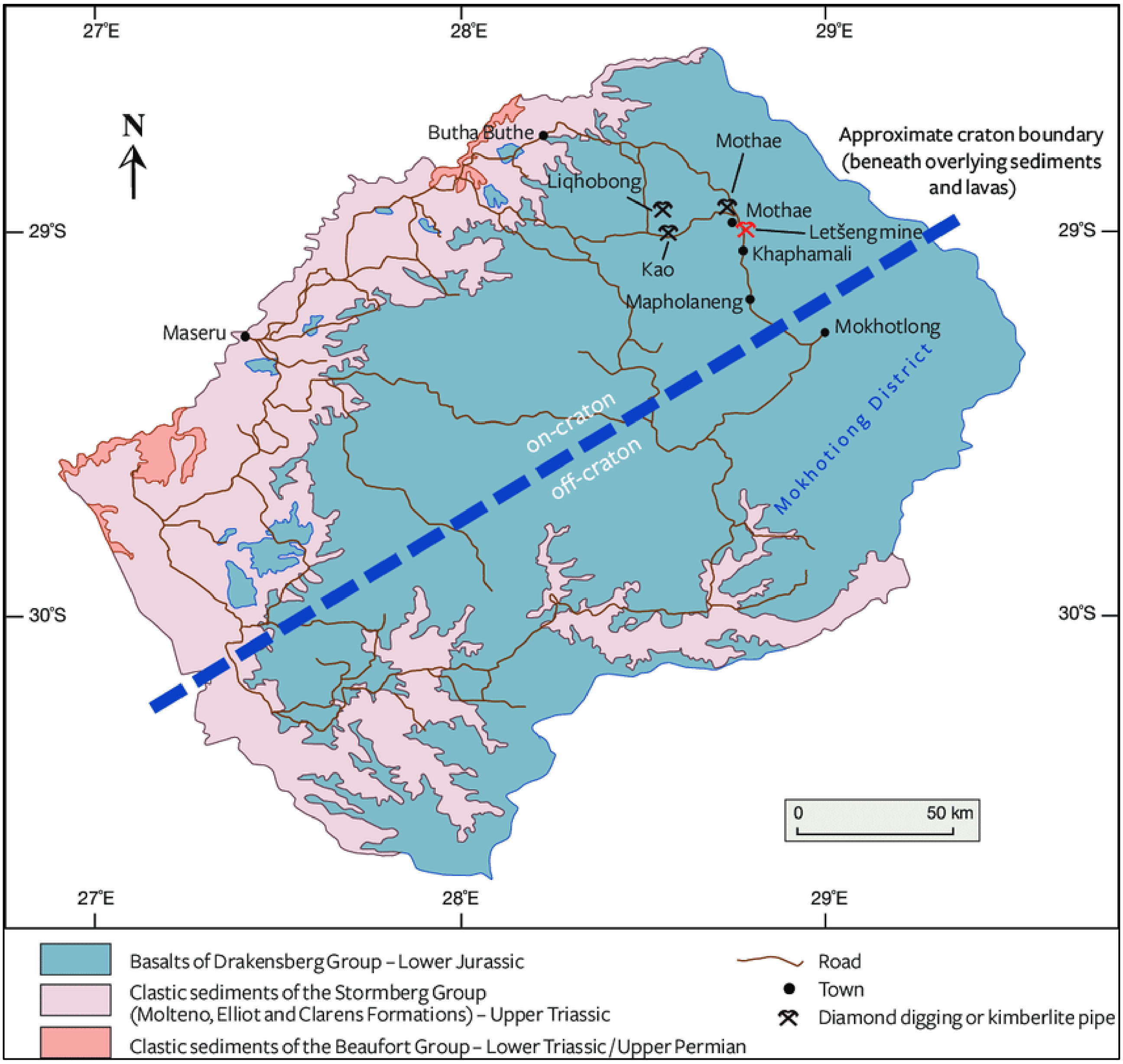

Figure 3-7 Geological map of Lesotho, location of mine indicated in red (Shor, 2014).

Generally, the occurrence of groundwater in Lesotho is variable with borehole yields varying from dry to 8.0 l/s. According to Davies (2003), groundwater in Lesotho occurs within fractured sedimentary and basalt rock aquifers, alluvial sediments and dolerite intrusion zones. The basaltic Lesotho Formation in particular has moderate to low groundwater potential. Several springs occur at almost all levels. The springs originate from weathered basalt horizons, at inter-basalt flow zones and adjacent to dolerite dykes at an average yield of 2.6 l/s (Viles et al., 2007).The basalts and kimberlites of the Lesotho Formation have low storage potential although water strikes emerging from joints, shear zones and dykes which account for secondary porosity (Lefu et al., 2017). Davies (2003) further adds that pumping test data analysis from holes drilled into and adjacent to dykes suggests that, despite the permeability, the storage capacities are generally low.

3.4 SUMMARY

The site description and data collected can be used to develop the groundwater model. The next chapter therefore covers the data review, which includes monitoring groundwater and surface water data. The data collected can be used to develop the conceptual model, which informs the numerical model.

4 DATA ANALYSIS AND MODEL CONCEPTUALISATION

Data required for this study was collected from the mine and was analysed to set up the conceptual and numerical model. The conceptualisation of the area details the physical hydrogeological system and its hydraulic behaviour. Including the hydrogeologic setting, hydrostratigraphic units and hydraulic properties, groundwater recharge and discharge as well as groundwater flow regimes. This information will assist in understanding the system and thus aid in developing the numerical model.

4.1 DATA REVIEW AND ANALYSIS

Model development requires a set of quantitative and hydrological data which can be classified into two groups, data defining the physical framework and data describing the hydrological framework. The construction of the physical framework involves data collection from the study area. Describing the physical limits of the area including the geological and hydrogeological characterisation of the area in terms of lithological variations, boundaries and hydrostratigraphic units, which are defined by data on rock properties, thickness and areal extent. The hydrological stresses include hydraulic head data, and the type and extent of recharge areas (Anderson and Woessner, 1992).

4.1.1 Geological and hydrogeological characterisation

4.1.1.1 Geology

Located within the Lesotho Formation, the geology of Letšeng comprises mainly of basaltic lavas which form country rock to kimberlite intrusions, these are formed from extensive volcanic eruptions or series of eruptions covering broad regions referred to as flood basalts. Due to their cooling process flood basalts usually have complex internal structures and unpredictable permeable zone distribution. Haskins and Bell (1995) suggest that flood basalts can be classified into an upper, central, and basal zone. The upper zone is characterised by fine-grained, highly amygdaloidal glassy basalt with some regions showing some indication of palea-weathering in form of thin, red-coloured oxidized zones. The central zone is characterised by few amygdales and is medium to coarse-grained. The basal zone is fine grained and moderately to highly amygdaloidal basalt Haskins and Bell (1995). A similar criterion can be used to classify the basalt Formation in the area.

In most cases borehole logs provide detailed geological information of an area, as they expose the subsurface for analysis. To obtain a more comprehensive understanding of the local geology, available borehole logs of the area were studied. However, due to limited data availability borehole logs from monitoring boreholes which were drilled in 2013 were used to provide an idea of the local geology. Figure 4-2 shows thirteen borehole logs which were drilled at different depths around the mine depending on the different objectives. The borehole logs show that the dominant lithology is basalt, varying from weathered to fresh basalt. It is noticeable that the weathering decreases with depth, where deeper zones are characterised by more competent basalt.

For more insight into the local geology, pictures of the pit high walls were taken, as these are exposures of the rock Formations in the area. Figure 4-1 therefore shows what could be classified as the upper zone, typically up to 15 to 35 mbgl. The zone is fine-grained, highly amygdaloidal, and moderately weathered. There are also regions of oxidisation within the zone. Due to weathering, the zone has cracks that allow water to flow through it.

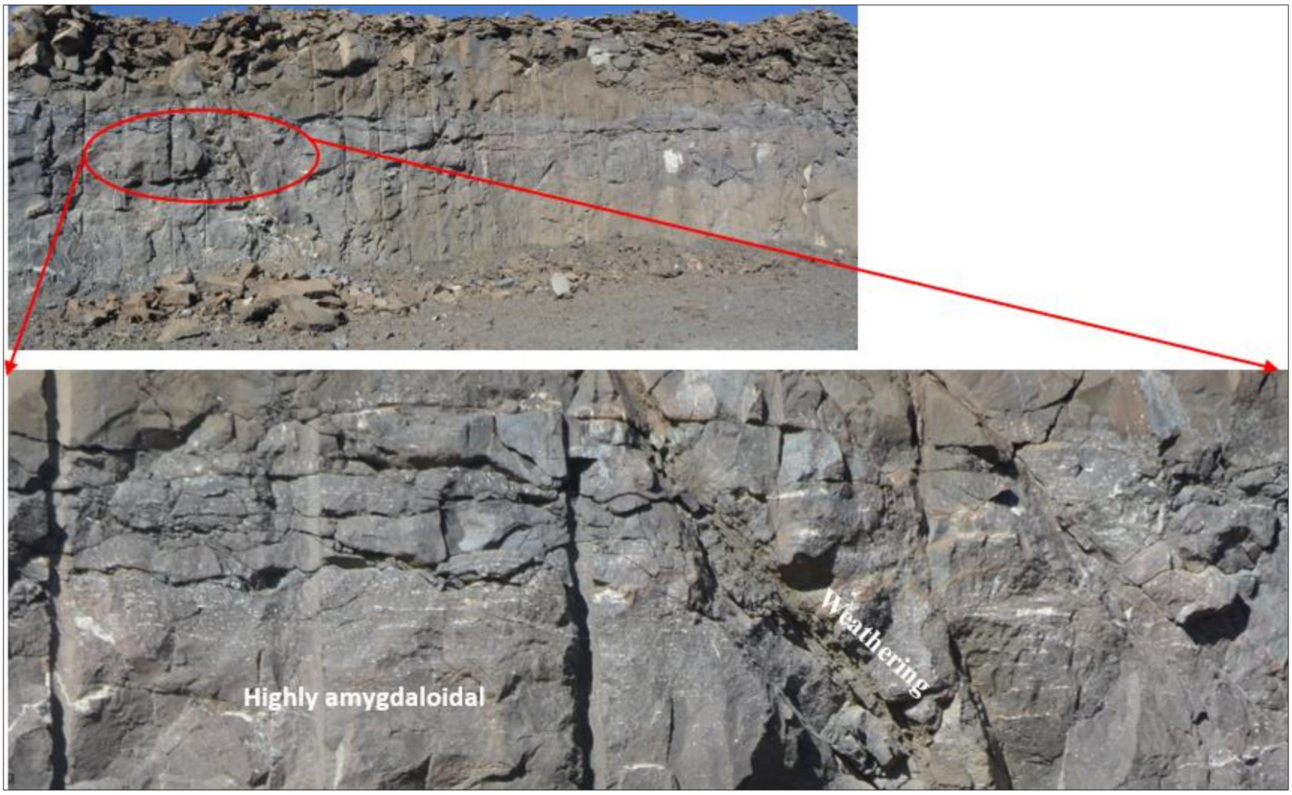

Figure 4-1 Upper basalt zone, weathered, highly amygdaloidal and fine grained.

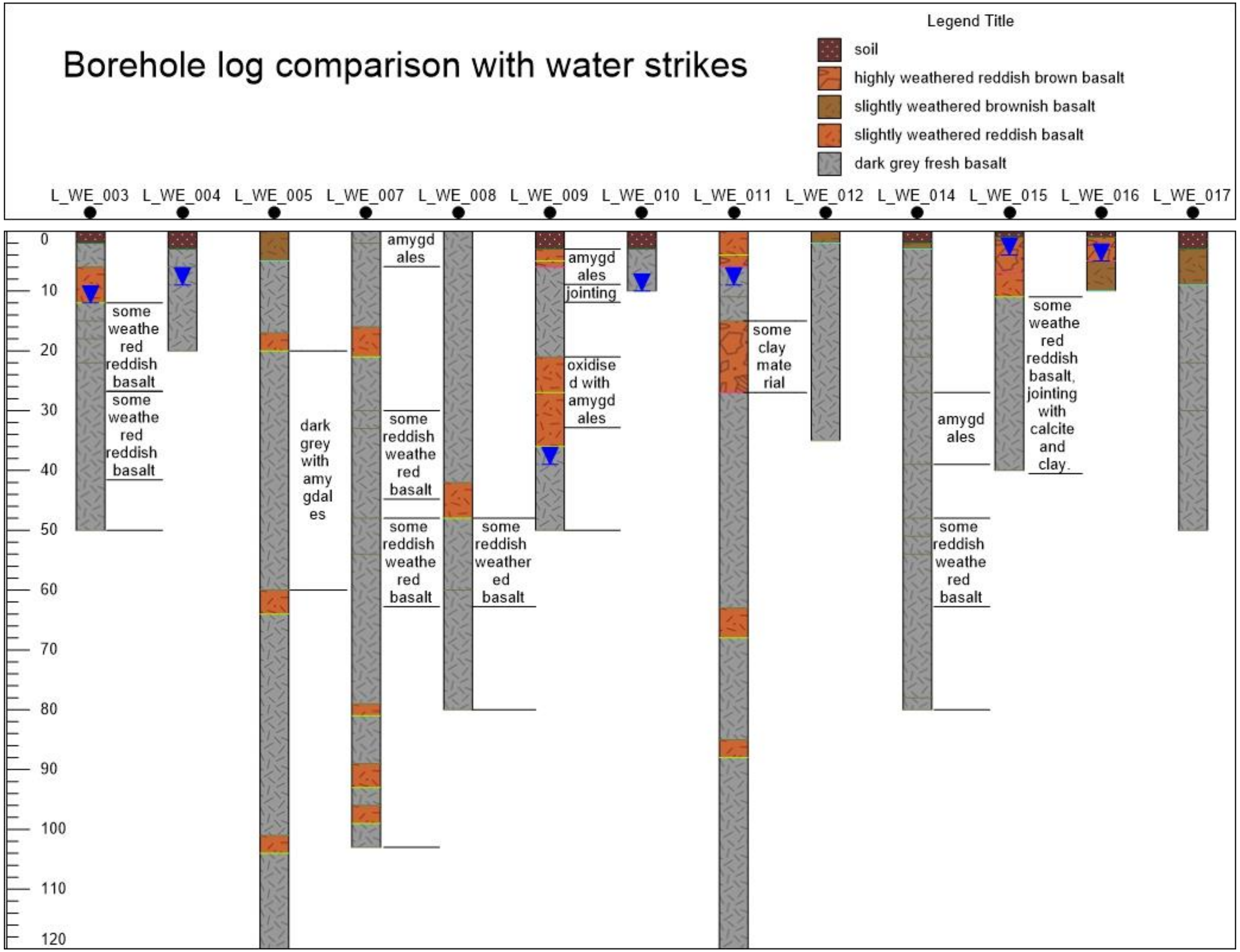

Figure 4-2 Borehole logs showing lithology of LDM monitoring boreholes.

The central zone is more massive with fractures, dykes, joints, and crack, some resulting from blasting. These structures are preferential pathways for groundwater flow, as water is seen seeping through the joints and dykes in the Figure 4-3 and

Figure 4-4, respectively.

Figure 4-5 shows a 14 m high wall of basalt at 2 780 mamsl. With depth, the basalt is more competent and has fewer structures. On this highwall, a joint is exposed. This joint also forms a possible preferential pathway for groundwater flow, although the flow may be limited compared to the upper zones. Figure 4-6 shows the weathering profile of basalts, providing a summary of what has been discussed above.

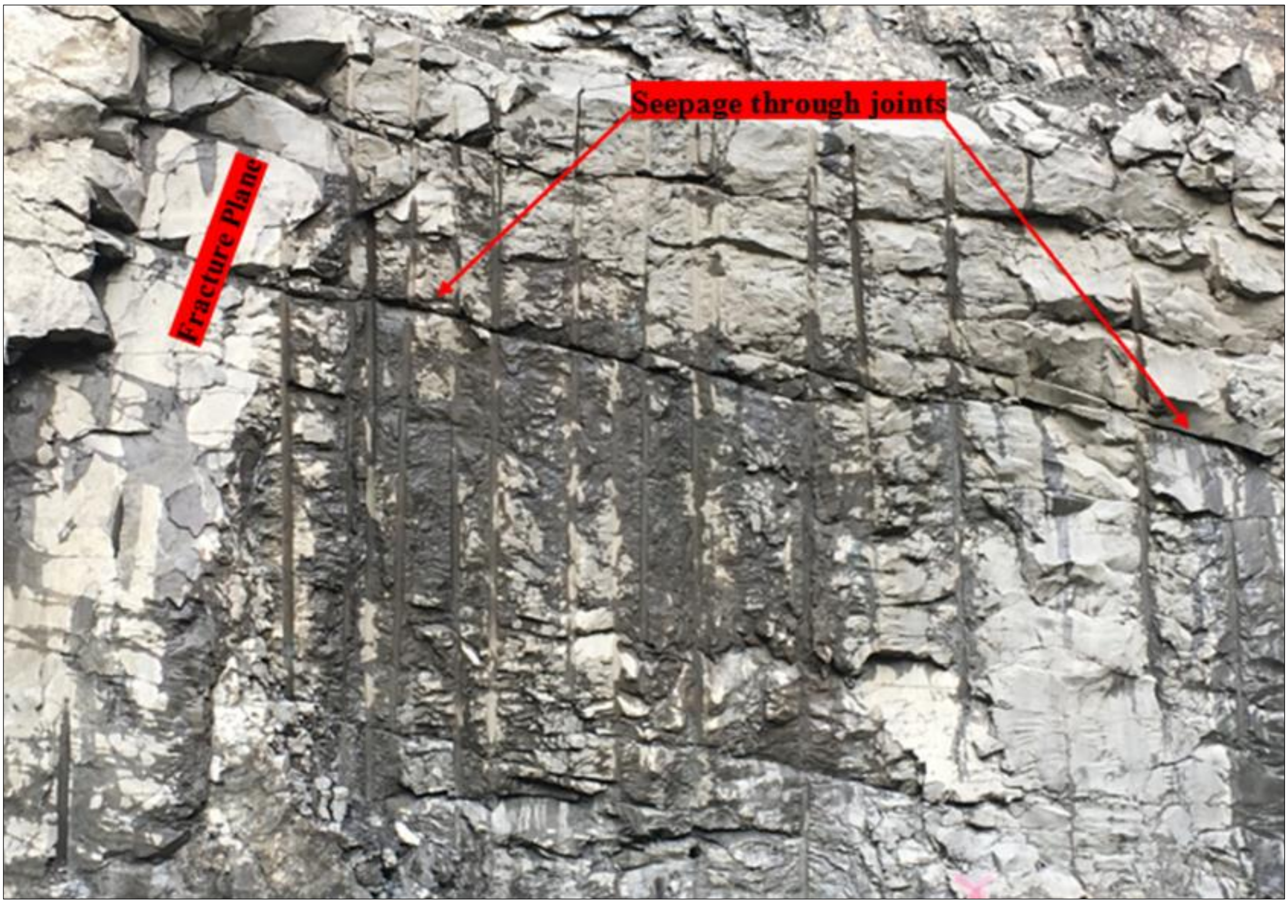

Figure 4-3 Central basalt zone, massive, with fractures, joints, and cracks from blasting.

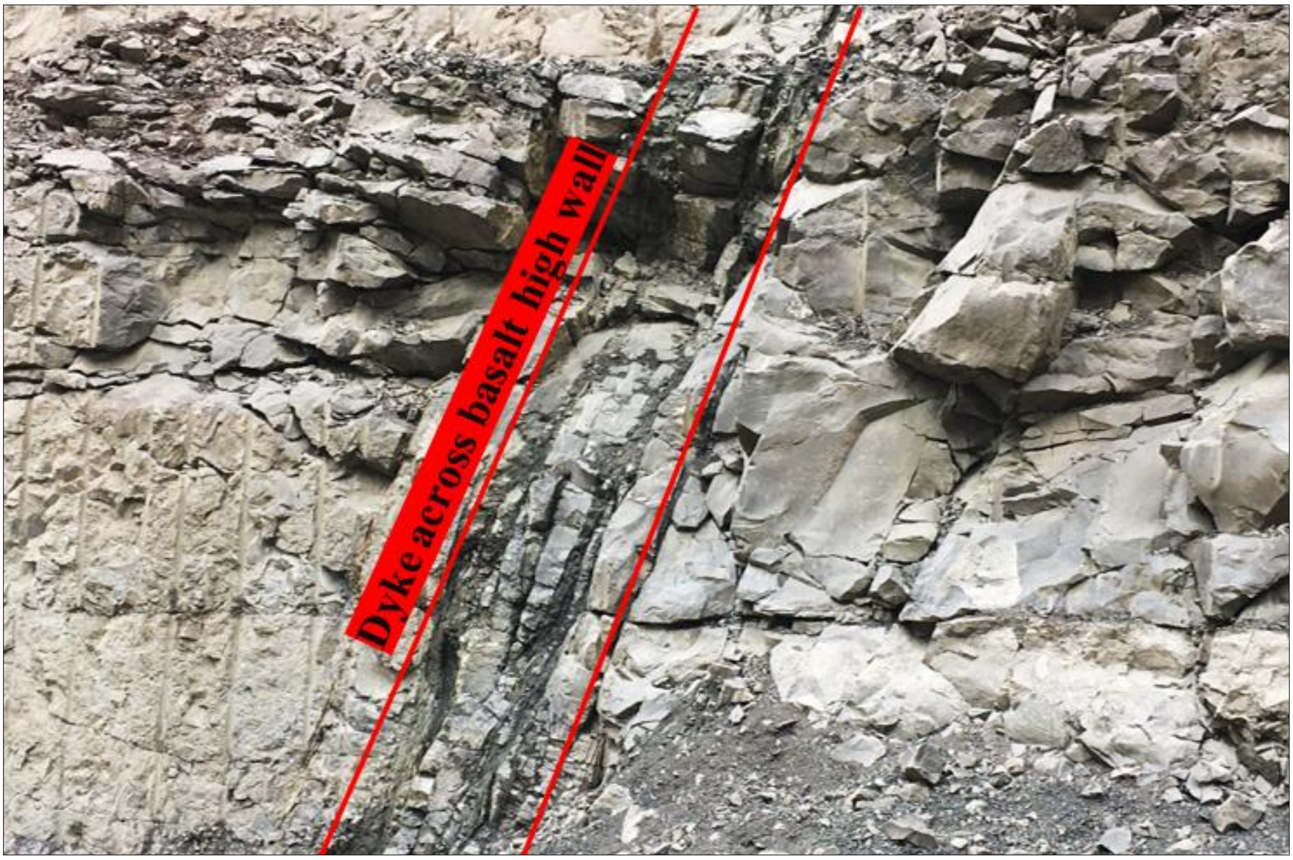

Figure 4-4 Dyke across the massive zone, a preferential flow path.

Figure 4-5 Basal zone, more competent basalt with some jointing.

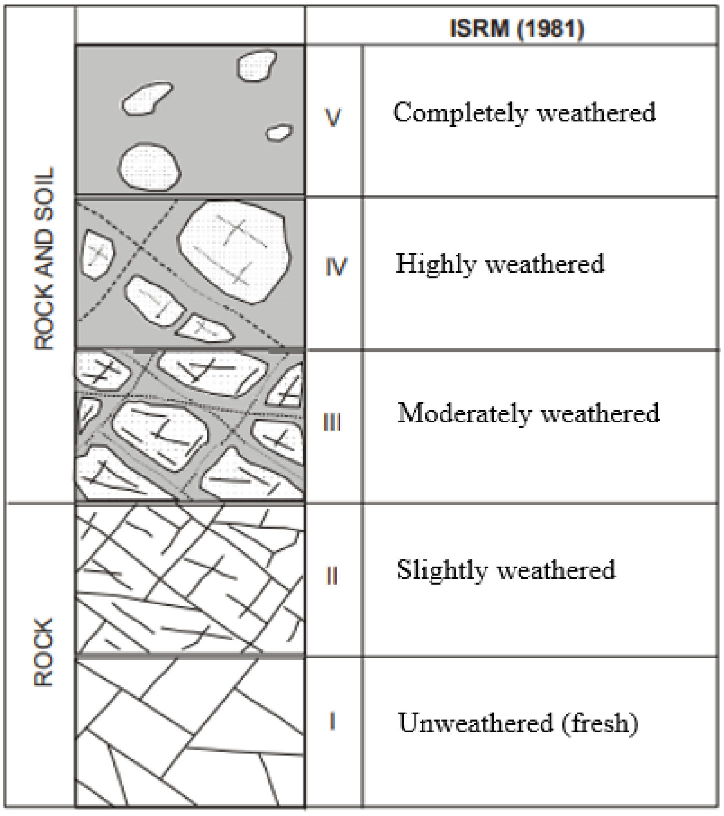

Figure 4-6 Weathering profile for basalt Formations (ISRM, 1981)

4.1.1.2 Hydrogeology

According to Navarro et al. (2020), flood basalts can be classified as multilayer aquifer systems where a highly permeable top overlies a centre of massive basalt with low permeability. In most cases, the highly permeable layer is weathered basalt. The rate and degree of weathering in basalt is increased by access of water in cracks which result from repeated hydration and dehydration of clay minerals exposed to the atmosphere (Haskins and Bell, 1995). Weathered basalt therefore increases groundwater potential as well as groundwater flow within the subsurface. In this zone, precipitation infiltrates into the weathered aquifer and flows laterally at the contact and with time, flows out as springs at the inter-basalt flow zones and along the dykes. Hence, the contact between basalt flows, and the presence of fractures, joints and shear zones within the massive basalt zone create preferential pathways for groundwater flow.

Hydrogeological units

This is also true for the hydrogeological setting of Letšeng. Based on available data and previous work on the area, there are two distinct hydrogeological units within the basaltic rocks of Letšeng. These are the upper weathered unit and a deeper fractured unit. The weathered hydrogeological unit has an average thickness of 15 mbgl and comprises medium to highly weathered basalt and residual soils. Based on the borehole logs in Figure 4-2 groundwater strikes were mainly intersected in the weathered unit, indicating that most of the groundwater flow occurs within this zone. The underlying hydrogeological unit (~35 to ~50 mbgl) is characterised by mainly competent basalt with predominant fracturing present at the top of the unit. The groundwater intersection frequency in the fractured basalt is generally lower than in the weathered zone and decreases with depth, indicating that the degree of fracturing decreases with depth as the basalt becomes more competent.

Although basalt is massive and competent, the presence of geological structures has created preferential pathways for groundwater flow. A moderately high-yielding hydrogeological unit is formed by preferential weathering and fracturing of the intrusive kimberlitic contact with the basalt, which affects seepage into the open pits. Figure 4-7 also shows geological structures around the pit area, giving an idea of the geological structures of the area. The area is highly jointed with the main geological structure being the shear zone which cuts through both pits and extends outwards. There are also several dykes that cut through the area. These structures therefore affect the hydrogeological properties of the units. However, there is limited data on these structures, as the available data only covers the area around the pits and not for the whole study area.

Hydraulic properties

Different tests have been carried out by different stakeholders to determine the aquifer properties of the area. These include the Borehole Magnetic Resonance survey and the conventional pumping tests. Results from the constant rate pumping test conducted during previous studies as summarised in Table B.

Table B Constant rate pumping test results from previous studies (ITASCA, 2021).

BH ID	**Depth (m)**	**SWL (mbgl)**	**Aquifer thickness (m)**	**Transmissivity during pumping (m^2/day)**	**Transmissivity during Recovery (m^2/day)**	***K* Pumping (m/day)**	***K Recovery (m/day)***
LWE012	27.7	2.17	25.53	2.32	10.04	0.09	0.39
LWE015	37.39	4.56	32.83	1.57	4.6	0.05	0.14
LWE017	44.94	4.82	40.12	1.6	5.45	0.04	0.14
LWE003	50.25	15.83	34.42	3.63	6.72	0.11	0.20
LWE008	81.4	7.73	73.67	1.78	1.16	0.02	0.02
LWE007	101.2	16.94	84.26	1.49	1.94	0.02	0.02

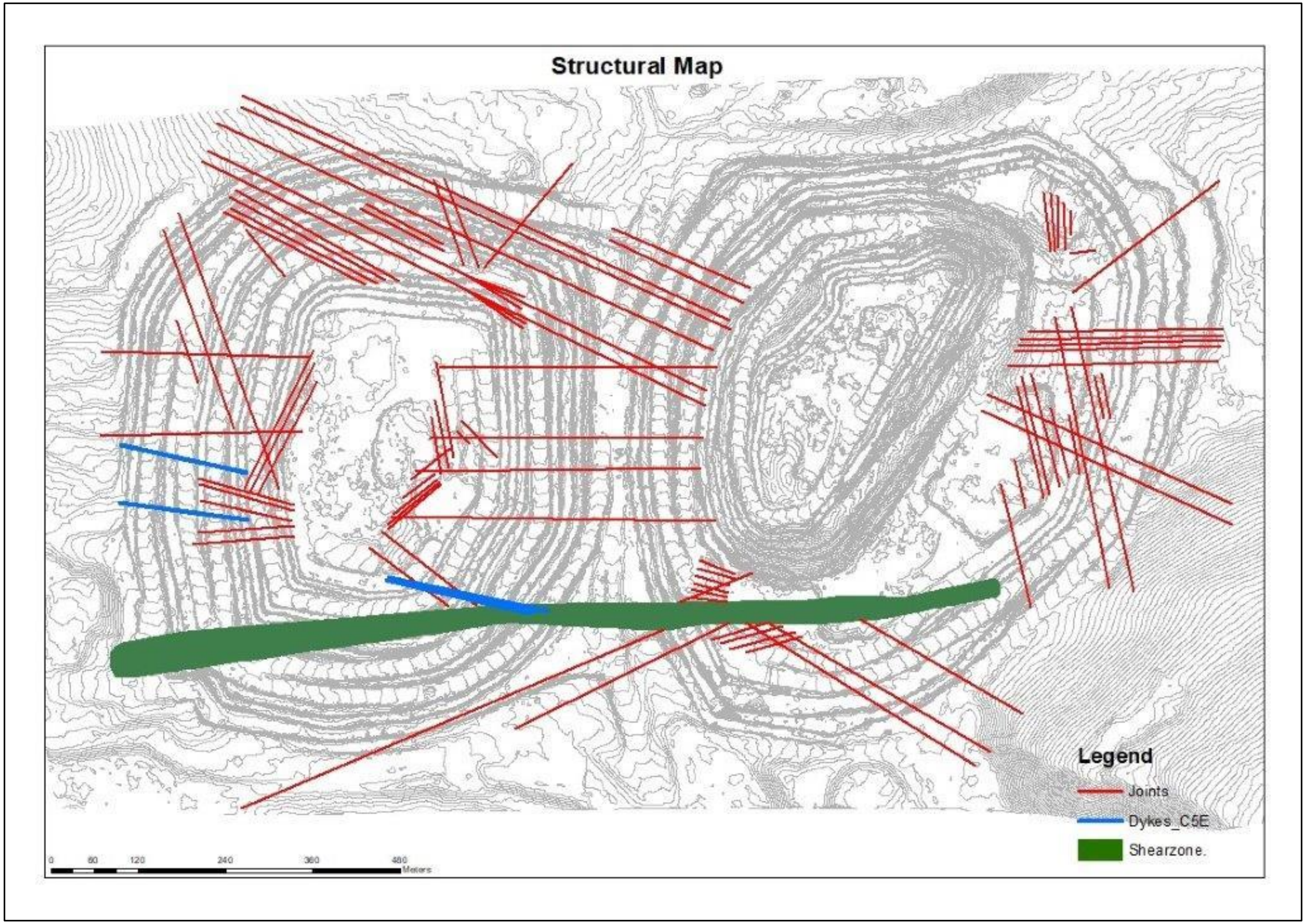

Figure 4-7 Structural Map of LDM, showing geological structures around the pits.

