



A risk assessment framework for geohydrological systems

G van Wyk



orcid.org 0000-0002-9858-2648

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Supervisor: Prof I Dennis

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“Everybody has the right to an environment not harmful to their health and well-being, to have an environment protected for the benefit of present and future generations, and to have access to sufficient food and water . . .”

-The Constitution of South Africa (1996)

ABSTRACT

Groundwater pollution stands as a formidable challenge in South Africa, impacting human health, the environment, and overall sustainability. This research endeavours to tackle this issue by crafting adaptive risk assessment frameworks tailored to both local and regional contexts. With sustainability at its core, the study accomplishes seven key objectives: a comprehensive literature review, development of a tiered risk assessment framework, strategic application of fuzzy logic, identification of contamination hazards, establishment of a data information system, creation of a practical Excel-based support tool, and a real-world case study demonstration.

To effectively meet the aims and objectives established for tackling the issue of groundwater pollution, the research delves into specific risk categories integral to the comprehensive assessment of the problem. These encompass Climate Change Impact, Aquifer Vulnerability, Groundwater Sustainability, and Human Health.

1. Climate Change Impact: Analysing climate patterns and groundwater dynamics is vital. Precipitation, temperature variations, and climatic shifts can significantly affect groundwater quality and contamination risks.
2. Aquifer Vulnerability: Evaluating aquifer vulnerability is crucial, considering geological and hydrological factors that influence susceptibility to pollutants, including soil characteristics and aquifer permeability.
3. Groundwater Sustainability: Ensuring the long-term sustainability of groundwater involves assessing borehole pumping rates and associated recharge of the area.
4. Human Health: Assessing health risks from groundwater pollution is paramount, involving the potential impact of contaminated water on human health, considering pollutant types, concentrations, and pathways affecting local communities.

While each category is assessed uniquely, an integrated system that holistically evaluates all these categories requires a combination of their outputs. Fuzzy logic, a mathematical tool modelling uncertain and imprecise information, offers the advantage of a nonlinear response.

Fuzzy logic functions by enabling a spectrum of truth values between 0 and 1, reflecting the extent of truth or membership of a specific proposition. This adaptability proves especially beneficial in scenarios characterized by uncertainty or incompleteness, such as in decision-making, control systems, and pattern recognition. Employing fuzzy logic, these categories can be skilfully amalgamated to formulate a novel risk indicator that captures the intricate and

nonlinear connections among the various risk factors related to groundwater pollution and sustainability.

The successful application of the risk assessment tool in a South African study area underscores its effectiveness in providing a nuanced analysis of groundwater pollution risks, emphasising the critical role of site-specific data. Recommendations include continual validation, integration of advanced modelling techniques, and the development of a user-friendly interface to enhance decision-making in groundwater pollution management. This study not only contributes to a holistic understanding of groundwater pollution risks but also offers practical tools for effective risk assessment and management, advancing the cause of sustainable groundwater resource utilisation in South Africa.

Keywords: Groundwater pollution, Risk assessment framework, Fuzzy logic, Aquifer vulnerability, Climate change impact.

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TABLE OF ABBREVIATIONS

Abbreviation	Full Name
1D	One-Dimensional
ADD	Average Daily Dose
AT	Averaging Time
BW	Body Weight
CoG	Center of Gravity
CPF	Cancer Potency Factor
CR	Cancer Risk
DART	Depth to groundwater, Aquifer media, Net recharge, Transmissivity
DEM	Digital Elevation Model
DoM	Degree of Membership
DRASTIC	Depth to Water, Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone, Conductivity
DVI	DRASTIC Vulnerability Index
DWS	Department of Water and Sanitation
ED	Exposure Duration
EPA	Environmental Protection Agency
EU	European Union
F	Favorable
FA	Factor Analysis
FAO	Food and Agriculture Organization
GOD	Groundwater Overdraft
GRII	Groundwater Resources Assessment Phase 2
HI	Hazard Index
HQ	Hazard Quotient
IPCC	Intergovernmental Panel on Climate Change
IR	Intake Rate
ISO	International Organization for Standardization
LADD	Lifetime Average Daily Dose
MAR	Mean Annual Runoff
Maxima	Maximum method
NGA	National Groundwater Archive
PCA	Principal Component Analysis
Q	Pumping Rate
r	Borehole Radius
RAST	Risk Assessment Support Tool
RfD	Reference Dose

Abbreviation	Full Name
S	Storativity
SRES	Special Report on Emissions Scenarios
T	Transmissivity
U	Unfavorable
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WHO	World Health Organization

LIST OF UNITS

Unit	Description
mg	Milligrams
kg	Kilograms
mg/L	Milligrams per liter
L/sec	Liters per second
mm	Millimeters
m ² /d	Square meters per day
m ²	Square meters
m ³	Cubic meters
t	Time

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1 INTRODUCTION

1.1 BACKGROUND

South Africa is home to numerous geohydrological systems, including aquifers, rivers, wetlands, and estuaries, providing essential ecosystem services such as water supply, irrigation, and recreation (UNEP, 2018:42). However, these systems are highly vulnerable to various hazards, particularly groundwater contamination, which is exacerbated by climate change and human activities such as land use changes, water abstraction, and pollution (UNESCO, 2017:75).

Contamination of groundwater and associated surface water bodies is often a result of anthropogenic activities. The increase in economic development, urbanisation, and human settlement development generates undesired waste and waste products that may be released into the environment (Water Research Commission, 2004a:28). Throughout South Africa, surface and groundwater resources are gradually depleting, posing a significant challenge given that a majority of South Africans depend on these resources, including boreholes, dams, rivers, and streams (DWAF, 2005:92).

Foster (2001:186) highlights that peri-urban wellfields surrounding cities and towns further degrade with increased human settlement, leading to increased pollution through industrial discharges, in-situ sanitation, or polluted watercourses infiltrating groundwater from downstream riparian areas. Contaminated groundwater has a profound impact on surface water bodies, particularly in rural areas where poverty is more widespread than in urban centres (FAO, 2020:53). Rural communities rely heavily on these surface and groundwater bodies for water, food, and socio-economic development. Therefore, contamination in urbanised areas can have significant repercussions on the surrounding rural regions.

Recognising the threat posed to water resources by undesirable substances, South Africa has implemented legislative measures to protect water resources from contamination, as outlined in the National Water Act (Act 36 of 1998) and the National Environmental Management Act (Act 107 of 1998).

Furthermore, it is crucial to consider the impact of climate change on water resources, particularly in Africa, identified as one of the most vulnerable continents due to various stresses and low adaptive capacity (IPCC, 2014:109). Climate change directly influences the livelihoods of African people, exacerbating water scarcity in regions like South Africa, which is already classified as water-scarce. This is further aggravated by population growth and socio-economic

development challenges. As climate change intensifies, groundwater becomes increasingly vital, with over 60% of South Africa's population depending on it (Braunne & Xu, 2008:75). Therefore, geohydrological studies must account for climate change impacts to ensure sustainable water resource management.

In this context, it is important to note that sustainability is a pressing issue in many wellfields across South Africa, given the interconnectedness of environmental, social, and economic factors impacting water resources.

This study aims to address groundwater pollution and sustainability in South Africa by developing a versatile risk assessment framework. Key objectives include a literature review, creating a tailored risk assessment framework, establishing a comprehensive data system, and developing an Excel-based support tool. Validation will occur through a real-world case study, demonstrating practical applications and effectiveness in assessing groundwater pollution risks for better resource management.

1.2 PROBLEM STATEMENT

Groundwater pollution is a pressing environmental concern with significant implications for human health, ecosystems, and sustainability (Gleeson et al., 2010:72). Groundwater, essential for drinking water and agriculture, faces contamination risks with long-lasting and sometimes irreversible consequences (UNESCO, 2012:45; Foster, 2001:103). Addressing these challenges necessitates robust risk assessment frameworks on local and regional scales (Gleeson et al., 2010:72).

Uncertainties in predicting contaminant behaviour in the subsurface pose a major obstacle (Freeze & Cherry, 1979:315). Despite advances, significant uncertainty persists, highlighting the need for flexible frameworks capable of incorporating new data (USGS, 2022: 3).

Effective risk assessment frameworks must consider local and regional factors, accounting for variability in contaminant transport processes and uncertainty (Dillon et al., 2005:208). These frameworks should be adaptable, integrating emerging information, particularly concerning health risks.

Sustainability is crucial, necessitating not only contamination remediation but also sustainable groundwater management (DWAF, 2005:92). Thus, sustainability, health considerations, and broader environmental and societal goals must guide the development of these frameworks.

1.3 RESEARCH QUESTION

How can a tiered risk assessment framework be tailored to address the unique challenges of groundwater pollution and sustainability in South Africa, considering factors such as climate change, aquifer vulnerability, sustainable use, and human health risks?

1.4 AIMS AND OBJECTIVES

The study aims to develop an effective risk assessment framework for addressing groundwater pollution and sustainability in South Africa, targeting both local and regional scales. Specifically, it seeks to enhance borehole risk management through a comprehensive risk assessment approach, addressing climate change, aquifer vulnerability, sustainable use, and human health risks.

The study objectives are as follows:

- Conduct a thorough literature review to identify methods for reducing uncertainty in groundwater risk assessments, focusing on techniques suitable for South Africa's geohydrological systems.
- Develop a tiered risk assessment framework tailored to South Africa's geohydrological systems, accommodating basic and detailed levels of analysis while addressing risks to human health and the environment.
- Establish a comprehensive data information system by sourcing data from literature reviews and existing databases, encompassing hazardous sources and substances across South Africa's primary industries.
- Create an Excel-based support tool aligned with the developed risk assessment methodology, facilitating the practical application of the framework.
- Validate the developed framework through a real-world case study in South Africa, utilizing the support tool to assess groundwater pollution risks and demonstrate the framework's effectiveness.

1.5 LAYOUT OF DISSERTATION

CHAPTER 1: INTRODUCTION

The introductory chapter discusses the challenges related to groundwater resources throughout South Africa. This chapter also includes a brief description of aims and objectives of the study as well as the general layout of the dissertation.

CHAPTER 2: LITERATURE REVIEW

The literature review discusses the primary risk assessment methodologies required for constructing a geohydrological framework for assessing risk.

CHAPTER 3: METHODOLOGY

Chapter 3 will discuss the methodology of the risk assessment frameworks utilised in this study and the associated methods applied.

CHAPTER 4: CASE STUDY

Case study on the farms surrounding the Crocodile River is presented as a case study in a mine impacted environment.

CHAPTER 5: RESULTS AND DISCUSSION

In this chapter, the developed risk assessment methodology is applied to a South African case study using the Excel-based tool, showcasing the tool's effectiveness and serves as validation of the methodology.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Conclusions regarding the research are discussed, assessing whether the objectives of the study are met and if the risk assessment support tool functions as intended. Recommendations are made based on the results of the case study.

2 LITERATURE REVIEW

2.1 RISK ASSESSMENTS

Risk assessment is a systematic process that is used to identify and evaluate potential risks and hazards, and to develop appropriate strategies to manage and mitigate them. Risk assessments are used in various industries and fields, including environmental, occupational, food safety, and health; to promote informed decision-making and ensure the safety of individuals, communities, and the environment. The process of risk assessment involves several steps, including hazard identification, risk estimation, risk evaluation, risk mitigation, and risk communication (Yoe, 2011:36).

The concept of risk assessment has been around for centuries, but it was not until the 20th century that it became a formalised process in many industries. In the mid-20th century, the United States began using risk assessment to evaluate environmental hazards such as air and water pollution (EPA, 1992:18). Today, risk assessment is widely used in many countries and industries, and it has become an essential tool for managing risks and protecting the public health and safety (ISO, 2018:42).

Ultimately risk assessment is a critical process that is used to identify, evaluate, and manage potential risks and hazards. It has become an essential tool in many industries and fields, and it is required by law in many countries.

2.1.1 PRECAUTIONARY PRINCIPLE

The precautionary principle is a fundamental concept in risk assessment that emphasises the importance of taking precautionary measures when faced with uncertain or potentially harmful situations. According to this principle, if an action or policy is likely to cause harm to the public or the environment, in the absence of scientific consensus, the burden of proof falls on those advocating for the action or policy to demonstrate that it is not harmful (Raffensperger & Tickner, 1999:65).

The precautionary principle is widely used in environmental and public health risk assessments and has been adopted by international organisations such as the World Health Organization (WHO), the United Nations Environmental Programme (UNEP), and the European Union (EU) (UNEP, 1992:28). It is commonly applied in situations where the risks are uncertain or unknown, and where the potential for harm is significant.

However, the precautionary principle has also been criticised for potentially limiting innovation and economic growth. Some argue that precautionary measures can lead to excessive regulatory burden and that they may be unnecessary in situations where the potential risks are small or uncertain.

Despite these criticisms, the precautionary principle remains an important principle in risk assessment, particularly in situations where potential harm is significant, and the risks are uncertain or unknown. It emphasises the importance of considering potential risks and taking action to prevent harm, even in the absence of conclusive scientific evidence (Goklany, 2002:94).

Figure 1 below illustrates the interplay between uncertainty in likelihood and uncertainty in consequences. In this study, our primary focus is on the green area, where we possess a sufficient scientific foundation to construct a model for addressing the associated risks.

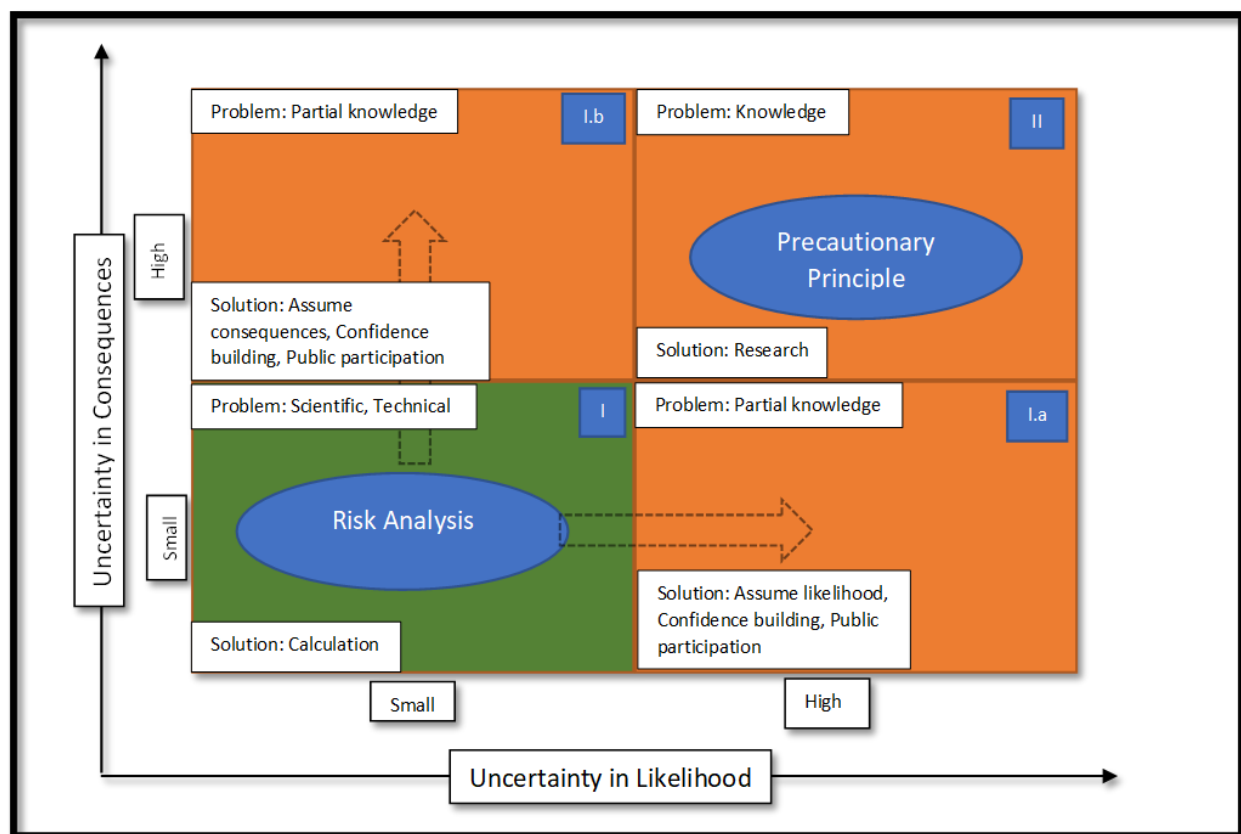


Figure 1: Domains of application of risk analysis (modified from Ganoulis, 2009)

The focus will only be on the risk calculation, if the risk cannot be defined, the precautionary principle will apply. This study considers the risks that can be defined with measurable values.

Using expertise and understanding, these risks will be applied to a model that will produce an answer in terms of the overall risk.