4.1.2 Hydrological stresses

4.1.2.1 Monitoring network

The mine has set up a monitoring network where boreholes are located upstream and downstream of different mining infrastructures considering the location of the potential groundwater pollutant sources and receptors. The spatial distribution of the monitoring boreholes around the site is shown in Figure 4-8. There are currently ten active boreholes on site, details of each borehole are shown in Table C.

Borehole L_WE_003 and L_WE_004 are located downstream of the Patiseng TSF, to monitor the quality of groundwater flowing from the TSF. Borehole L_WE_007 is located upstream of the Patiseng TSF and adjacent to the main pit. From this borehole, any seepage from the TSF into the pit can also be monitored. Another borehole is L_WE_011, monitoring groundwater that may flow into or from the main pit. Down-gradient from the WRD are boreholes L_WE_012, L_WE_010 and L_WE_008, monitoring the water flowing from the dumps. Boreholes L_WE_015 and L_WE_016 are downstream of the Mothusi dam. While L_WE_017 is monitoring the Old TSF. Where boreholes are in pairs, one is shallow and the other is deeper, monitoring groundwater conditions at both levels.

Table C Borehole details for LDM monitoring network.

BH ID and site location description	BH depth (m)	SWL (mbgl)	Head (mamsl)
L_WE_003 Patiseng Valley	50.25	16.43	2870.75
L_WE_004 Patiseng Valley	20.54	11.23	2875.02
L_WE_007 Patiseng Valley	101.20	17.67	3030.14
L_WE _008 RTZ Upstream	81.04	8.47	3091.93
L_WE_010 RTZ Valley	10.84	3.45	2874.38
L_WE_011 Main Pit	121.00	86.19	2997.38
L_WE_012 Qaqa Valley	27.70	2.85	3011.50
L_WE_015 Mokoalibane Valley	37.39	5.18	2925.83
L_WE_016 Mokoalibane Valley	10.68	5.03	2926.41
L_WE_017 Process Plant 1	44.94	5.14	3071.71

4.1.2.2 Groundwater levels

The groundwater monitoring programme started in 2013. The boreholes are monitored monthly for groundwater quantity. However, there are some gaps in the data where groundwater level measurements were not taken for several reasons such as faulty equipment. Because of the data gaps, only data up to August 2021 was analysed for groundwater quantity. Groundwater levels for all the active ten boreholes is shown in Figure 4-9. In January 2016, the boreholes were purged hence the sudden drop in measured groundwater levels. The average groundwater level is about 7.0 mbgl, showing that the groundwaterlevel in most of the boreholes is quite shallow. This could be a result of the wells being in the upper zone, which is weathered and fractured, which forms preferential pathway for groundwater into the boreholes. Another factor could be water that percolates into these zones through recharge. Borehole L_WE_011 is an outlier with relatively deeper groundwater levels of 80 mbgl on average. This is a deep borehole (121 m), meaning it could be in the more competent zone where groundwater flow intothe borehole is limited. A somewhat similar trend to L_WE_011 is seen in borehole L_WE_007 which is at depth 101 m. Initially, the groundwater level was lower than in other boreholes, but started to increase in early2018. Based on its location, there is a possibility of seepage from the nearby Patiseng TSF into the borehole thus increasing the groundwater level.

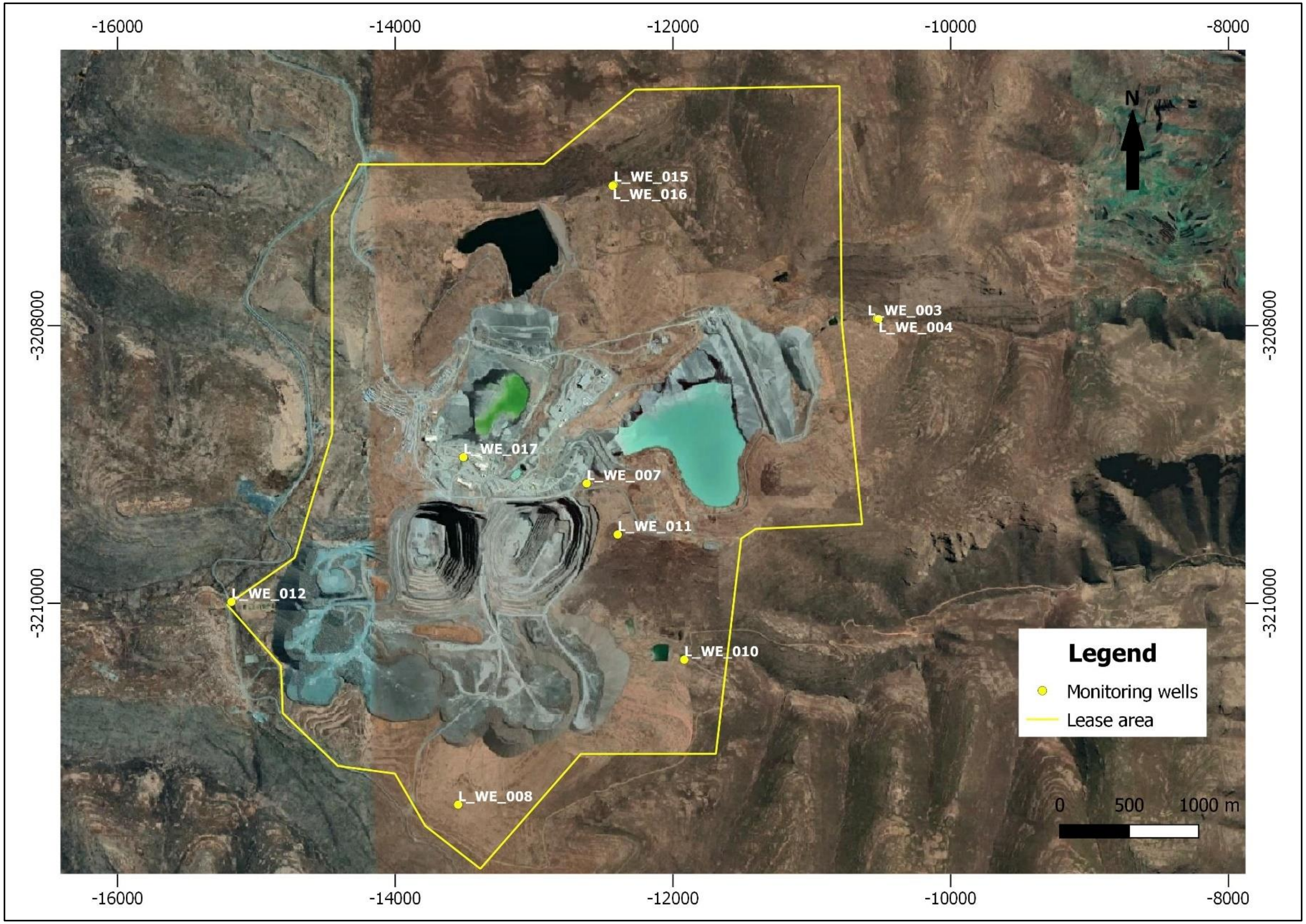

Figure 4-8 Groundwater monitoring network for LDM, showing the location of boreholes around different mine infrastructures.

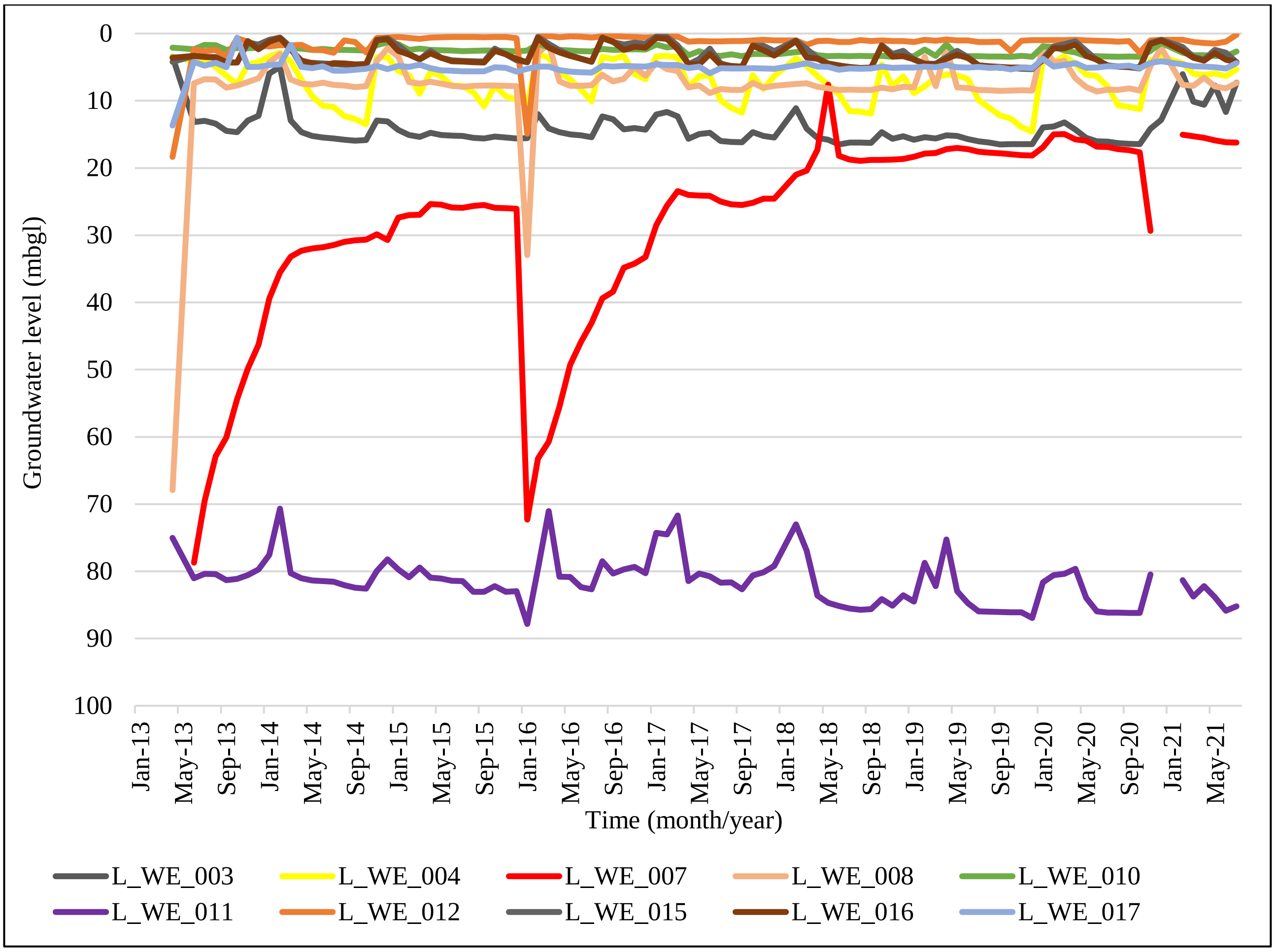

Figure 4-9 Groundwater levels for boreholes at LDM throughout the monitoring period.

4.1.2.3 Rainfall and Groundwater level

Due to the hydrogeological conditions in the area, groundwater responses to changes in rainfall. According to Jan et al. (2007), rainfall reaching the surface may discharge into the stream as surface runoff or it can percolate into groundwater aquifer to be stored in the surface or later emerge as spring water or even as seepage into streams. An increase in groundwater level therefore indicates recharge into the groundwater system. On average, groundwater levels at the site show fluctuation with seasonal changes, particularly changes in rainfall. The region receives summer rains and winter snowfalls, which infiltrate the weathered aquifer and thus contributing to recharge in the subsurface. However, recharge is limited to the weathered aquifer and the deep aquifer within the competent basalts receives less recharge. In Figure 4-10, sharp fluctuations are seen in shallow boreholes showing good correlation with rainfall patterns. Although a deep borehole, L_WE_011 also shows good correlation with rainfall, it could mean that there is actually very limited groundwater flow into the borehole and most of the water flowing from rainfall and not necessarily groundwater recharge.

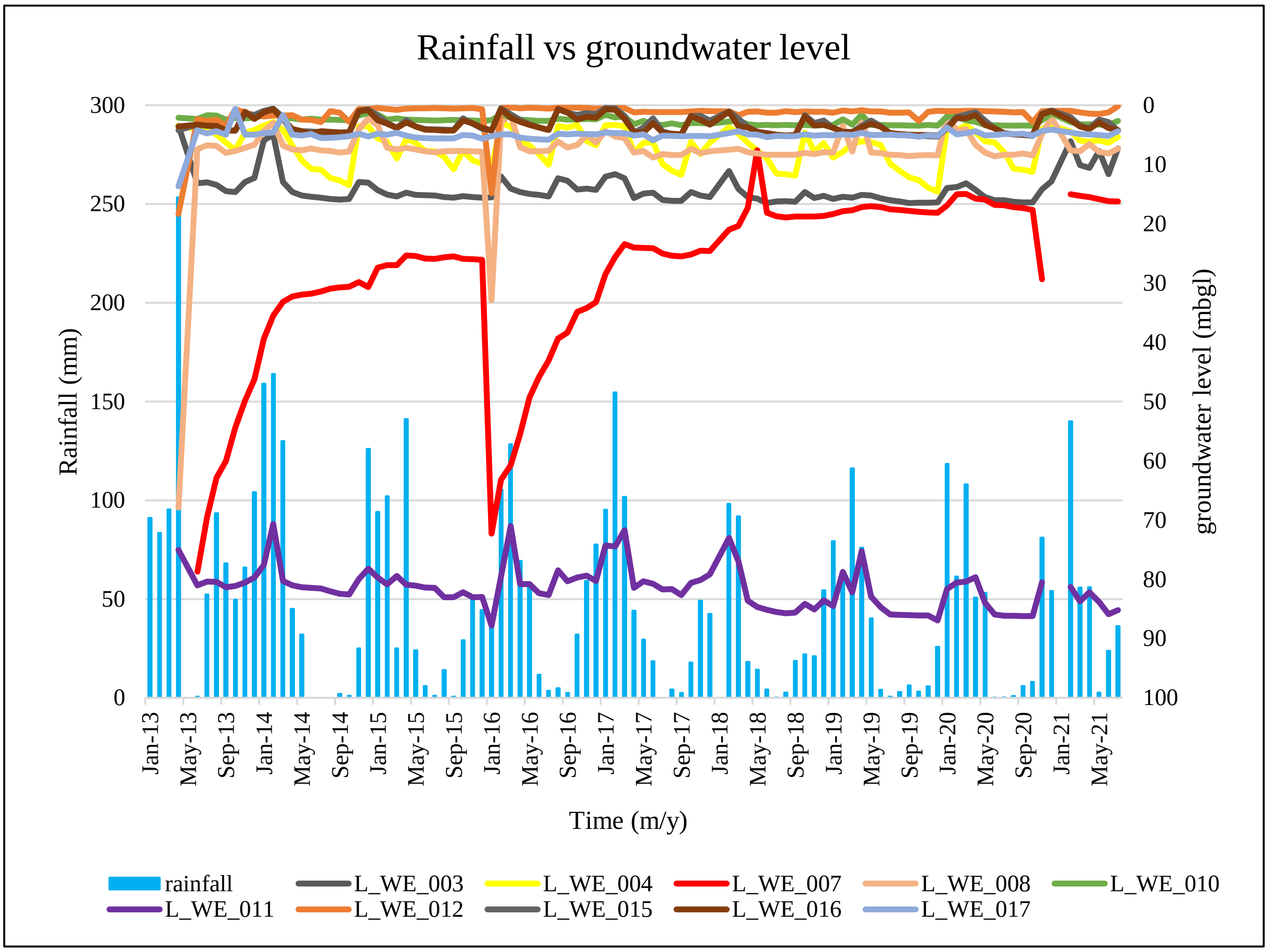

Figure 4-10 Rainfall vs Groundwater level graph showing how groundwater levels change with rainfall.

4.1.2.4 Groundwater flow direction

According to Oborie and Nwankwoala (2017), it is important to know the direction in which groundwater flows. Determining the direction of groundwater flow informs knowledge on recharge and discharge zones. Groundwater flows from high groundwater elevation to low elevation. Therefore, activities occurring at higher groundwater elevations directly influence the conditions of groundwater at lowerelevations. Figure 4-11 shows the groundwater flow direction within the area based on initial groundwater level monitoring data from 2013. The direction is perpendicular to groundwater elevation contours, from high to low groundwater elevation. The map shows that groundwater flowat the mine generally flows eastwards from areas with high elevation downstream to lower elevationswhere there are rivers and streams which supply water for nearby communities. For instance, mine water flows from the TSF area downstream east to the Patiseng stream which provides water for the Patiseng community. It is therefore important to monitor the quality of water flowing downstream and to ensure that the quality of water reaching the communities is of good quality.

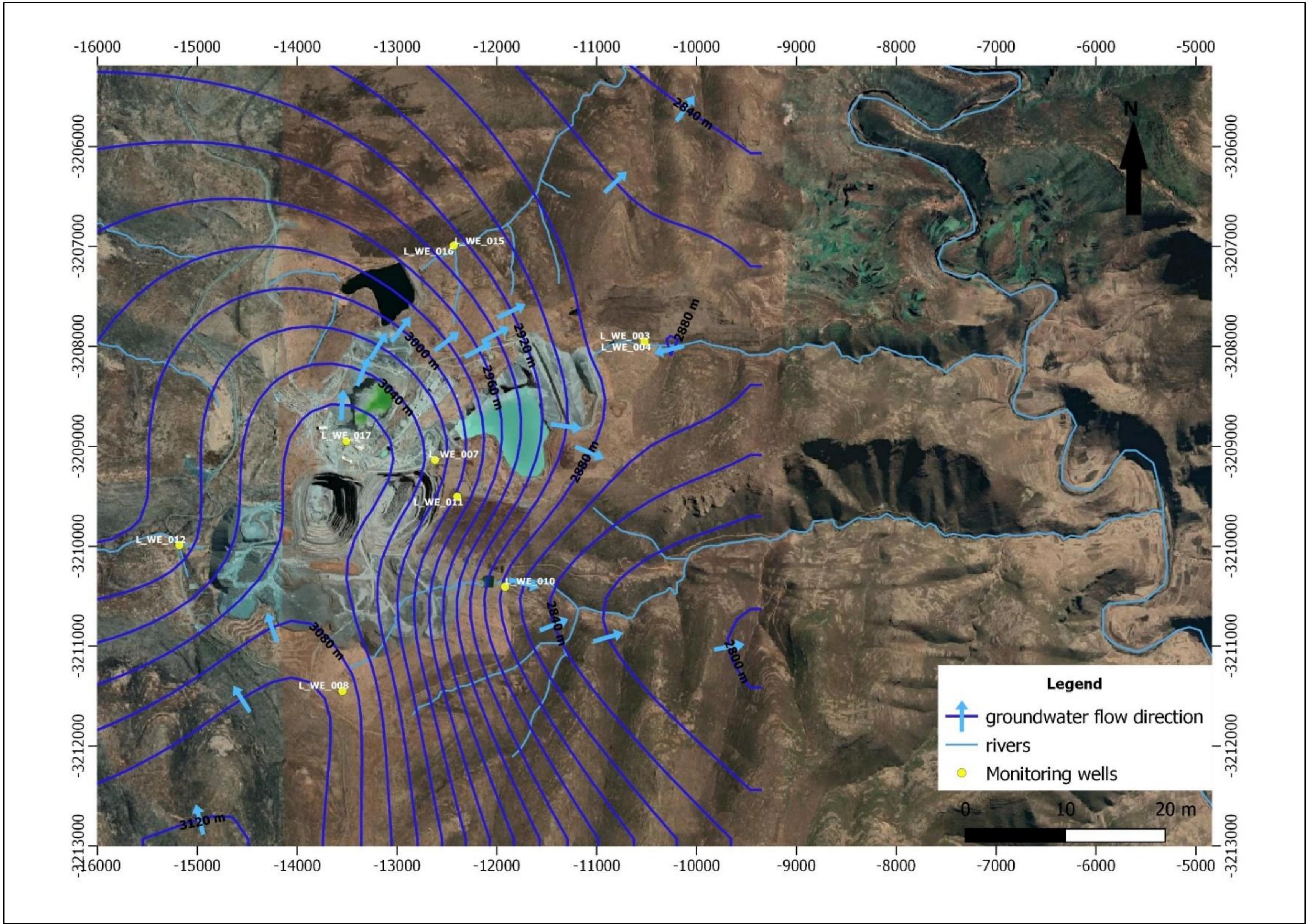

Figure 4-11 Groundwater flow direction map for LDM, mainly towards the east of the mine following topography.

4.1.3 Water Quality

4.1.3.1 Hydrochemical spatial distribution

In order to define the groundwater system of an area, it is important to understand the spatial distribution of water quality in aquifers and how the water quality changes over time. The maps in Figure 4-12 show the hydrochemical spatial distribution of chemical components around the area. The first figure shows the groundwater chemical composition during the initial groundwater monitoring period (2013), this can be considered as background conditions while the second figure shows the current groundwater chemical compositions. These visualise how the groundwater chemistry has changed over time as mining operations proceed and how it varies spatially. Both maps show that the groundwater in the area is highly concentrated in calcium, sulphates, sodium and magnesium. There are also traces of nitrates in some boreholes.

In particular, borehole L_WE_012 located downstream of the Eastern WRD shows a 40% increase in sulphates and 1.3% increase in nitrates from 2013 to 2022. Similarly, increases in concentrations are seen in boreholes L_WE_010 in the Western WRD and L_WE_017 by the OLD TSF, showing an increase in sulphates concentrations of 26% and 32%, respectively; and of 2% in nitrates for borehole L_WE_010. Uncontaminated water resources have relatively low concentrations of nitrates and sulphates, therefore the increase in these concentrations poses a risk on the groundwater quality. Although the graphs do not show a significant increase in nitrate concentrations, previous studies on the area show that there is an increase in nitrates concentrations associated with different activities around the mine. Based on these observations, it is important to closely look at the trends for both sulphates and nitrates concentration in groundwater throughout the monitoring period to determine the water quality in the area has been impacted by mining.

4.1.3.2 Water quality monitoring

As part of the monitoring protocol, LDM collects water samples monthly, quarterly and biannually. The water quality analysis results are compared against limits or standards. The water quality is compared against water quality limits guided by the Lesotho Water Quality Standards, South African Water Quality Guidelines and South African National Standards. When the concentration level for water quality parameters exceeds the set recommended standard, there needs to be action taken towards water quality management. When sampling for chemical constituents it is important to classify the water resource based on its use and the applicable guideline or standard thereof.

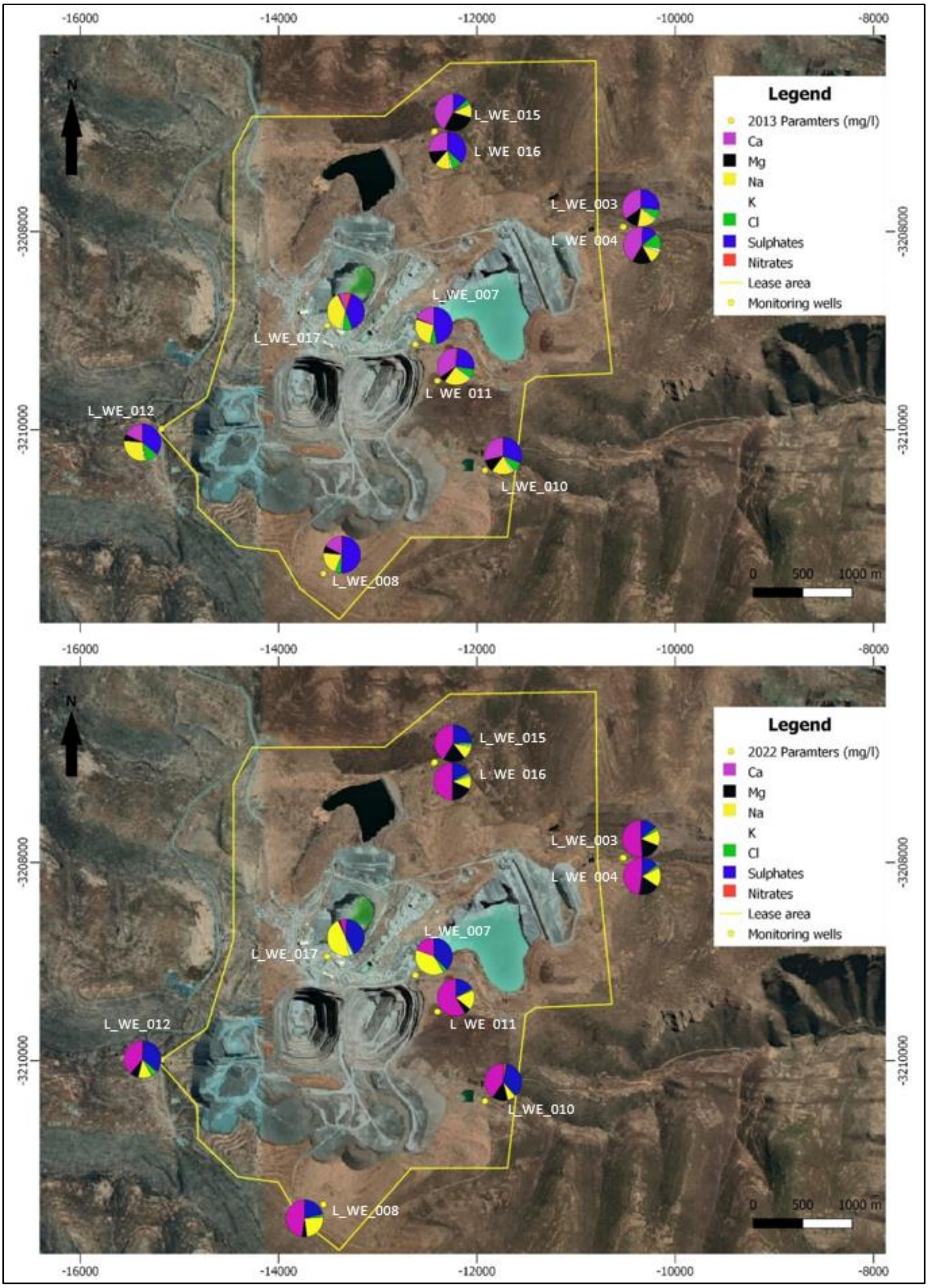

Figure 4-12 Hydrochemical spatial distribution maps showing concentration of different chemical constituents around the mine in 2013 compared to 2022.

4.1.3.3 Surface water monitoring

For this section, the focus will be on water samples collected near different mine infrastructures (industrial water), which are potential sources of contamination and samples along drainage lines to determine the status of water quality upstream and downstream of the site (environmental water). The data analysis was based on data from 2012 to 2021 over the dry and wet season for nitrate concentrations, which are one of the main indicators of contamination in water resources. Figure 4-12 also shows that the sulphate concentration in the area is elevated, hence it would be important to determine the potential source of sulphates and how its concentration varies over time within the study area.

4.1.3.3.1 Sources of potential contamination (Industrial water)

Sources of potential contamination can be classified as Industrial water, which are compared to industrial standards for nitrate concentration as provided by the Lesotho Water Quality Standards (2007) as 20 mg/l. However, industrial water quality standards for sulphates are not provided and the environmental standard of 500 mg/l is used for reference. Water quality analysis is from water samples collected by the Old TSF, Pits, WRD and Patiseng TSF as highlighted on the surface water monitoring points map (Figure **4-13**). The sample points are DDB02, DSL01, MPM01, MPS01, WQQ01, WRT01 and DPS01 respectively.

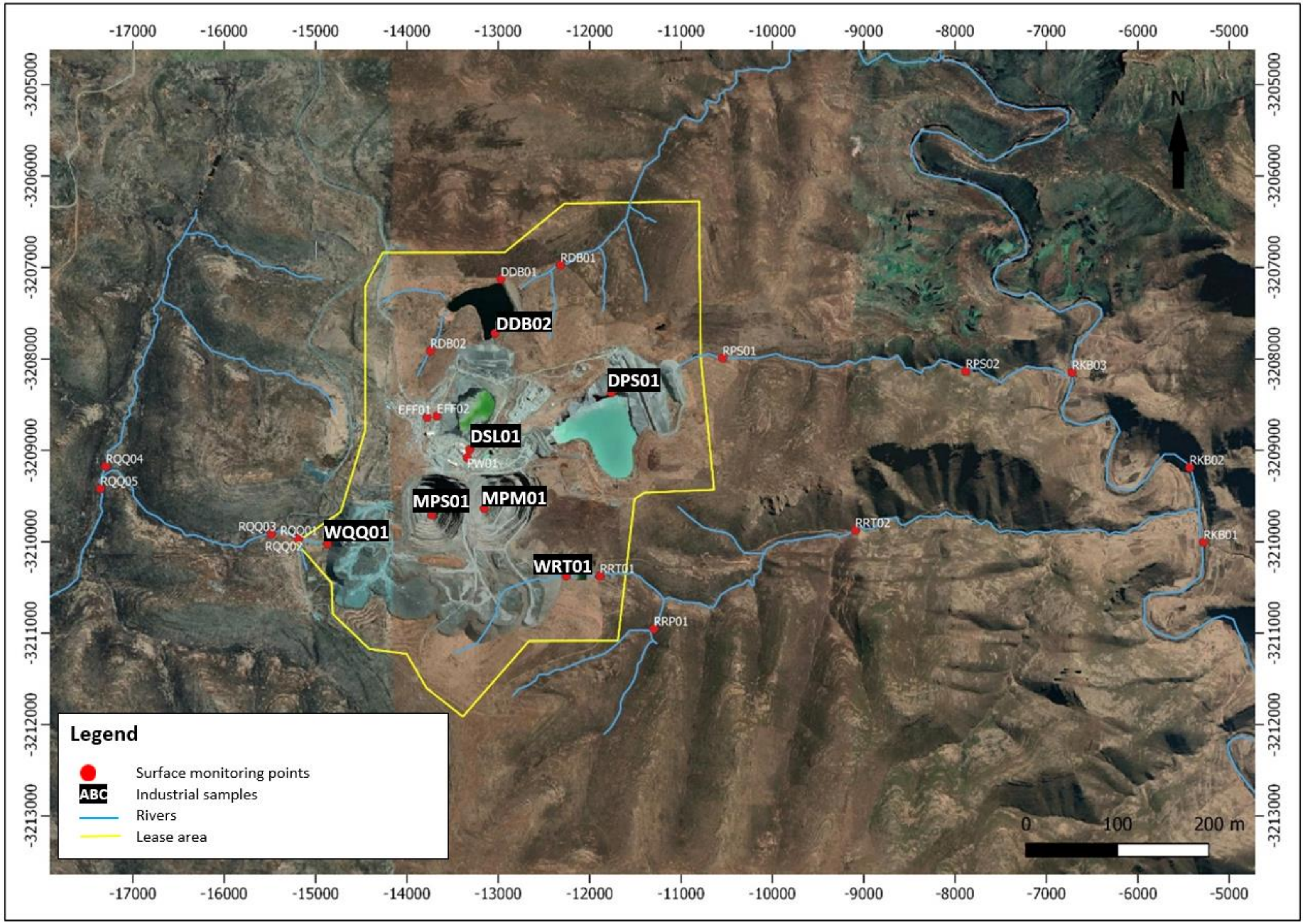

Figure 4-13 Surface water monitoring points map, highlighting sample points close to potential sources of contamination to be analysed against industrial standards.