Figure 2 outlines the comprehensive risk assessment process, with particular emphasis on the green areas. It is worth noting that, consistent with Figure 1, the precautionary principle remains beyond the scope of this study as detailed in the methodology section.

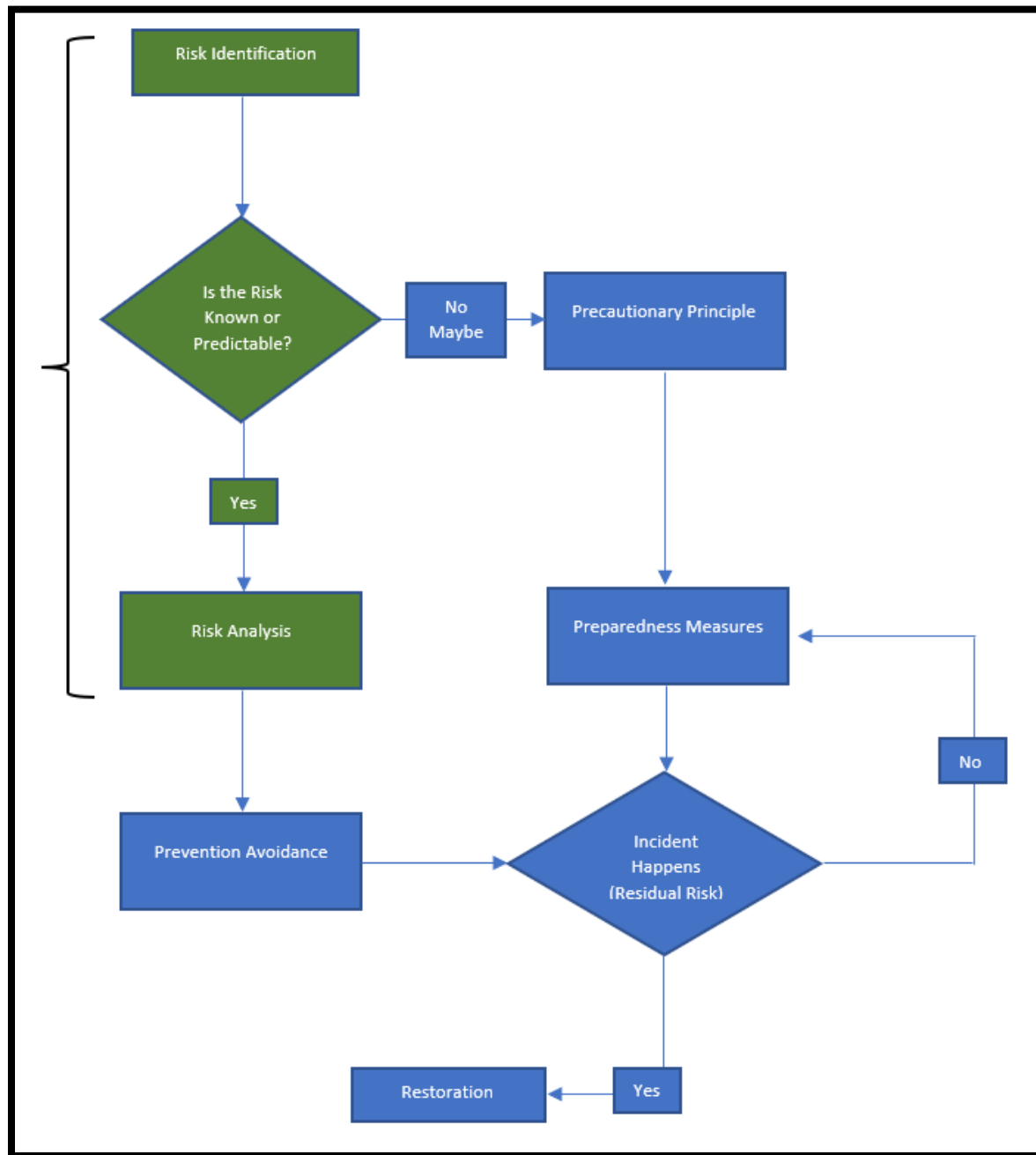


Figure 2: Flow diagram for risk policy (modified from Ganoulis, 2009)

2.1.2 GROUNDWATER POLLUTION

Groundwater pollution is a specific and critical dimension of water pollution that demands focused attention due to its direct impact on human health and the environment (Howard, 2003:45). In various regions, such as South Africa, the prevalence of pit latrines significantly contributes to groundwater pollution, exacerbating the urgency of addressing this issue (Nkhuwa et al., 2018:67). In addition to the immediate concerns of water contamination, the vulnerability of aquifers further underscores the need for a comprehensive understanding of groundwater pollution (Barlow et al., 2019:112). This section will delve into the intricacies of groundwater pollution, emphasizing its relevance to risk assessments, and highlighting specific challenges associated with addressing this form of water pollution, particularly in the context of aquifer vulnerability.

Risk assessments play a crucial role in addressing groundwater pollution, given the severe consequences, ranging from the spread of diseases to the contamination of drinking water sources (EPA, 2018:23). To effectively manage and mitigate these risks, the United States Environmental Protection Agency (EPA) has established a comprehensive four-step framework for conducting risk assessments specific to water pollution: hazard identification, dose-response assessment, exposure assessment, and risk characterization.

Various methods are employed in risk assessments for groundwater pollution, encompassing quantitative, qualitative, and semi-quantitative approaches. Quantitative risk assessment involves the utilisation of numerical data and models to estimate the likelihood and consequences of risks. For instance, it can be applied to assess the probability of specific water pollutants from pit latrines causing adverse health effects in humans (Reif & Hatch, 2008:92). Qualitative risk assessment relies on expert judgment and subjective data to evaluate risks based on their likelihood and consequences. Semi-quantitative risk assessment combines elements of both quantitative and qualitative approaches, incorporating both numerical and subjective data to assess risks associated with groundwater pollution.

Despite the importance of risk assessments in managing groundwater pollution, several challenges exist. One significant hurdle is the limited availability of data on potential risks associated with specific pollutants found in groundwater, such as those emanating from pit latrines (Krewski et al., 2010:78). For example, there may be insufficient data on the long-term health impacts of exposure to these pollutants. Additionally, there might be significant uncertainty associated with the available data.

The examination of the first quadrant of the domains of application of risk analysis and the precautionary principle (Figure 1) minimises uncertainty, enabling a reliable risk calculation (Bernknopf et al., 2019:105). This deliberate approach, outlined in the methodology section, ensures that our assessment of groundwater pollution, considering aquifer vulnerability, is grounded in robust data and supports effective risk management strategies. Appreciating the intricate interplay between groundwater pollution and aquifer vulnerability becomes paramount for safeguarding water resources and mitigating potential impacts on both human health and the environment.

2.1.3 GROUNDWATER SUSTAINABILITY

Groundwater is an essential natural resource that supports various human activities such as agriculture, industry, and domestic use (Foster & Chilton, 2003:54). However, groundwater sustainability faces threats from various factors, including overexploitation, contamination, and the overarching influence of climate change (Foster & Chilton, 2003:54). Risk assessment emerges as a crucial tool for comprehensively evaluating the potential risks associated with groundwater sustainability, considering the evolving dynamics of climate change and its impact on this vital resource. This section aims to provide an overview of risk assessments in the context of groundwater sustainability, emphasising the critical components of the process (Foster & Chilton, 2003:54).

In the context of groundwater sustainability, risk assessments provide a framework for evaluating the potential risks associated with groundwater use. Groundwater utilisation introduces a range of risks, encompassing depletion of aquifers, contamination of groundwater sources, and adverse impacts on ecosystems reliant on groundwater. These assessments gauge the likelihood and consequences of these risks, developing strategies to manage and mitigate them in the face of changing environmental conditions, including those driven by climate change (Gleeson *et al.*, 2017:33).

The complexity and uncertainty inherent in groundwater systems present critical challenges in risk assessments for sustainability. These systems are dynamic, with sustainability contingent on factors such as recharge rates, groundwater levels, and water quality (Sophocleous, 2002:68). Moreover, external factors like climate change, alterations in land usage, and population growth significantly influence the sustainability of groundwater resources. Thus, it becomes imperative to factor in the potential impacts of these external variables in the risk assessment of groundwater sustainability, particularly in the context of addressing the challenges posed by climate change.

Beyond the natural dynamics, regulatory frameworks and management strategies play a pivotal role in groundwater sustainability risk assessments. In South Africa, the National Water Act of 1998 (Republic of South Africa, 1998:105) forms the cornerstone of groundwater management, establishing the legal framework for sustainable water resource use and protection. Regional legislation and policies within South Africa's provinces offer specific guidance on groundwater management. These frameworks and strategies, aligned with the National Water Resource Strategy (DWS, 2013), are integral in safeguarding the availability and sustainability of groundwater resources. They address issues such as water allocation, licensing, resource protection, monitoring, and conflict resolution, serving as a comprehensive approach to support various sectors of the economy and society amid the challenges posed by climate change.

2.1.4 RISK CALCULATION UNDER UNCERTAINTY

Risk calculation under uncertainty is a crucial aspect of risk assessment applicable across diverse fields such as finance, engineering, and environmental management (Kaplan & Garrick, 1981:73). Uncertainty arises when there is incomplete knowledge about the system being evaluated, impacting the accuracy of risk calculations. Consequently, risk calculations under uncertainty involve incorporating probabilities and other forms of uncertainty to yield more robust risk estimates (Kaplan & Garrick, 1981:73).

Widely utilised in finance, risk calculations under uncertainty address the future values of investments influenced by various factors. For example, fluctuations in commodity prices, such as oil and gold, can significantly impact the value of investments in these assets (Geman & Ohana, 2018:42). In engineering, assessing the reliability of structures like bridges, dams, and pipelines relies on risk calculations under uncertainty. Sources of uncertainty in engineering systems include material variability, load variability, and environmental effects (Zhang *et al.*, 2021:72). In environmental management, evaluating the potential impacts of human activities on ecosystems and public health necessitates risk calculations under uncertainty, considering factors like incomplete data on environmental processes and the influence of climate change (Bui *et al.*, 2020:125).

Various methods are employed to incorporate uncertainty into risk calculations, including probabilistic methods, sensitivity analysis, and Monte Carlo simulation (Helton, Johnson, & Sallaberry, 2006:27). Probabilistic methods utilise probability distributions to estimate the likelihood of different outcomes (Helton, Johnson, & Sallaberry, 2006:27). Sensitivity analysis evaluates how changes in different input parameters affect the output of risk calculations. Monte Carlo simulation involves generating random samples from probability distributions and using

these samples to estimate risk. These methods provide decision-makers with insights into the potential range of outcomes associated with different risk scenarios, aiding in informed decision-making across a spectrum of applications (Helton, Johnson, & Sallaberry, 2006:27).

2.1.5 DIRECT EVALUATION

Direct evaluation is a method for calculating risk under uncertainty that involves the multiplication of hazard and vulnerability to obtain an estimate of the risk (Kaplan & Garrick, 1981:73). This method is widely used in various fields, including engineering, economics, and public health, among others (Kaplan & Garrick, 1981:73). The concept of direct evaluation is based on the idea that risk is a function of both the probability of an event occurring (hazard) and the potential consequences of that event (vulnerability) (Kaplan & Garrick, 1981:73).

One advantage of the direct evaluation method is that it allows for the consideration of multiple hazards and vulnerabilities, which can provide a more comprehensive assessment of risk (Kaplan & Garrick, 1981:73). For example, in the field of disaster risk management, direct evaluation can be used to estimate the risk of various hazards, such as earthquakes, floods, and hurricanes, and their potential impact on vulnerable populations.

Research has shown that the direct evaluation method can be an effective tool for assessing risk under uncertainty. In a study on the risk assessment of groundwater contamination, researchers used the direct evaluation method to estimate the risk of contamination from a variety of sources. The study found that the method was useful for identifying high-risk areas and for evaluating the effectiveness of different risk management strategies (Lundgren and Aspelin, 2003:125).

Overall, the direct evaluation method is a useful tool for calculating risk under uncertainty, particularly in situations where multiple hazards and vulnerabilities need to be considered (Cutter *et al.*, 2006:42). However, it is important to note that the method is not without limitations. For example, the accuracy of the estimates obtained using this method depends on the accuracy of the hazard and vulnerability assessments. In addition, the method assumes that the hazards and vulnerabilities are independent, which may not always be the case (Cutter *et al.*, 2006:42).

2.1.6 PROBABILISTIC APPROACHES

Probabilistic methods are another approach for calculating risk under uncertainty. These methods involve the use of probability distributions to estimate the likelihood of an event occurring and the potential consequences of that event (Stedinger *et al.*, 2008:145).

Probabilistic methods can be used to estimate the likelihood of exceedance of water quality standards or thresholds for a given water quality parameter and using time series data (Stedinger *et al.*, 2008:145).

One advantage of probabilistic methods is that they allow for the inclusion of uncertainty in risk calculations. This can be particularly important in situations where the consequences of an event are difficult to predict, or where there is a high degree of variability in the data. For example, in the field of climate change, probabilistic methods can be used to estimate the likelihood of various climate scenarios and their potential impact on different sectors of the economy (IPCC, 2014:277).

Research has shown that probabilistic methods can be an effective tool for assessing risk under uncertainty. In a study on the risk assessment of chemical spills in rivers, researchers used a probabilistic approach to estimate the probability of a spill occurring and the potential impact on river ecosystems. The study found that the probabilistic approach was useful for identifying high-risk areas and for evaluating the effectiveness of different risk management strategies (Fowler and Brown, 1999:312).

Probabilistic methods are a valuable tool for calculating risk under uncertainty, particularly in situations where the consequences of risk can be quantified in monetary terms (Pate-Cornell, 1996). However, it is important to note that the accuracy of the estimates obtained using these methods depends on the accuracy of the probability distributions used and the assumptions made about the underlying data (Pate-Cornell, 1996:98).

2.1.7 FUZZY LOGIC

Fuzzy logic is a mathematical tool that is used to model uncertain and imprecise information. It is a generalisation of classical binary logic, where the truth values of propositions are restricted to only two values: true or false. In contrast, fuzzy logic allows for a continuum of truth values between 0 and 1, representing the degree of truth or membership of a given proposition. This approach is particularly useful in situations where the information available is uncertain or incomplete, such as in decision making, control systems, and pattern recognition (Pokoràdi, 2002:37).

Fuzzy logic has its origins in the work of Lotfi Zadeh in the 1960s, who proposed the concept of fuzzy sets (Zadeh, 1965:1). A fuzzy set is a set where the membership of an element is not restricted to only true or false, but can be any value between 0 and 1. This allows for the modelling of imprecise information and the handling of vague concepts. Zadeh proposed the

use of fuzzy set theory to model human reasoning and decision-making, which led to the development of fuzzy logic.

Fuzzy logic has been successfully applied in various fields such as engineering, computer science, and artificial intelligence (Klir & Yuan, 1995:65). In control systems, fuzzy logic is used to model the behaviour of complex systems, such as automobiles and power plants, where the relationship between the inputs and outputs is not well-defined or may vary, depending on the conditions. In decision-making, fuzzy logic is used to model the preferences and judgments of decision makers, allowing for the handling of uncertain and imprecise information. In pattern recognition, fuzzy logic is used to model the relationship between patterns and the classes they belong to, allowing for the handling of uncertain and imprecise information (Hasanali *et al.*, 2011:112).

Despite its many successes, fuzzy logic is not without its limitations. One of the main criticisms of fuzzy logic is that it is overly dependent on subjective judgment (Klir & Yuan, 1995:67). The membership functions used to define the fuzzy sets are often based on expert opinion and may vary between assessors. Additionally, fuzzy logic can become computationally complex and may require significant computational resources (Hasanali *et al.*, 2011:114).

Some of the terminology used in fuzzy logic includes:

Membership Function: A membership function is a mathematical function that defines the degree of membership of an element in a set. It assigns a value between 0 and 1, indicating the extent to which an element belongs to a particular category within the set.

Crisp Ranking: In the context of fuzzy logic, a crisp ranking refers to a precise and well-defined value or ranking derived from the fuzzy conclusion set. It is the outcome of the defuzzification process, transforming the fuzzy, imprecise information into a clear and actionable result.

The fuzzy logic process, illustrated in Figure 3, comprises several sub-processes that collectively enable the handling of imprecise or vague information.