DDB02 samples are collected monthly from the Old slimes dam wall as seepage into the Mothusi dam (Figure 4-14). The nitrate concentration were observed to exceed the industrial water quality standards from 2015 throughout the monitoring period. Although slightly below the recommended standard, sulphate concentrations are constantly elevated during the dry and wet season, meaning there in no significant dilution of the contaminant with increased rainfall and therefore indicating that there is a high risk of contamination of both nitrates and sulphates from the Old slimes Dam.

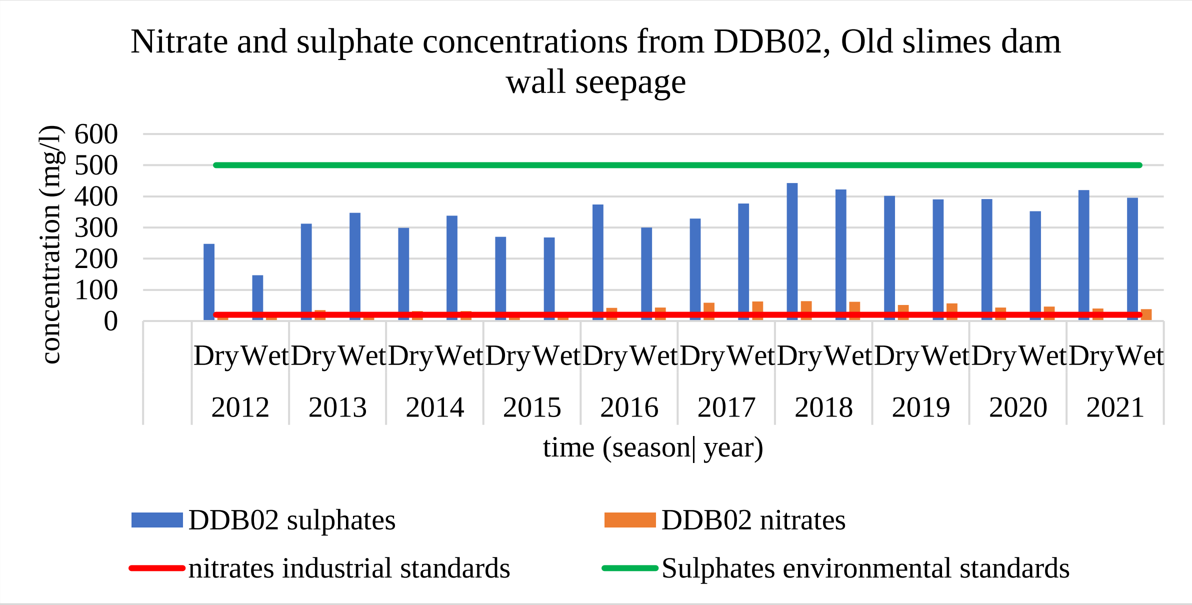

Figure 4-14 Nitrate and sulphate concentrations from 2012 to 2021 on DDB02, a sampling point downstream of Old slimes dam.

DSL01 sampling point at of the Old slimes dam is sampled on a quarterly basis. DSL01 has had nitrate concentrations above recommended nitrates standards since 2012 to date, however the concentrations remain below 100 mg/l . DSL01 sulphate concentrations started increasing significantly in 2016 and have been fluctuating around 400 mg/l throughout the monitoring period, with a sharp increase in 2019 and a decrease thereafter (Figure 4-15). This also confirms the Old slimes dam as potential sources of contamination.

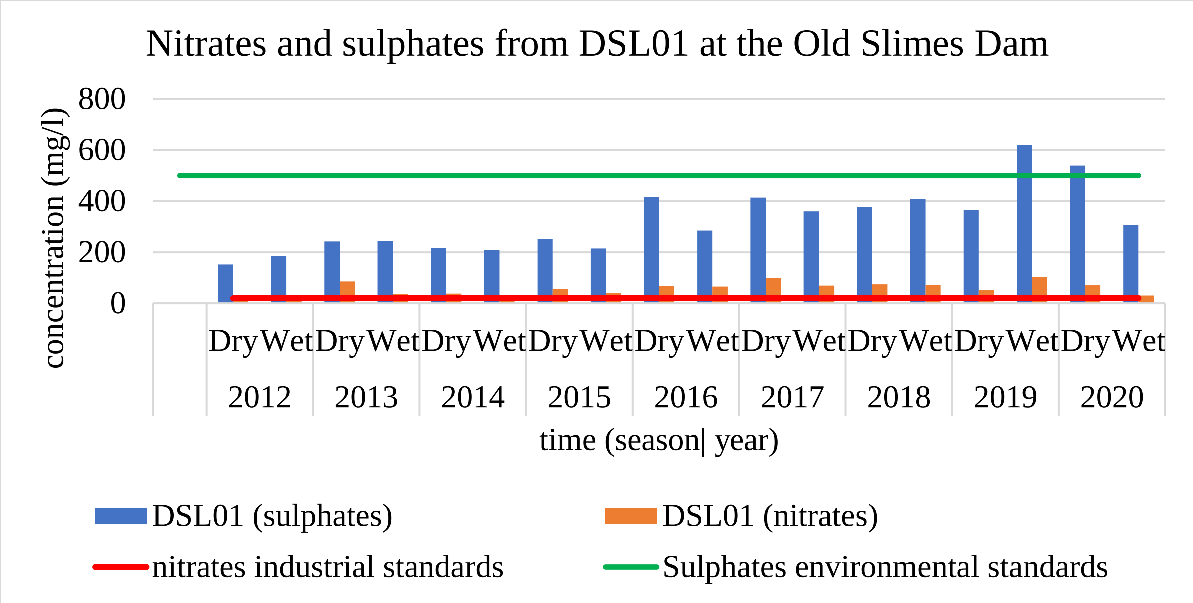

Figure 4-15 Elevated concentrations of nitrates and sulphates at DSL01 a sampling point at the Old slimes dam, confirming potential source of contamination.

Samples were also collected from both pits, MPS01 from Satellite pit and MPM01 from Main pit from 2015 to 2021. Figure 4-16 shows concentrations from Satellite pit, the nitrate concentration is constantly above the recommended standard throughout the monitoring period. Sulphate concentrations are lower throughout the monitoring period, this means the main contaminant of concern from the Satellite pit is nitrate. Although nitrates concentrations are still above standard in the Main pit, the concentration of sulphates is higher compared to concentrations in the Satellite pit. Sulphate concentrations also exceed the recommended standards over during certain sampling periods, going up to 2000 mg/l during the 2021 monitoring period Figure 4-17. The elevated sulphates concentrations could be from the exposed shear zone in the Main pit, which consist of sulphur-rich pyrite.

A significant difference is seen in concentrations during dry and wet seasons, decreasing in the wet season. This could be a result of surface run off into the pits during wet seasons, diluting the water. Water that is pumped from the pits can therefore be a source of contamination and therefore needs to be managed appropriately.

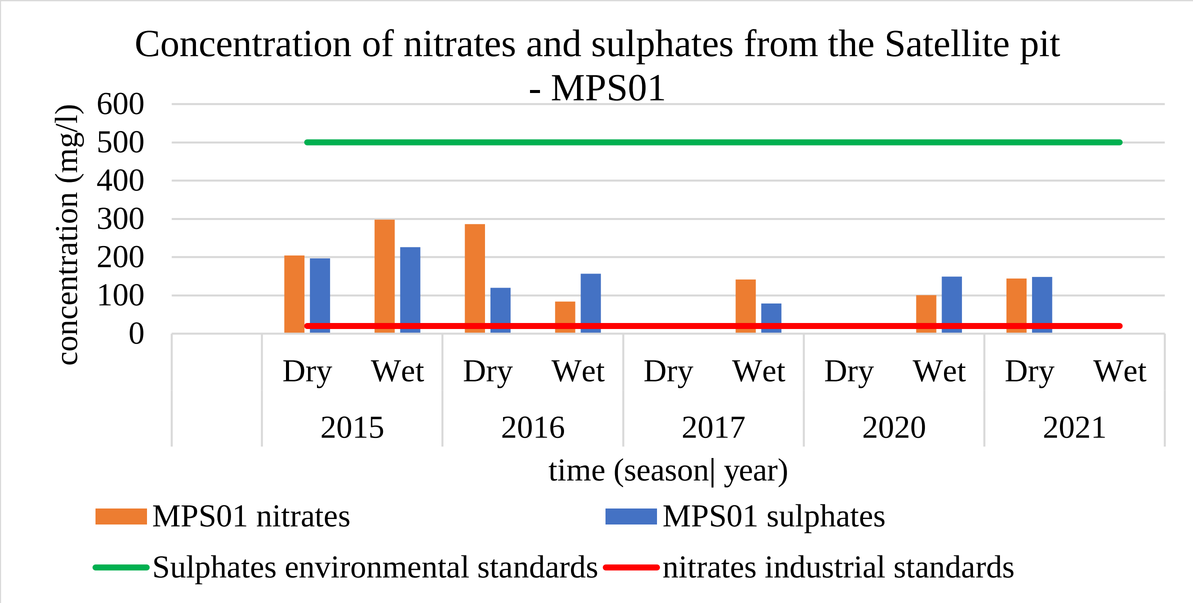

Figure 4-16 Concentration of nitrates and sulphates from the Satellite pit, showing elevated nitrate concentrations from 2015 to 2021.

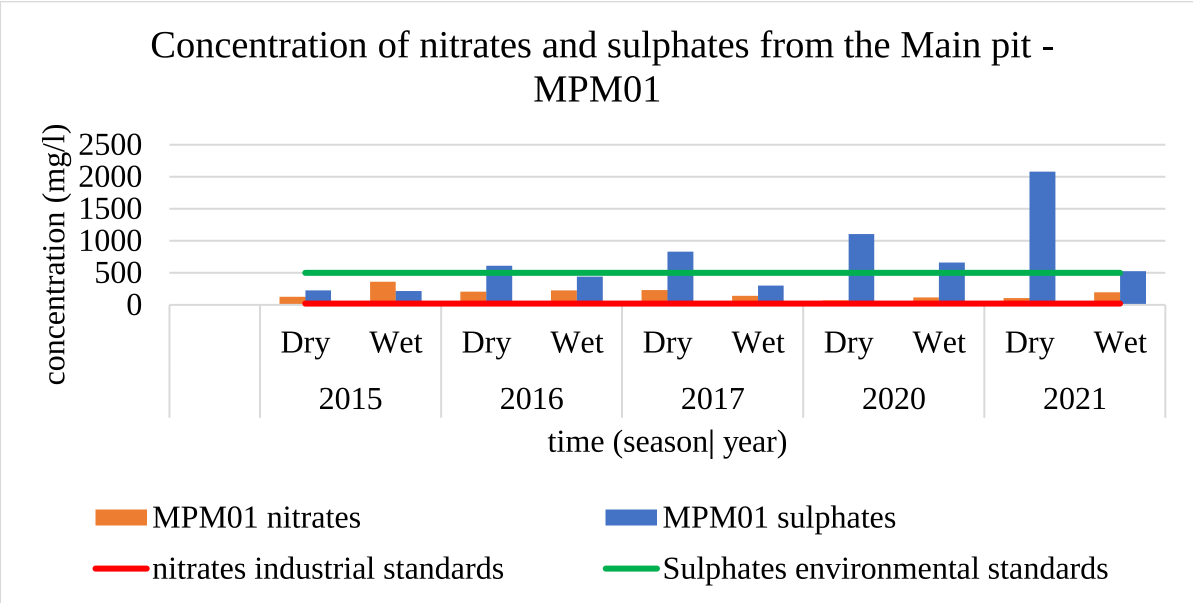

Figure 4-17 Plot showing elevated concentration of nitrates and sulphates from Main pit exceeding recommended limits.

To determine the water quality around the WRDs, outflow from both the western (WQQ01) and eastern (WRT01) waste rock dumped is tested. The graphs presented in Figure 4-18 and Figure 4-19 show concentration of nitrates and sulphates during the dry and wet season throughout the sampling period. WQQ01 shows elevated nitrate concentrations exceeding the recommended standards throughout the monitoring period, with an average of 200 mg/l. A similar trend is seen for sulphate concentrations for this sampling point. Where the limit is exceeded during some monitoring periods, particularly during the dry season.

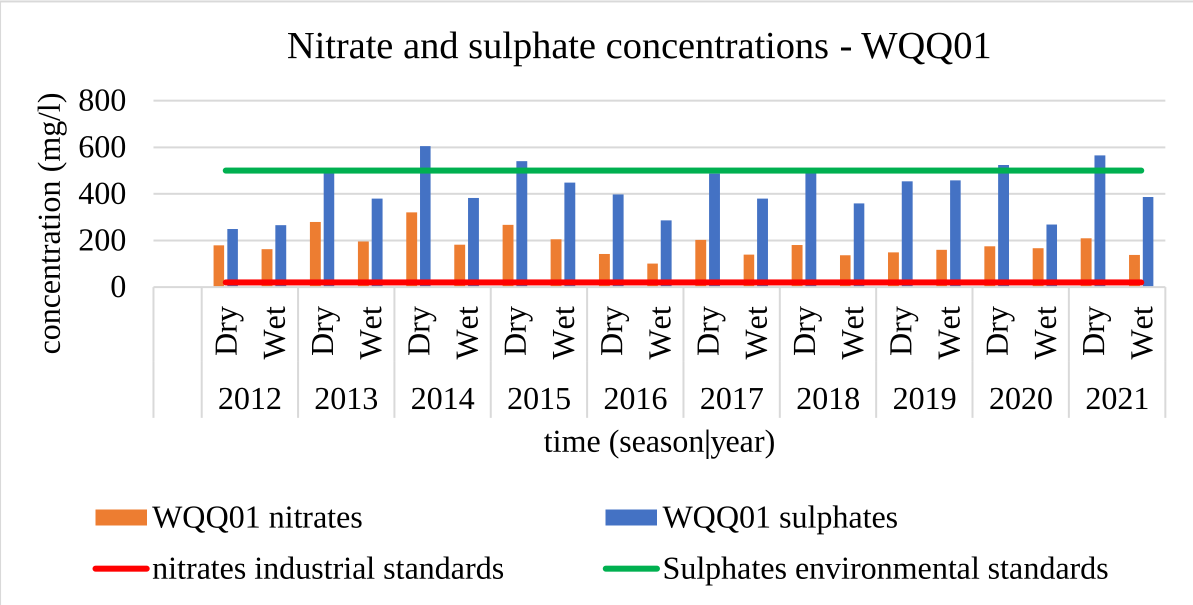

Figure 4-18 Nitrate and sulphate concentrations from WQQ01 showing elevated concentrations Western WRD outflow.

Nitrate and sulphate concentrations are also elevated for WRT01, with increasing concentrations overtime from 2014 to 2021 (Figure 4-19). However, there is generally a drop in concentration level from dry to wet seasons. Rainy seasons create buffer system for the contaminant hence the decrease in concentration during the wet seasons. Both areas can therefore be identified as significant sources of contamination through outflow or seepage from WRD. This could be a result of WRD leachate from nitrate containing explosives.

Seepage from Patiseng TSF is sampled at DPS01 and the results showed nitrate concentrations exceeding environmental water quality standards as well as high sulphate concentrations with average of 400 mg/l (Figure 4-20). The nitrate concentrations have also remained above recommended nitrates standards since 2012, decreasing from 2020. Although there is a drop in concentration during the wet season, the difference is not significant, meaning the concentration levels here are not significantly affected by seasonal variations. It can therefore be confirmed that the Patiseng TSF is a potential source of contamination of both nitrates and sulphates.

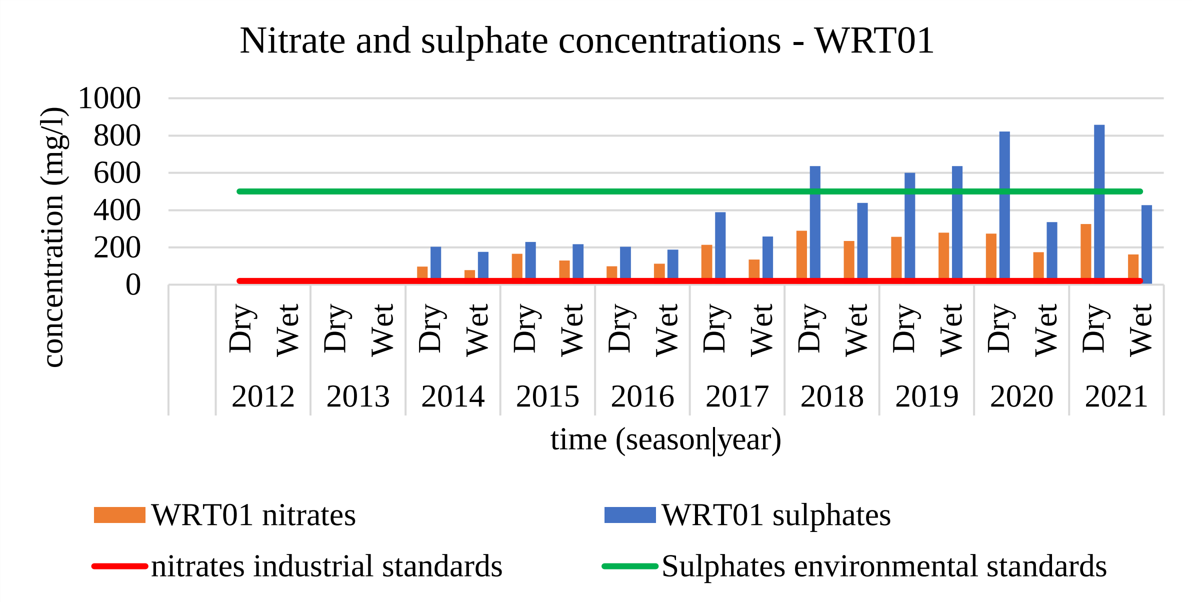

Figure 4-19 Concentration of nitrates and sulphates from the Eastern WRD out flow exceeding recommended standards.

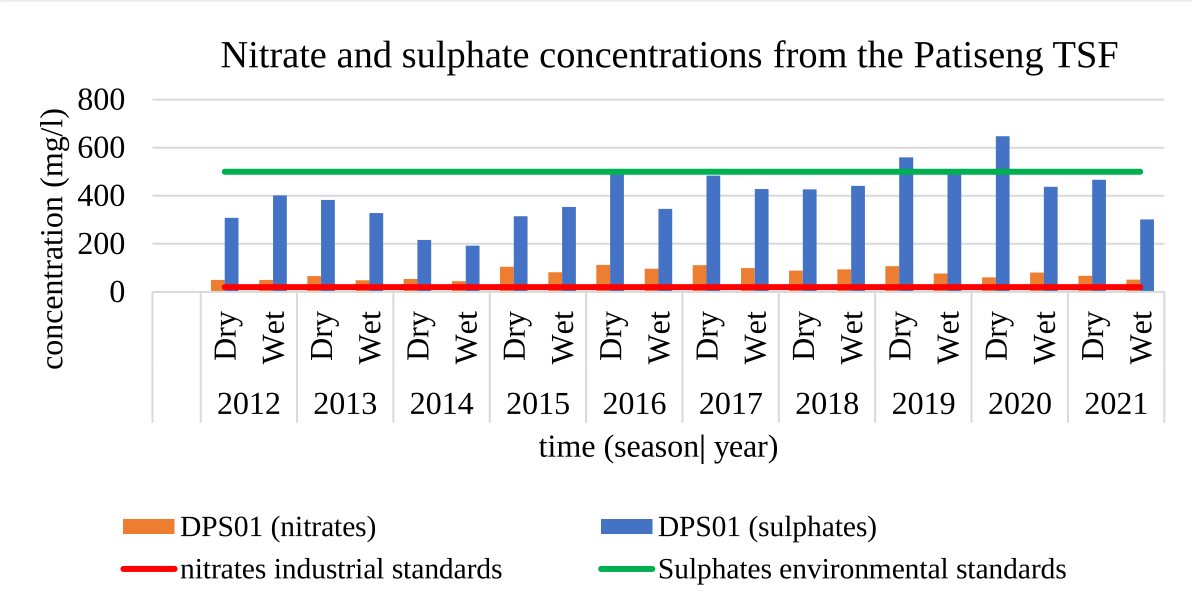

Figure 4-20 Elevated concentrations of nitrates and sulphates from DPS01 at the Patiseng TSF, thus a potential source of contamination.

Based on results from the water samples collected along the mine infrastructures and mining operations, the nitrate and sulphate concentrations are generally high and, in some areas, exceed the recommended standards for industrial water quality. This concludes that the mine water quality is non-compliant to the water quality standards, and therefore needs to be managed adequately to minimise water contamination. It is also important to assess whether these activities affect the surrounding environment.

4.1.3.3.2 Environmental water sampling

Data from sampling points around the mining area was analysed to determine the status of water quality of the environment surrounding the mine. The water quality is compared to recommended environmental water quality standards by SANS 241 (2015) and DWAF (1996) guidelines. For nitrate concentration the environmental limit is 6 mg/l, while for sulphate concentration the limit is 500 mg/l. Figure 4-22 highlights the sample points which were analysed, these are points mainly downstream of the identified potential sources of contamination into the surrounding environment and beyond the mine lease area.

Sampling point DDB01 is located at Mothusi dam. Both nitrate and sulphate concentrations are below the recommended limits, with a slight increase above the nitrate limits in 2021 (Figure 4-21). Water quality of Mothusi Dam therefore needs to be carefully monitored for nitrates overtime, to determine how the nitrate concentrations will change overtime and whether there is a chance of the dam being contaminated.

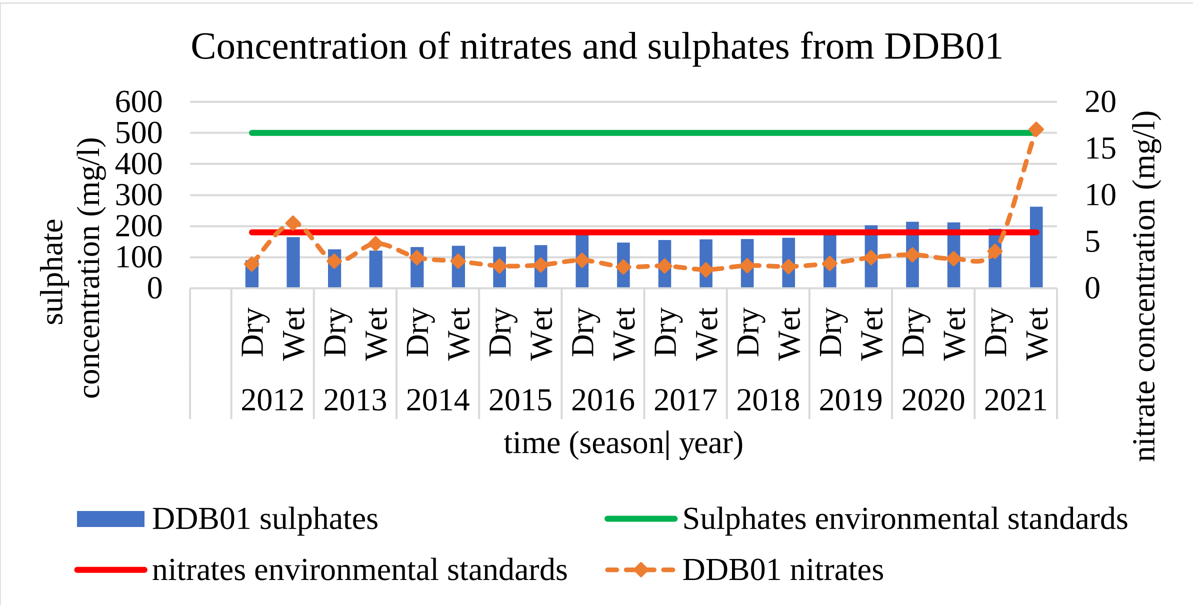

Figure 4-21 Concentration of nitrates and sulphates from sampling point at out flow from Mothusi dam, with a sharp increase in 2021.

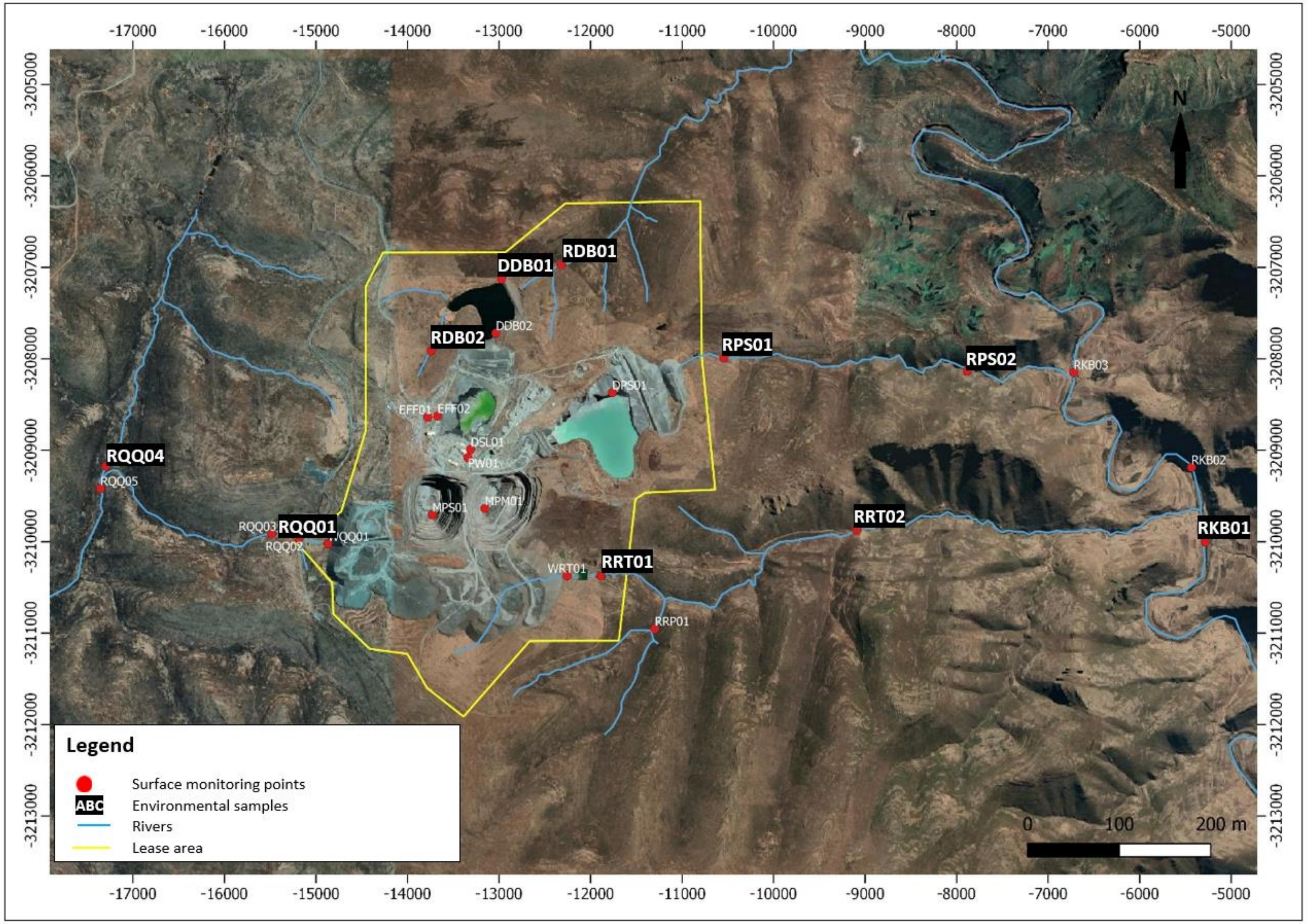

Figure 4-22 Surface monitoring points map, highlighting sample points analysed for water quality against environmental standards. The points are downstream of potential sources of contamination.

Other sampling points in this area are RDB01 which is downstream of Mothusi dam (Figure 4-23) and RDB02 (Figure 4-24), a wetland upstream of the mine. Both points show relatively good water quality similar to water quality from the dam itself. This could mean that there is no significant contamination in the vicinity of Mothusi dam, and there area can be ruled out as a potential source of contamination.

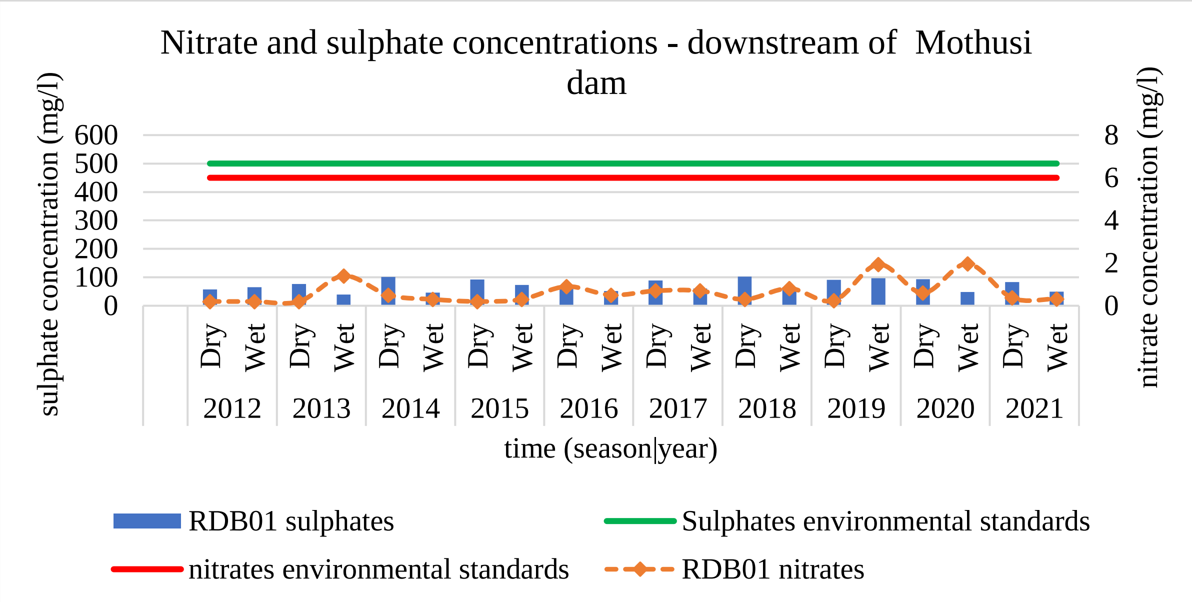

Figure 4-23 Nitrate and sulphate concentrations downstream of Mothusi dam showing compliant water quality, with concentrations well below the recommended standard.

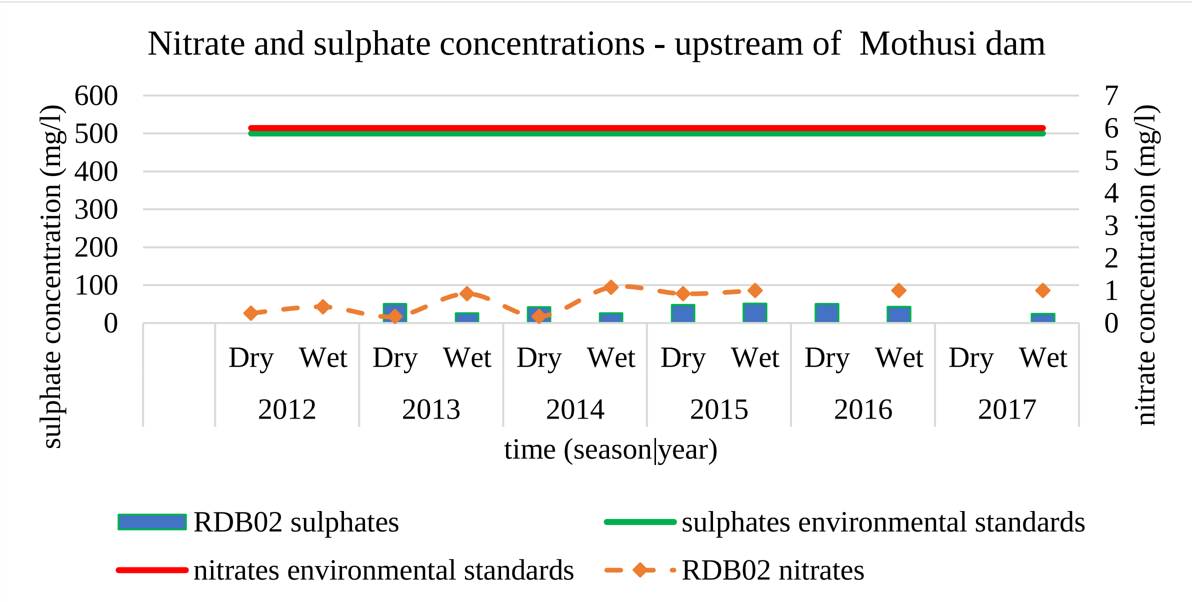

Figure 4-24 Nitrate and sulphate concentrations upstream of Mothusi dam showing compliant water quality, with concentrations well below the recommended standard.

Within the Patiseng catchment, RPS01 (downstream of the TSF) and RPS02 (further downstream, flowing into the main river) sampling points monitor water flowing from the mine into the Patiseng stream showed poor water quality with nitrate concentrations up to 100 mg/l and sulphate concentrations that exceed 700 mg/l for RPS01 (Figure 4-25 and Figure 4-26). For RPS02, nitrate and sulphate concentrations were measured that exceed 800 mg/l. The nitrate concentration is from blasting residue leaching through the tailings. Therefore, there is a risk of contamination of water within this catchment, which could affect the surrounding environment.

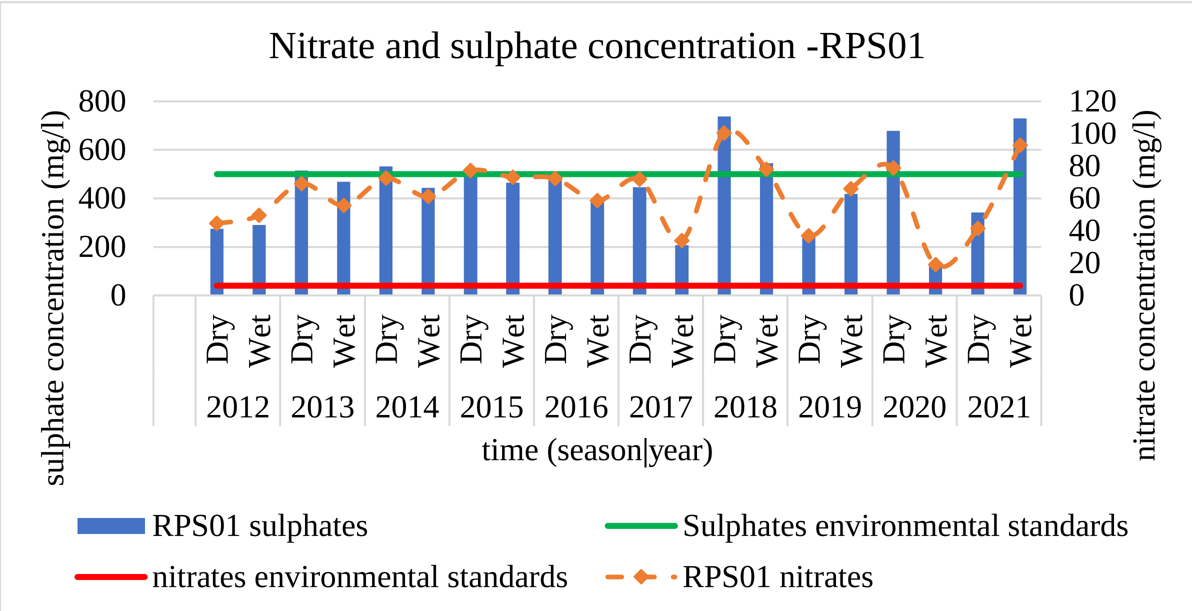

Figure 4-25 Nitrate and sulphate concentrations downstream of the Patiseng TSF seepage showing elevated concentrations, thus risk of contamination.

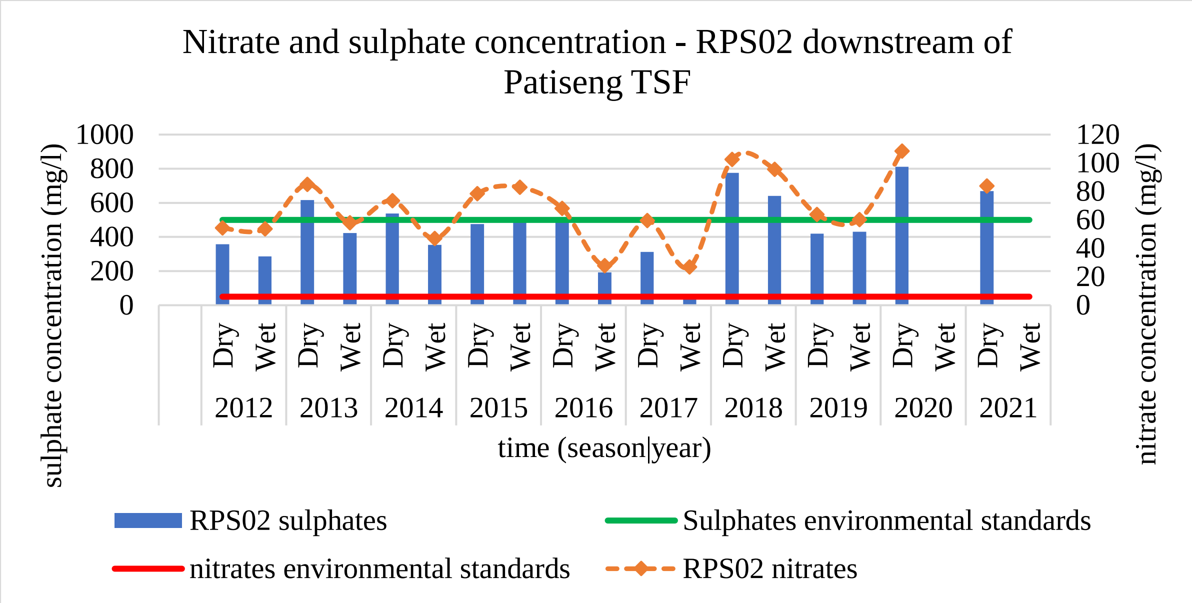

Figure 4-26 Nitrate and sulphate concentrations further downstream of Patiseng TSF towards the Khubelu river, exceeding the recommended limits.

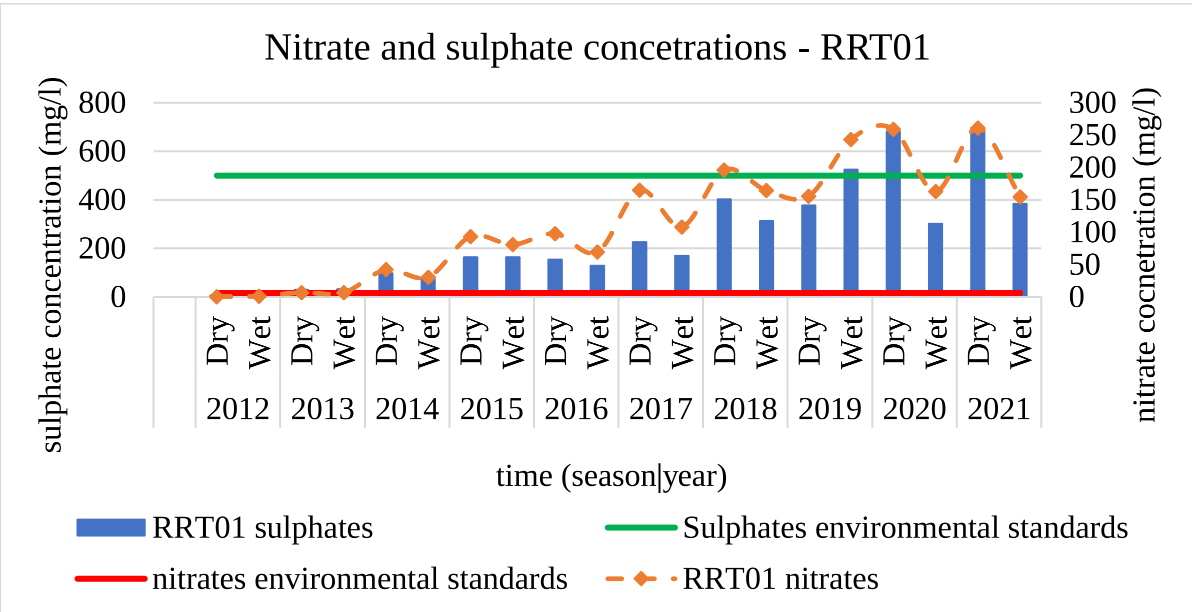

Figure 4-27 Nitrate and sulphate concentrations downstream of seepage from Eastern WRD increasing overtime.

The RRT01 sampling point is located downstream of the WRD in the east, while RRT02 is further downstream towards the river. Both samples show elevated concentrations of nitrates and sulphates, both being non-compliant to environmental water quality standards. RRT01 shows the highest concentrations for nitrates and sulphates (Figure 4-27) as compared to RRT02 which is further downstream (Figure 4-28). It can also be seen that the concentrations are higher during dry periods as compared to wet periods. With RRT01 and RRT02 trends, there is a risk of the Khubelu River in the far East of the mine being contaminated from sources upstream, namely Patiseng TSF and the WRD.

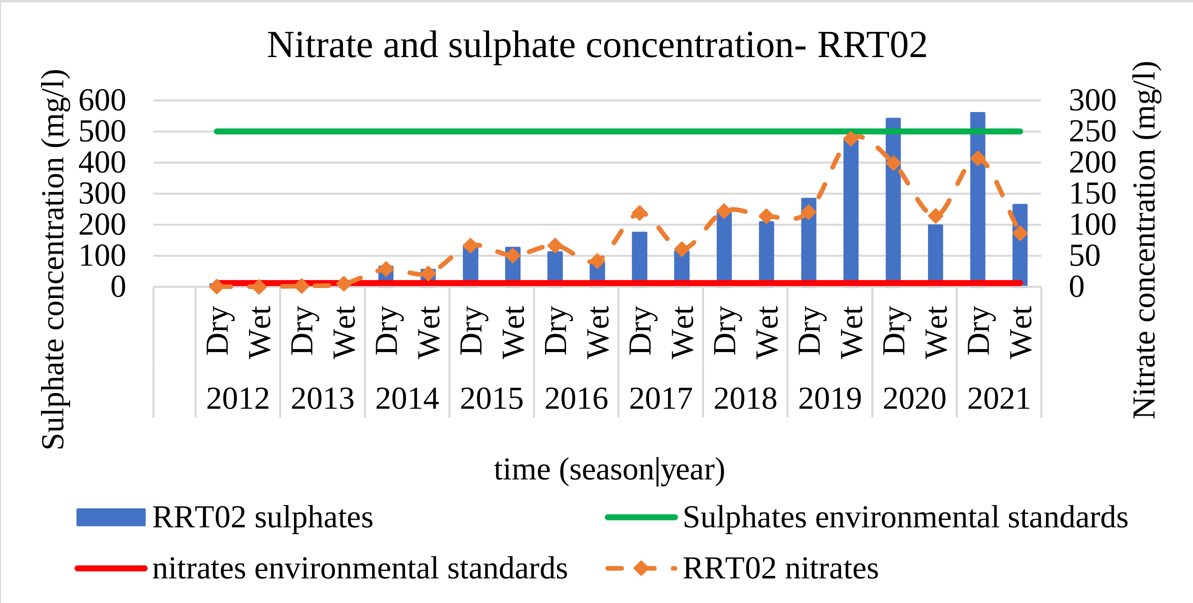

Figure 4-28 Nitrate and sulphate concentrations further downstream of the Eastern WRD into the stream increasing overtime and exceeding recommended limits.

RKB01 is a point at the main river (Khubelu River), which is important to sample for potential contamination from upstream. The nitrate concentrations in RKB01 are fluctuating throughout the monitoring period, exceeding the recommended limits during most monitoring periods. Sulphate concentration however remain below the environmental limits throughout the monitoring period (Figure 4-29). Taking into consideration sampling points upstream of the tributaries draining the mine (RPS01, RPS02 and RRT02), contaminant concentrations are constantly increasing overtime, this could imply a contribution to the increasing concentrations in the Khubelu river. It therefore important to put in place actions towards controlling and mitigating the impacts.

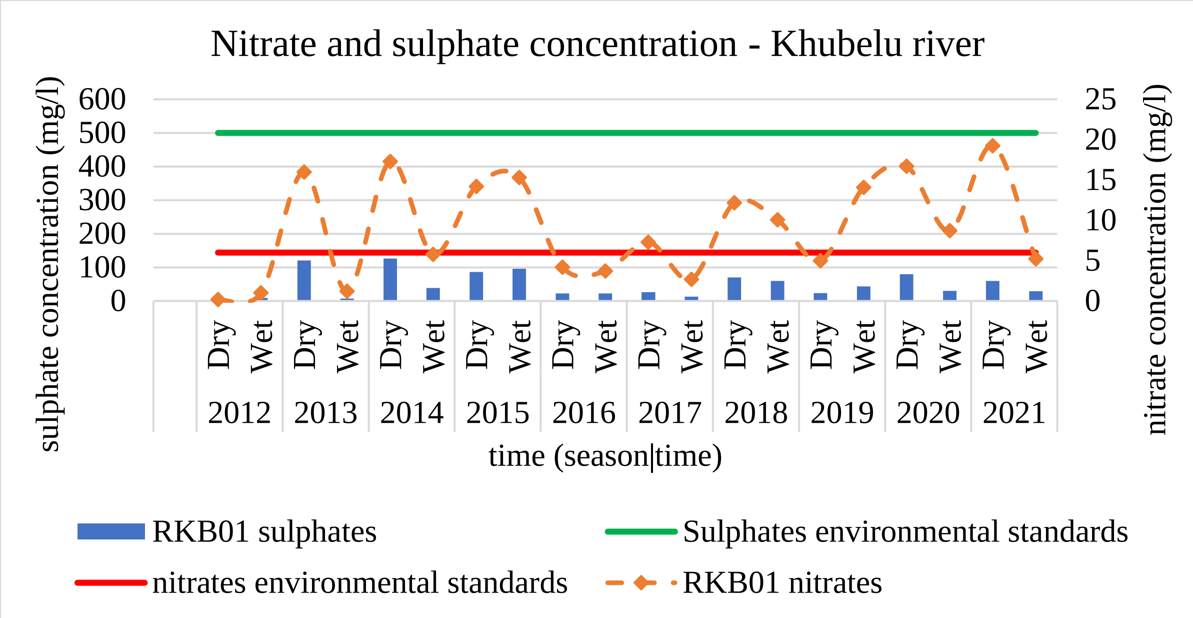

Figure 4-29 Elevated nitrate concentrations and lower sulphate concentrations along the Khubelu River, further downstream of the mine in the East.

RQQ01 and RQQ04 samples are collected downstream of the Western WRD. RQQ01 is closer to the WRD while RQQ04 is further downstream along the Qaqa River (also considered to be reference sampling point). Figure 4-30 shows that RQQ01 concentrations for nitrates are consistently high above the limits throughout the monitoring period. The Sulphate concentrations are also high throughout the monitoring period and slightly exceed the recommended standard during the dry season of the 2014, 2015 and 2021 monitoring period. These trends suggest that that there is a risk of contamination from the WRD into the nearby environment. This should be addressed to minimize contamination further downstream. This means the river is at risk of contamination and action should be taken towards this.

From the RQQ04 sampling point, both sulphate and nitrate concentrations are relatively low throughout the monitoring period, although an increase is seen from 2020, where both concentrations start to increase and nitrate concentrations exceed the limits (Figure **4-31**). Mitigation measures therefore need to be put in place to minimize contamination into the river from the WRD.

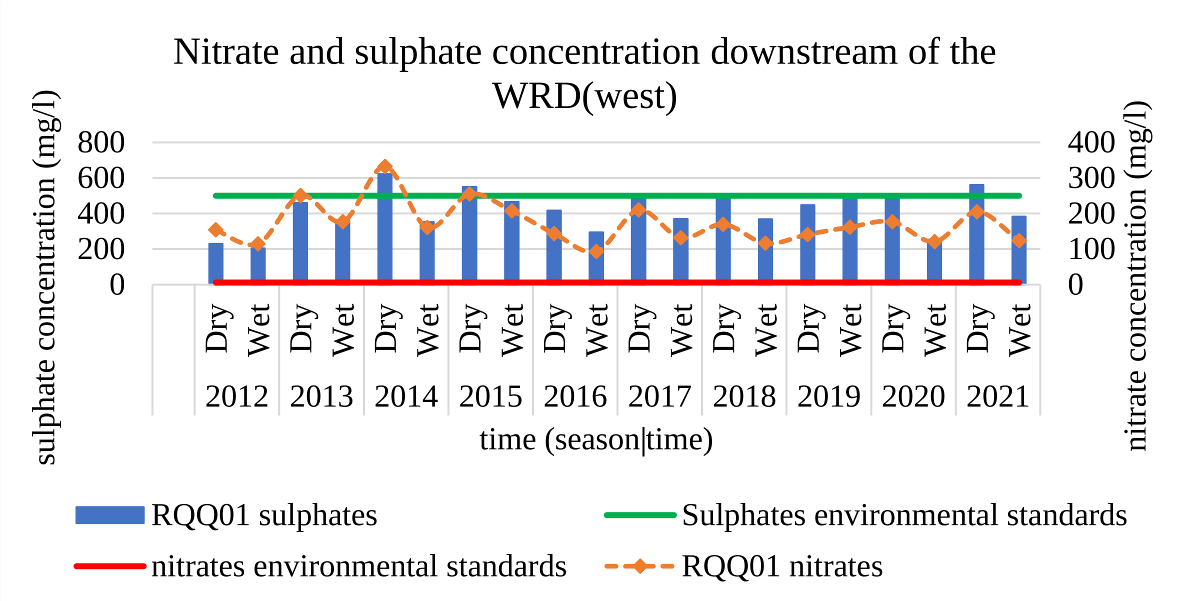

Figure 4-30 Elevated nitrate and sulphate concentrations downstream of the seepage from western WRD.

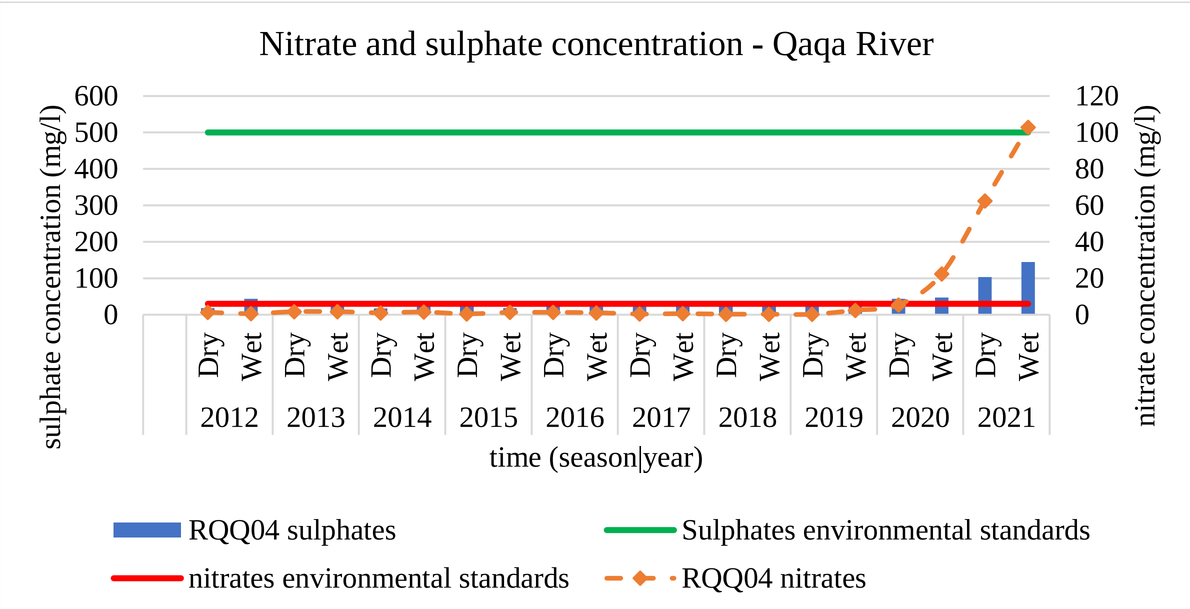

Figure 4-31 Nitrate and sulphate concentrations further downstream of western WRD along the Qaqa river, with increase in concentration from 2020.

Based on the surface water quality analysis discussed above, it can be noted that the water from the Old slimes dam, Pits, WRDs and Patiseng TSF show elevated nitrates and sulphates concentrations exceeding the recommended industrial limits. These areas can therefore be classified as potential sources of contamination. With increasing concentrations over time there is a risk of contamination of other water resources which feed from these areas, as samples downstream from these sources show increasing concentrations, in some cases exceeding the recommended environmental standards. Data also shows that contaminant concentrations are starting to increase along the main rivers which surround the area, making them possible receptors of contamination. The Qaqa River which is on the West of the area is at the risk of contamination by the WRD upstream, while the Khubelu River is prone to risk by contamination from both the eastern WRD and the Patiseng TSF. Hence both areas are potential pathways of contaminants considering the concentration levels along these streams.

4.1.3.4 Groundwater quality

The groundwater monitoring network has been designed to monitor the six potential pollution sources: Patiseng TSF, Old Slimes Dam, Mine pits, Workshop, Waste Rock Dump (WRD) West and Waste Rock Dump (WRD) East and their associated pathways. Groundwater samples are collected quarterly from the monitoring boreholes located around these areas to determine the status of groundwater quality (Figure 4-8). Nitrates and sulphates concentrations in groundwater over the monitoring period (2013-2022) are analysed against the SANS (241) drinking water standards. For nitrates concentrations, the recommended limit is 11 mg/l and 500 mg/l for Sulphate concentrations.

At the Patiseng TSF, borehole L_WE_003 and borehole L_WE_004 are sampled to determine the impact of the TSF on the groundwater quality. The boreholes both indicated acceptable water quality with nitrate concentrations fluctuating overtime although remaining below the recommended limits Figure 4-32. The sulphate concentrations are also constantly below recommended limits throughout the monitoring period. This means that there is currently no significant contamination of nitrates or sulphates from the TSF into groundwater.

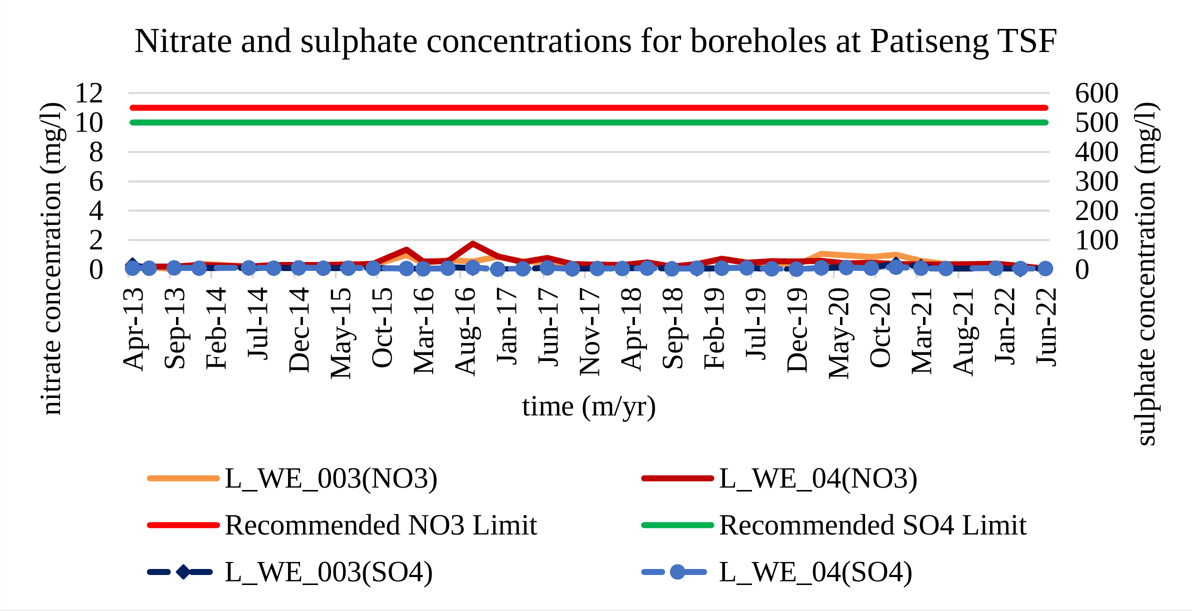

Figure 4-32 Nitrate and sulphate concentrations for boreholes L_WE_03 and L_WE_04 showing complaint groundwater quality.

Boreholes L_WE_007 and L_WE_011 located by the Main Pit show low concentrations of sulphates and nitrates over time (Figure 4-33). This could imply that there are no significant impacts from mining activities surrounding the Main Pit on groundwater.

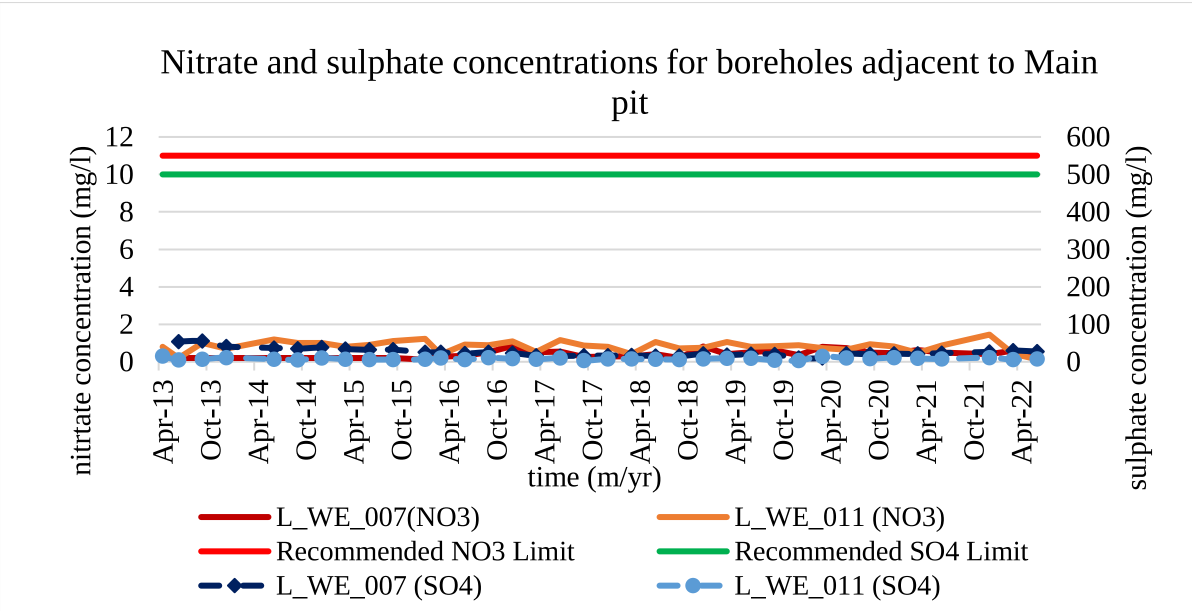

Figure 4-33 Nitrate and sulphate concentrations for boreholes L_WE_07 and L_WE_11.

Borehole L_WE_008 is in the south of the WRD-east, while borehole L_WE_010 is down-gradient of the WRD-east. When compared to the Lesotho Water Quality standards, borehole L_WE_008 was compliant with the standard for both nitrate and sulphate concentrations. This borehole is considered to have background groundwater quality, where there are not impacts from mining activities. It can be used as a reference point for other boreholes. On the other hand, borehole L_WE_010 consistently shows nitrate concentrations exceeding the recommended water quality standards, while remaining below the limits for sulphate (Figure 4-34). This could be a result of seepage from WRD which then contaminants the groundwater. Measures need to be put in place to minimise groundwater contamination from this source.

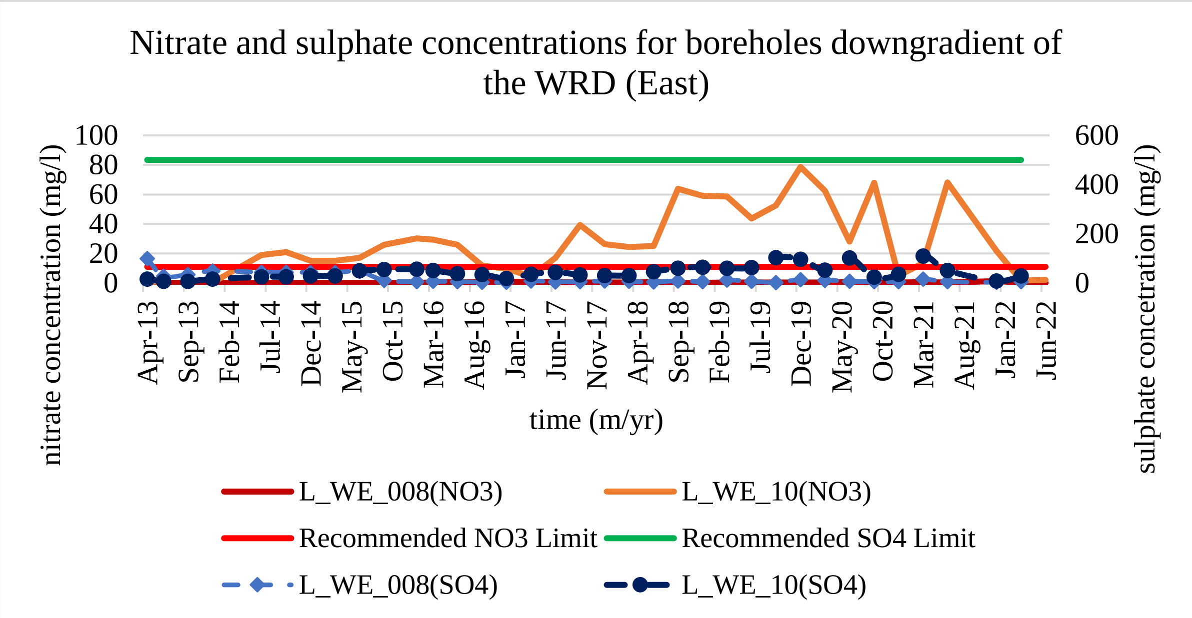

Figure 4-34 Nitrate and sulphate concentrations for boreholes L_WE_08 with good groundwater quality and L_W_010 with elevated Nitrate concentrations beyond the recommended limit.

In the Qaqa valley, down-gradient of the WRD-west is borehole L_WE_012. The water quality for this borehole is compliant to the water quality standards with nitrate concentrations decreasing from 2014 and remaining relatively constant over the years. A sharp increase has been observed in the 2019 monitoring period into 2021/22. A similar trend is also seen with sulphate concentrations (Figure 4-35). The groundwater quality here is complaint to recommended standards but must be monitored for potential contamination from the WRD.