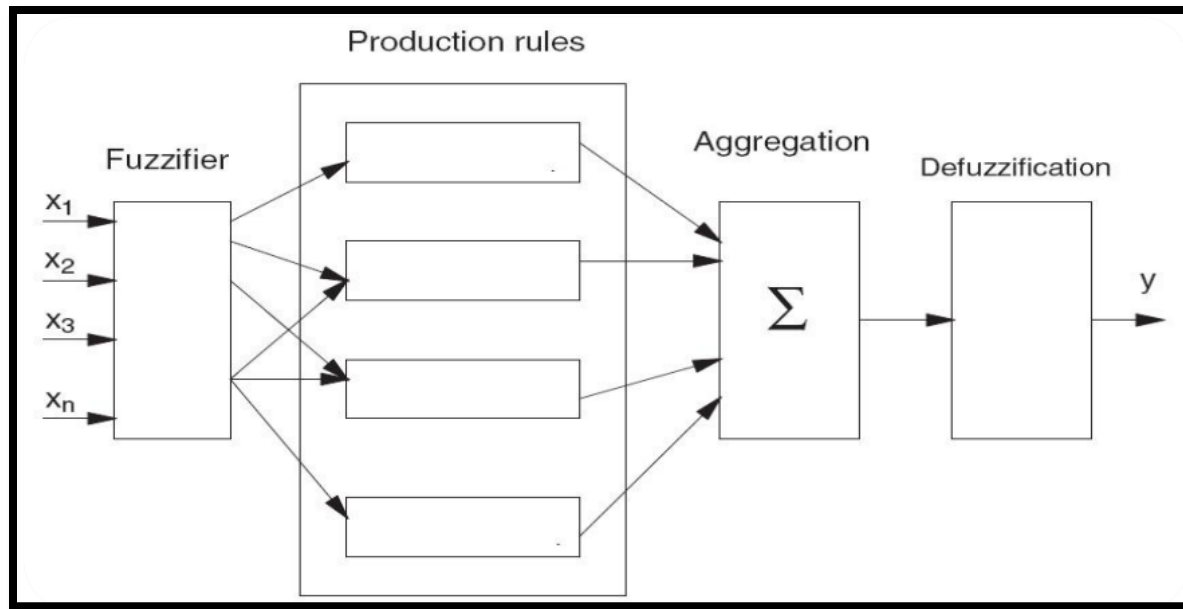


Figure 3: Fuzzification process summary (modified from Pokoràdi, 2002:69 & Fuzzy Logic Fundamentals, 2007:21)

Let's delve into each sub-process to gain a better understanding:

Fuzzification:

Fuzzification involves the application of membership functions to input values. Membership functions are mathematical representations that assign degrees of membership to elements in a set. In the context of fuzzy logic, these functions convert precise input values into fuzzy sets, allowing for the representation of uncertainty or vagueness. For instance, if the input is temperature, the membership function might categorize it as "hot," "warm," or "cold" with varying degrees of membership for each category.

Inference (Rules):

Inference, governed by rules, assigns a degree of truthfulness to each rule. Rules in fuzzy logic are if-then statements that define the relationships between input and output variables. Each rule has an associated degree of truthfulness, representing the strength of the relationship. These degrees of truthfulness guide the decision-making process in fuzzy logic systems.

Aggregation:

Aggregation involves combining fuzzy subsets for each variable into a single fuzzy subset. As the rules generate fuzzy subsets for different output variables, aggregation brings these subsets

together to form a unified fuzzy conclusion set. This step considers the combined influence of all rules on each output variable, providing a comprehensive and integrated perspective.

Defuzzification:

Defuzzification is the process of converting fuzzy output into crisp values that can be used for decision-making. In environmental management, two common defuzzification methods are the Center of Gravity (CoG) and the Maxima methods.

The Center of Gravity (CoG) method calculates the weighted average of the fuzzy set, and it provides a single crisp value that represents the most likely value of the fuzzy set. This method is widely used in environmental management because it allows decision-makers to convert complex and uncertain information into a single value that can be used for decision-making. For example, the CoG method has been used in environmental risk assessment to convert fuzzy outputs into risk scores for different pollutants (Cadenas *et al.*, 2017:136).

The Maxima method selects the maximum value of the fuzzy set as the output, and it is commonly used when the most important output value is the maximum value of the fuzzy set. In an environmental management context, the Maxima method has been used to identify the most critical environmental risk factors. For example, a study used the Maxima method to identify the most important risk factors for oil spills in the Arctic region (Zhang *et al.*, 2015:98).

An example of the two defuzzification methods are presented in Figure 4 to show how the results may differ from each other.

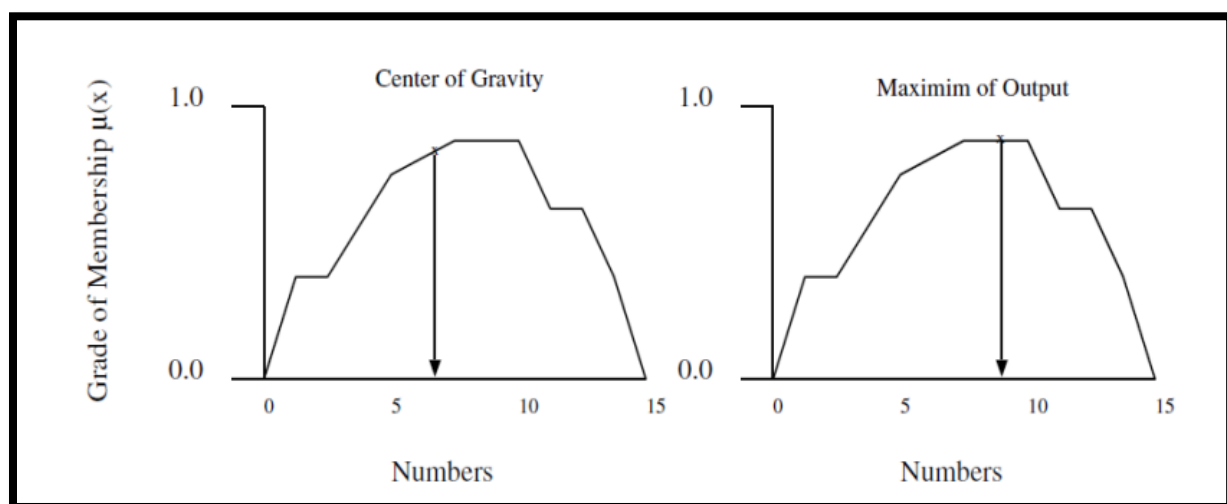


Figure 4: Defuzzification example to highlight difference between CoG and Maximum method (Shepard, 2005:72)

Both defuzzification methods have advantages and disadvantages in environmental management, depending on the specific application. In general, the CoG method is more suitable for applications where a single crisp value is required, while the Maxima method is more suitable for applications where the maximum value of the fuzzy set is the most important output value.

2.1.8 SUMMARY

In summary, the exploration of "Risk Calculation Under Uncertainty" underscores the critical importance of accurate risk assessment across various fields. Recognising the inevitability of uncertainty from diverse sources, the study emphasises the need to address this uncertainty to enhance the precision of risk calculations.

To address this uncertainty, the study emphasises the importance of incorporating probabilistic methods, sensitivity analysis, and Monte Carlo simulation into risk calculations. These techniques enhance the robustness of risk assessments, enabling decision-makers to evaluate potential outcomes across different risk scenarios, facilitating well-informed and sound decision-making processes.

The direct evaluation method is a valuable tool within this framework, offering a comprehensive approach to calculating risk under uncertainty. Its capacity to consider multiple hazards and vulnerabilities contributes to a more thorough risk assessment. Despite inherent limitations, this method has demonstrated its effectiveness in diverse applications, spanning disaster risk management and environmental risk assessment.

Probabilistic methods, which allow for the inclusion of uncertainty in risk calculations, play a crucial role in scenarios where the consequences of risk can be quantified in monetary terms. While the accuracy of these methods hinges on the precision of probability distributions and underlying data assumptions, they have proven effective in applications such as environmental risk assessment and financial risk management.

Furthermore, the choice between the Center of Gravity and Maxima defuzzification methods in environmental management depends on the requirements of the specific application. The Center of Gravity method is preferred when a single crisp value is essential, while the Maxima method becomes particularly valuable when prioritizing the maximum value within a fuzzy set holds utmost significance.

Ultimately, the geohydrological risk assessments study emphasizes the foundational role of accurate risk calculations under uncertainty for decision-making across diverse fields. The methods discussed, including probabilistic techniques, direct evaluation, and defuzzification approaches, collectively contribute to the precision and reliability of risk assessments. This comprehensive understanding provides decision-makers with essential tools to navigate complex risk landscapes and make informed decisions within the geohydrological context.

2.2 THE USE OF INDICES

The use of indices in risk assessments serves as an indirect method for performing weighted averages. In a broader sense, indices are mathematical models that consolidate diverse parameters e.g. geology, hydrogeology, land use, and soil characteristics into a unified value (Savic et al., 2010:145). As specific examples, DRASTIC and DART are instances of such indices, employing this amalgamation approach to assess and quantify groundwater vulnerability based on a combination of key factors (Gogu and Dassargues, 2000:72). The appeal of using indices lies in their simplicity, ease of application, and cost-effectiveness. Nonetheless, indices have their constraints as generally they are formulated as a linear combination of the inputs or otherwise known as weighted averages and therefore cannot model a non-linear responses.

The weighted averages principle serves as a prevalent technique for evaluating the risk in various fields (Yager, 1996:53). This approach entails the assignment of weights and ratings to each parameter featured in the index. The weighted averages procedure encompasses three key steps: parameter selection, weighting, and rating. Initially, the parameters to be incorporated in the index are chosen based on their relevance to the system under assessment. Subsequently, each parameter is allocated a weight reflecting its importance relative to other parameters, with weights assigned via expert judgment or statistical techniques like principal component analysis (PCA) or factor analysis (FA). Lastly, parameters are rated according to their respective values or value ranges, with higher ratings signifying heightened susceptibility to pollution.

2.2.1 DRASTIC

Groundwater pollution studies often leverage indices, with the DRASTIC index (Aller *et al.*, 1987:92) and the Groundwater Overdraft (GOD) index (Foster and Hirata, 1988:117) being commonly utilised for assessing vulnerability. The DRASTIC index encompasses seven parameters: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of

vadose zone, and Conductivity of the aquifer. On the other hand, the GOD index relies on three parameters: Groundwater occurrence, Overlying strata, and Depth to water.

The DRASTIC index, developed by the US Environmental Protection Agency (EPA) in the early 1990s, serves as a standardised method for evaluating aquifer susceptibility to contamination. It offers a consistent approach for comparison across diverse regions and hydrogeological settings. The index assigns numerical values between 1 and 10 to seven hydrogeological parameters, including depth to water table, net recharge, aquifer and soil media, topography, impact of vadose zone, and hydraulic conductivity. The cumulative score provides an overall vulnerability assessment for the aquifer.

Globally, the DRASTIC index's popularity stems from its simplicity, enabling non-experts to employ it easily, and its effectiveness in identifying high-risk aquifers for contamination (Karunanithi & Subramani, 2019:205). Nevertheless, critiques point out its lack of precision and subjective judgment dependence, as values assigned to parameters are based on expert opinion and may vary between assessors. Additionally, the index does not account for groundwater quality or the presence of pollutants, impacting its holistic evaluation of aquifer vulnerability.

For South African aquifers, the C parameter's significance is diminished due to low hydraulic conductivity resulting from the prevalence of low-permeability layers (Wu et al., 2020:87). This, coupled with limited and unreliable data on hydraulic conductivity in many areas, makes the C parameter less valuable for accurately assessing groundwater vulnerability. Consequently, the DRASTIC index is adapted to the DRASTI index for South Africa. Please refer to APPENDIX A for a thorough breakdown of the calculations pertaining to the DRASTIC Index as applied in South Africa.

2.2.2 DART

Africa is one of the continent's most susceptible to climate change and vulnerability due to multiple stresses and low adaptive capacity. Braunne and Xu (2008:42), contend that even if this is only a tiny contribution to water bulk supply, more than 60% of South Africa's population is dependent on groundwater. When considering this fact, it is clear that climate change directly influences the livelihoods of African people. Climate change is a reality and therefore needs consideration in the field of hydrology.

Dennis & Dennis, (2012:418) elaborate that the interaction between aquifers and the atmosphere could indicate how groundwater sources are affected by variations in climate

conditions. The respective groundwater use and climate directly account for the groundwater levels and aquifer recharge.

Using the DRASTIC vulnerability index as a basis, the DART Methodology was developed. The parameters considered in the DART methodology are as follows (Dennis & Dennis, 2012:418):

- Depth to groundwater (D) - Indicates the maximum distance that a contaminant needs to travel to reach the aquifer.
- Aquifer media (A) – the composition of different lithologies and rocks serving as the aquifer.
- Net recharge (R) - Indicates the amount of water that infiltrates into the ground surface to recharge the water table.
- Transmissivity (T) - a measure of the ability of an aquifer to transmit water, combining the hydraulic conductivity of the aquifer material with the thickness of the aquifer, and it is crucial for understanding the potential for water flow and well productivity in groundwater systems.

Please refer to APPENDIX B for a thorough breakdown of the calculations pertaining to the DART Index (Dennis & Dennis, 2012:418)

2.2.3 SOURCE-BASED SCREENING

The assessment of existing and potential groundwater contamination from specific sources has been a subject of interest for decades. While researchers have explored various methods to comprehensively rate groundwater contamination sources, designing an all-encompassing method proves challenging, resulting in a limited number of comprehensive approaches. Table 1 provides an overview of some of these source-based screening methods:

Table 1: Source based screening methods.

Method	Type of source	Approach	Principle	Reference
Foster-Hirata	General	General screening	Qualitative, 4 classes	Foster and Hirata, 1988
Swedish EPA	Contaminated land	General screening	Qualitative, 4 classes	Swedish EPA, 1995
Danish EPA	General	General screening	Qualitative, 3 classes	Danish EPA, 1995
Rao et al	Pesticides	General screening	Quantitative, equation	Rao et al., 1985

Zaporozec *et al.* (2004:24) suggests that general methods for rating groundwater contamination sources are user-friendly and can effectively raise awareness about groundwater protection. These methods quickly identify and prioritise sources for more detailed studies, aiding risk managers in allocating resources efficiently. The application of a generalised rating system has proven effective in influencing broader decision-making processes, policy formulation, and physical planning related to groundwater protection (Johansson and Hirata, 2002:52).

In 2004, UNESCO collaborated on the development of a comprehensive guide titled "Groundwater Contamination Inventory," emphasising the assessment of groundwater contamination linked directly to its sources (Zaporozec *et al.*, 2004:24). Table 2 provides a summary of groundwater contamination sources categorised by their origin. Each category includes source types, typical characteristics, and their usual locations.

Table 2: Summary of groundwater contamination sources by origin

Origin	Source Type	Usual Character	Normal Location
Industry	Solid waste	Point	Surface/Unsaturated zone
	Effluent wastewater	Point and line	Surface/Unsaturated zone
Agriculture	Fertilisers	Diffuse	Surface
	Pesticides	Diffuse	Surface
	Feedlots	Point	Surface
Mining	Mine tailings	Point	Surface/unsaturated zone
	Mine water	Point and line	Various
	Wastewater	Point and line	Surface/unsaturated zone
Waste disposal	Animal waste	Diffuse/Point	Surface/unsaturated zone
	Urban waste sites	Point	Surface/unsaturated zone
	Wastewater	Point and line	Surface/unsaturated zone

The groundwater contamination inventory's general rating system, depicted in Figure 5 assigned rankings to each source type based on its origin, providing a comprehensive understanding of

contamination sources in different sectors and their characteristics for effective groundwater pollution assessment and management.