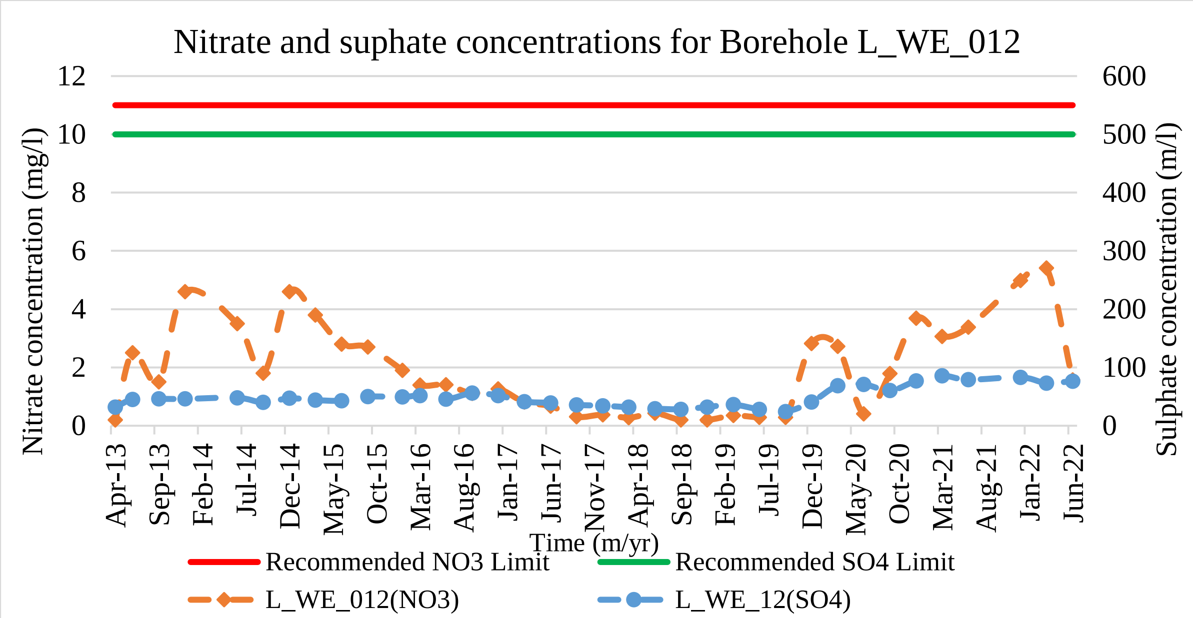

Figure 4-35 Nitrate and sulphate concentrations for borehole L_WE_12 downgradient of the WRD (west), below recommended limits.

Boreholes L_WE_015 and L_WE_016 are located down-gradient of Mothusi dam and Old Slimes dam, respectively. For both boreholes, nitrate and sulphate concentrations have remained low over time (Figure 4-36). Both boreholes are compliant to water quality standards and have not been exposed to significant contamination.

Boreholes L_WE_014 and L_WE_017 are situated up gradient of the Old slimes dam and plant area. The hydrochemical results for both boreholes indicated non-compliant water quality (Figure 4-37 and Figure 4-38). Boreholes L_WE_014 was not accessible in 2020 and was not sampled. Nitrate concentrations were elevated, exceeding the Lesotho Water Quality Guidelines limit since September 2016 and June 2017, respectively. A similar trend is seen for sulphate concentrations. Although the sulphate concentrations are below recommended limits throughout the monitoring period, they start showing an increase from 2018, implying possible seepage from the Old slimes dam or from stockpiling nearby, which eventually affects the groundwater quality in this area

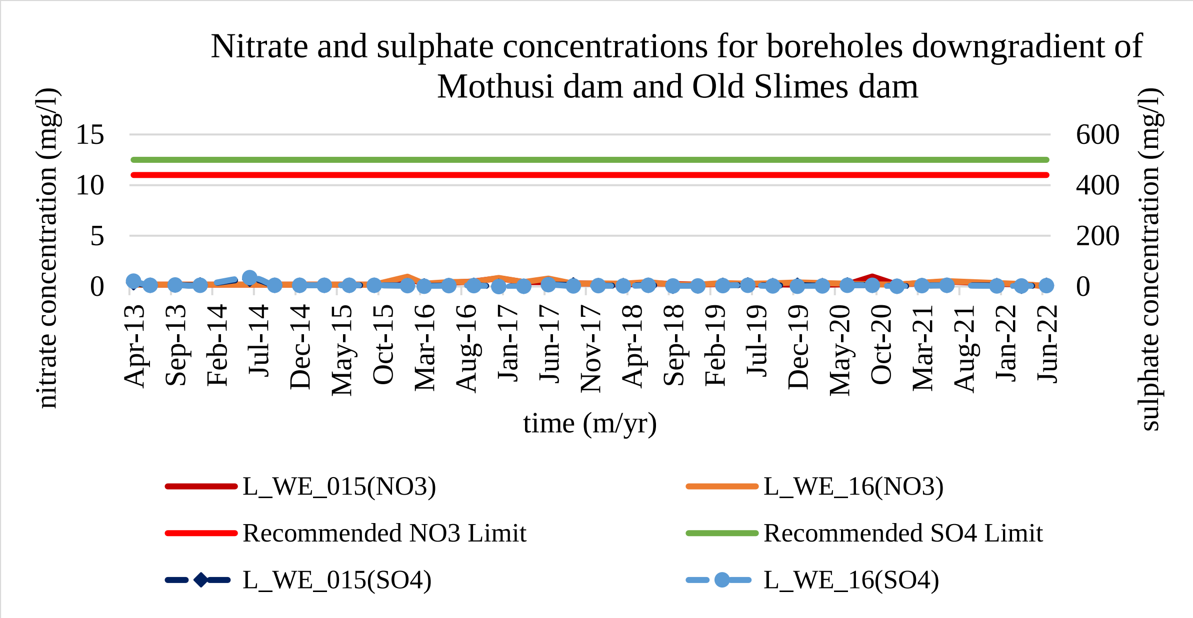

Figure 4-36 Nitrate and sulphate concentrations for boreholes L_WE_15 and L_WE_16, with compliant groundwater quality.

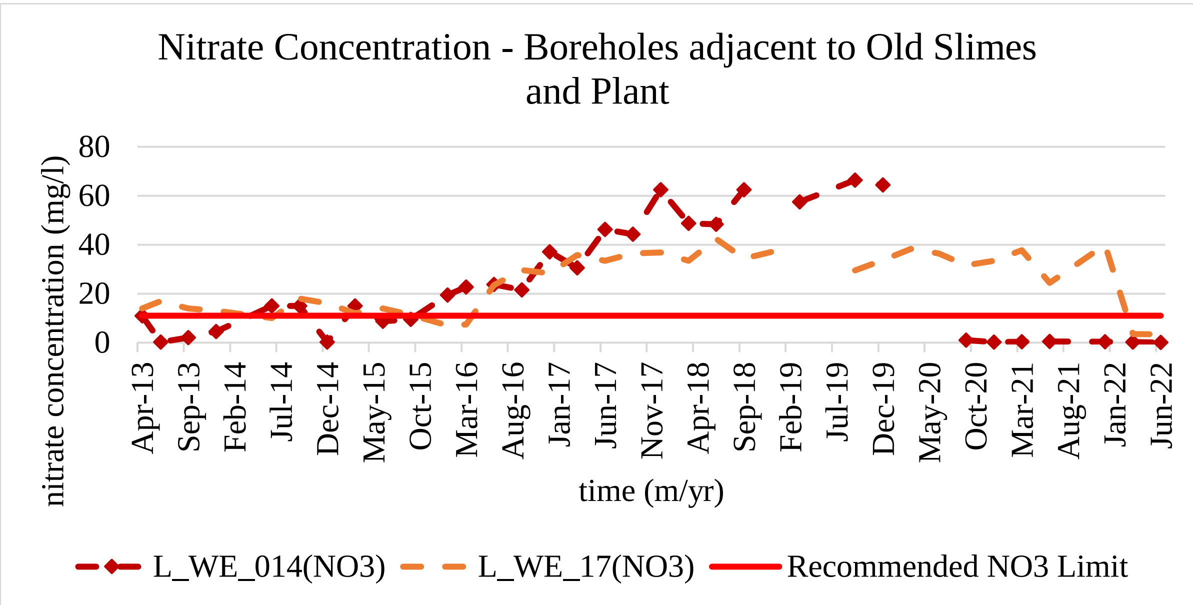

Figure 4-37 Nitrate concentrations for boreholes L_WE_014 and L_WE_017 exceeding limits from 2016.

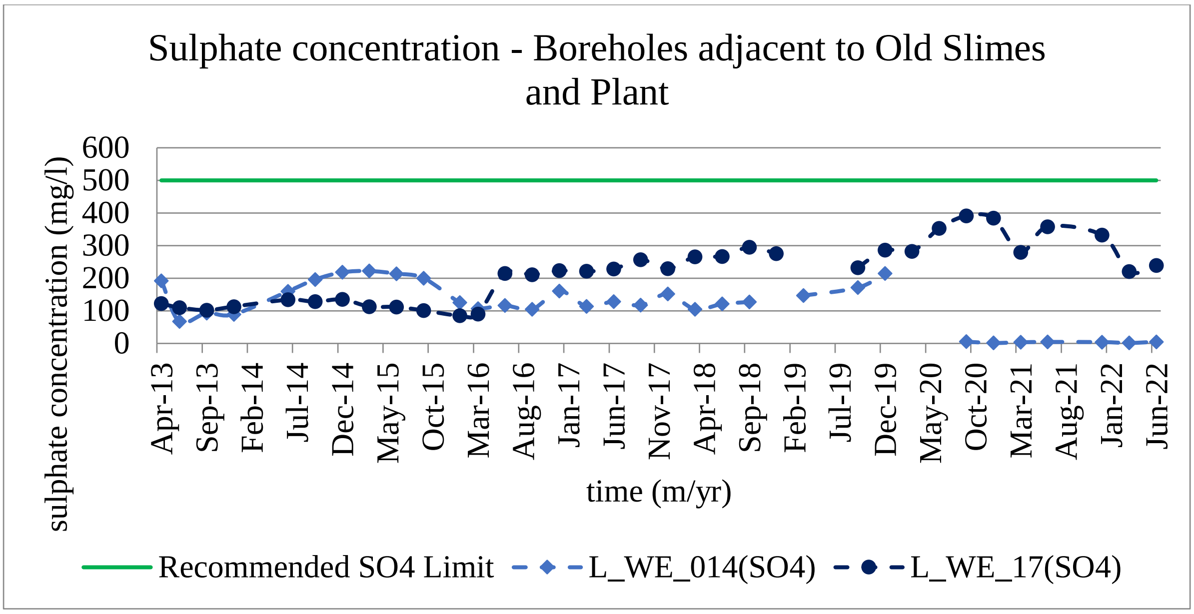

Figure 4-38 Sulphate concentrations for boreholes L_WE_014 and L_WE_017, below the limits throughout the monitoring period.

Although the groundwater quality data shows that most areas do not indicate significant impact from the mine, such as boreholes L_WE_003, L_WE_004, L_WE_008, L_WE_011, L_WE_015 and L_WE_016. There are still areas of concern which show exceeding concentrations such as boreholes L_WE_010, L_WE_014 and L_WE_017 which are currently affected by localised mining activities. Collating both the surface water and groundwater quality data gives a holistic understanding of status of the water quality of the area. It can therefore be concluded that based on the data, the areas with the highest potential for contamination are Patiseng TSF, Old Slimes dams and WRDs. These areas will therefore be the focal point for modelling the impacts of mining on groundwater quality at LDM.

4.2 CONCEPTUAL MODEL

To establish the impacts of mining at LDM on groundwater, it is important to understand the hydrogeological system of the area. A conceptual model is a pictorial representation of the groundwater system in relation to the hydrogeologic units, system boundaries, hydraulic and transport properties as well as their spatial variability (Peach and Taylor, 2022). The purpose of a conceptual model is to gain a good understanding of the groundwater system to identify pressures on the system and the relevant physical processes within it.

The conceptual model can be utilised for groundwater status risk assessment and pollution risk assessment. It can also be used as a basis for building a numerical flow model for both the saturated and unsaturated zones, to determine the impacts on groundwater quality (Nakic et. al., 2013). Risk assessment seeks to establish a relationship between the occurrence of a risk or pressure along an environmental pathway and adverse effects on human health or the environment. This is typically referred to as an SPR (source-pathway-receptor) paradigm (Nakic et. al., 2013). This approach was employed into the conceptual model to describe how pollutants move from a source along a conducting pathway to a receptor in the field of environmental contamination (Holdgate, 1979).

The conceptual model therefore contains the geological and hydrogeological characterisation of the groundwater system and the description of the most significant sources and pathways of contamination and the processes that influence its behaviour in the groundwater system (Figure 4-38). The preceding sections provide information which can be summarised to understand the hydrogeological regime of the area and thus be used to develop the conceptual model.

4.2.1 Physical framework

The geology of LDM comprises of basaltic lavas which form country rock to kimberlite intrusions. The borehole logs and field observations provide an insight on the local geology, where the upper zone is mostly weathered and fractured while the middle zone is moderately fractured, and the lower zone is mostly competent.

Aquifer geometry and estimation of hydrodynamic properties

Due to the competent nature of basalt, there is low to moderate groundwater potential at Letšeng. The groundwater system can be defined by the saturated and unsaturated zone. The unsaturated zone lying within the upper weathered zone, while the saturated zone is characterised by joints and fractures which form preferential pathways for groundwater flow in the competent basalt at deeper levels. The upper zone can be classified as an unconfined system, whereas the competent zone, with limited groundwater flow can be classified as a confined system.

Based on the data collected, the hydraulic conductivity within the study area is relatively low and varies spatially implying that groundwater movement is mainly controlled by the presence of fractures. The upper zones of the basalt are highly weathered influencing higher hydraulic conductivity as compared to the lower zones, where the hydraulic conductivity is lower, and the water movement is mainly controlled by the secondary permeability along minor fractures and the contact zone between the basalts and kimberlite intrusions.

Based on the data analysis, the hydraulic conductivity for the upper weathered zone ranges between ~0.01 - 0.4 m/day and ~0.001 - 0.3 m/day for the fractured zone. As the basalt becomes more competent with depth, the hydraulic conductivity decreases. At greater depth of up to 430 mbgl, the hydraulic conductivity decreases further, ranging between ~ $1x10^{-4}$ – $1x10^{-3}$ m/ day. Table D summaries the hydraulic conductivities for each hydrogeological unit.

Table D Hydraulic conductivity range for each hydrogeological unit.

Geological zone	Hydrogeological units	Thickness (mbgl)	K (m/d)
Weathered Basalt	Unconfined	15	~0.01 - 0.4
Fractured Basalt	Confined	35-50	~0.001 - 0.3
Competent/ Fresh Basalt	Confined	>430	$1x10^{-4}$ – $1x10^{-3}$

4.2.2 Hydrological framework

4.2.2.1 Recharge and Drainage

Rainfall, snowmelt, and anthropogenic sources contribute to recharge in the area. As recharge infiltrates into the subsurface, the geological structure and composition of rocks determine the flow of water into the groundwater storage. In this case, the basalt rocks are not good sources of groundwater, unless they are weathered or fractured. Taking this into account, the recharge rates for the location were estimated to be between 1% and 10% of Mean Annual Precipitation (MAP), although the basaltic aquifer loses a significant amount of potential recharge through interflow, therefore reducing the effective recharge rate (GCS, 2019).

Precipitation either infiltrates into the subsurface or flows as surface runoff. The catchment system in the area consists of four main catchments which originate from the topographical highs around the mine. Surface water therefore flows from the mine, downhill into streams and rivers following topography. The general surface drainage of the area is mainly from west to east. There are several other drainages that leads towards the west; however, these drainages are higher in elevation than the eastern drainage system.

4.2.2.2 Groundwater responses

As indicated in Figure 4-11, groundwater flow follows topography. Groundwater flow direction at LDM also mainly from the west to the east. There are currently ten active monitoring boreholes on site. Monthly measurements of groundwater levels show that the groundwater level is quite shallow with an average of 7 mbgl, meaning that the flow of groundwater is limited to the upper weathered and fractured zone.

4.2.3 Chemical framework

Groundwater and surface water chemistry can provide a better understanding of the groundwater system in terms of the flow regime, its origins, and the flow paths. Monitoring data analysed in previous section shows the quality of both surface water and groundwater. Most surface water samples taken within the vicinity of mining infrastructure or mining activities showed elevated levels of contaminants exceeding recommended limits, which could suggest mine water contamination. These areas can be identified as potential sources of contamination, namely the Old slimes dam, Patiseng TSF, Mine pits and Waste rock dumps. Additionally, water quality samples downstream of these areas also showed increase in contaminant concentration, although in some cases remaining below the recommended limits. These results suggest that there is a risk of mining activities affecting the water quality in resources in the surrounding environment. Water management strategies therefore need to be put in place to mitigate this risk.

Similarly, groundwater quality samples are taken quarterly, and the results were analysed in the previous section. The results show that there is currently no significant contamination of groundwater. However, samples from boreholes L_WE_010, L_WE_014 and L_WE_017 show contaminant concentrations levels that exceed the recommended limits. Mining activities within the vicinity of these boreholes can therefore be identified as potential sources of groundwater contamination, and these are the WRD and Old Slimes Dam. Groundwater management plans need to be put in place to avoid increase in groundwater contamination.

4.2.4 Source-Pathways-Receptors

Based on the water quality data analysis, the surface water and groundwater sampling results show that there are areas where concentration of nitrates and sulphates exceed the recommended water quality standards. This implies that there is a risk of water contamination in the area. The source-pathway-receptors concept can be used to assess this risk, by identifying the sources of contamination, the pathways, and receptors of contamination.

Sources of contamination

It is important to acknowledge that groundwater and surface water are interconnected. If surface water is contaminated, there is a risk of groundwater being contaminated. The surface water results in the previous section show that nitrate and sulphate concentrations are high around the Patiseng TSF, Old Slimes Dam, Pits and WRDs, this means that the groundwater within these areas is also as the risk of contamination. This is also evident in groundwater samples in these areas, which show increasing concentration of nitrates and sulphates with time. The sources of contamination can be deduced from different mining activities around the site. During mining, the bedrock is usually blasted with ammonia-based explosives. Residues from blasting is disposed with waste rock or remains in muckpiles. The waste is deposited onto WRD, where the nitrates can be dissolved when exposed to rainfall and then leached out into surface and groundwater resources, thus contributing to elevated nitrate levels around the dumps (Bosman, 2009)

Similarly, residues of blasting that remain in muckpiles can be dissolved in pit water that collects at the bottom of the pit from rainfall or ingress from surrounding aquifers. This leads to high concentrations of nitrates in pit water as seen from the water quality samples collected from the pits. The water can seep into the surrounding aquifers, thus contaminating the groundwater. In some cases, the pit water is pumped out and discharged into Pollution Control Dams (PCD) which can also be a direct source of nitrate contamination when not lined.

During processing as well, nitrogen containing chemicals are used, for example, nitric acid. These, together with ammonia-nitrate explosives adds to increased nitrogen levels. Effluent from processing is then deposited into the TSF as tailings. When leached through the unsaturated zone, the ammonia-rich undergoes nitrification thus producing nitrates which the contaminate the water. Based on this, the high concentration of nitrates from sampling points around the Patiseng TSF and Old Slimes Dam area are validated.

In the case of LDM, sulphate concentrations originate from sulphur-bearing rock, pyrite found along the shear zone in the Main pit. When exposed to water and air in similar processes explained above, sulphuric acid can be produced depending on the buffering capacity of the system. Leachate from affected sources can therefore result in elevated sulphate concentrations as seen in the water quality sampling results.

Pathways

Contamination may move within the aquifer in the same way as that the groundwater moves, depending on the physical, biological, and chemical properties of the contaminant. Forinstance, smaller ions such as nitrates are dissolved faster in water and move faster in the unsaturated zone than bigger ions such as sulphates. Hence, elevated levels of nitrates are observed earlier than sulphate concentrations. Movement in the saturated zone is generally slow, and therefore contaminants tend to remain concentrated in a plume. The size and velocityof the plume will depend on the properties of the groundwater system (Piga et at., 2017). In fractured rocks as in the case of the LDM, the flow of groundwater and contaminant is more rapid and therefore contamination can get to receptors faster. Contaminants can also flow through surface water into other receptors, which is generally faster than flow within the groundwater system. Based on the water quality results, contamination flows mainly through surface water. This is seen by elevated concentrations in sampling points downstream of the potential sources as opposed to concentrations in monitoring boreholes downstream of potential sources.

Receptors

Streams and rivers that surround the mine are possible receptors of contaminated water. These water sources support local communities with water for drinking, domestic uses and for agriculture, meaning that any contamination that may get to these receptors may result in detrimental health effects on the people, animals, and the environment, especially from the nitrate concentrations.

The information discussed in this chapter, the geological and hydrogeological characteristics of the area, hydrologic data and the hydrochemical information is summarised into the conceptual model in Figure 4-38 . The conceptual model includes the three hydrogeological units in the area, where the upper unit and the middle unit are weathered and fractured respectively, as well as how the hydraulic conductivity varies within the different unit. The water table is also represented, with the flow mainly from west to east towards the Khubelu River, on which the local community depends. The conceptual model also includes potential sources of contamination as well as their movement through the system. The conceptual model provides a pictorial representation of the groundwater system, and then be used as the basis of the groundwater flow model.

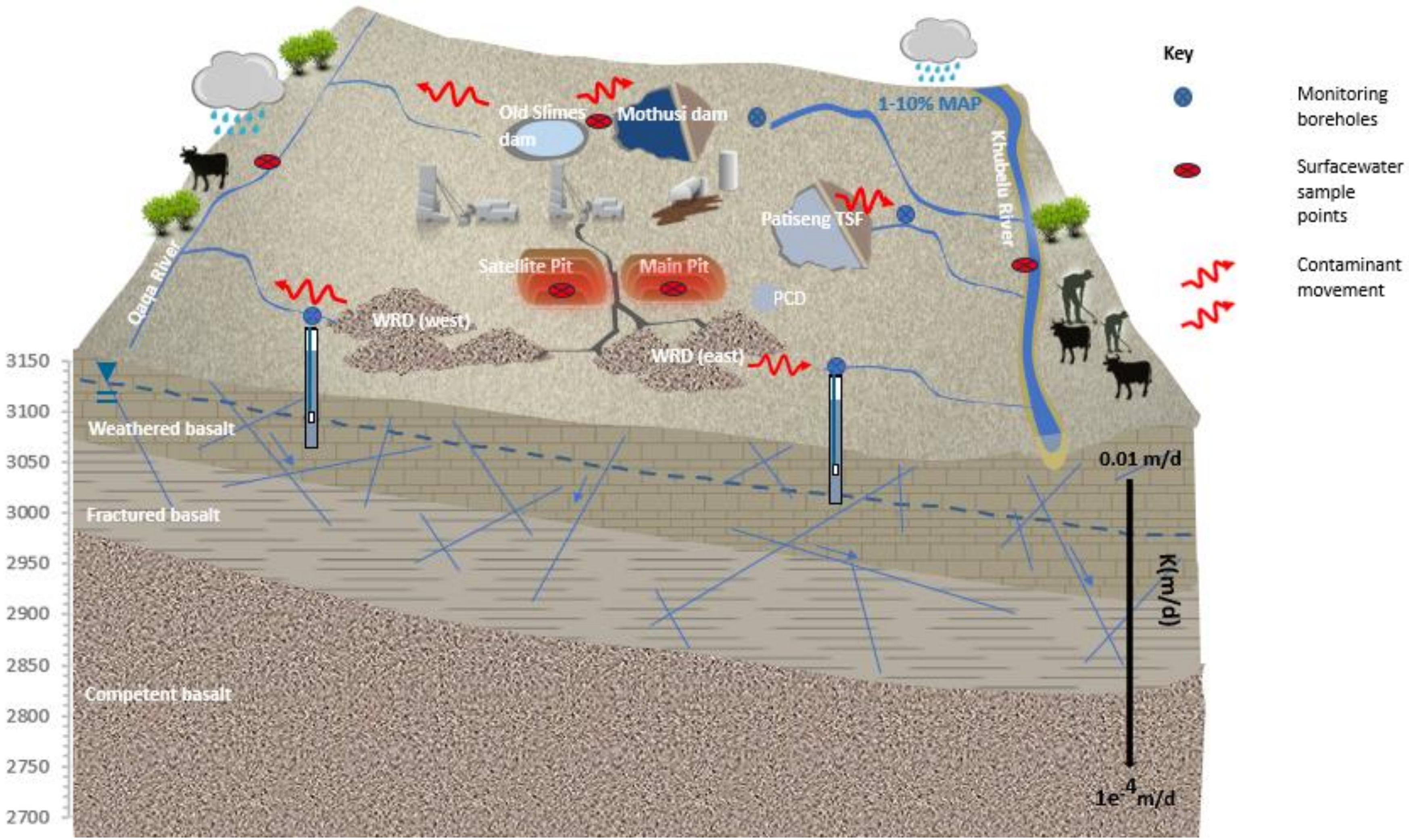

Figure 4-38 LDM Conceptual Model showing different properties of the groundwater system, mining activities and their impacts based on the S-P-R model.

4.3 SUMMARY

This chapter is a review of data used to develop the conceptual model, this includes the geological and hydrogeological data which was used to inform the physical framework of the conceptual model. This was used to define the hydrogeological units of the area as well as their hydraulic properties. The upper weathered zone was classified as the unconfined aquifer, while the fractured and competent zones were defined as confined aquifers. The hydraulic conductivity therefore decreases with depth, as the rock becomes more competent. Monitoring data was used to define the chemical framework of the conceptual model. This information was used to identify the potential sources of contamination and possible receptors based on the source-pathway-receptor concept. Areas with high concentrations, such as the Patiseng TSF, Old slimes dam, and waste rock dumps were identified as potential sources of contamination posing a risk on possible receptors.

5 NUMERICAL GROUNDWATER MODEL

As discussed in the previous chapter, Letšeng mining activities at LDM have a potential risk to the environment. The activities include dumping of rocks on waste rock dumps and disposing of tailing into tailings storage facilities. Leachate from these facilities can flow into surface water, and can infiltrate the vadose zone, contaminating the groundwater. Without proper management used to mitigate this problem, there is a risk of the water resources within the surrounding environment being contaminated. According to Tafreshi et. al. (2019), an essential step in protecting and managing groundwater resources against contamination is through recognition and predictions of the contamination origin. Groundwater modelling provides the necessary tools to achieve this. Using the conceptual model as the foundation, a numerical groundwater flow model is developed to determine how groundwater flows within this system. The groundwater flow model is then used as a predictive tool to determine the cumulative impacts of mining on the groundwater quality, by means of particle tracking. Particle tracking involves simulation of advective transport of solutes within the groundwater system by calculating the flow paths and travel times.

5.1 MODEL DESIGN

5.1.1 Model selection

The numerical model was based on the MODFLOW code with the appropriate packages to simulate the groundwater flow with the area, using ModelMuse a software package that provides a GUI for creating the flow and transport input files for groundwater models (Winston, 2019).

MODFLOW is a modular three-dimensional groundwater flow modelling program. To represent the distribution of hydrogeologic characteristics and hydrologic boundaries within the model domain, MODFLOW uses the finite-difference method to divide the groundwater flow model domain into a series of rows, columns, and layers, which define a set grid blocks or model cells. When creating a groundwater model, properties and boundaries are applied to the model cells. MODFLOW then utilises the dimensions to build a set of finite-difference equations that it then solves to determine the hydraulic head at the centre of each model cell, thus simulating the groundwater flow (Anderson et al., 2015)

To determine the origin and pathway of contaminants, the particle tracking model is developed using the MODPATH module. According to Pollock (2016), MODPATH is a particle-tracking post-processing program designed to work with MODFLOW. In each finite-difference grid cell, each particle's flow path can be expressed analytically using the semi-analytical particle tracking technique used by MODPATH. The process of computing particle pathways involves tracking a particle from one cell to the next until it encounters a boundary, an internal sink or source, or meets another termination point. MODPATH can be used to study ground-water flow systems in both steady-state and transient conditions, by simulating the entire range of forward- and backward-tracking scenarios, hence its applicability in this study in terms of cumulative impact assessment on the groundwater quality (Pollock, 2016).

5.1.2 Model domain and model grid design

The first step in groundwater modelling is identifying the modelling area and its boundaries. The model domain is defined by distinguishing the study area from the surrounding environment. To select the modelling area, the topographical, geological and structural aspects are taken into consideration. These features also reflect the geometry of the groundwater system. In this case the topographical highs in the North and South, the rivers in the West and East of the area were used as borders to define the model geometry as outlined in Figure 5-1 below. To construct the model geometry, a polygon that outlines these boundaries was created using QGIS 3.4 and was imported into the modelling software. The model geometry shapefile was then used to define the grid.

The modelled area is approximately 91.5 km^2, with a regular model grid of 202 rows and 247 columns, discretised with a finite difference grid of cell size 50 m. The total number of active cells was 366 053. The model domain is divided into eight major layers, where layer 3 and 4 were further vertically discretised by 2, uniform spacing. In total the model consists of ten layers, with layer 1 representing the unconfined upper weathered unit set, with an approximate thickness of 15 m. The other layers represent the fractured rock and are considered as confined units. The bottom layer represents depths beyond the 2550 mamsl projected for the Life of Mine (LOM). This information is summarized in Table E

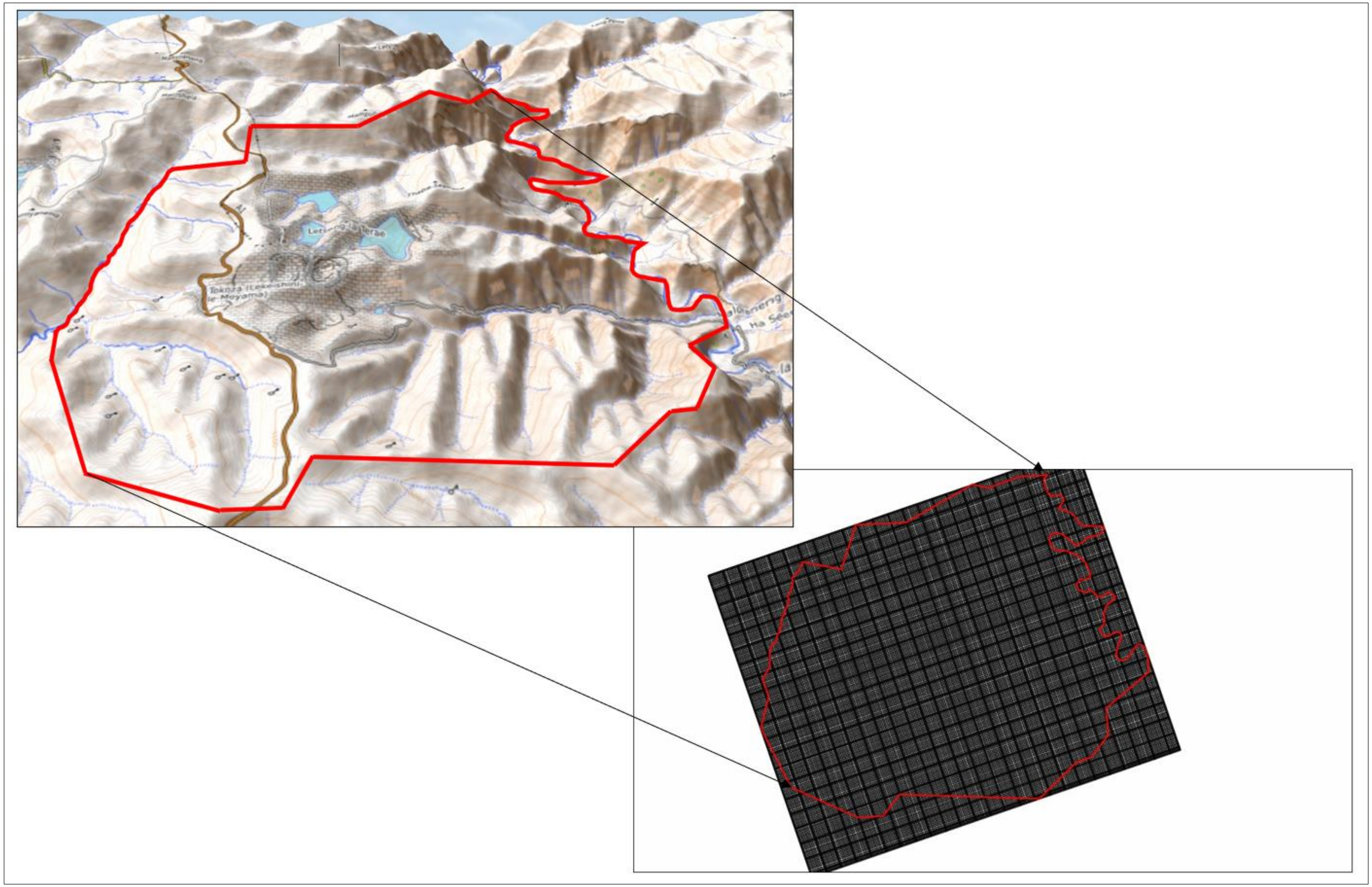

Figure 5-1	Topographical map delineating features used to define the model geometry.