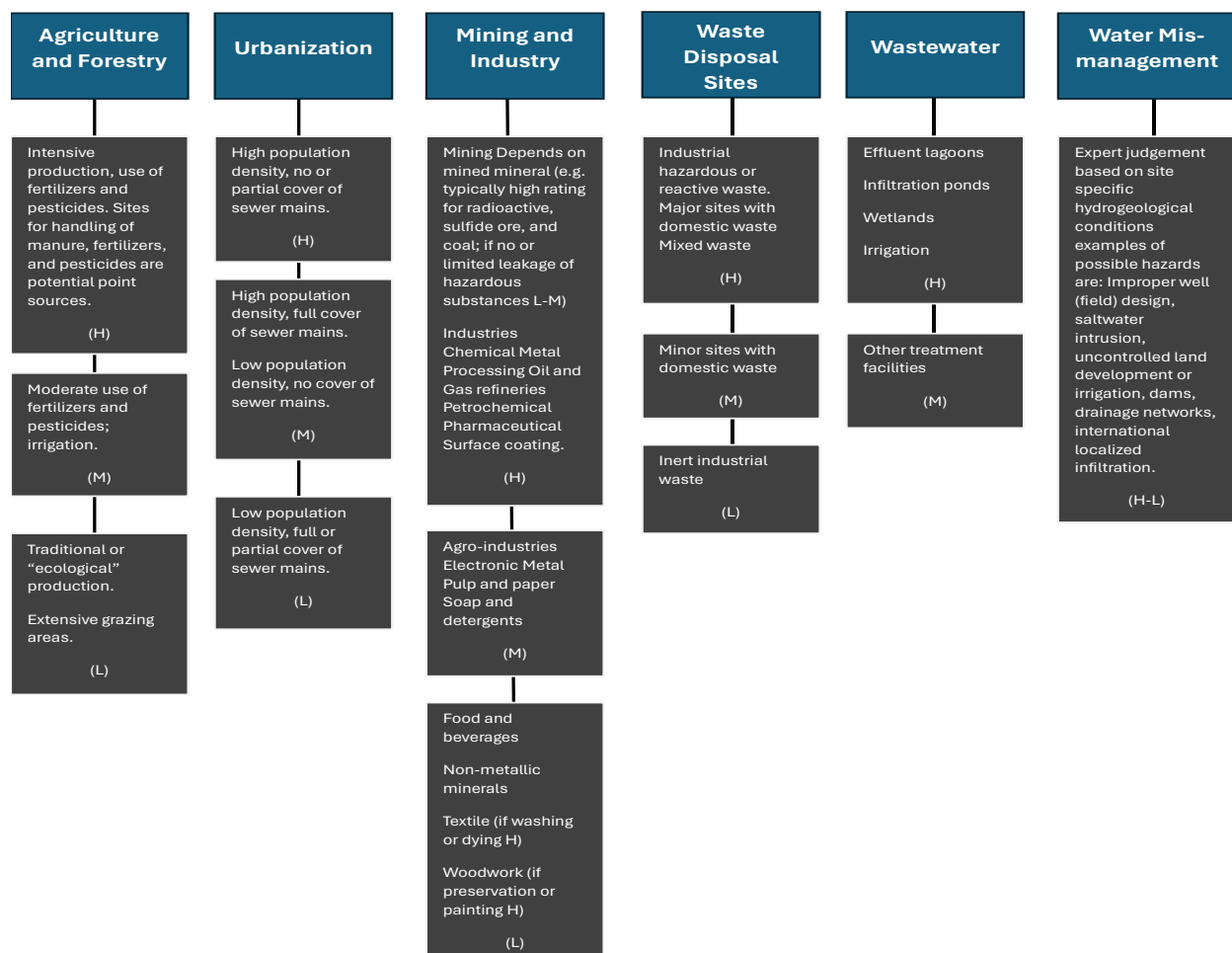


Figure 5: Classification of activities that pose a potential threat of groundwater contamination. (Zaporozec et al., 2004)

SUMMARY

In summary, the utilisation of indices emerges as a pivotal approach in evaluating groundwater pollution, offering a rapid and standardised method for vulnerability assessment and the identification of areas necessitating further investigation or monitoring. However, it is imperative to acknowledge the inherent limitations of indices and complement their application with other techniques such as site characterisation and monitoring to ensure the precision and reliability of results. Nevertheless, the selection of appropriate weights and parameters must align with the specific context to achieve accurate outcomes in line with the assessment objectives.

The enduring popularity of the DRASTIC index in evaluating groundwater vulnerability underscores its effectiveness in pinpointing vulnerable areas and guiding prioritised efforts for further investigation and protection. Despite its value, it is crucial to recognise the limitations of the DRASTIC index, emphasizing the need for its combined use with other methodologies for a holistic assessment.

In contrast, while the DRASTIC index focuses on vulnerability to pollution, the DART methodology aligns more with sustainability studies, particularly concerning the impact of drought on water quality. Serving as a valuable tool, DART aids in predicting potential water quality deterioration during drought periods, considering factors such as the increase in dissolved solids and salinity in response to declining water levels. The integration of source-based screening methods further enhances the understanding of contamination sources, contributing to a comprehensive and informed groundwater pollution assessment and management strategy.

Source-based screening methods, such as Foster-Hirata and Swedish EPA, offer efficient ways to assess groundwater contamination. UNESCO's "Groundwater Contamination Inventory" categorizes contamination sources by origin (agriculture, industry, mining, and waste disposal), emphasizing their diverse characteristics. Source-based screening aids in ranking and understanding contamination sources, making source-based screening a practical tool for informed decision-making in groundwater protection and pollution management.

2.3 MODELLING TECHNIQUES

2.3.1 NUMERICAL MODELLING

Numerical modelling is a useful tool for assessing the sustainability of groundwater resources and predicting the transport and fate of pollutants in groundwater systems. Numerical models can simulate complex hydrogeological processes and provide a quantitative basis for making management decisions. However, the accuracy and reliability of these models are highly dependent on the quality and quantity of input data (Bear & Cheng, 2010:201).

In the context of sustainability, numerical modelling plays a pivotal role in assessing the enduring consequences of groundwater extraction and in optimizing pumping rates to avert resource overexploitation and depletion. Multiple studies have leveraged numerical modelling to explore these aspects and propose sustainable management strategies. For instance, Singh *et al.* (2016:324) conducted an extensive analysis in a semi-arid region of India, employing numerical modelling to evaluate the sustainability of groundwater resources. Their findings

underscored a critical issue of groundwater overexploitation, advocating for a reduction in pumping rates to attain sustainable utilization. Similarly, studies by Gupta *et al.* (2018:145) in the Indo-Gangetic Plain and by Smith *et al.* (2019:449) in California employed numerical modelling to assess groundwater sustainability, shedding light on the necessity of informed pumping rate adjustments to ensure resource preservation in these distinct hydrogeological settings. Numerical modelling, as demonstrated in these studies, provides a valuable tool for evaluating and safeguarding groundwater resources over the long term (Singh *et al.*, 2016:324; Gupta *et al.*, 2018:145; Smith *et al.*, 2019:449).

Numerical modelling serves as a valuable tool for simulating the transport and fate of pollutants within groundwater systems, a crucial aspect in contamination prevention and mitigation. Multiple studies have harnessed numerical modelling to investigate these processes and propose effective remediation strategies. For instance, Wu *et al.* (2016:55) conducted an extensive investigation, utilizing numerical modelling to assess the fate and transport of chlorinated solvents within a contaminated groundwater system. Their study highlighted the complex nature of the contamination issue, ultimately recommending a multifaceted approach combining pump-and-treat and in-situ remediation technologies to attain the desired cleanup objectives. This aligns with the findings of other investigations such as Smith and Brown (2017:615) and Patel *et al.* (2018:462), who similarly employed numerical modelling to address the transport and fate of contaminants in groundwater systems and suggested innovative remediation strategies. The multifaceted utilization of numerical modelling in these studies underscores its critical role in understanding and managing groundwater contamination processes (Wu *et al.*, 2016:55; Smith and Brown, 2017:615; Patel *et al.*, 2018:462).

The accuracy and reliability of numerical models are limited by the quality and quantity of input data. Data requirements for numerical modelling include geological, hydrological, and chemical parameters, such as permeability, porosity, hydraulic conductivity, recharge rates, and pollutant concentrations. Obtaining accurate and representative data can be challenging, particularly in complex and heterogeneous aquifer systems. Incomplete or inaccurate data can result in significant errors and uncertainties in model predictions (Vrba and Zaporozec, 1994:58).

2.3.2 ANALYTICAL APPROXIMATIONS

Analytical approximations are mathematical solutions that can be derived using algebraic or calculus-based techniques (Kundu & Cohen, 2004:550). They provide a simplified representation of complex systems and can be used to estimate key parameters and relationships without requiring intensive computational resources (Kundu & Cohen, 2004:550).

In comparison to numerical modelling, analytical approximations offer several benefits, including speed, transparency, and ease of interpretation (Kundu & Cohen, 2004:550).

One major advantage of analytical approximations is speed. These methods can provide solutions in real-time or near-real-time, making them suitable for use in decision-making processes and other time-sensitive applications (Dawson & Wilby, 2001:112). In contrast, numerical models require significant computational resources and can take hours or even days to generate results (Dawson & Wilby, 2001:112).

Another benefit of analytical approximations is transparency. These methods are often simpler and more straightforward than numerical models, making it easier to understand the assumptions and limitations related to each individual analytical model. This can be particularly important when communicating results to stakeholders or policymakers who may not have a technical background.

Analytical approximations can also be more easily interpreted than numerical models. The results of analytical approximations are typically expressed in mathematical equations or formulas, which can provide insights into the underlying relationships between variables. This can help to identify key drivers of system behaviour and inform future research and management efforts.

One example of the use of analytical approximations in environmental management is in the estimation of groundwater recharge rates. In a study by Sophocleous (2000:30), an analytical method was used to estimate recharge rates for a groundwater system in Kansas. The method was based on the water balance equation and required only a few input parameters, making it a simple and efficient tool for estimating recharge rates in areas where data may be limited (Sophocleous, 2000a:230).

2.3.2.1 HEALTH RISKS

The US Environmental Protection Agency (EPA) has developed analytical tools to assess health risks related to groundwater pollution, that includes the Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR) (US EPA, 2009:1). These variables are summarised as:

Hazard Quotient (HQ):

- Evaluates potential non-cancerous health effects.
- Calculated by dividing the estimated exposure dose by the reference dose.
- $HQ > 1$ suggests potential adverse health effects.

Hazard Index (HI):

- Assesses potential non-cancerous health effects from multiple contaminants.
- Calculated by summing HQs for each contaminant.
- $HI > 1$ indicates potential adverse health effects.

Cancer Risk (CR):

- Evaluates potential cancerous health effects.
- Calculated by multiplying the exposure dose by the cancer slope factor.
- $CR > 1$ in a million suggests a risk above the acceptable level.

The human health assessment methodology systematically evaluates risks from toxicity and carcinogenicity resulting from exposure to hazardous substances, inspired by EPA practices (EPA, 2021:1).

Risk calculations primarily follow the guidelines set by the EPA in part A of the RAGS manual concerning human health (EPA, 1989:1). We will focus solely on oral intake as a pathway for human exposure to contaminated groundwater. In this context, we need to calculate a relevant dosage for this pathway as outlined Equation 1:

$$Dose = C \times IR \times ED \quad (1)$$

Where:

- $Dose$ = Dosage related to the pathway under consideration
- C = The measured concentration of a substance in groundwater
- IR = The average intake rate as dictated by the exposure route
- ED = The total duration of exposure, usually in days

Oral ingestion

According to the Risk assessment guidance superfund (EPA, 1989:1), the calculation for ingestion of chemicals in drinking water is indicated in Equation 2:

$$\text{Intake} \left(\frac{\text{mg}}{\text{kg}}/\text{day} \right) = \frac{CW * IR * EF * ED}{BW * AT} \quad (2)$$

Where:

- CW = Concentration of the chemical in water in milligrams per liter
- EF = Exposure frequency as days per year
- BW = Body weight measured in kg
- AT = Averaging time, measured in days

For the toxicity assessment, the average daily dose (ADD) is determined by dividing an estimate of the total dose accrued during the exposure duration from a pathway by an averaging time or an expected lifetime as displayed in Equation 3:

$$\text{Average daily dose} = \frac{\text{Dose}}{\text{Bodyweight} * \text{Exposure duration}} \quad (3)$$

- Exposure duration as specified by the user (days)
- Bodyweight = 70kg

The risk associated with chemical toxicity is calculated by using Equation 4:

$$\text{Risk} = \frac{ADD}{RfD} \quad (4)$$

Where:

- ADD = Average Daily Dose
- RfD = Reference Dose

Reference Dosages (RfDs): RfDs constitute a cornerstone in evaluating potential health risks attributed to non-carcinogenic toxic substances. These dosages offer approximations of the highest daily exposure levels to a chemical that an individual can tolerate throughout their lifetime without suffering adverse health effects. The EPA arrives at RfDs after scrutinizing toxicological data from animal studies and, where applicable, human investigations (EPA, 2021:1). The reference dose estimates daily exposure to the population that is likely to be without considerable risk of harmful effects during a lifetime. The reference dose may be adjusted for specific scenarios.

Cancer Risk Calculation: The methodology extends to the computation of the Cancer Risk, a quantifiable metric gauging the probability of cancer development arising from exposure to a given chemical. This calculation entails multiplying the projected lifetime exposure level of a chemical by its corresponding CPF (EPA, 2021:1). This computation provides insights into the potential cancer risk associated with the given exposure scenario.

In general, carcinogenic assessments focus on the chronic intake of a substance. For the carcinogenic assessment, the average human lifespan is considered. Therefore, the lifetime average daily dose (LADD) needs to be calculated as indicated in Equation 5:

$$\text{Lifetime average daily dose} = \frac{\text{Total dose}}{\text{Bodyweight} * \text{Human lifespan}} \quad (5)$$

- The human lifespan is expressed as days (70 years * 365 days = 25550 days)
- Bodyweight = 70kg

Once the Lifetime average daily dose (LADD) is determined, the carcinogenic risk is calculated using a Poisson model as displayed in Equation 6 (EPA, 2021:1) :

$$\text{Risk} = 1 - e^{-LADD * CPF} \approx LADD * CPF \quad (6)$$

Cancer Potency Factors (CPFs): In the assessment of potential carcinogenic risks linked to specific substances, CPFs play a pivotal role. These factors estimate the likelihood of an individual developing cancer over their lifespan due to exposure to a specific chemical. The determination of CPFs involves meticulous analysis, incorporating findings from animal studies, epidemiological research, and other pertinent information (EPA, 2021:1). The cancer potency factor (CPF) is the slope of the percentage of animals developing cancer versus the dosage of a particular chemical. Because of the complex uncertainty involved with calculating the CPF, this field has to be specified by the risk assessor.

Assumptions

- **Linear Carcinogenicity:** The methodology assumes linear relationships in terms of carcinogenicity, without considering potential non-linear effects or threshold concentrations for carcinogens.

- **Homogeneous Exposure:** The methodology assumes consistent exposure to toxic substances and might not fully account for variations in exposure patterns.

Limitations

- **Extrapolation from Animal Studies:** The methodology relies on extrapolating findings from animal studies to predict human health effects, which might not always accurately mirror human responses.
- **Limited Data Availability:** The accuracy of the assessment hinges on the availability of comprehensive toxicological and epidemiological data, which might be scarce for certain substances.

Analytical approximations offer a practical approach to assess health risks associated with groundwater pollution. However, caution is needed due to underlying assumptions. These tools should be used in conjunction with other risk assessment methods to ensure a comprehensive evaluation.

2.3.2.2 POLLUTION PLUME MOVEMENT

The Domenico 1D Analytical model provides valuable insights into contaminant behaviour within environmental systems, employing two modes of analysis. The non-steady state analytical model focuses on continuous but time-variable contaminant releases, resembling pulse injections. Rooted in mass balance principles, it utilises the advection-dispersion equation to describe contaminant transport. Advection represents movement with fluid flow, while dispersion involves spreading due to factors like molecular diffusion (Domenico and Schwartz, 1990:348). This model is crucial in scenarios with fluctuating release rates, offering flexibility in real-world applications. Mathematical equations depict contaminant distribution, considering advection, dispersion, and decay processes (Domenico and Schwartz, 1990:348). Notably, it predicts contaminant movement in groundwater, aiding in identifying contamination-prone areas and formulating effective remediation strategies.

The Domenico 1D Transport method is utilised to simulate the transport and fate of contaminants in aquifers. By incorporating first-order decay algorithms and considering hydrogeological and contaminant characteristics, this methodology enables the assessment of contaminant migration and behaviour within the subsurface environment (Domenico, 1987:328).

Key Elements of Domenico 1D Transport Method:

- Advection and Dispersion: Accounts for contaminant movement and spreading in subsurface environments.
- Concentration Profile Analysis: Examines contaminant distribution along the vertical aquifer axis over time.
- Contaminant Transport Equations: Utilises mathematical equations for one-dimensional vertical flow.
- Boundary and Initial Conditions: Considers concentration at aquifer boundaries and initial conditions.
- Aquifer Properties: Hydraulic conductivity and porosity influence contaminant transport.
- Time-Dependent Analysis: Examines contaminant transport over varying time intervals.
- Model Calibration and Validation: Adjusts parameters to match observed contaminant concentrations.

This study's risk assessment framework comprehensively considers both continuous injection and pulse injection scenarios, employing the Domenico 1D equation.

2.3.2.2.1 Continuous Injection

Continuous injection simulates contaminant movement in groundwater with constant releases, considering factors like advection, dispersion, and reaction kinetics. In the event where pollution is released into the system at a constant rate, the constant source equation is utilised. The equation for the Domenico continuous injection model for a contaminant in a one-dimensional flow field is indicated in Equation 7:

$$C(x, t) = \frac{Q}{2\pi D} * \exp\left(-\frac{x^2}{4Dt}\right) \quad (7)$$

where:

- $C(x, t)$ = The concentration of the contaminant at point x in the flow field at time t .
 Q = The rate of continuous injection of the contaminant into the flow field.
 D = The dispersion coefficient of the contaminant in the flow field.
 x = The distance from the center line of the flow field in the x -direction.
 t = Time

The typical concentration response expected from the continuous injection model is shown in Figure 6.