.Table E Model discretisation and hydrogeologic units for each layer.

Layer	Vertical Discretisation	Hydrogeological units	Type	Thickness (m)
1	1	Weathered	Unconfined	15
2	2	Mostly fractured	confined	20
3	3	Moderately fractured	confined	25
	4			25
4	5	Moderately fractured	confined	50
	6			50
5	7	Competent Basalt	confined	100
6	8	Competent Basalt	confined	100
7	9	Competent Basalt	confined	150
8	10	Competent Basalt	confined	200

Following the model discretisation, the model elevation was determined using a Digital Elevation Model of the area. The DEM was acquired from the NASADEM website. The DEM of the study area was extracted and exported as a surfer grid file, which was then used to define the elevation of the model in ModelMuse, using interpolation. Figure 5-2 shows the cross-section of the model discretisation, from layer 1 to layer 8.

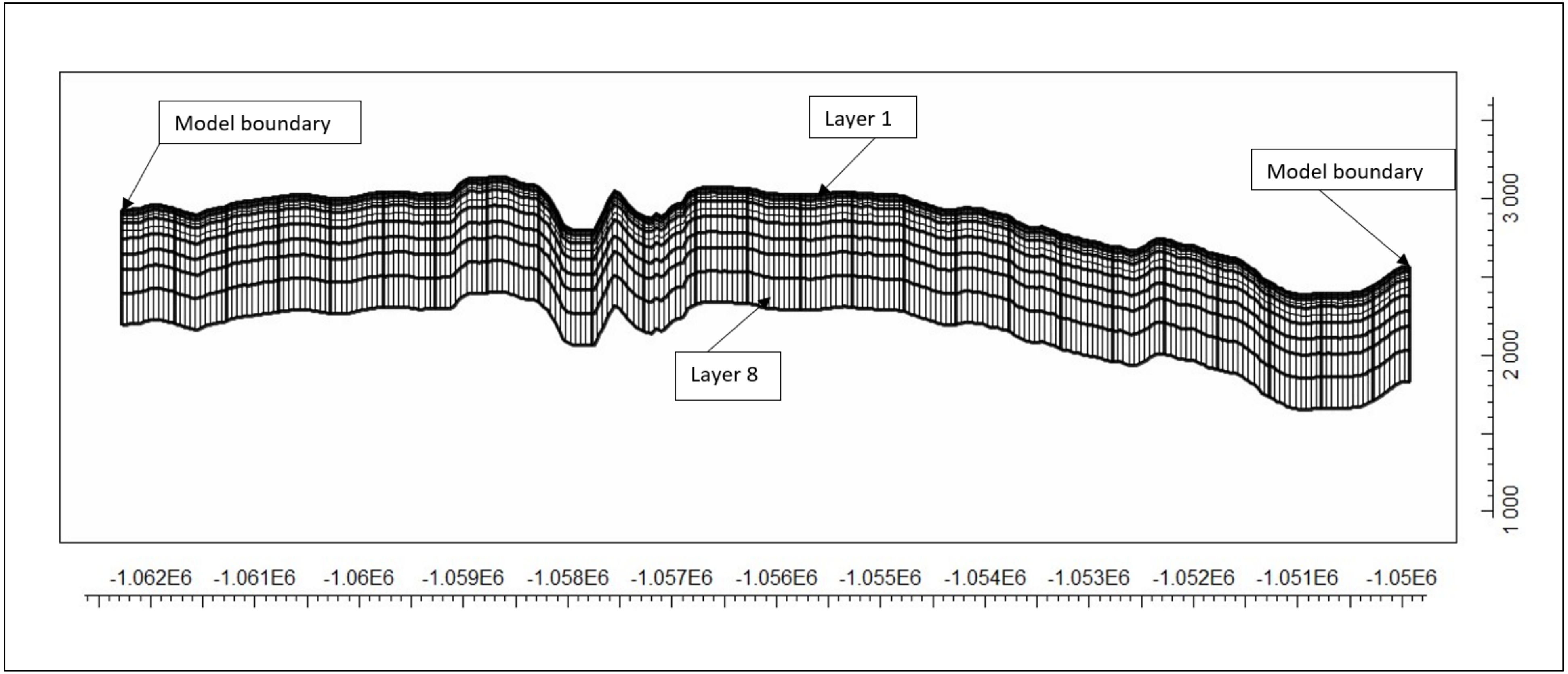

Figure 5-2 Cross-section of the model discretisation for the eight model layers.

5.1.3 Model boundaries

For the entire model domain, model boundaries need to be specified. Boundary conditions express the way in which the considered domain interacts with its environment. Different boundary conditions result in different solutions, hence the importance of stating the correct boundary conditions. Criteria for selecting boundary conditions are primarily topography, hydrology, geology, and structure (Anderson and Woessner, 1992). For this model the topographical highs in the North and South of the area were be categorised as no flow boundaries Figure 5-3.

Specified Head Boundary: The eastern boundary along the river is set as a Specified-Head package (CHD) with starting and ending heads specified at Modeltop. Based on the specified head value, the model calculates the flow across the boundary. Considering the perennial river, assigning the head elevation to Modeltop (which was interpolated from the topography of the area) thus assuming there is direct hydraulic connection between the river and groundwater.

Head-Dependent Flux Boundary Packages: The small streams around the area, the non-perennial rivers along the western boundary as well as both pits were classified as drains as they are not considered as sources of groundwater contamination. For these, the Drain package was applied with the elevation for streams and rivers assigned to Modeltop with conductance of 0.2 m^2/d. The elevation of the pits was assigned to layer 3 to representthe top to the pits and layer 5 to represent the bottom of the pits, with conductance of 11.

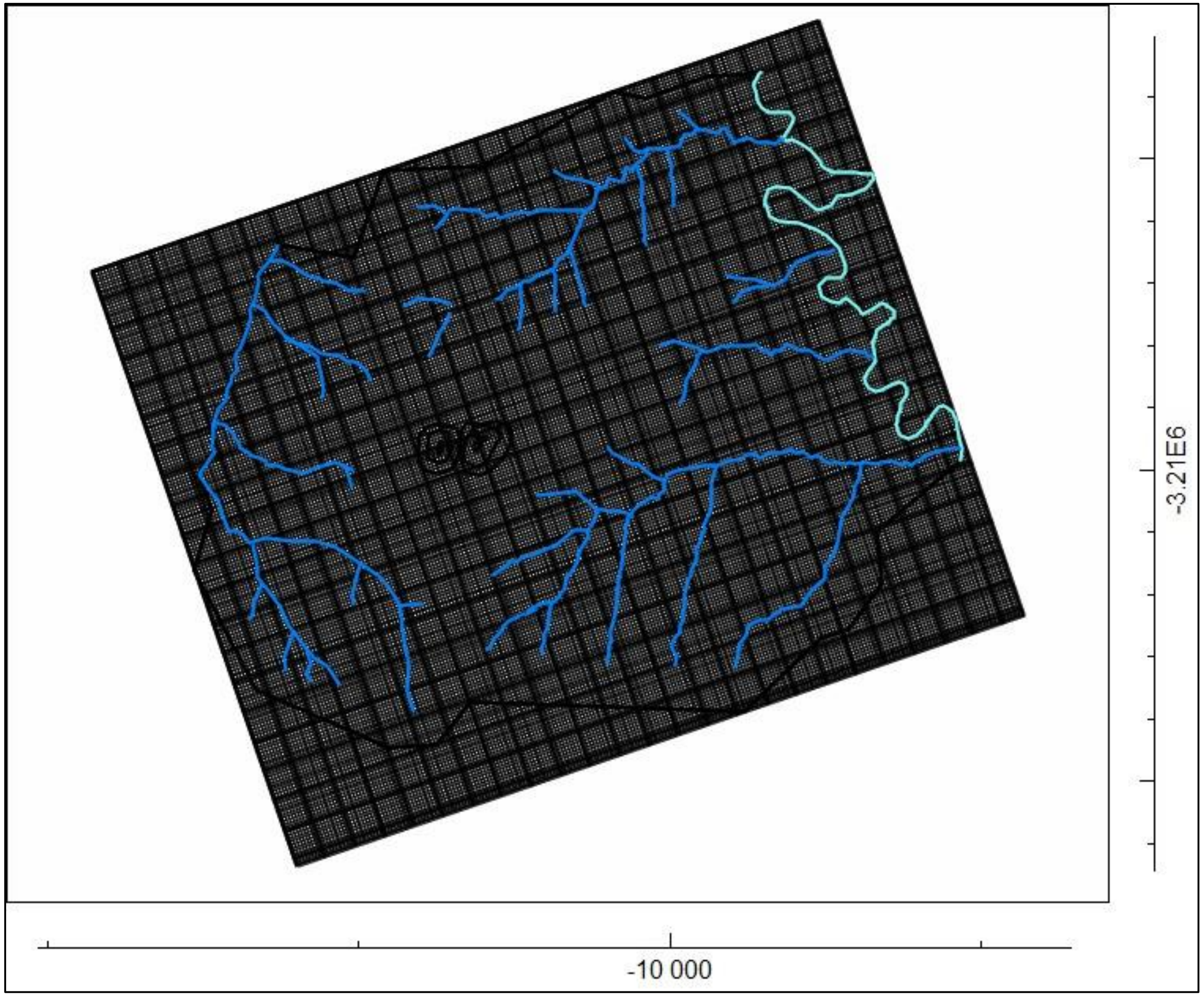

Figure 5-3 Boundaries that define the model, the eastern river as a CHD boundary, pits and other rivers as Drains, north and south borders as No-flow boundaries.

5.1.4 Numerical formulation

Groundwater is recharged by percolation of precipitation through the unsaturated zone. Typically, it is assumed that recharge infiltrates vertically through the unsaturated zone into a groundwater system. Depending on the local hydraulic gradient and geological conditions, it can move vertically or horizontally when it reaches groundwater in the saturated zone (Humm, 2021). Since unsaturated zone transport affects the fate of contaminants as they are transmitted between land surface and the water table as well as to streams, models that incorporate the unsaturated zone can improve understanding of both human impacts and climate variability on the quality of groundwater resources (Morway, 2012). Based on this perspective, the UZF (Unsaturated Zone Flow) Package for MODFLOW 6 in the weathered regolith layer is used to simulate water flow and storage in the unsaturated zone.

Figure 5-4 shows the concept that drives the UZF package, where recharge first flows vertically through the unsaturated zone and then horizontally in the saturated zone. By simulating the flow through the unsaturated zone, the influence of the unsaturated zone on the quantity and timing of the recharge can be identified (Humm, 2021). To achieve this, the UZF Package uses a kinematic wave approximation to Richards' equation, which is solved using the method of characteristics. It makes use of initial and saturated water contents, saturated vertical hydraulic conductivity, and the Brooks-Corey function exponent which relates the unsaturated hydraulic conductivity and water content (Niswonger et.al., 2006).

The UZF Package is employed because it first removes evapotranspiration from the unsaturated zone and subsequently from the groundwater reservoir, simulating the observed infiltration rate to the model surface. It simulates recharge and evapotranspiration as a variable thick plane over the 3D saturated zone model. The thickness of the unsaturated zone within each cell is identified by computing the difference between the user-specified land elevation data at each cell and the hydraulic head computed by the model. The package then calculates the specific retention as a specific yield and subtracts it from the saturated water content to estimate the mass balance from the remaining water content (Humm, 2021). Another important application as explained by Morway (2012) is the package`s functionality for simulating saturation excess and spring discharge. When the simulated water table is above a specified depth below the land surface the UZF package inserts a dynamic condition at water-table cells which allows seepage discharge to the land surface and reduced recharge from infiltration. Seepage to the land surface arises automatically as a model output from the specification of the model geometry, boundary conditions, infiltration rates, and aquifer properties (Morway, 2012)

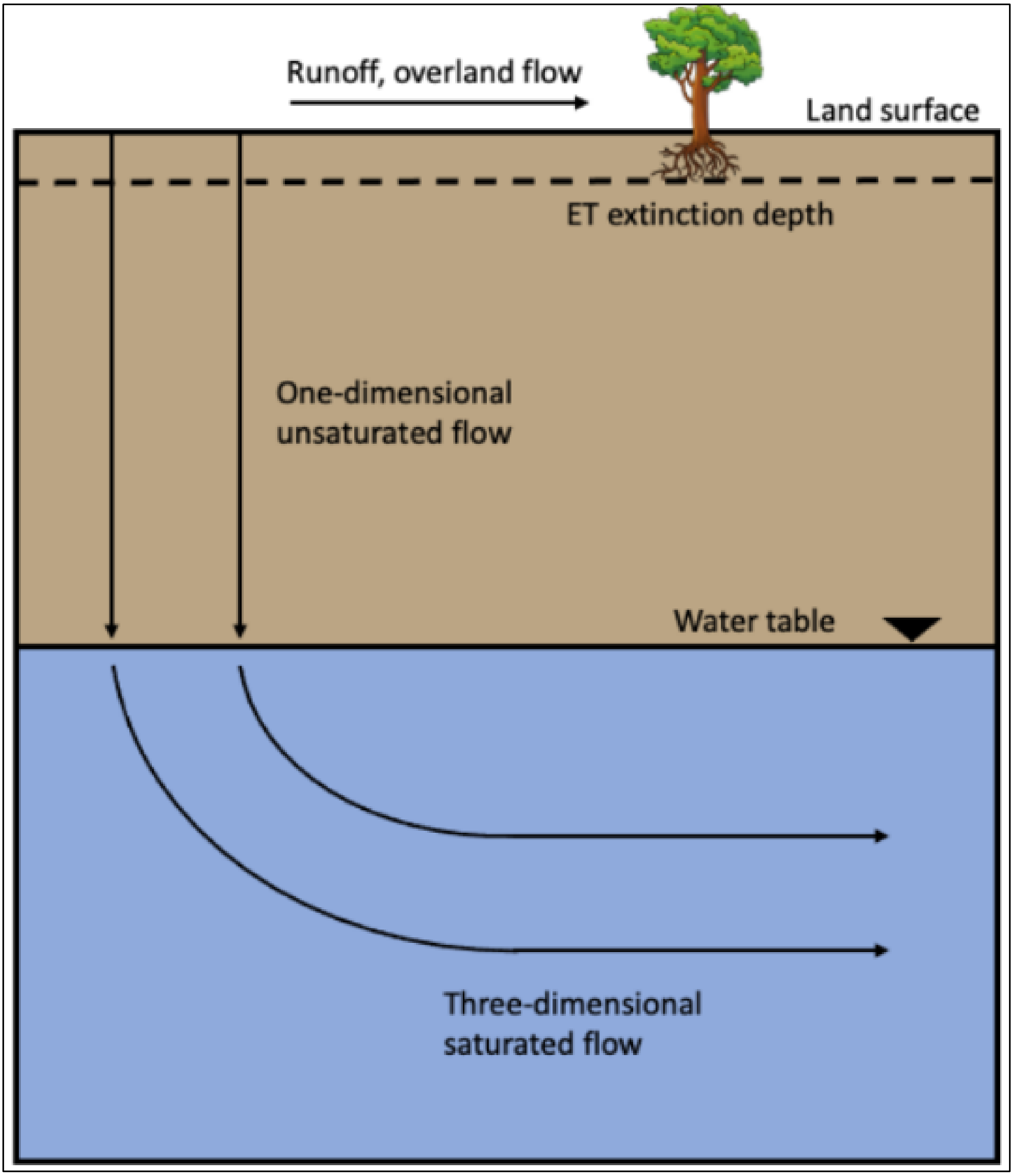

Figure 5-4 Conceptual model for the UZF package, where flow in the unsaturated zone is one-dimensional (Niswonger et al., 2006)

5.1.5 Model Input Parameters

Initial conditions

The initial conditions describe the hydraulic head distribution throughout the model domain at the start of the simulation (Anderson and Woessner, 1992) The initial head conditions for the model were estimated based on the most recent measured groundwater levels.

Hydrogeological parameters

The initial estimates for hydraulic properties i.e. input before model calibration, were assigned based on previous aquifer testing of monitoring boreholes as seen outlined in Table **F**. Additionally, Recharge for the entire model was 4E-5 m^3/d and infiltration rate (UZF) 0.1 – 0.0005 m^3/d for the dams, TSF and WRDs, which differs based on the properties of each feature.

Table F Model input parameters

Layer	**Thickness (m)**	**Hydraulic conductivity (m/d)**	**Transmissivity (m^2/day)**
1	50	0.1	5
2	20	0.01	0.5
3	25	0.001	0.025
4	25	0.001	0.025
5	50	0.001	0.05
6	50	0.001	0.05
7	100	0.0001	0.01
8	100	0.0001	0.01
9	150	0.0001	0.015
10	200	0.0001	0.02

Observations

Monitoring boreholes in the area were assigned to the Observation utility package (OBS). In MODFLOW 6, the package calculates simulated equivalents of the observations using the hydraulic heads for the entire model grid. The output is a file which reports the simulated values, which can then be compared to the observed values.

5.1.6 Solvers

The Iterative Model Solution (IMS) Package is used to solve the model simulations. The package uses linear and nonlinear set of finite difference equations produced by the model.

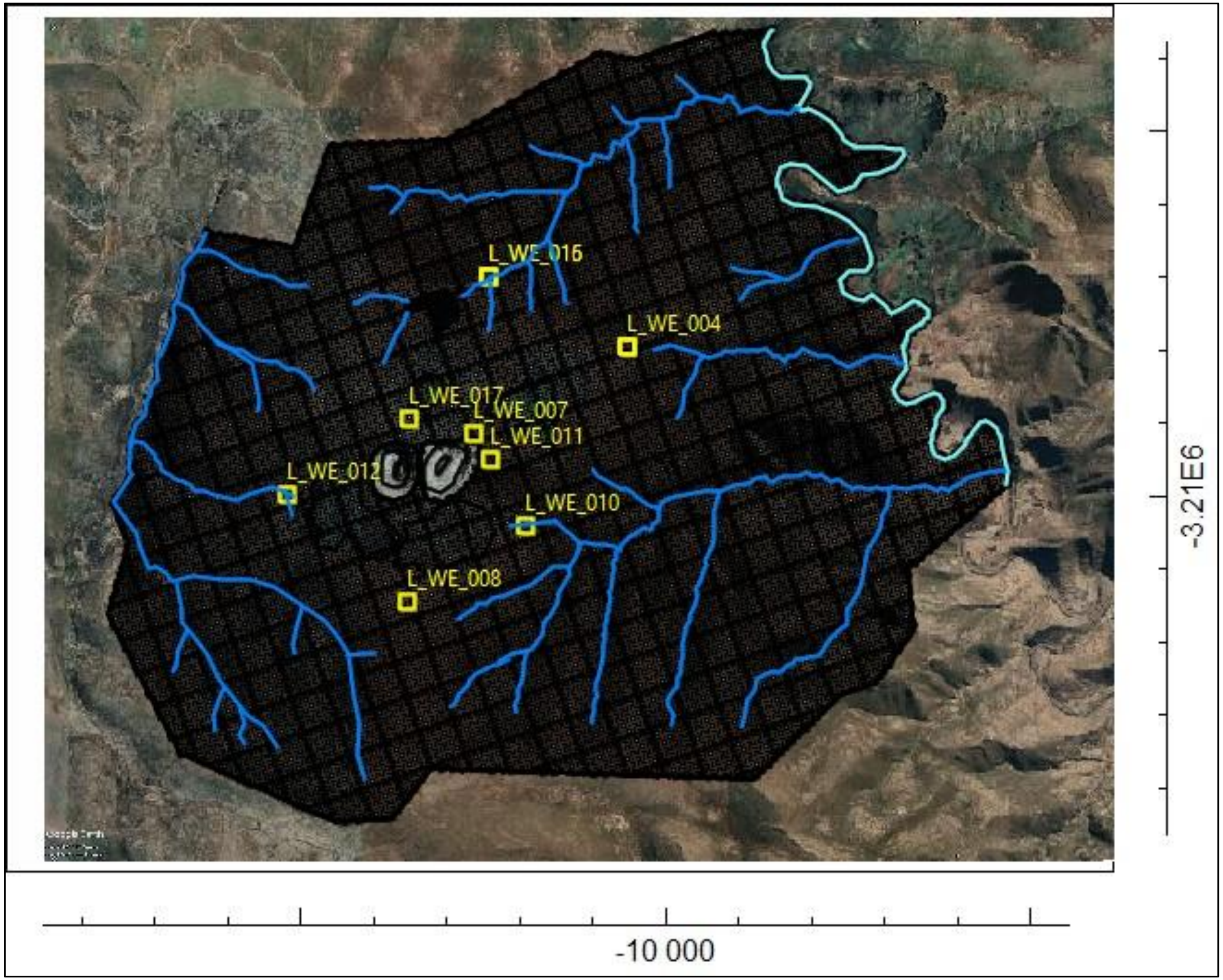

Figure 5-5 Monitoring boreholes assigned as observation points for the OBS package in ModelMuse.

5.2 MODEL CALIBRATION

For this model, groundwater levels in monitoring boreholes at Letšeng were used as calibration targets for the steady state model. The hydraulic conductivity was manually adjusted through trial and error to simulate head distributions. The parameters were adjusted until an acceptable correspondence between the observed and simulated head distributions was obtained. According to Anderson and Woessner (1992), calibration undergoes both qualitative and quantitative assessment. A qualitative assessment involves assessment of the general correspondence, while the quantitative assessment uses residual techniques where head residuals are calculated, correlation between residuals is detected and flow-rate residuals are calculated. In this case, the model calibration assessment was based on the residual technique in terms of residual statistics where R is residual mean, RA is absolute residual mean, RMS is root mean square and NRMS is normalised root mean square. As per the general rule, for an acceptable calibration, NRMS % should be less than 10% and less than 5% for a good calibration.

Groundwater levels for ten boreholes measured in 2013 were used for calibration. The steady-state calibration was regarded as sufficient at R= -6.2 m, RA =11.6 m, RMS = 19.2 m and NRMS = 9.9 %, which lies within the acceptable range of <10%. The graph in Figure 5-6 shows a satisfactory calibration with R-squared value of 0.96, which is acceptable considering factors such as variation in hydraulic conductivity and the present mining activities. However, boreholes L_WE_008 and L_WE_011 are outliers with a difference of approximately 40 mamsl. Both were deemed abnormally deep and could not calibrate successfully. Excluding these boreholes in the calibration resulted with an R-squared value of 0.99, thus improved calibration.

After the trial-and-error process during calibration, a sensitivity analysis was carried out to determine how sensitive the hydraulic heads were to model parameters. According to Anderson and Woessner (1992), sensitivity analysis quantifies the uncertainty in the calibrated model brought on by aquifer parameter, stress, and boundary condition uncertainty. For this model, a sensitivity analysis of the hydraulic conductivities was carried out, results are shown in Table G. The results show that the groundwater levels are sensitive to changes in hydraulic conductivity. Although, the variation with factor 0.5 shows a lower RMSE, the water-table was slightly above the ground surface, hence the calibrated model is still the best fit. Variations in recharges and drains were also carried out but they did not show any significant effect on the model.

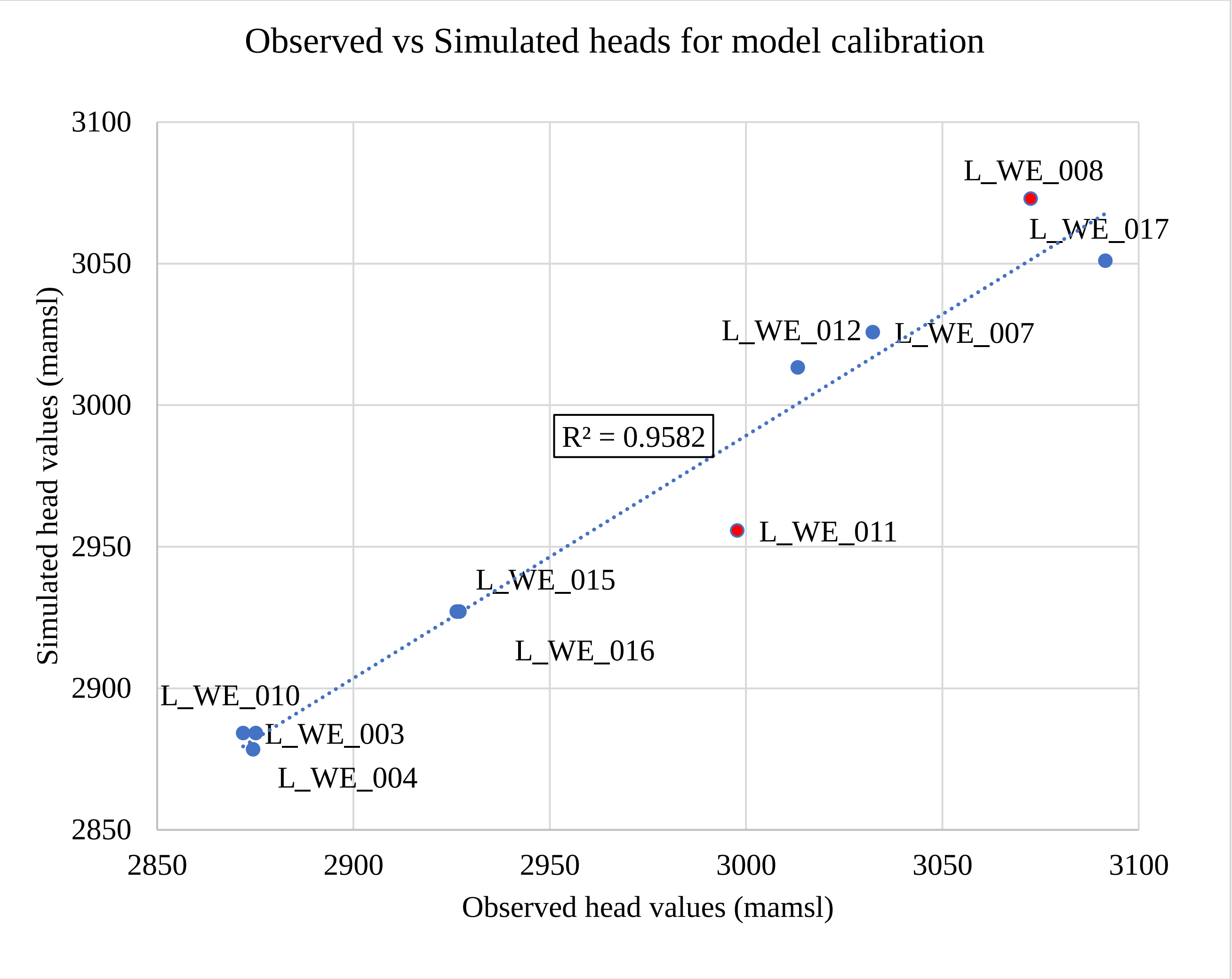

Figure 5-6 Model calibration results based on observed and simulated heads.

Table G Sensitivity analysis of hydraulic conductivities

Variations in K	K (m/d)	RMSE (m)
No variations	0.1-1e-3	14.13
Multiply by factor 0.5	0.05-5e-4	9.55
Multiply by factor 2	0.2-2e-3	51.27
Multiply by factor 4	0.4-4e-3	107.84

5.3 SIMULATION RESULTS

Groundwater flow model

Based on the model design and set up in the previous chapter, a calibrated steady state model was developed. MODFLOW simulates the hydraulic head distribution over the model domain. The simulated hydraulic head distribution is shown in Figure 5-7. Based on the simulated head distribution, the groundwater flows from the west to the east of the area, following topography, from highest levels of over 3050 mamsl to 2350 mamsl. However, within the vicinity of the pits, the flow is directed into the pits. The groundwater level follows a gentle slope around the centre of the area, where the mine infrastructures are located. The groundwater contours are steeper along the south-eastern area.

As an indication of the validity for the simulation, the results from the simulated water budget for the entire model domain where the magnitude and direction of flow is constant with time, thus, steady state stress period show a percentage discrepancy of 0.00% indicating that model equations are correctly solved, and the solutions were acceptable. The inflow and outflow components of the water balance are shown in Table H. Based on set boundaries, water flows into the model mainly through recharge, flowing out through the Drains and significantly through the Discharge.

Table H Simulated water budget for LDM indicating a balance between water flowing in and out of the system.