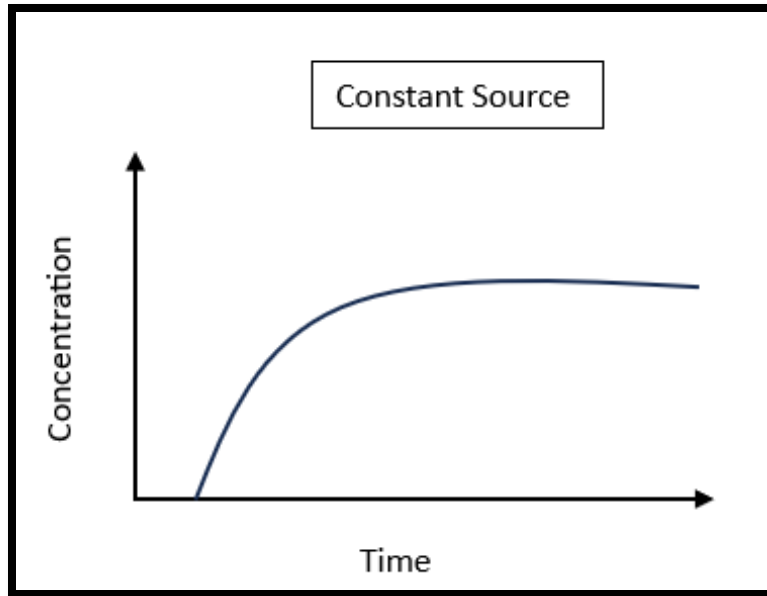


Figure 6: Constant Source of Pollution Graph

2.3.2.2.2 Pulse Injection

Pulse injection models concentrated contaminant pulses introduced and monitored in subsurface environments, accounting for spreading and attenuation. The equation used for the Domenico slug injection model for a contaminant in a one-dimensional flow field is displayed in Equation 8:

$$C(x, t) = \frac{Q}{(v\sqrt{4\pi Dt})} * \exp\left(-\frac{(x - vt)^2}{4Dt}\right) \quad (8)$$

where:

- $C(x, t)$ = The concentration of the contaminant at point x in the flow field at time t .
- Q = The rate of continuous injection of the contaminant into the flow field.
- V = The linear velocity of the flow
- D = The dispersion coefficient of the contaminant in the flow field.
- x = The distance from the centre line of the flow field in the x -direction.
- t = Time

The typical expected concentration response from the pulse injection is shown in Figure 7.

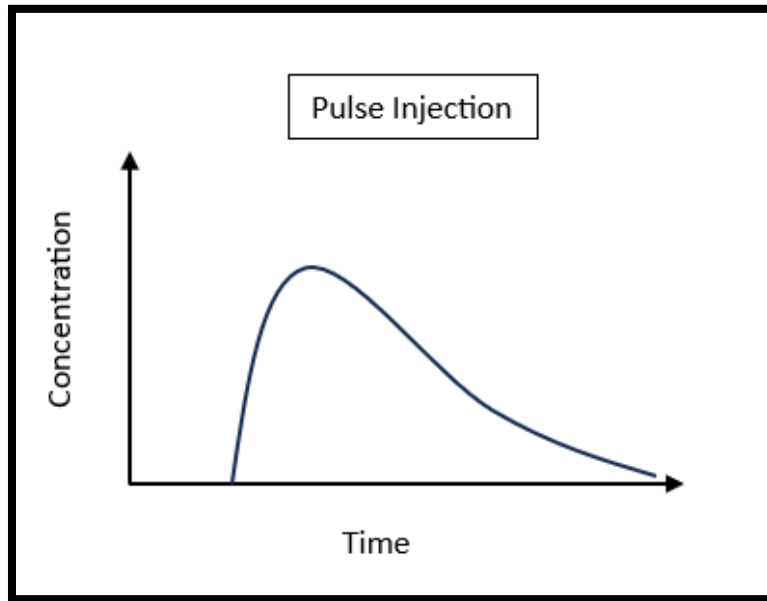


Figure 7: Pulse/Slug Injection of Pollution Graph

Assumptions

- **Homogeneous Aquifer Behaviour:** The methodology assumes homogeneity in aquifer behavior and does not account for spatial variability that could impact contaminant transport and decay rates.
- **Downgradient Receiver:** The receiver is assumed to be downgradient of the source.
- **Steady-State Conditions:** The assessment assumes steady-state conditions for contaminant transport and decay, not capturing transient changes over time.

Limitations

- **Simplified Decay Model:** The method utilizes first-order decay algorithms, which might not fully represent the behaviour of contaminants with more complex degradation mechanisms.
- **Data-Intensive Requirements:** The methodology requires extensive hydrogeological and contaminant data, which might not be readily available, leading to potential uncertainties in modelling outcomes.

The Domenico 1D Analytical Model, in its non-steady and steady state variants, offers a comprehensive understanding of contaminant transport in groundwater (Domenico and Schwartz, 1990:348). Its application aids in predicting contaminant movement, evaluating remediation effectiveness, and informing groundwater resource management decisions.

2.3.2.3 PREDICTED DRAWDOWN

The Cooper-Jacob method is a popular analytical solution for predicting the drawdown in a pumping well or borehole (Cooper & Jacob, 1946:44). The method is based on the assumption that the aquifer is homogeneous, isotropic, and of infinite extent, and that the well is fully penetrating and fully screened. The method relies on the use of a dimensionless borehole function that characterises the response of the aquifer to pumping.

The Cooper-Jacob method allows for the prediction of the drawdown at various distances from the borehole, which can be used to generate a drawdown curve. The drawdown curve can be used to estimate parameters such as hydraulic conductivity, transmissivity, and storativity.

The assessment of borehole sustainability centres around the quantification of drawdown, considering critical water strike levels and the potential influence of neighbouring boreholes (Cooper & Jacob, 1946:44). Through an evaluation of these elements, this methodology provides insights into sustainable pumping rates that underpin long-term management of groundwater resources. In the context of geohydrological sustainability assessment, the potential failure of borehole pumping was appraised through the calculation of drawdown under specific pumping rates.

2.3.2.3.1 Borehole Failure due to Exceeding Critical Water Strike

The calculation procedure considers the plausible borehole failure occurring when the pumping drawdown surpasses the critical water strike. This critical water strike denotes the minimum water level required to sustain optimal borehole productivity. Should the drawdown surpass this critical threshold, the borehole might encounter a decline in water yield or even total failure. The determination of this critical level usually stems from site-specific hydrogeological data and an understanding of aquifers. Figure 8 illustrate areas associated with low and high risk. The high risk scenario could typically be where the main water strike represents the critical water level and the closer the drawdown to this position the higher the risk of dewatering the fracture and the borehole failing.

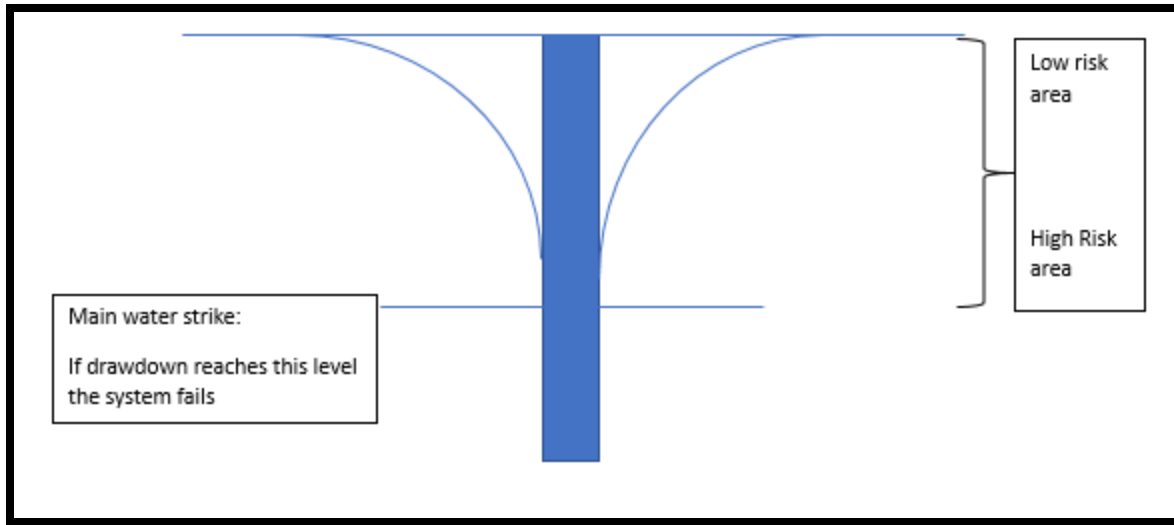


Figure 8: Borehole failure risk in relation to critical water strike

The assessment of pumping sustainability involves calculating borehole drawdown using the Cooper Jacob equation. The overall extent of the drawdown is then compared to the critical water strike of the borehole. If the drawdown surpasses the critical water strike level, it signifies an unsustainable borehole and system that is likely to fail.

Cooper Jacob Equation 9:

$$s = \frac{2.3Q}{4\pi T} \log \frac{2.25Tt}{r^2 S} \quad (9)$$

Where:

- s = Drawdown(m)
- Q = Pumping Rate(l/s)
- T = Transmissivity(m²/d)
- t = time(days)
- S = Storativity
- r = Borehole Radius(m)

2.3.2.3.2 Drawdown of Interference Boreholes

The calculation method considers the drawdown caused by nearby interference boreholes. When multiple boreholes are pumping from the same aquifer, they can influence each other's water levels. This interference effect is accounted for by estimating the drawdown caused by neighbouring boreholes based on their pumping rates, distances, and aquifer properties. This ensures that the sustainability assessment incorporates the impacts of surrounding pumping activities on the target borehole.

During the calculation of the interference borehole's radius of influence, it is possible to estimate the drawdown that the interference borehole would induce at the main borehole's location. If the aggregate drawdown caused by both the main borehole and the interference borehole surpasses the critical water strike of the main borehole, the system is likely to fail. The effect the boreholes have on one another due to interference is depicted in Figure 9.

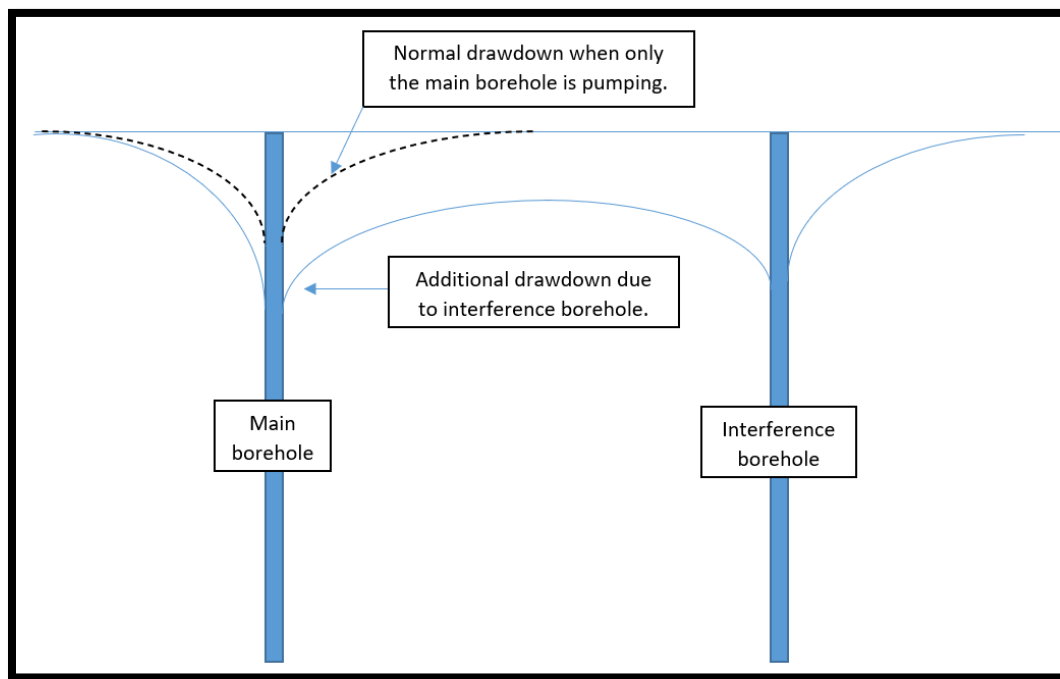


Figure 9: Drawdown effects of Interference Boreholes

The Cooper-Jacob method has been widely used in hydrogeology and has been shown to provide accurate predictions of drawdown in a variety of aquifer systems. For example, Bredehoeft and Papadopoulos (1965:74) used the Cooper-Jacob method to analyse the response of a well to pumping and found good agreement between the predicted and observed drawdown values. Similarly, Hantush (1964:221) used the method to predict drawdown in a groundwater system and demonstrated its accuracy in predicting the drawdown in the system.

Assumptions

- **Homogeneous Aquifer Characteristics:** The methodology assumes relatively homogeneous aquifer characteristics and does not consider the potential heterogeneity of aquifer properties that could affect drawdown calculations.
- **Steady-State Pumping:** The assessment assumes steady-state pumping rates and does not account for transient changes in pumping rates or aquifer responses.

Limitations

1. **Site-Specific Data Requirement:** The method heavily relies on accurate and detailed hydrogeological data for the aquifer, including characteristics like critical water strike, aquifer properties, and recharge rates. Limited or inaccurate data could introduce uncertainties in the assessment outcomes.
2. **Simplification of Hydrogeological Complexities:** The method assumes a simplified representation of aquifer behaviour and interactions. It may not fully capture intricate hydrogeological complexities, such as heterogeneity of aquifer properties, preferential flow paths, and seasonal variations.

2.3.2.4 RECHARGE IN THE PROTECTION ZONE

This calculation method addresses situations where pumping rates are not sustainable in terms of groundwater recharge. This means that the pumping rate exceeds the natural recharge rate of the aquifer, leading to long-term groundwater depletion (Parsons & Wentzel, 2007:45). The method considers the recharge rate, which is influenced by factors such as precipitation and infiltration. By comparing the pumping rate with the recharge rate over the borehole radius of influence, the sustainability of groundwater extraction can be evaluated. If the pumping rate exceeds the recharge rate, it suggests an unsustainable practice.

To determine the extent of the wellfield protection zone, the radius of influence or cone of depression needs to be determined using the Cooper Jacob Equation 10. (Parsons & Wentzel, 2007:58):

$$r = 1.5 \sqrt{\frac{Tt}{S}} \quad (10)$$

Where:

r = Cone of depression radius(m)

T = Transmissivity(m²/d)

S = Storativity

t = time(days)

Assumptions

- **Homogeneous Aquifer Characteristics:** The methodology assumes relatively homogeneous aquifer characteristics and does not consider the potential heterogeneity of aquifer properties that could affect drawdown calculations.
- **Steady-State Pumping:** The assessment assumes steady-state pumping rates and does not account for transient changes in pumping rates or aquifer responses.

Limitations

- **Site-Specific Data Requirement:** The method heavily relies on accurate and detailed hydrogeological data for the aquifer, including characteristics like critical water strike, aquifer properties, and recharge rates. Limited or inaccurate data could introduce uncertainties in the assessment outcomes.
- **Simplification of Hydrogeological Complexities:** The method assumes a simplified representation of aquifer behaviour and interactions. It may not fully capture intricate hydrogeological complexities, such as heterogeneity of aquifer properties, preferential flow paths, and seasonal variations.

2.4 SUMMARY

In summary, various methodologies play essential roles in evaluating groundwater pollution, sustainability, and associated risks. The exploration of "Risk Calculation Under Uncertainty" highlights the importance of accurate risk assessment across different fields, emphasizing the need to address uncertainty through probabilistic methods, sensitivity analysis, and Monte Carlo simulation. These techniques enhance the robustness of risk assessments, aiding decision-makers in evaluating potential outcomes and facilitating sound decision-making processes.

The utilisation of indices, such as the DRASTIC index and the DART methodology, emerges as pivotal approaches in evaluating groundwater pollution vulnerability and sustainability. While

indices offer rapid assessment methods, their limitations necessitate complementing them with techniques like site characterisation and monitoring to ensure precision and reliability. The enduring popularity of the DRASTIC index in pinpointing vulnerable areas underscores its effectiveness, although its combined use with other methodologies is crucial for holistic assessment. Conversely, the DART methodology focuses on sustainability studies, particularly concerning drought impacts on water quality, contributing to a comprehensive pollution assessment and management strategy.

Numerical modelling serves as a crucial tool in assessing groundwater sustainability and predicting pollutant transport, facilitating effective remediation strategies. While providing a quantitative basis for management decisions, numerical modelling's accuracy depends on data quality and model assumptions. Analytical approximations offer simplified solutions, such as the Cooper-Jacob method for predicting drawdown, aiding sustainable groundwater management. However, these methods have limitations, including assumptions of aquifer homogeneity and steady-state conditions.

Health risk assessment methodologies, such as those developed by the US EPA, provide tools for evaluating health risks associated with groundwater pollution. Despite their utility, these assessments rely on data availability and assumptions, requiring careful consideration.

Overall, these methodologies offer valuable tools for understanding groundwater dynamics, assessing sustainability, and evaluating health risks. However, their limitations highlight the importance of careful consideration and combined use to ensure accurate and reliable results in groundwater management and decision-making processes.

3 METHODOLOGY

3.1 INTRODUCTION

To effectively address the issue of groundwater pollution, it is essential to examine specific risk categories integral to comprehensively assessing the problem. These categories include:

- **Climate Change Impact:** Analyzing climate patterns and groundwater dynamics is crucial, as precipitation, temperature variations, and climatic shifts can significantly affect groundwater quality and contamination risks.
- **Aquifer Vulnerability:** Evaluating aquifer vulnerability involves assessing geological and hydrological factors that influence susceptibility to pollutants, considering soil characteristics and aquifer permeability.
- **Groundwater Sustainability:** Ensuring the long-term sustainability of groundwater requires assessing borehole pumping rates and associated recharge of the area.
- **Human Health:** Assessing health risks from groundwater pollution is paramount, involving the evaluation of the potential impact of contaminated water on human health, considering pollutant types, concentrations, and pathways affecting local communities.

While each category is assessed independently, the research aims to integrate these assessments into a holistic system, necessitating a combination of their outputs. Considering the potential limitation of a linear combination, a research question arises: How can a new risk index be created to effectively capture the nuanced and nonlinear relationships among diverse risk factors associated with groundwater pollution and sustainability? Fuzzy logic, a mathematical tool known for modeling uncertain information, offers a potential solution, allowing for a flexible and nonlinear response. The study will explore the application of fuzzy logic in combining these risk categories to create a new risk indicator, offering insights into nuanced relationships and nonlinear scenarios in groundwater pollution and sustainability.

3.2 RISK QUANTIFICATION

This section will discuss available methodologies for the risk calculations of the different risk categories identified in the previous section. In the absence of an existing methodology for any particular risk category, a new methodology will be formulated.

3.2.1 Climate Change Impact

The quantification of climate risk is based on the DART index discussed in Chapter 2. This index predicts the impact on groundwater levels for a likely future climate change scenario. Appendix A present the inputs and calculations associated with the DART index.

3.2.2 Aquifer Vulnerability

The quantification of aquifer vulnerability is based on the DRASTIC index discussed in Chapter 2. Appendix B presents the associated calculations and input parameters used to calculate the index as it relates to the version developed for South Africa.

3.2.3 Groundwater Sustainability

The quantification of risk associated with borehole pumping sustainability was discussed in Section 2.3.2.3 where a borehole was considered sustainable if the drawdown does not reach the critical water level specified. The effect of borehole interference on drawdown was also discussed to account for the effect neighboring pumping boreholes.

In addition, the determination of the protection zone around a borehole, or the radius of influence, is outlined in Section 2.3.2.4. Subsequent calculations based on this protection zone determination have been conducted to ascertain the volume of direct recharge contributing to the wellfield protection zone. This methodology takes into account the recharge rate, influenced by factors such as precipitation and infiltration. By comparing the pumping rate to the recharge rate over the radius of influence, the sustainability of groundwater extraction can be assessed.

Once the radius of influence has been determined, the total area influenced can be calculated as shown in Equation 11.

$$A = \pi r^2 \quad (11)$$

Where,

A = Area associated with the radius of influence (m^2)

r = Radius of influence calculated from Equation (10)

Once the area being influenced has been determined, the recharge volume entering the system for the pumping period can be calculated making use of Equation (12).

$$V = AR_e t \quad (12)$$

Where,

- V = Volume of recharge (m^3)
- A = Area associated with the radius of influence (m^2)
- t = Time associated with pumping (days)
- R_e = Recharge over period t

The volume of recharge is then compared to the volume being pumped. If the recharge is greater than the abstraction, the system is sustainable.

Assumptions

- **Homogeneous Aquifer Characteristics:** The methodology assumes relatively homogeneous aquifer characteristics and does not consider the potential heterogeneity of aquifer properties that could affect drawdown calculations.
- **Steady-State Pumping:** The assessment assumes steady-state pumping rates and does not account for transient changes in pumping rates or aquifer responses.

Limitations

- **Site-Specific Data Requirement:** The method heavily relies on accurate and detailed hydrogeological data for the aquifer, including characteristics like critical water strike, aquifer properties, and recharge rates. Limited or inaccurate data could introduce uncertainties in the assessment outcomes.
- **Simplification of Hydrogeological Complexities:** The method assumes a simplified representation of aquifer behaviour and interactions. It may not fully capture intricate hydrogeological complexities, such as heterogeneity of aquifer properties, preferential flow paths, and seasonal variations.

3.2.4 Human Health

The health risk associated with toxicity and carcinogenicity is quantified as detailed in Section 2.3.2.1 of Chapter 2. Additionally, the source-based screening, discussed in Section 2.2.3, has been refined to outline risk levels (High, Medium, or Low) as presented in Table 3. This environmental risk ranking, derived from information gathered in the groundwater contamination inventory and comprehensive literature review on potential sources, is assigned to each hazardous source (refer to Table 3).

Table 3: Possible hazardous sources identified within South Africa with their respective source-based risk rating.

Risk:	Industry	Agriculture	Mining	Waste disposal
High	Metallurgical Wool Processing Chemical manufacturing Rubber and plastic Paints Pharmaceutical Electricity Petroleum Automotive manufacturing	Agricultural chemicals	Gold Platinum	Hazardous waste Stormwater/ Sewer systems
Moderate	Paper/pulp Textile manufacturing	Crop cultivation Feedlots	Coal Diamonds	Domestic/general waste Wastewater treatment
Low	Wood Processing Food and Beverage Glass	Ecological Production		Inert industrial waste

Assumptions

- **Causality of Sources:** The assessment assumes a direct causality between identified sources and potential contamination, not accounting for indirect pathways or complex interactions.
- **Source Ranking Accuracy:** The methodology assumes that the assigned hazard rankings accurately reflect the potential risks associated with each source.

Limitations

- **Lack of Quantitative Analysis:** The source-based screening might not provide a quantitative measure of the magnitude of contamination risks, which could limit its ability to prioritise interventions accurately.
- **Sensitivity to Ranking Criteria:** The assigned risk rankings might be sensitive to the criteria used for categorisation, potentially leading to variations in prioritisation outcomes.

3.3 RISK FRAMEWORK FORMULATION

This section discusses the tiered approach applied as well as the fuzzy logic methodology to combine all the risk categories in a composite overall risk assessment figure.

3.3.1 Tiered Approach

The utilization of tiered approaches in risk assessment constitutes a methodical strategy aimed at tailoring the depth and scope of evaluations to the unique characteristics of the site under scrutiny. This approach is crucial for minimizing unnecessary investigations and making efficient use of available resources.

By implementing tiered approaches, risk managers can systematically determine the appropriate level of assessment required for a given site, thereby avoiding resource-intensive investigations where they are not warranted. The overarching goal is to strategically allocate resources, ensuring that more detailed and resource-demanding assessments are reserved for situations where a higher degree of certainty or specific information is essential.

In the specific context of this study, the tiered approach to risk assessment encompasses two distinct levels of evaluation. Tier 1 initiates the assessment with a comprehensive overview of the quaternary catchment. This phase utilizes regional indices and source-based screening to establish foundational estimations. It serves as a broad-scale assessment that imparts valuable regional insights into potential risks, laying the groundwork for subsequent stages.

Advancing to Tier 2, the assessment becomes site-specific, delving into more granular parameters such as depth to groundwater, net recharge, aquifer characteristics, and sustainability factors. This tier focuses on the distinctive attributes of the site itself, providing a more detailed analysis that goes beyond the regional overview offered in Tier 1.

The tiered methodology represents a purposeful and strategic approach aimed at optimizing the use of resources. It acknowledges the variability in data availability and the unique characteristics of each site, recognizing the necessity for diverse levels of risk assessment.

While Tier 1 furnishes a broad understanding of potential risks across a wider region, incorporating regional data such as catchment area, aquifer vulnerability, average water level, and recharge, this regional data serves as a baseline for constructing the risk assessment. This is particularly valuable in cases where data may be scarce or costly.

Tier 2 refines the assessment to provide site-specific results, incorporating geohydrological data gathered directly from the site. In instances of data scarcity, the baseline information from Tier 1 can act as a suitable substitute. This adaptable approach ensures efficiency in risk management, allowing for flexibility in the face of varying data availability scenarios, all while upholding a commitment to thorough evaluation.

3.3.2 Fuzzy Logic Approach to Combining Risk Categories

The fact that fuzzy logic accommodates a nonlinear response as well as the fact that it encapsulates expert knowledges, makes it the ideal approach to combine the various risk categories. The sections that follow relate to the various components shown in *Figure 3* to setup a complete fuzzy logic expert system.

3.3.2.1 Degree of Membership

3.3.2.1.1 Introduction

Degrees of Membership (DoM) functions are fundamental mathematical tools used to model risk transitions across various categories. These functions define the extent to which an element belongs to a particular category within a set, assigning values between 0 (False) and 1 (True). In the context of risk assessment, DoM functions describe the transition between favourable and unfavourable states of input parameters, capturing expert knowledge not only in the applied ruleset but also in the selection of favourable and unfavourable limits.

DoM functions typically comprise two curves: the favourable curve and the unfavourable curve. While these curves may not be inherently related, it is common practice to choose them as inverses of each other. The subsequent sections will illustrate the DoM curves for each risk category utilized as inputs to the fuzzy logic system, culminating in a composite risk assessment figure that considers all risk categories.

3.3.2.1.2 Climate Change Impact

The derived Degree of Membership (DoM) function, as delineated in Figure 10 and founded upon the DART index, is elucidated herein. Notably, a linear function has been adopted to traverse the transitional domain between favourable (1) and unfavourable (-1) thresholds. Essentially, the DART index manifests three conceivable outputs:

- A positive DART index value signifies resilience to the degradation of groundwater resources attributed to climate change.
- A value of 0 denotes an absence of discernible impact on groundwater resources attributable to climate change.
- A negative DART index value denotes a susceptibility to the deterioration of groundwater resources due to climate change.

Associated with these output classifications, degrees of membership have been ascribed, with 1 denoting a favourable outcome, 0 representing a neutral outcome, and -1 indicative of an unfavourable outcome.

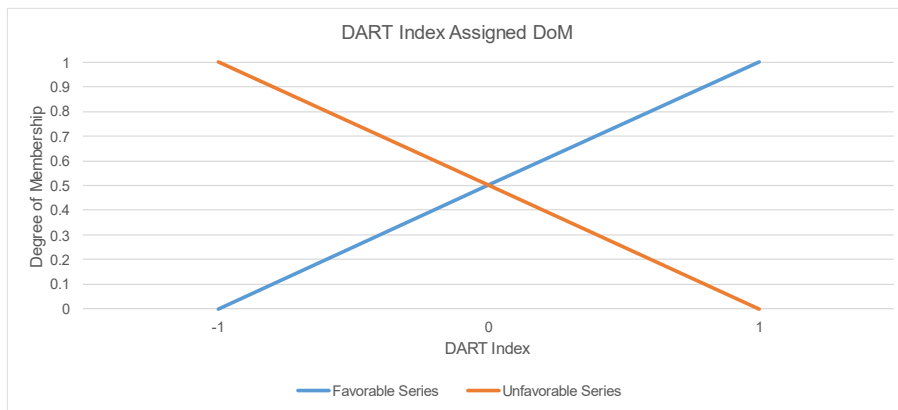


Figure 10: Climate Change Impact DoM

3.3.2.1.3 Aquifer Vulnerability

The evaluation of groundwater vulnerability is conducted through the utilization of the DRASTIC index system, as discussed in section 2.2.1. The DRASTIC index spans a range from 1 to 160, with higher values indicating greater vulnerability to groundwater contamination. In the context of this study, the identification of a "tipping point" is crucial for understanding when the system transitions from a favourable to an unfavourable outcome.

Based on the various literature reviewed from:

- Aller et al., 1987;
- Scanlon & Goldsmith, 1997;
- Sophocleous, 2002; and
- World Health Organization [WHO], 2011

The following thresholds for groundwater risk has been established:

- **Low Risk (Favourable Outcome):** DRASTIC Index below 70
 - Groundwater is deemed to be at a lower risk of contamination.
- **Moderate Risk (Transition Zone):** DRASTIC Index between 70 and 100
 - The system enters a transitional state, signifying a moderate risk. This range is identified as a critical zone, prompting the need for preventative measures to avert a shift to unfavourable conditions.
- **High Risk (Unfavourable Outcome):** DRASTIC Index above 100
 - Groundwater is considered at a higher risk of contamination, necessitating immediate intervention to prevent or mitigate potential adverse effects.

These thresholds provide a structured framework for interpreting the DRASTIC index results and enable the identification of vulnerable zones within the study area. It is important to note that these thresholds are based on general guidelines, and regional (South African) data provided by Groundwater Resources Assessment Phase 2 (GRII) and Vegter maps. Referring to local guidelines and incorporating expert knowledge enhances the reliability and applicability of the vulnerability assessment.

The DoM function based on the DRASTIC index is presented in Figure 11. A piecewise linear function was chosen across the transitional area between favorable (<40) and unfavorable (>160) limits.

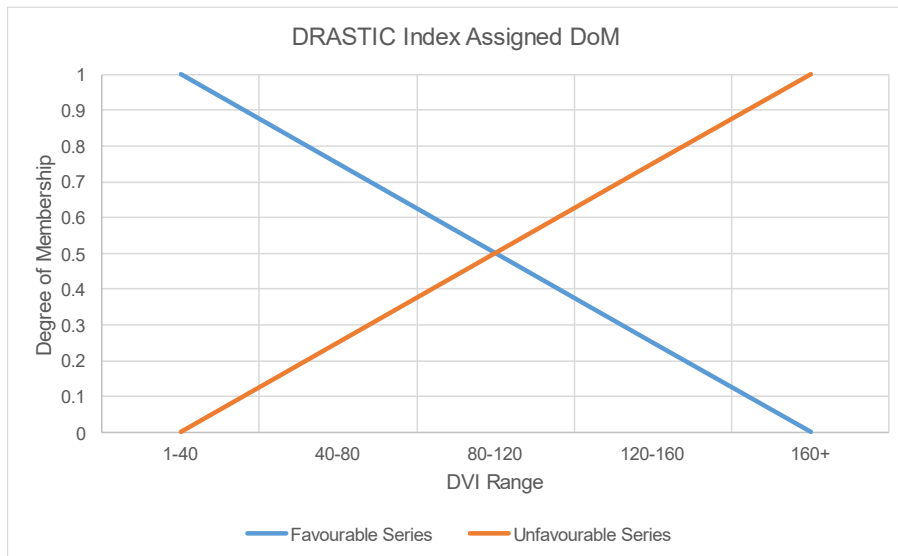


Figure 11: Aquifer Vulnerability DoM

3.3.2.1.4 Groundwater Sustainability

Borehole Sustainability

As discussed earlier, the likelihood of borehole failure is closely linked to the percentage of drawdown concerning the critical water strike, as illustrated in Figure 8. Degrees of membership were assigned based on this correlation. Following consultations with field experts, it was recommended to establish the threshold at 10-20% before reaching the critical water strike. This precautionary measure is crucial since borehole failure risk significantly escalates when drawdown approaches this range. Therefore, the transitional zone from favourable to unfavourable outcomes has been set at 85% of the drawdown threshold (Figure 12). Importantly, this parameter is flexible within the Excel tool, allowing for expert adjustments or accommodation of specific site conditions. For this assessment, we will assume only a single aquifer is present, simplifying the analysis and focusing on the key factors influencing borehole performance.

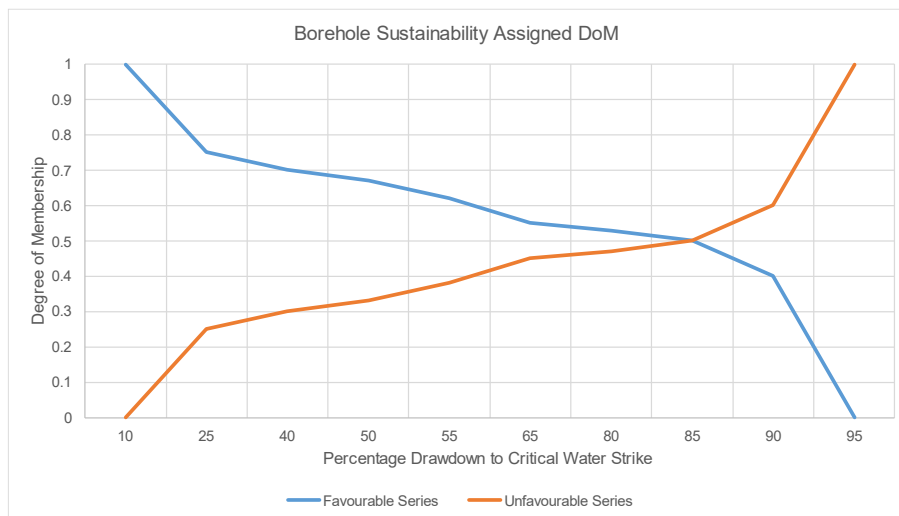


Figure 12: Borehole Sustainability DoM

System Sustainability

The concept of system sustainability, introduced within this framework, lacks pre-existing data to determine an appropriate DoM. Initially, the attempt to gauge sustainability by comparing recharge to sustainable yield proved challenging due to considerable variability. Subsequently, expert consultations led to the conclusion that the system's water balance is a key indicator of risk, with a negative balance signalling an unsustainable state. Recognizing the need for a safety buffer, even a slightly positive water balance, such as extracting 85% of recharge volume, remains in proximity to potential failure. To address this, a transition zone was established: a water balance not exceeding 85% of recharge is considered favourable, while surpassing this threshold is deemed unfavourable (Figure 13). This defined demarcation serves to clearly distinguish between sustainable and precarious conditions.