Component	Flow In (m^3/day)	Flow Out (m^3/day)
Drain (DRN)	0.00	217.21
Constant Head (CHD)	888.49	781.96
Recharge (UZF-GWRCH)	10091.34	0.00
Discharge (UZF-GWD)	0.00	9980.67
Total flow	10979.8377	10979.8413
Summary	In-Out	% Difference
Total	-3.6894E-03	-0.00

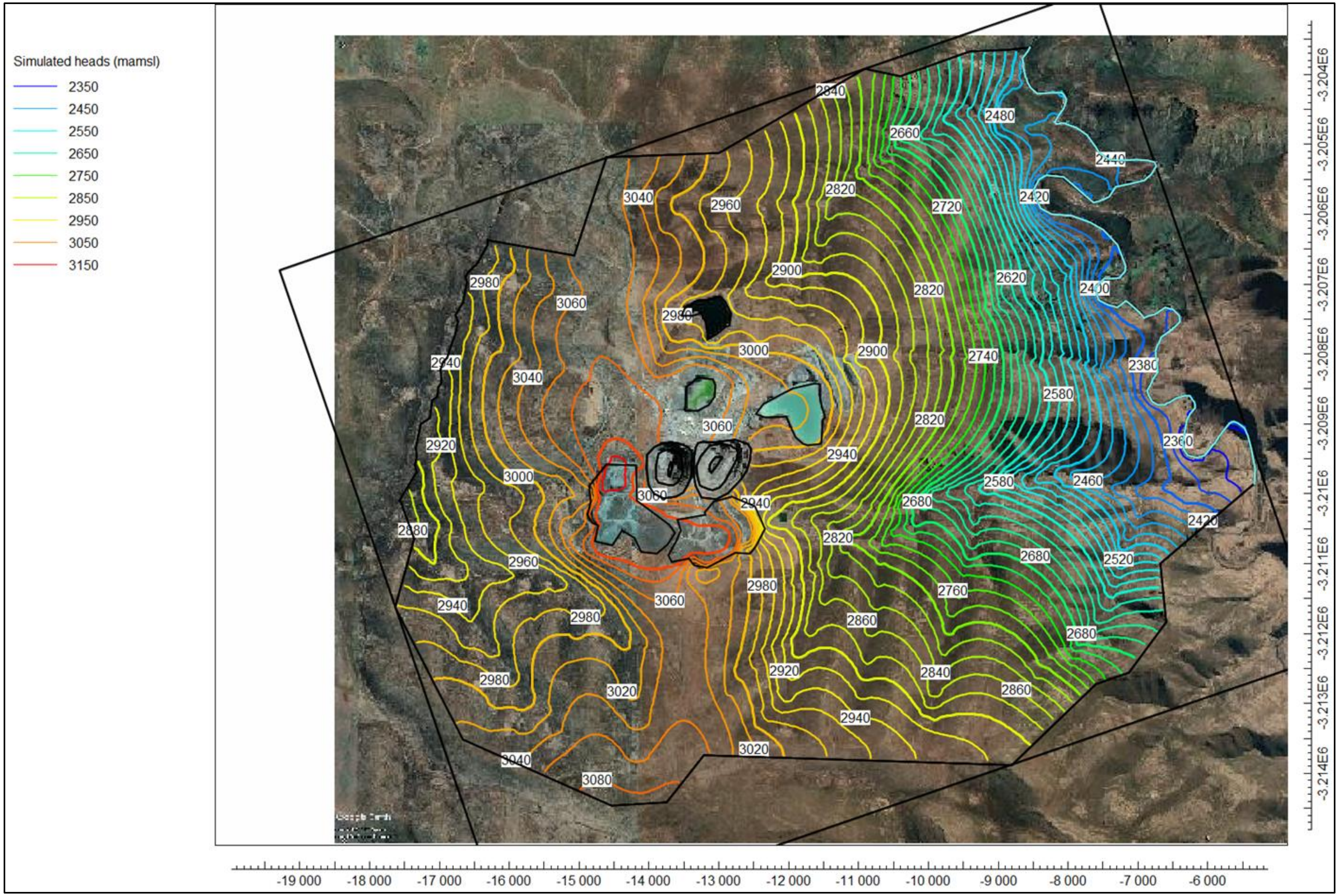

Figure 5-7 Contour map representing simulation of hydraulic heads for LDM, indicating the flow of groundwater within the system.

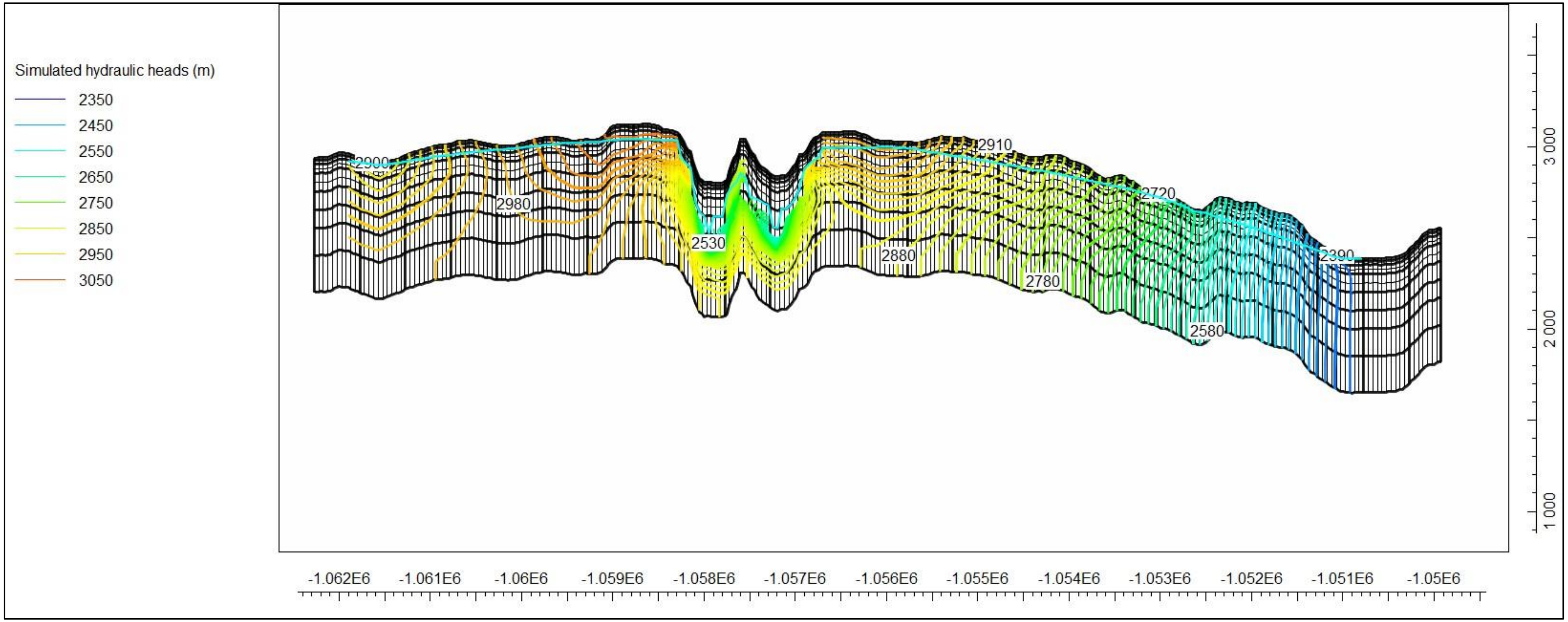

Figure 5-8 South-east cross-section of the groundwater flow map, with the water table highlighted.

5.4 SUMMARY

Based on the data collected, that includes site characterization data and monitoring data, the physical framework was defined, and the hydrological stresses were described. These led to the development of the conceptual model from which the numerical model was developed. The groundwater flow model developed was deemed appropriate for use, thus it can now be applied to address the objective of the study. The next chapter involves processing of the groundwater flow model using MODPATH to determine the movement of particles within the system. The results will aid in determining the fate of contaminants in the system.

6 MODEL APPLICATION FOR CUMULATIVE IMPACT ASSESSMENT

The main objective of the research is to determine the cumulative impacts of mining on groundwater quality using groundwater modelling. This chapter therefore covers the findings of the study by analysing and interpreted the results as obtained from the modelling process, such that the objective of the study is achieved. The groundwater flow model will be analysed for a better understanding of the groundwater system. From specified locations, which are potential sources of contamination, flow path of particles is tracked over time to determine to potential receptors, and thus potential impacts.

6.1 PARTICLE TRACKING

In combination, MODFLOW and MODPATH provide the appropriate method for tracking and predicting contaminant transport in the subsurface. Using the output from MODFLOW as a basis, MODPATH is a postprocessing tool used to calculate the travel paths and travel times for advective transport of particles in groundwater flow. The method can only be implementedfor linear velocity in FD models and requires estimates of porosity in order to calculate successive particle positions (Hussein et. al., 2014). During particle tracking, a particle is placed at a specific location and tracked through the velocity flow field at successive intervalsof flow time.

A particle can be tracked forward in time as it moves down gradient from the specific locationor backward in time from its origin. Forward tracking shows movement of particles occurringover the length of the model simulation, while backward tracking simulations occur over infinite time (Anderson, et. al., 2015). For this study, the simulation involved assigning of particles at potential sources, Patiseng TSF, Old Slimes Dam and both WRDs (Figure 6-1). At an estimated porosity of 0.007, forward movement of the particles were visualised. The particletracking is conducted on the steady state groundwater flow model but assessed over 20 years.

Particle tracking was used to simulate contaminant movement within the system, based on the advective conditions of the steady-state model. The path lines are determined by monitoring particles from cell of origin to the next cell until the particles terminate at boundary faces, strong source or sink cells or another termination requirement, depending on whether an outflow can occur or not. For instance, strong sink could represent extraction of water from the entire aquifer depth as opposed to a weak sink where some water passes underneath or over the sink. The MODPATH results as shown in Figure 6-2 indicate that total potential contaminants travel paths and time from theirsources along their travel paths into release locations or termination points. The colour changesfrom blue to red represents the travel time, where red is the latest release time.

The particles from Patiseng TSF flow through the rivers downstream of the area towards the east into the Khubelu River overtime, while some of the particles flow into the nearby Main pit. From the Old Slimes Dam, particles mainly flow from the dam towards both pits as well as the Mothusi Dam downstream. Particles from the WRD East are released in both pits and the river downstream, while particles from the WRD West are released toward the highest level of the Satellite pit. Some of the particles are released into the streams downstream from the source, although they do not reach the main Qaqa River. This could also be a contributing factor in the monitoring of these streams.

MODPATH was then evaluated over 20 years, under steady-state flow conditions, to simulate potential contaminant movement over time as mining operations proceed. The results of forward tracking show path lines of particles released from potential contaminant sources after1 year, 5 years, 10 years, and 20 years travel time. Generally, the travel time is slow, due to thelow hydraulic conductivity of the rocks. However, in 1-year results show that the particles fromall the potential sources remain contained within the mine lease area and are limited within thevicinity of their sources (Figure 6-3).

In 5 years, some particles from the western WRD start to flow beyond the site by approximately 760 m and 770 m from the eastern WRD. The particles flow towards the smaller streams down-gradient from the sources. Particles from the TSFs are still contained within the site (Figure 6-4). In 10 years, more particles are released from the western WRD, with a maximum travel distance of approximately 1 km from the site, while particles from the eastern WRD show maximum travel distance of approximately 2.4 km from the site. Particles from the Patiseng TSF also start flowing beyond the site, with an approximate maximum travel distance of 240 m from the site. Particles from the Old Slimes Dam are site contained within the site but start to migrate towards the Mothusi Dam (Figure 6-5).

Although most particles are still contained within the site throughout the simulation time, some particles are seen to travel further after 20 years. From the Patiseng TSF, a maximum travel distance of approximately 1.5 km is seen. Particles from the western WRD do not show a significant change in maximum travel distance compared to the 10 years. The maximum travel distance for particles from the eastern WRD is approximately 5.2 km and are closely approaching the Khubelu River. Particles from the Old Slimes Dam are also showing significant travel distance into the stream down-gradient of the Mothusi Dam, although remaining within the mine lease area (Figure 6-6).

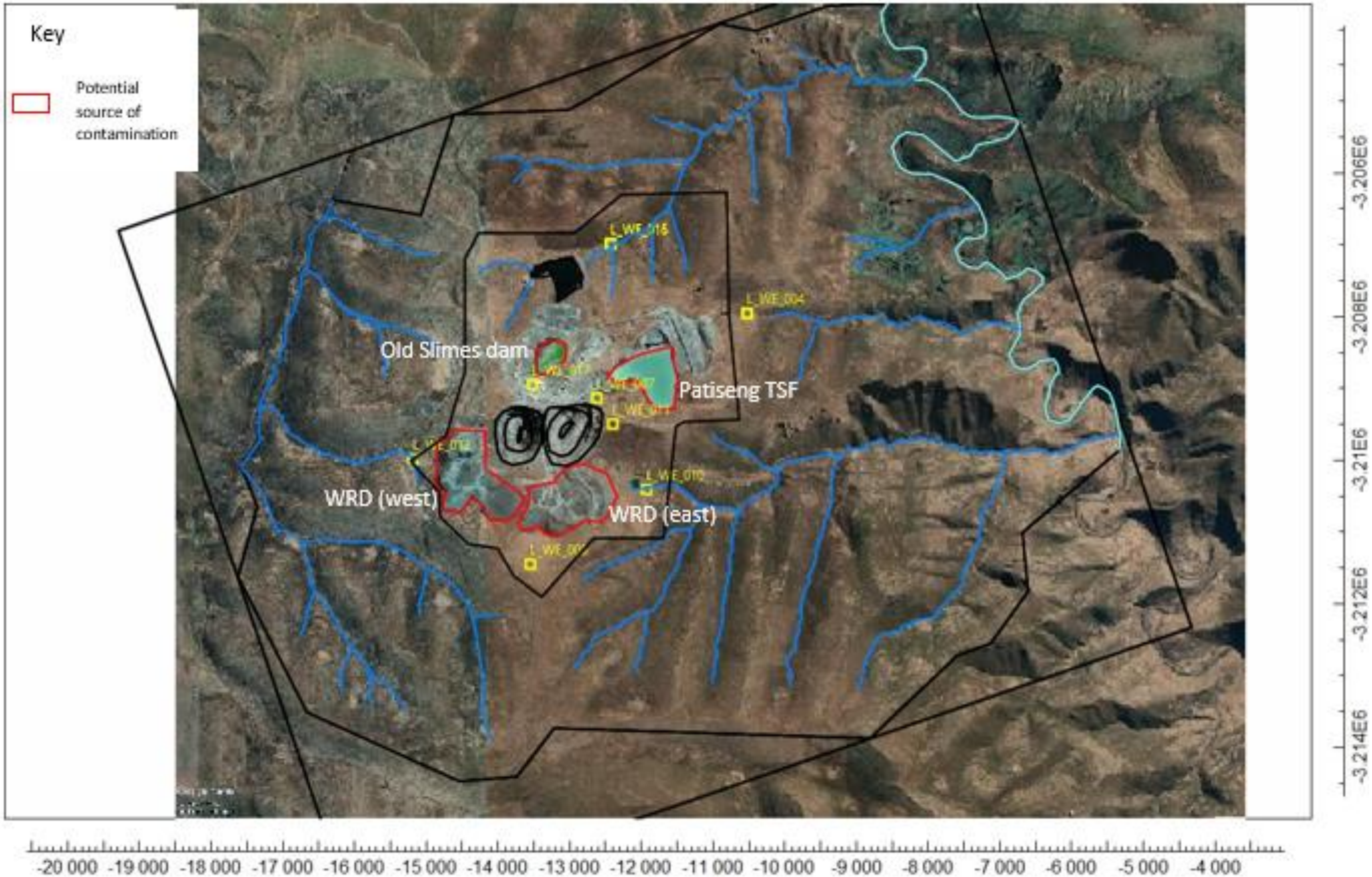

Figure 6-1 Map showing potential source of contamination, assigned as origins for the particles.

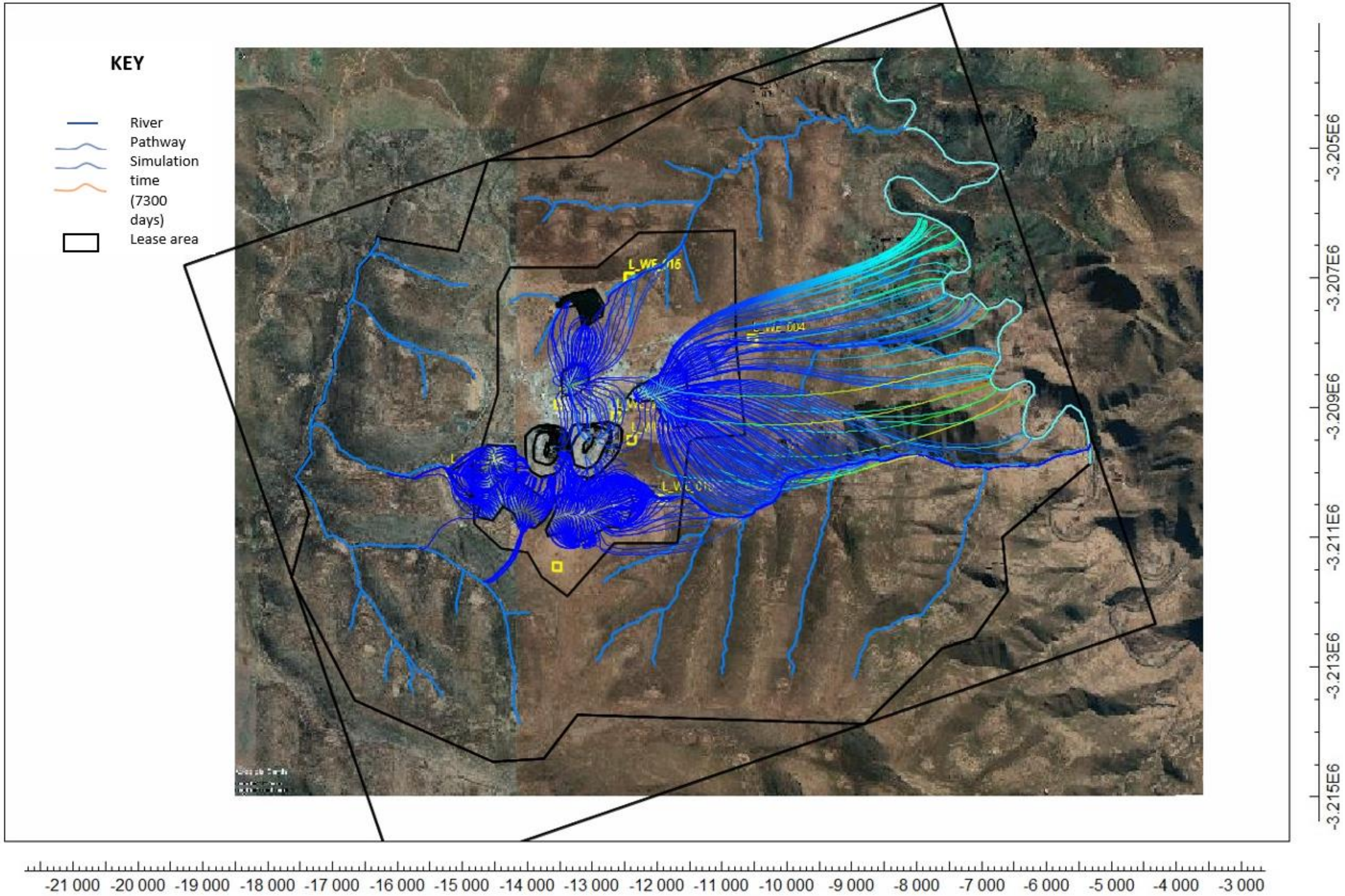

Figure 6-2 Particle pathways from all potential sources of contamination simulated over total simulation time (7300 days).

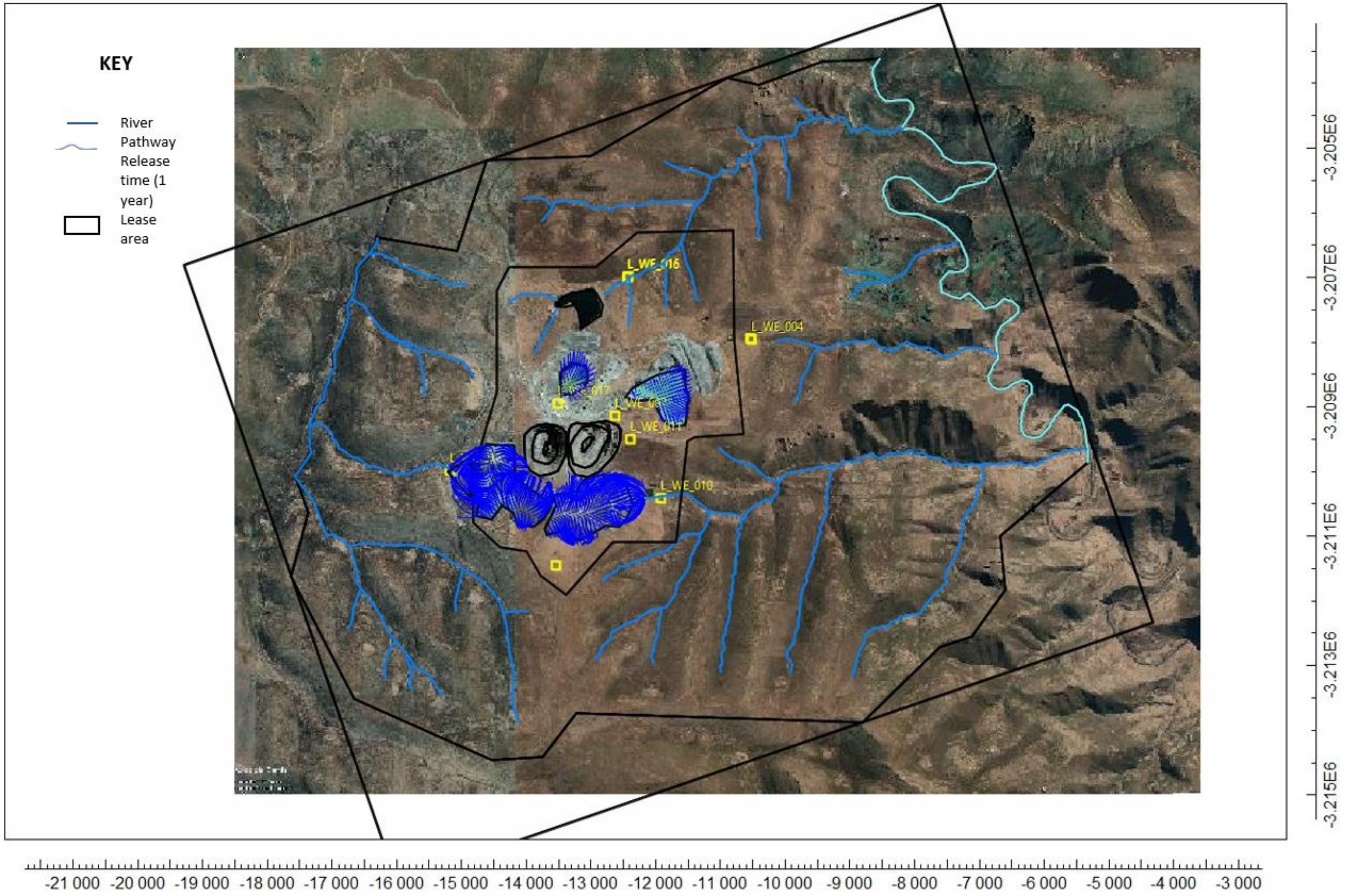

Figure 6-3 Pathways for particles released in 1 year from all potential sources of contamination, showing short travelling distance from the source.

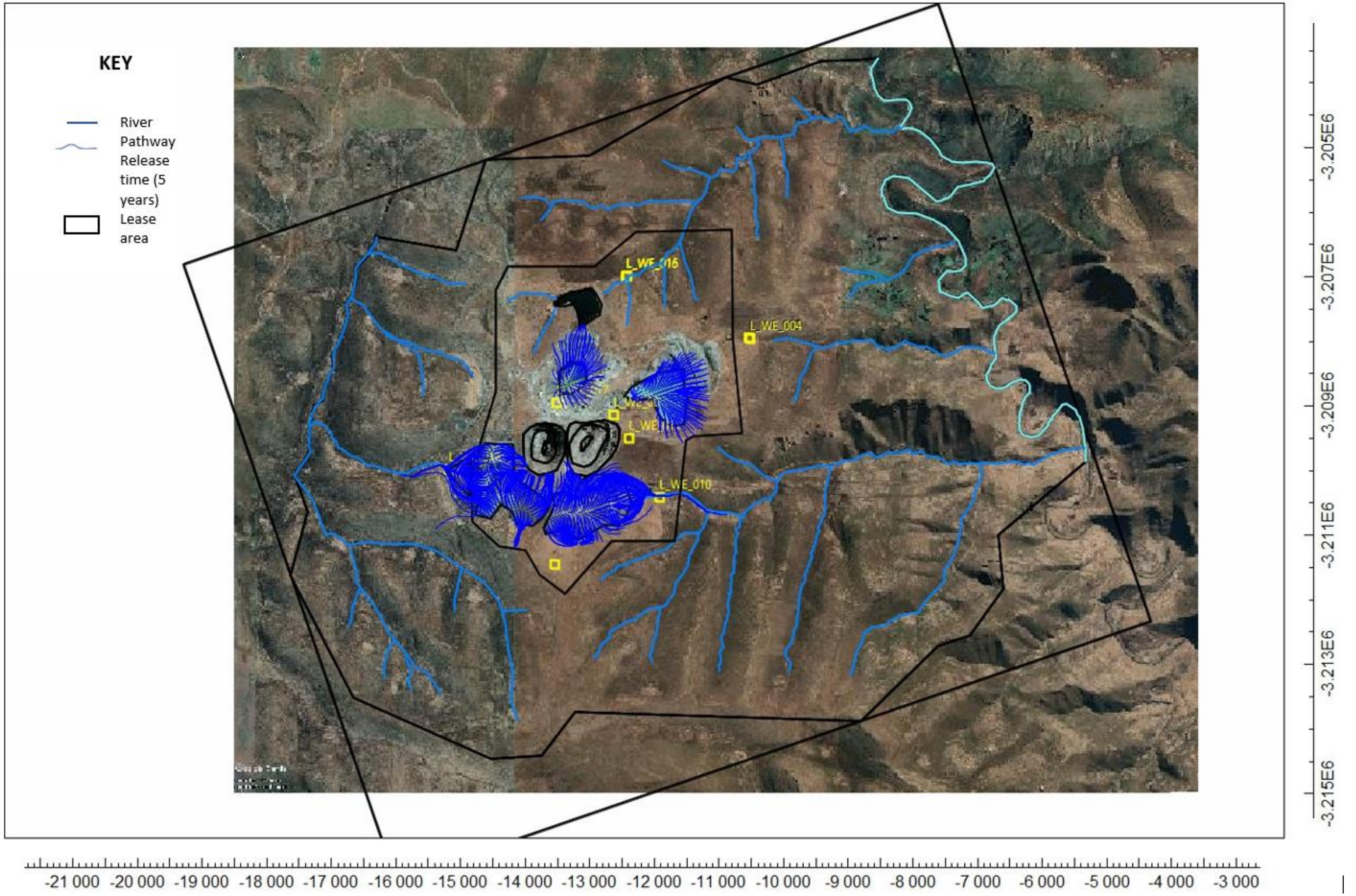

Figure 6-4 Pathways for particles released in 5 years from all potential sources of contamination, with particles from both WRDs migrating beyond the lease area.

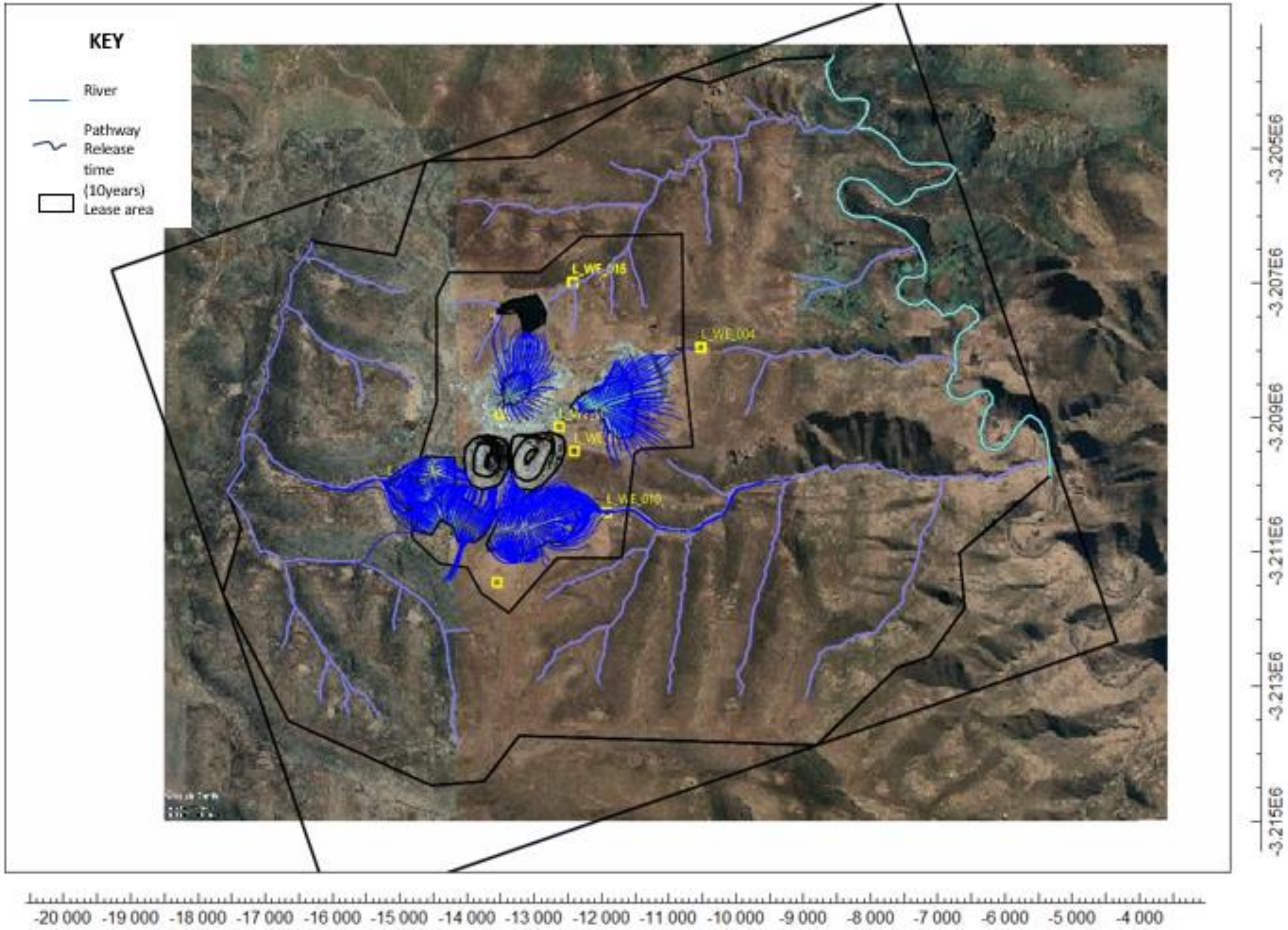

Figure 6-5 Pathways for particles released in 10 years from all potential sources of contamination, with further travelling distance beyond the lease area from the WRDs and Patiseng TSF.

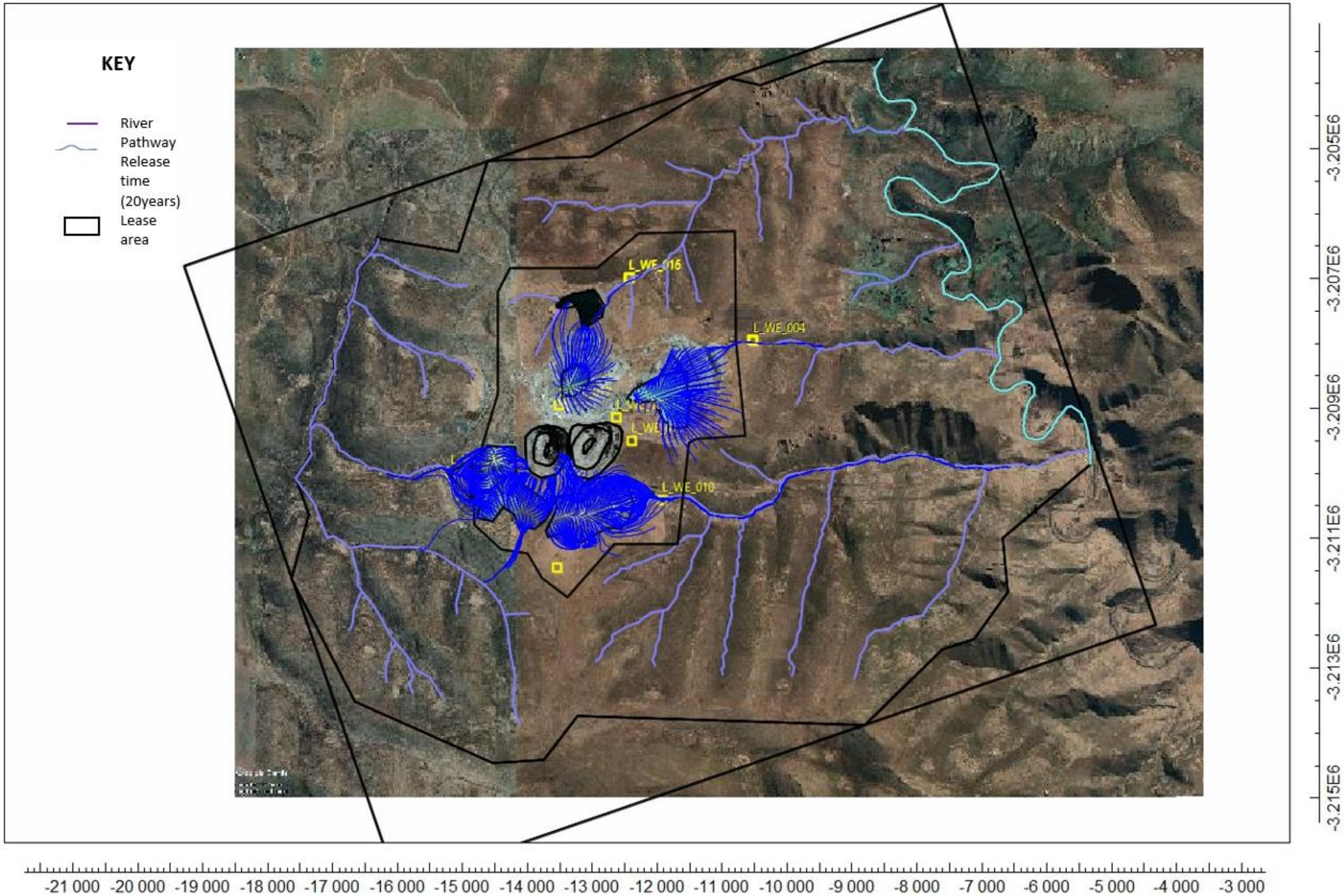

Figure 6-6 Pathways for particles released in 20 years from all potential sources of contamination, with particles from the Old TSF contained within the lease area.

The results obtained suggest that contamination from the potential sources is mainly confined to the weathered layer, which has a higher hydraulic conductivity than the deeper zones and represents the first receptor of contamination. And that at current extents, contamination is still within the site boundary, only future scenarios indicate contamination extending off-site, though still limited to the upper courses of the streams, mainly the northern stream and the western stream. The model results also confirm seepage of contaminated water from the eastern WRD towards borehole L_WE_010 whose water quality results show elevated nitrate concentrations.

Borehole L_WE_012 down-gradient of the western WRD also shows increasing contaminant concentrations overtime, and this is also depicted by the model, with particles moving towards the borehole. There is seepage of contaminated water from the Old TSF towards boreholes L_WE_017 and L_WE_014 as was concluded from the water quality results, however, there is limited movement of particles towards these boreholes according to the model results. This could be related to heterogeneous conditions within the weathered zone in this area not simulated by the attributed model material zones. Lastly, borehole L_WE_015 and L_WE_016 show very low contaminant concentration as per water quality results, this is also evident from the model, where particles only move towards these boreholes after 20 years. These results are further analysed in the next section to determine the cumulative impacts of mining on the groundwater quality.

6.2 CUMULATIVE IMPACT ASSESSMENT

Due to multiple activities that take place in mining, the results show that there is a risk on the groundwater quality. To assess the cumulative impacts of mining on the groundwater quality, the risk-based approach is employed. This approach considers the Source-Pathway-Receptor concept, taking into account the concentration of contaminants at the source, how the contaminants migrate along different pathways, as well as consequences on the receptors.

As discussed in Chapter 2, when carrying out a CIA, the first step is to define the scope. This includes the identification of spatial and temporal boundaries, valued environmental components (VEC) or receptors, stressors, as well as indicators on status of the receptors (McGregor et al., 2013). This process was informed by conceptualisation of the model in the previous chapter. The model defined the boundaries of the model, based on the geographical features around the study area where impacts may occur, in this case the groundwater and surface water resources that support the surrounding environment. Local boreholes, the Qaqa River and Khubelu River being at risk of contamination from mining activities, thus receptors of contamination. Data analysis from water quality monitoring also assisted in identifying the stressors on the valued environmental components. This was based on analysing trends for nitrate and sulphate concentrations as indicators. The source is considered to be a risk when the concentration of contaminants exceeds the recommended water quality standards. Areas around the mining activities which indicted high concentration of nitrates and sulphates were identified as potential sources or stressors, namely, the Old Slimes dam, Patiseng TSF and Waste Rock Dumps whose impacts in combination can be considered as cumulative impacts, in this case, nitrate concentrations from human and animals were not included due to limited activities that exist around the area.

The second step in CIA is collecting and analysing of data on the baseline conditions defining the status of the water quality at the beginning of mining and changes as mining activities proceed overtime. Based on data analysis in previous chapter, nitrate concentrations from the Old Slimes dam (DDB02) exceed the recommended limit from 2016, while sulphate concentrations are constantly high although within the limits (Figure 4-14). Trends for the WRD west (WQQ01) show that contaminant concentrations were constantly above the recommended limits from 2013 (Figure 4-18). Nitrate concentrations from the WRD east (WRT01) were above the recommended limits from 2014 and increased with time, while sulphate concentrations exceed the recommended limits from 2018 (Figure 4-19). Lastly, nitrate concentrations from the Patiseng TSF (DPS01) exceed the recommended limits throughout the monitoring period, while sulphate concentrations are constantly high, exceeding the recommended during some periods (Figure 4-20). Monitoring data therefore shows that nitrate and sulphates concentrations were relatively low and within acceptable limits at the start of monitoring in 2012, and increased overtime as mining continued, eventually exceeding the recommended limits.

The third step involves evaluating the significance of the cumulative impacts, in terms of the sensitivity of the receptors and magnitude of the impacts. The magnitude of the impact is defined by the intensity, extent and duration of the impact. Groundwater modelling was used to estimate the current groundwater quality conditions and simulate the changes that will occur as mining proceeds, in terms of magnitude and sensitivity. To achieve this, the groundwater flow model was processed with MODPATH to simulate travel time and travel path lines of particles from their origins, thus deduce the travel times and travel path lines of contaminants from potential sources. As seen in Figure 6-3, the one-year simulation shows the current conditions on the groundwater quality. Particles or contaminants are limited to around their origins (sources), there is limited migration of contaminants from the source. This means that in a period of 1 year, the impacts of mining are limited around the potential sources and there is no significant impact beyond the mine lease area and the contamination does not affect any receptor.

With five-year simulations, the contaminants show significant travel distance from the source. In particular, path lines from the Old Slimes dam reach the Mothusi Dam after the five-year time period. Considering that there are no surface water flows between the Old Slimes dam and Mothusi dam, it can be deduced that contaminants seep through groundwater into Mothusi dam and due to the proximity of the dams, the Mothusi dam is therefore at high risk of being contaminated over a short period of time. The mine currently uses the Mothusi Dam for domestic purposes, meaning if it is at the risk of contamination from the Old Slimes dam within five years, it can be considered as the most sensitive receptor. During this period, path lines of contaminants from the WRDs migrate beyond the mine lease area, intersecting boreholes L_WE_010 and L_WE_012 (Figure 6-4). This indicates that in a period of five years, there could be significant impacts on the groundwater quality from these sources. Considering the water quality of both the Old slimes dam and WRDs, with nitrates and sulphate concentrations that exceed the recommended limits, these area can be considered to have the highest risk of contamination on the water quality.

During the 10-year simulation, the particles from the Patiseng TSF travel beyond the mine lease area and intersect the borehole downstream (Figure 6-5). This means that migration of contaminants from the TSF is relatively slow. Further travel distance is also seen from other sources, suggesting an increase in the magnitude of impacts with time. Similarly, for particles released at 20 years, particles or contaminants travel further downstream from the mine into the surrounding environment (Figure 6-6) along the surrounding streams, which also act as pathways for contaminant transport. Only during this simulation do the path lines intersect all the boreholes downgradient of the point sources, implying it may take up to 20 years for groundwater to be significantly affected by the mining activities of concern. The results also shows that particles or contaminants from the WRD east travel longer distance towards the Khubelu River, which supports the local community with clean water. The river is therefore at the risk of contamination from the WRD (east) upstream. Mitigation measures must be put in place to control contamination from the WRD.

Based on this information, the significance evaluation can be concluded by Figure 6-7 and Table I. Figure 6-7 shows a map overlying the sources of contamination based on the concentration of contaminants, movement of particles after a 20-year period and most the sensitive receptors. The total contaminant concentrations are based on the cumulative concentrations of sulphates and nitrates for each surface water sampling point.

The highest concentration of contaminants is from the WRDs, followed by the Patiseng TSF, and lastly, the Old Slimes dam. High concentration of contaminants however, does not necessarily suggest significant impact from the source. For instance, modelling results show that despite lower concentration of contaminants from the Old Slimes dam the risk is higher as contaminants reaches a sensitive receptor (in terms of importance) over a short period of time. Over the same period, contaminants from the WRD do not reach a sensitive receptor although the contaminant concentrations are higher.

Results show that over 20 years contaminants from the WRDs are confined to just beyond the mine and do not reach sensitive receptors (Khubelu and Qaqa Rivers). It can therefore be suggested that the impacts from the Old Slimes dam are more significant compared to the impacts from the WRDs, based on the receptor exposure. Contaminants from the WRD do get to groundwater resources over short periods of time. However, for this area, the groundwater resources are not sensitive receptors and therefore the contamination of groundwater from WRDs has less significant impacts.

Table I shows the criteria used to evaluate the significance of the impacts from the potential sources of contamination based on the analysis of the modelling results (guideline for the criteria is shown in Appendix A).

The procedure involves evaluating the significance of the impact by determining the magnitude of the impacts caused by mining activities over time. Which describes the change predicted to occur to a receptor due to an activity. This is derived from the intensity, extent and duration of the impact (McGregor et al., 2013) The significance is also evaluated based on the sensitivity of the receptor, based on its importance or vulnerability to the impacts. The ratings are determined based on the discretion of the assessor, where an overall rating of both the magnitude and sensitivity are used to evaluate the significance of the impacts.

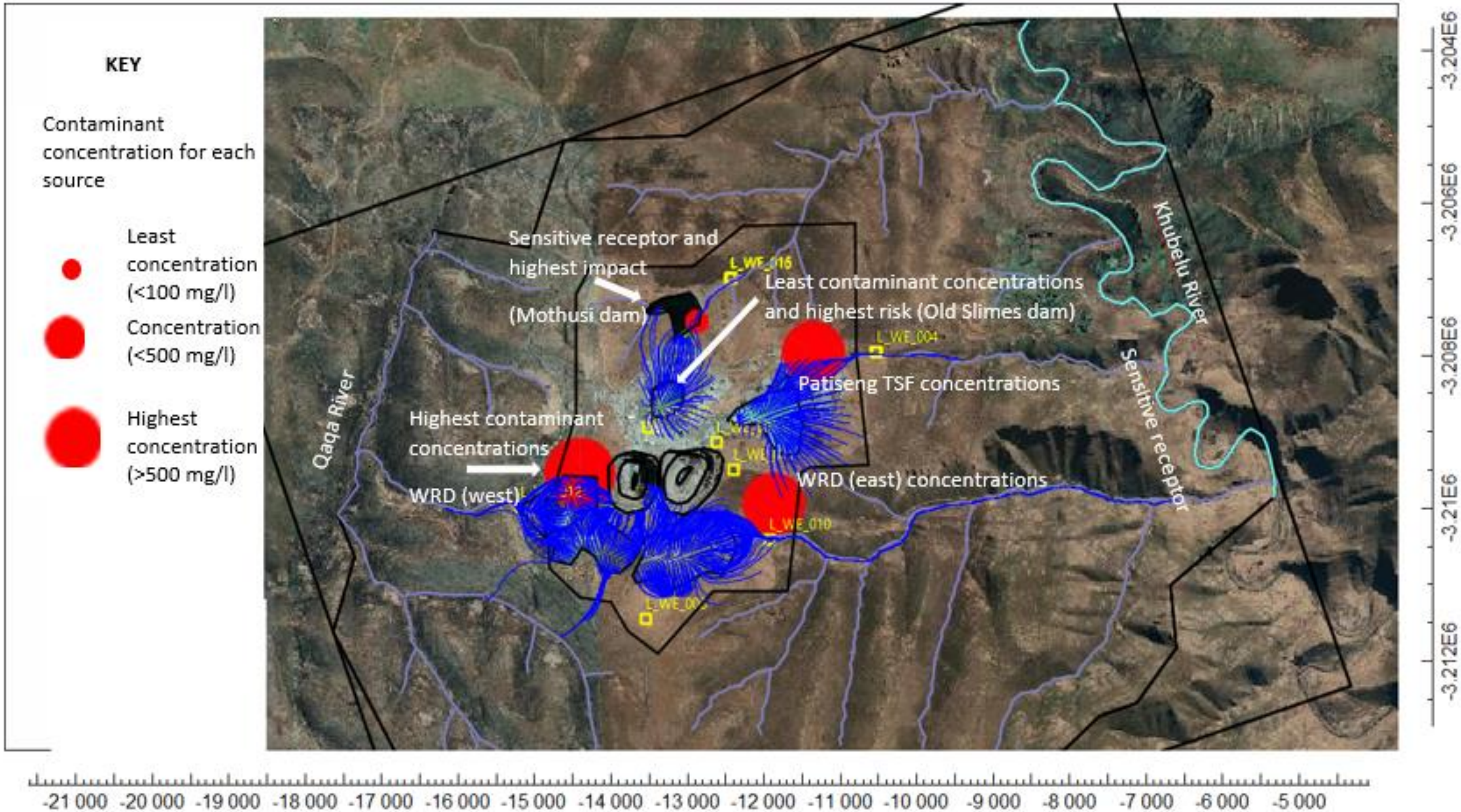

Figure 6-7 Map showing area with high contaminant concentration, path lines for contaminants and sensitive receptors.

Table I Criteria for evaluating the significance of impacts of mining at LDM by rating the magnitude of the impact and the sensitivity of the receptors.

Evaluation	**Ratings per area**					**Overall rating**
Magnitude of Potential source	**Patiseng TSF**	**Old slimes dam**	**WRDs**			
Intensity	moderate	low	high			
Extent	local	local	local			**LOW**
Duration	mid-term	short-term	long-term			
Sensitivity of receptors	**Mothusi Dam**	**Boreholes**	**Local streams**	**Qaqa River**	**Khubelu River**	
Low				*		
Medium		*	*		*	**MEDIUM**
High	*					
Significance	**High**	**Medium**	**Low**			
Magnitude				*		**LOW**
Sensitivity		*				

The evaluations shows that in combination, the magnitude of the impacts is sufficiently low and within normal variations and acceptable standards. The impacts are limited to the local environment although varying from short to long-term based on modelling simulations. The sensitivity of receptors is medium, as some of the sensitive receptors are at a higher risk of contamination than other receptors. With low magnitude and medium sensitivity, the impacts are of low significance and require monitoring to ensure contaminant controls and mitigation measures that can reduce or avoid the cumulative impacts, which is the fourth step in CIA. Mitigation in CIA follows the mitigation hierarchy, which prioritizes prevention over minimisation. In the case of LDM, impacts can however be mitigated mainly through minimisation controls, which includes applying procedures on site to abate the impacts by reducing amount of contamination produced or improving ways in which waste is disposed.

6.3 SUMMARY

The chapter investigates the impacts of mining on water resources. The groundwater flow model was used to evaluate contamination fate by mean of particle tracking. Particles were assigned to identified sources of contaminations and were tracked to determine their flow path and their end points over 20 years simulation. The results showed that the movement of particles was very slow and was mostly confined within the mine lease area. However, with time, particles do move into the surrounding environment posing a risk on the receptors. The results were then used to conduct the cumulative impact assessment, based on the magnitude of the impacts, sensitivity of the receptors and thus the significance of the impacts.

7 DISCUSSION

Contaminants flow into the subsurface by percolation through the soil. Within the subsurface,the fate of contaminants is controlled by advection-dispersion and diffusion processes. In this study, advection transport of contaminants in flowing groundwater was taken into consideration. Advective transport is based on flow velocity in relation to the average bulk aquifer properties and the hydraulic gradient (Anderson et al., 2015). In conjunction to this, results show that the flow path of contaminants follows the groundwater flow gradient. The results also show that the flow path of contaminants is mainly limited to the upper zones, which are mostly weathered, this confirms that fractures are generally the main paths for advective transport (Anderson et al., 2015).

Contaminant fates studies on the area show that the contamination plume from sources of contamination is confined within the mining area and slowly exceeds the area over time as mining activities continue. Similarly, results from this study though limited to advection transport also show that currently, the contaminants are confined within the mine lease area and with increased simulation time, particles or contaminants are released into potential receptors within the area and beyond. Particle tracking showed that contaminants eventually get to boreholes downgradient of sources of contamination indicating groundwatercontamination, although the impacts were considered to have low significance, based on the magnitude of the impact and the sensitivity of the receptor. Despite having successfully estimated the flow of contaminants on the area and assessing the impact thereof, there were limitations to the study. The limitations are discussed below based on different aspects of the study.

Data and conceptual model development limitations

- There was limited data regarding site characterisation especially geological data. Most of the data was based on the regional geology and not the local geology. Where available, the data was limited around the pit area, for example, geological structures such as joints and fractures were only mapped around the pits. To describe the geology of the area, borehole log data was extrapolated, and this was very limiting.
- Similarly, the hydraulic properties were also deduced from previous pumping test results, and some properties were not estimated.
- Additional drilling and hydraulic testing are required to determine the field hydraulic conductivities for the area.

- Natural recharge was also estimated based on topography and hydrogeological conditions as encountered on-site.
- To explicitly and accurately represent each hydrogeological feature likely to affect the behaviour of a complex and highly heterogeneous groundwater system in the conceptual model, a better understanding of the spatial variation of hydraulic parameters and geological complexity is acquired, and this can be achieved by improving the data quality.

Model design and numerical modelling

- Topography for the site was taken from SRTM data and used to define the elevations of the model layers. Topographic data collected from the mine was limited to the lease area. The topographic features used to delineate the model were not included.
- The current model has some limitations in that it simulates a simplified hydrogeology of the area, as is the case with any model. The zones included in the model represents the hydrogeology; however, they do not include detailed heterogeneity or explicit discontinuities.
- One-dimensional flow was assumed in the unsaturated zone, hence the use of the UZF package.
- The model layers were assigned average hydraulic conductivities within the ranges indicated by previous aquifer testing. The hydraulic conductivity of model layers was assumed to decrease with depth.
- Transient hydraulic parameters, such as storage parameters, were not available for transient model runs, hence the model was run under steady-state conditions which does not assess the time-dependent impacts. Running the model under steady state conditions was limiting in terms of addressing the temporal aspect of cumulative impact assessments.

Limit of using particle tracking only, instead of transport

- Actual measured seepage rates were not available for the Old Slimes Dam, Patiseng TSF (including dam wall), and waste rock dumps as well as data for parameters that define transport models. Limiting the study to particle tracking under steady-state conditions, which are not accurate for simulating contaminant transport, advection anddispersion processes could be incorporated into the model.

- Particle tracking method therefore did not consider the physical and chemical propertiesof water and the behaviour of the contaminant in this aspect.
- The movement of particles during particle tracking was very slow due to the small advective component of groundwater flow in the low K rocks. Diffusion would play a large role in this type of environment.
- Backward tracking would be useful in identifying the past sources of contamination, however, due to the data limitations especially in terms of discharge rates, this could not be evaluated.

CIA limitations

- Limited guidelines of how to conduct a CIA.
- CIA involves assessment of past, present, and future impacts, however, the model results only provided estimates for current and future impacts, past impacts were not evaluated (due to the model restrictions and data constraints), thus limiting the assessment.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

A satisfactory groundwater flow model of the mine was achieved and used to predict contaminant flow from sources of contamination to receptors. Based on the modelling results, the following conclusions are made in response to the main objectives of the study:

Conceptualisation

Based on the data review and analysis, the site was characterised, and the conceptual model was developed. The mine is located within the basalt Formations, where kimberlite pipes intrude the basalt host rocks. Data relating to geology of the area led to the classification of hydrogeological into the unconfined zone and confined. The upper zone is highly fractured, and competency increases with depth. Results from previous tests were used to estimate the hydraulic properties of the area. Main contribution of recharge was from summer rainfalls, this is evident with the changes in groundwater level with rainfall.

Mining of the kimberlite pipes involves excavating of waste to access the ore. Waste is deposited as coarse-grained waste in waste rock dumps and as fine-grained waste into tailings facilities. It is from these deposits that contaminants are leached into groundwater contaminating it with nitrates and sulphates. Mine water sampling results indicate the waste rock dump, water discharged from the pits and the Patiseng TSF and the Old slimes dam as likely on-site sources for sulphates and nitrates. The primary source of nitrate is likely the explosives used for blasting. The primary source of sulphate is likely the pyrite found in the shear zone present in both pits. The source-pathway-receptor model was then used to identify the sources of contamination, how the contaminants flow through the system and possible receptors of contamination. Providing a basis for the conceptual model.

Determining Contaminant fate

The conceptual model was then used as a foundation for the numerical model. The model design and setup were based on the properties of the conceptual model. Based on these conditions, the groundwater flow model was constructed to determine the flow of groundwater in the area. The model indicated that flow from the high west to the east of the site. The calibrated groundwater flow model was then used as a basis for particle tracking. Under steady-state conditions over 20-years, one year evaluation showed that currently, contaminants are limited around their sources. At five years, particles of contaminants reach the Mothusi dam from the Old slimes dam. At 10 years, more particles migrate beyond the mine lease area, while at 20 years contaminants are released into all the boreholes around the site. The flow path model showed that contaminants flow mainly through the highly fractured zone and surface water posing a risk on water resources downstream which are the receptors.

Modelling application to CIA

The flow path model was incorporated into the CIA to determine the impact of mining on groundwater quality. The outcome of the CIA was that the impact of mining on groundwater exists although the significance of the impact is low. This is because, the flow path model indicated that contaminants from different sources were currently contained within the mine lease area. As mining continues, the particles may migrate beyond the boundary however with limited interaction with sensitive receptors. The main impact is seen on the Mothusi dam. Where contaminant particles from the Old Slimes dam are released into the dam from as early as 5 years. The impact is significant considering that the dam is an important receptor. From 5 years to 10 years, contamination is released into the surrounding boreholes also indicating an impact on the groundwater quality although of low significance due to the time it takes. Despite its limitations, the model was therefore successful in determining the cumulative impacts of mining on groundwater.

A thorough evaluation of the Letšeng diamond mine outlines a substantial interaction between groundwater quality and mining operations. This comprehensive analysis clarifies the slow but significant effects of mining operations on groundwater and surface water resources over time. The results highlight the need for ongoing monitoring and mitigation measures to reduce cumulative effects on vulnerable receptors including the Khubelu, Qaqa Rivers and Mothusi Dam. The study highlights the significance of taking pre-emptive steps and recommends a strategic focus on minimizing contamination through updated waste disposal procedures and strict on-site controls. The conclusion of this assessment emphasizes the critical need for ongoing environmental management within mining practices to protect the quality of nearby water resources. This is achieved by addressing the sources and pathways of contamination that have been identified, putting in place rigorous monitoring, and strengthening mitigation measures.

8.2 RECOMMENDATIONS

The goal of this study was to stimulate and enhance appropriate levels of regulatory effort needed or currently underway to mitigate or minimise impact on water resources and working towards strengthening current practice to ensure minimal or zero impact.

Based on the results obtained from the study, the following recommendations can be made.

- Further study is recommended to better understand the hydrogeology of the area. This could include characterizing the geological structures within the area, which will assist in understanding of the aquifer system and the hydraulic properties of the area. This includes conducting of aquifer hydraulic tests.
- Confirm Old Slimes dam and Patiseng TSF, as well as WRDs as contaminant sources by performing geochemical testing on all the facilities.
- Stable isotope studies could determine the seasonality of the tributary streams as sources or drains of groundwater.
- It is recommended to continue the quarterly groundwater and surface water monitoring and sampling as being done currently to obtain a better understanding of the interaction between groundwater and surface water; and verify the model results.
- Samples should also be taken at water sources supporting the surrounding areas to determine the changes in water quality, thus impacts on the receptors.
- The groundwater model should be updated regularly to have a better understanding of the groundwater system and to also be used a tool to assist in groundwater management.
- Where impacts are identified, the mitigation hierarchy should be followed in efforts to mitigate and minimize the impacts. For instance, by containing and treating surface water runoff from potential sources of contamination, contaminants entering the groundwater system can be minimised. An example of treating contaminated water could be implementing of bioremediation techniques to remove nitrates and sulphates from the water.

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APPENDIX A

The definitions in the tables are used to define the impacts and provide a rating for each of the categories. Table A set a criterion for determining the Intensity, Extent and Duration which will be used to determinise the Magnitude of the impacts. The Magnitude rating and the sensitivity rating are then used to determine the significance of the impact in Table C.

Table A Criteria for determining the Intensity, Extent and Duration for determining the Magnitude of the impacts.

Criteria	Ratin g	Description
Criteria for ranking of theINTENSITY of environmental impactstaking into account reversibility and scale	**VERY LOW**	Negligible change, disturbance or nuisance which is barely noticeable or may have minimal effect on receptors or affect a tiny proportion ofthe receptors.
	LOW	Minor (Slight) change, disturbance or nuisance which is easily tolerated. and/or reversible in the short term without intervention, or which mayaffect a small proportion of receptors.
	MEDIUM	Moderate change, disturbance or discomfort caused to receptors or which is reversible over the medium term, and/or which may affect amoderate proportion of receptors.
	HIGH	Prominent change, or large degree of modification, disturbance ordegradation caused to receptors or which may affect a large proportion of receptors, possibly entire species or community and which is noteasily reversed.
Criteria for ranking the EXTENT / SPATIAL SCALE of impacts	**SITE**	Impact is limited to the immediate footprint of the activity andimmediate surrounds within a confined area.
	LOCAL	Impact is confined to within the project concession / licence area andits nearby surroundings.
	REGIONAL	Impact is confined to the region, e.g. coast, basin, catchment, municipalregion, district, etc.
	NATIONAL	Impact may extend beyond district or regional boundaries with nationalimplications.
	INTERNATIONA L	Impact extends beyond the national scale or may be transboundary.
Criteria for ranking theDURATION of impacts	**SHORT TERM**	The duration of the impact will be < 1 year or may be intermittent.
	MEDIUM TERM	The duration of the impact will be 1-5 years.
	LONG TERM	The duration of the impact will be 5-25 years, but where the impact willeventually cease either because of natural processes or by human intervention.

	PERMANENT	The impact will endure for the reasonably foreseeable future (>25 years) and where recovery is not possible either by natural processesor by human intervention.

Magnitude (or Consequence) Rating	**Description ***
VERY HIGH	Impacts could be EITHER: of ***high intensity*** at a ***regional level*** and endure in the ***long term***;OR of ***high intensity*** at a ***national level*** in the ***medium or long term***. OR of ***medium intensity*** at a ***national level*** in the ***long term.***
HIGH	Impacts could be EITHER: of ***high intensity*** at a ***regional level*** and endure in the ***medium term***;OR of ***high intensity*** at a ***national level*** in the ***short term***. OR of ***medium intensity*** at a ***national level*** in the ***medium term***. OR of ***low intensity*** at a ***national level*** in the ***long term***;OR of ***high intensity*** at a ***local level*** in the ***long term***; OR of ***medium intensity*** at a ***regional level*** in the ***long term.***
MEDIUM	Impacts could be EITHER: of ***high intensity*** at a ***local level*** and endure in the ***medium term***;OR of ***medium intensity*** at a ***regional level*** in the ***medium term***. OR of ***high intensity*** at a ***regional level*** in the ***short term***; OR of ***medium intensity*** at a ***national level*** in the ***short term***;OR of ***medium intensity*** at a ***local level*** in the ***long term***; OR of ***low intensity*** at a ***national level*** in the ***medium term;*** OR of ***low intensity*** at a ***regional level*** in the ***long term.***
LOW	Impacts could be EITHER. of ***low intensity*** at a ***regional level*** and endure in the ***medium term***;OR of ***low intensity*** at a ***national level*** in the ***short term***; OR of ***high intensity*** at a ***local level*** and endure in the ***short term***;OR of ***medium intensity*** at a ***regional level*** in the ***short term***; OR of ***low intensity*** at a ***local level*** in the ***long term***; OR of ***medium intensity*** at a ***local level*** and endure in the ***medium term.***
VERY LOW	Impacts could be EITHER. of ***low intensity*** at a ***local level*** and endure in the ***medium term***; OR of ***low intensity*** at a ***regional level*** and endure in the ***short term***; OR of ***low or medium intensity*** at a ***local level*** and endure in the ***short term.*** OR **Zero to very low *intensity*** with any combination of extent and duration.

Table B Criteria for deriving sensitivity of ecological receptors.

Sensitivity Rating	Definition
High	Species, habitats or ecosystems listed as globally Endangered (EN) or Critically Endangered (CR) by IUCN, or listed as EN/CR on national or regional Red Lists; or which meet IUCN criteria for range- restricted species[1] or which meet the definition of migratory and congregatory species[2], but which do not qualify as Critical Habitat based on IUCN Key Biodiversity Area thresholds[3]. It includes habitats or ecosystems which are important for meeting national conservation targets based on expert-driven national or regional systematic conservation planning processes, but which do not meet global IUCN thresholds. It can also include protected areas such as national parks, marine protected areas or ecological support areas designated for biodiversity protection containing species that are nationally or globally listed as EN or CR, or other designated areas important for the persistence of EN/CR species or habitats.
Very High	Species, habitats, or ecosystems listed as globally Endangered (EN) or Critically Endangered (CR) by IUCN or listed as EN/CR on expert-verified national or regional Red Lists; or which meet IUCN criteriafor range-restricted or migratory /congregatory species and which meet IUCN thresholds for Key Biodiversity Areas. It includes habitats or ecosystems which are of high importance for maintaining the persistence of species or habitats that meet critical habitat thresholds. Habitats of high sensitivity may typically include legally protected areas that meet IUCN categories 1, 1a and 1b[4], or KBAs or Important Bird Areas (IBAs) with biodiversity features that meet the IUCN KBA criteria and thresholds.
Physical Abiotic Receptors	**Water quality, sediment quality, air quality, noise levels**
Very Low	Receptors are highly resilient to project-induced change and changes remain undetectable and within any applicable thresholds.
Low	Receptors are resilient to project-induced change and changes, while detectable, are within the range of natural variation and remain within any applicable thresholds.
Medium	Receptors are moderately resilient to project-induced changes, but these changes are easily detectable, exceed the limit of the normal range of variation on an intermittent basis and / or periodically exceed applicable thresholds.
High	Receptors are vulnerable to project-induced change and changes are readily detectable, well outside the range of natural variation or occurrence, and regularly exceed any applicable thresholds.
Very High	Receptors are highly vulnerable to project-induced change and changes are easily detectable, fall well outside the range of natural variation or occurrence, and will continually exceed any applicable thresholds.

Table C Criteria for deriving Significance of the impacts.

		SENSITIVITY				
		VERY LOW	LOW	MEDIUM	HIGH	VERY HIGH
MAGNITUDE (OR CONSEQUENCE)	VERY LOW	NEGLIGIBLE	NEGLIGIBLE	VERY LOW	LOW	LOW
	LOW	VERY LOW	VERY LOW	LOW	LOW	MEDIUM
	MEDIUM	LOW	LOW	MEDIUM	MEDIUM	HIGH
	HIGH	MEDIUM	MEDIUM	HIGH	HIGH	VERY HIGH
	VERY HIGH	HIGH	HIGH	HIGH	VERY HIGH	VERY HIGH