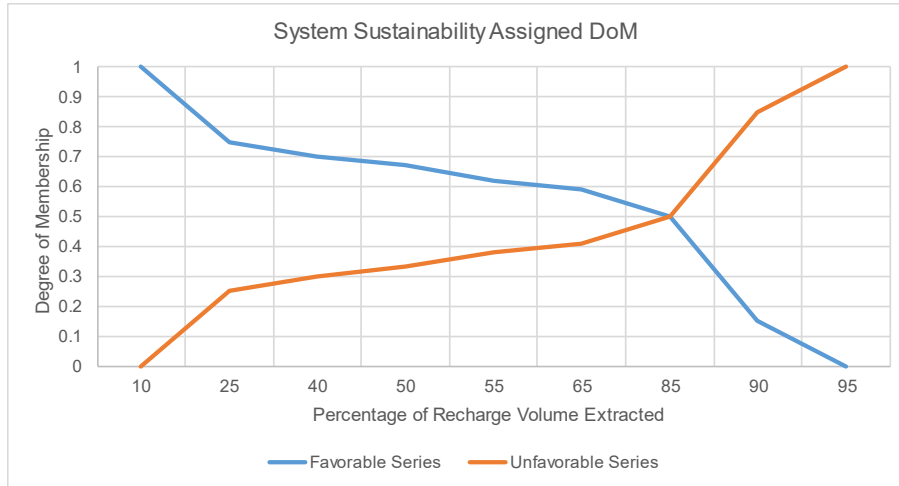


Figure 13: System Sustainability DoM

3.3.2.1.5 Human Health

Toxicity Assessment

In assigning degrees of membership for the toxicity assessment, a crucial reference point is the Reference Dose (RfD), a value established with a deliberate margin of safety, as discussed in section 2.3.2.1. The RfD is designed to ensure protection for the overall population, encompassing sensitive subgroups, by representing a level of exposure considered improbable to cause adverse health effects throughout a lifetime of exposure. The significance lies in the RfD's comprehensive consideration of the general public, coupled with a safety margin.

This choice is substantiated by the direct correlation between the risk and the percentage of the reference dosage detected in the water sample. By aligning the risk assessment with the percentage of the allowable reference dosage, the approach offers a transparent and quantifiable measure (Figure 14). This method ensures that the risk determination mirrors the degree of exposure relative to established safety thresholds, providing a more nuanced and accurate evaluation of potential health risks in the water sample.

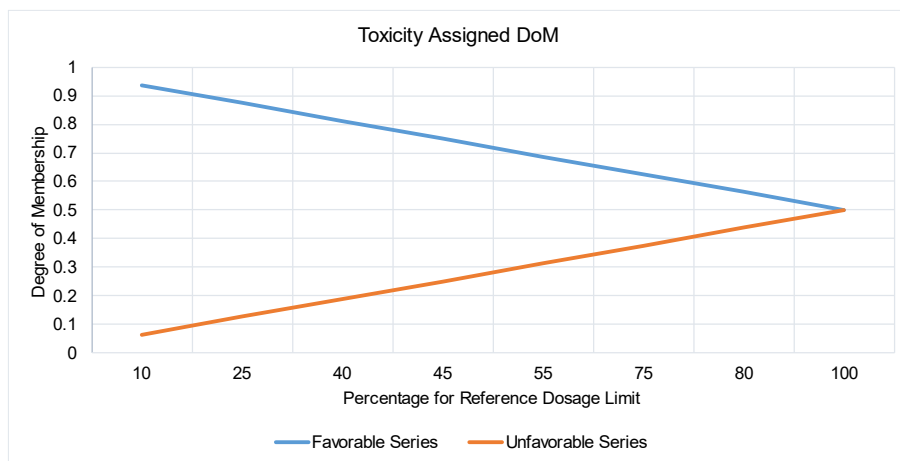


Figure 14: Toxicity DoM

Carcinogenic Assessment

The DoM function based on the carcinogenic health risk is presented in Figure 15. A linear function was chosen across the transitional area between favourable (non-carcinogenic) and unfavourable (carcinogenic) limits, although the transition function in this instance is irrelevant as the input parameter only has two states; non-carcinogenic and carcinogenic which relates to the favourable and unfavourable states.

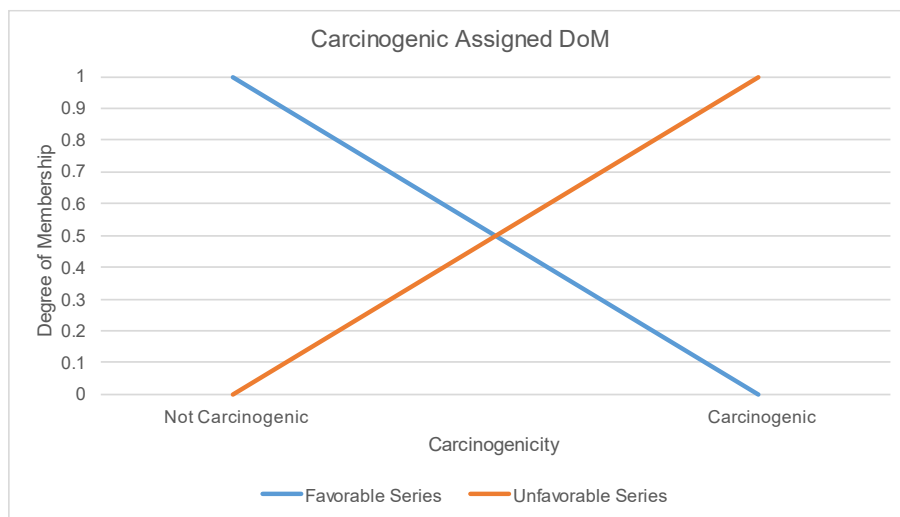


Figure 15: Carcinogenic DoM

The decision to default the overall risk to 100% in case of an unfavourable assessment reflects the recognition that certain critical factors within a specific risk category can have a profound impact on the entire groundwater system. This precautionary measure emphasizes the conservative nature of the methodology, ensuring heightened sensitivity to conditions that pose

a severe threat to human health and environmental sustainability. The default to 100% risk underscores the philosophy that immediate attention and intervention are warranted when crucial risk thresholds are breached, prioritizing the protection of communities and ecosystems. This approach is rooted in a careful consideration of potential consequences associated with specific risk factors, enhancing transparency and the reliability of the risk assessment results.

3.3.2.2 Fuzzification

The DoM play a crucial role in fuzzy logic systems, particularly in the fuzzification process, where qualitative information is translated into quantitative values. These values represent the degree to which an element belongs to a specific category within a set, ranging between 0 and 1 based on the current input value.

The DoM values derived from the functions mentioned in section 3.3.2.1 are utilised in subsequent fuzzy logic calculations to determine the overall risk in each category. Fuzzy logic allows for a more nuanced and flexible representation of uncertainty and imprecision in risk assessments, enabling a more realistic modelling of complex systems.

This process can be better illustrated in Figure 16, which serves as an example of fuzzification—a method used to predict erosion risk by considering various factors such as slope, rainfall, and soil erodibility (see Figure 16). Fuzzification combines these factors to assess overall risk. Notably, even if certain factors are not extreme individually, a high risk can arise if one specific factor, such as soil erodibility, is significant. The method entails simultaneous processing of these factors to ensure equitable outcomes. It is essential to emphasize the practitioner's judgment in selecting the appropriate method for a specific situation.

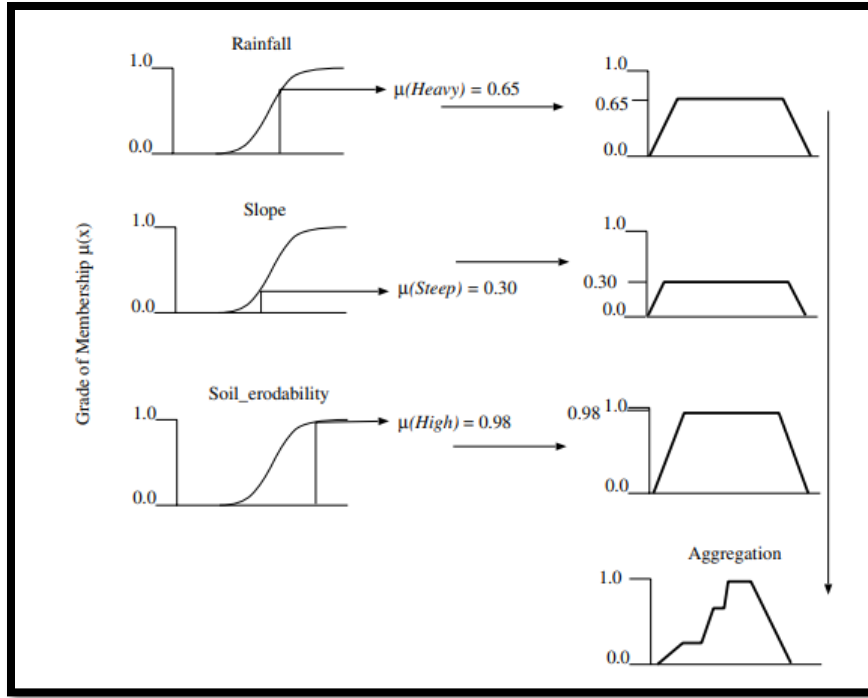


Figure 16: Fuzzification Process by Combining Factors to Assess Erosion Risk

3.3.2.3 Rule Set

In the fuzzy logic process, after determining DoM as described in section 3.3.2.1, the next step involves creating a rule set. The rule set defines the logic and decision-making criteria that guide the assessment of overall risk based on the DoM values derived from specific functions. Each rule corresponds to a combination of favourable and unfavourable states in different categories, and these rules are then translated into natural language for expert evaluation, ensuring that experts can understand and validate the logic behind the risk assessments.

This translation into natural language is critical for expert validation, as it allows domain experts to review, interpret, and potentially refine the logic embedded in the fuzzy logic model. It promotes transparency and ensures that the fuzzy logic system aligns with the expertise and judgment of the human evaluators.

The rule set in a fuzzy logic system comprises 2^N number of rules, where N represents the number of inputs. This exponential growth in the number of rules is a drawback, particularly when dealing with a large number of inputs, as it can lead to a complex and extensive rule set.

The resulting rule set for the five input (32 rules) are presented in Table 4.

Consider rule 7 in Table 4 as an example. This set of outcomes suggests that System Sustainability, Borehole Sustainability, and Human Health risk fall within a favourable range, while Aquifer Vulnerability and Climate Change are deemed unfavourable. When combining these outputs, the overall risk conclusion from Table 4 is 15%.

Table 4: Fuzzy logic rule set

Decision making rules						
Rule No	System Sustainability	Borehole Sustainability	Aquifer Vulnerability	Climate Change	Human Health	Conclusion (Risk)
1	F	F	F	F	F	0
2	F	F	F	F	U	1
3	F	F	F	U	F	0.05
4	F	F	F	U	U	1
5	F	F	U	F	F	0.1
6	F	F	U	F	U	1
7	F	F	U	U	F	0.15
8	F	F	U	U	U	1
9	F	U	F	F	F	1
10	F	U	F	F	U	1
11	F	U	F	U	F	1
12	F	U	F	U	U	1
13	F	U	U	F	F	1
14	F	U	U	F	U	1
15	F	U	U	U	F	1
16	F	U	U	U	U	1
17	U	F	F	F	F	1
18	U	F	F	F	U	1
19	U	F	F	U	F	1
20	U	F	F	U	U	1
21	U	F	U	F	F	1
22	U	F	U	F	U	1
23	U	F	U	U	F	1
24	U	F	U	U	U	1
25	U	U	F	F	F	1
26	U	U	F	F	U	1
27	U	U	F	U	F	1
28	U	U	F	U	U	1
29	U	U	U	F	F	1

Decision making rules						
30	U	U	U	F	U	1
31	U	U	U	U	F	1
32	U	U	U	U	U	1

Additionally, within the fuzzy logic system, weighting is often assigned to different rules based on their significance or relevance. This allows certain rules to have a more pronounced impact on the overall decision-making process. For instance, an expert may assign a higher weight to a rule that involves a critical input parameter or a scenario with higher potential risk.

Furthermore, one notable feature of fuzzy logic is its non-linear capability. In the evaluation process, a single unfavourable input, regardless of the other input parameters, can result in the entire system being flagged as unfavourable. This reflects the concept that certain critical factors or conditions may have a disproportionate influence on the overall assessment. In practical terms, an expert has the authority to fail the entire system based on the severity of a single unfavourable input, showcasing the non-linear and context-sensitive nature of fuzzy logic. This characteristic allows the system to capture the nuanced and often nonlinear relationships inherent in complex real-world scenarios, providing a more realistic representation of uncertainty and imprecision.

The rule set is the backbone of the fuzzy logic system, guiding a comprehensive evaluation of groundwater pollution risks. Each rule combines DoM values from different risk categories, enabling a holistic assessment. Translated into natural language for expert validation, the rule set handles unfavourable conditions conservatively, defaulting to 100% risk in critical scenarios. Weighted for significance, it adapts to nonlinear relationships and undergoes sensitivity analysis for robustness. In essence, it aligns with project objectives, providing a transparent and structured approach to interpret the intricate dynamics of groundwater pollution risks.

3.3.2.4 Defuzzification

In the defuzzification process, the centre of gravity method is employed to calculate the overall risk based on the assigned fuzzy logic rule sets. This method combines the minimum DoM for each rule with its corresponding weight using a weighted average formula. The equation for calculating the percentage of risk is presented in Equation 13.

$$\%Risk = \frac{\sum_{i=1}^n Wi * \mu(Wi)}{\sum_{i=1}^n \mu(Wi)} * 100 \quad (13)$$

Where,

n = number of rules assigned

μ = Minimum function

W_i = Weight of rule i

μW_i = Minimum degree of membership (DoM) for rule i

This approach allows the system to integrate the importance assigned to each rule (via weights) and the corresponding degrees of membership associated with those rules. The centre of gravity method provides a comprehensive and weighted assessment of risk, considering the nuanced contributions of various rules in the fuzzy logic system.

3.4 SUMMARY

In this chapter, the focus is on developing a comprehensive risk assessment framework for groundwater pollution, addressing key categories: Climate Change Impact, Aquifer Vulnerability, Groundwater Sustainability, and Human Health. Fuzzy logic is introduced for its ability to handle uncertain information.

The chapter outlines methodologies for quantifying risks in each category, utilizing indices like DART and DRASTIC. Human Health risks are quantified, considering toxicity and carcinogenicity, with refined source-based screening. The tiered approach distinguishes between regional and site-specific assessments, optimizing resource allocation.

The final section applies fuzzy logic to combine risk categories. Degree of Membership functions for each category, including DoM curves and thresholds, are discussed. The fuzzy logic process involves fuzzification, rule set creation, and defuzzification, providing a nuanced representation of uncertainty. The rule set, translated into natural language, incorporates expert knowledge and assigns weights for significance. The defuzzification process calculates the overall risk percentage based on the fuzzy logic rule sets, ensuring a comprehensive evaluation of groundwater pollution risks. Figure 17 attempts to visually represent the total system described in this chapter, comprising the various risk categories which are combined through a fuzzy logic expert system to yield a composite risk assessment result for a specific site.

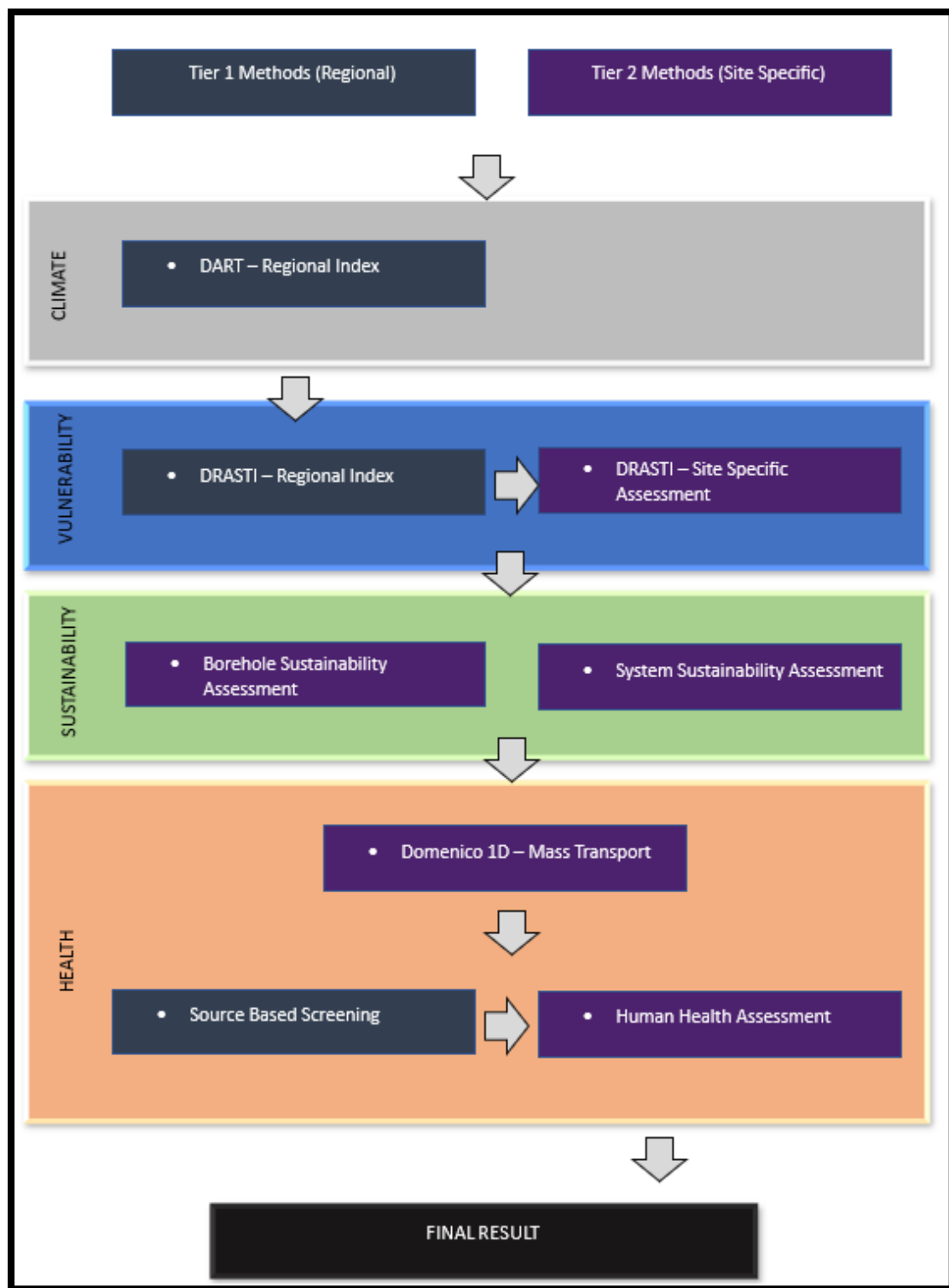


Figure 17: Risk Assessment Flow Diagram

4 CASE STUDY

4.1 BACKGROUND

In this case study, the focus is on the farmlands enveloping the Crocodile River, an area chosen for its unique hydrogeological setting and its critical role in sustaining local agricultural activities. Within this landscape, local mining operations in close proximity to the farmlands have raised concerns about potential repercussions on the natural groundwater resource that plays a pivotal role in irrigation practices.

Figure 18 illustrate the existing agricultural activities surrounding the Crocodile River area. However, this area is now influenced by the expanding quarry activities undertaken by a local mine. The expansion of the quarry raises alarms as blasting operations, inherent in such activities, have the potential to impose a threat to the groundwater resources of the region.

To assess the interactions between agriculture, mining, and groundwater, comprehensive data were gathered from the wellfield demarcated in Figure 18. The collected data served as the basis for the geohydrological risk assessment, with the ultimate goal of understanding and quantifying potential risks that mining activities may pose to the groundwater resource that is integral to the surrounding farmlands' irrigation practices.

As this case study unfolds, a deeper comprehension of the intricate interplay among the various factors becomes evident. This enhanced understanding informs resource management decisions. Furthermore, it underscores the critical importance of establishing a comprehensive framework for the evaluation of risks associated with groundwater and the surrounding environment.

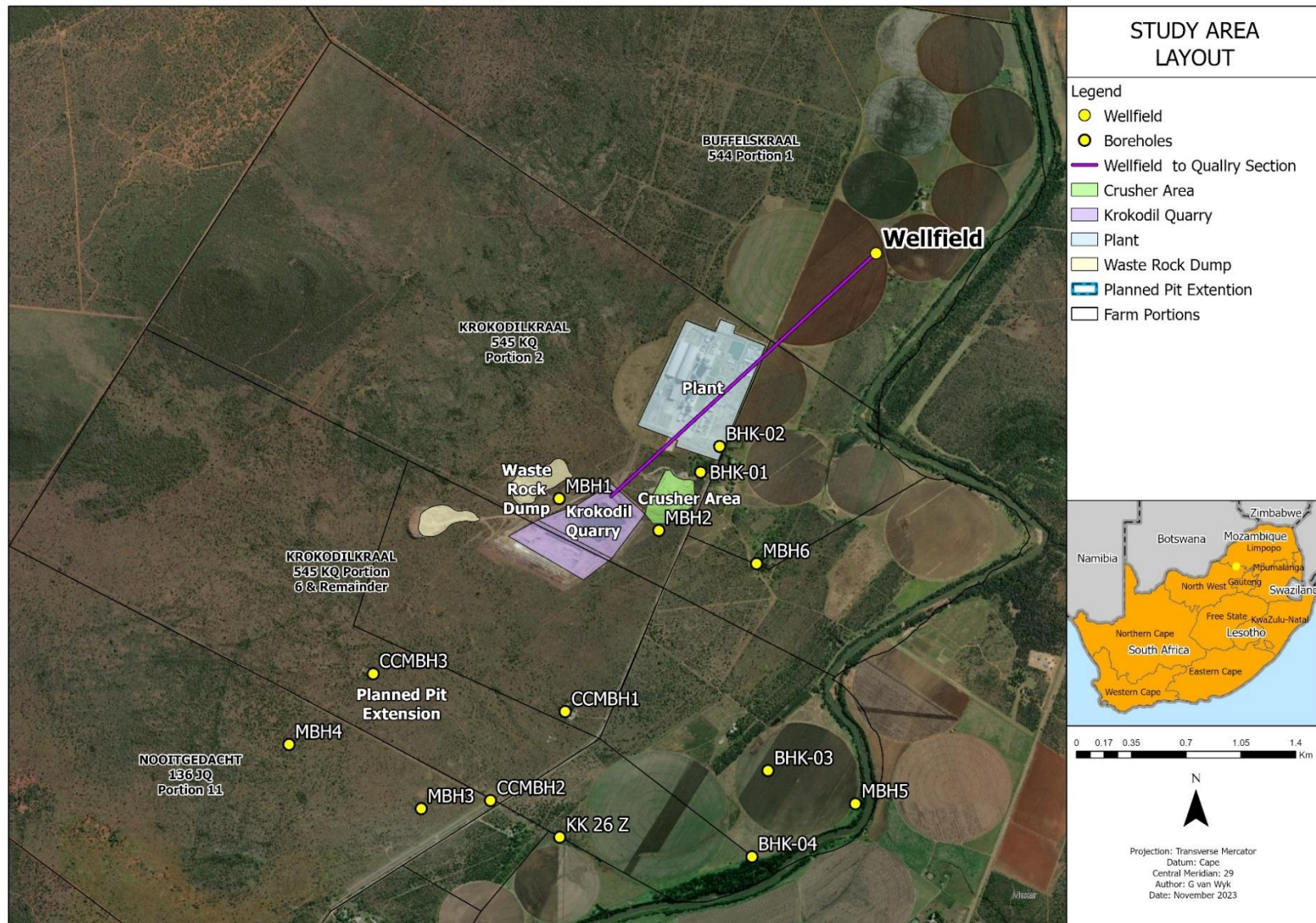


Figure 18: Study Area Layout

4.2 STUDY AREA

4.2.1 LOCATION

The Crocodile River farms, positioned approximately 46 km southeast of Thabazimbi in the Limpopo province, lie within the jurisdiction of the Waterberg district municipality and the Thabazimbi local municipality. The precise geographical coordinates of the mining operations are depicted in Figure 19. The mining operation is nestled within the Crocodile West and Marico water management area (WMA). The site resides within the confines of quaternary catchment A24B, with a catchment area of 710 km². Notably, the perennial Crocodile River courses to the south-east of the site, flowing in a northerly direction.

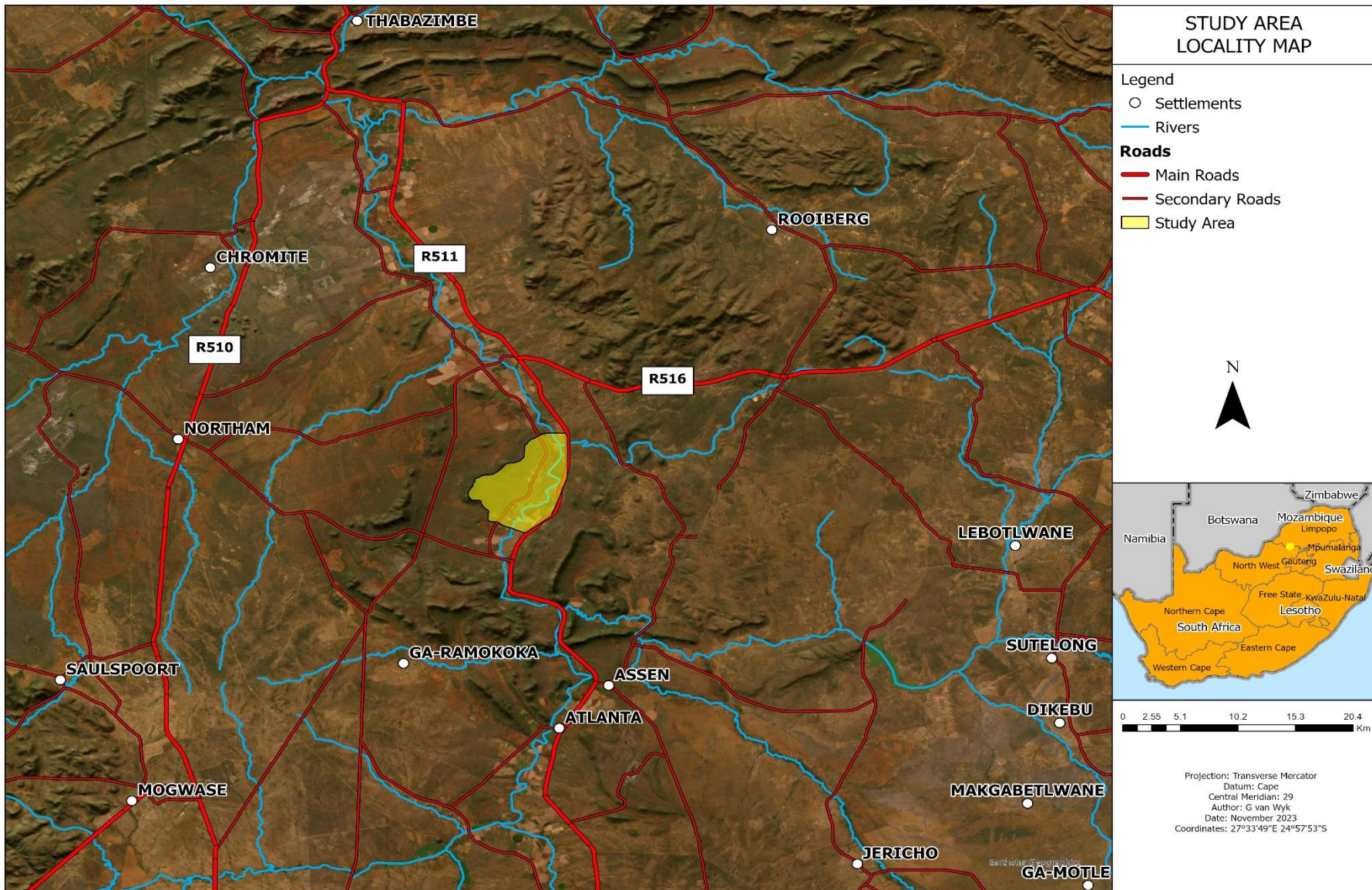


Figure 19: Study Area Locality Map

4.2.2 CLIMATE

The climate of the Thabazimbi area is characterised by scorching summer months and mild, dry winters (Le Roux, 2018). The region experiences high maximum temperatures during summer, with an average of 30.8°C. Winter brings cooler temperatures, with the average minimum dropping to 2.9°C in July (Le Roux, 2018). This locale falls under the classification of a summer rainfall region (Le Roux, 2018). The bulk of annual rainfall occurs in the summer months, primarily December through February. Precipitation during the drier winter months is minimal. The mean annual precipitation (MAP) for the region is estimated at 640 mm/a, as illustrated in Figure 20.

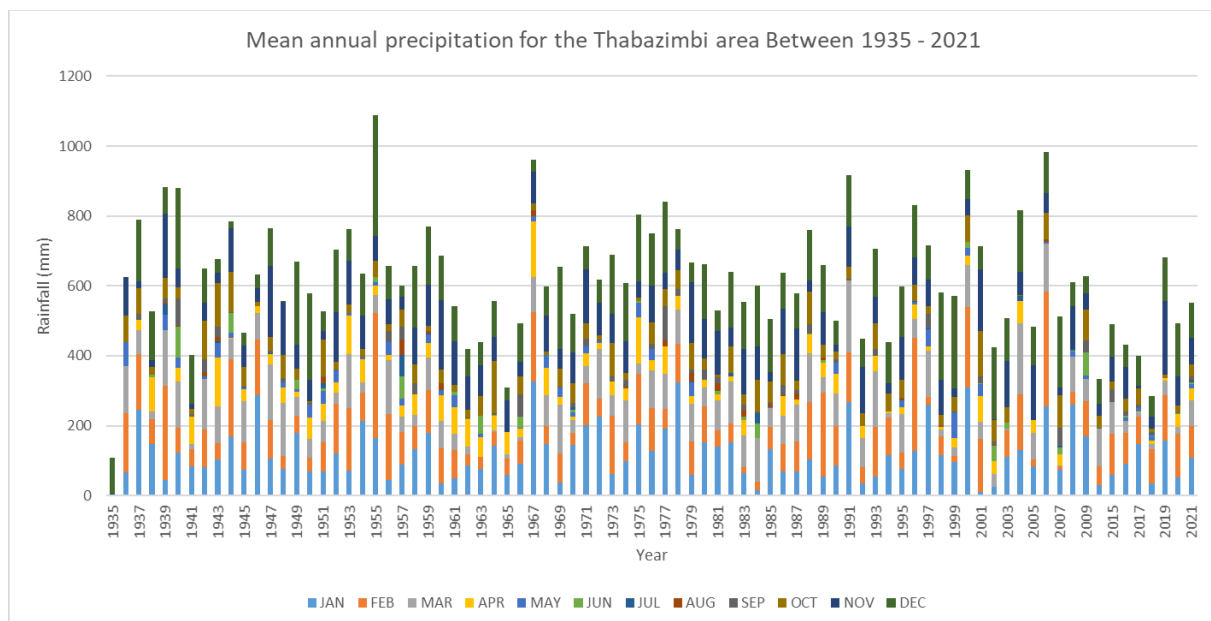


Figure 20: Annual precipitation for the Thabazimbi area

4.2.3 TOPOGRAPHY AND DRAINAGE

The study area is situated at an elevation ranging from approximately 1000 to 1300 metres above mean sea level (mamsl). This region is predominantly utilised for agricultural purposes, featuring numerous farmlands that envelop the Crocodile River.

The topography of the study site exhibits a gradual incline in a north-eastern direction, channelling its natural flow towards the Crocodile River. Consequently, the western bank of the river showcases a north-eastern slope, while the eastern side presents a north-western gradient. The surrounding area is characterised by small hills, all of which slope in the direction of the river, contributing to the overall drainage patterns.

Utilising a Digital Elevation Model (DEM), a watershed has been meticulously delineated for the study area. Watersheds represent geographic regions where all surface water runoff converges into a common water body. Understanding these watershed boundaries is of paramount significance for effective water resource management and informed environmental planning.

It is worth noting that traditional topographical maps do not depict additional drainages or non-perennial rivers within the study area. However, satellite imagery investigations have uncovered potential drainages on the south-western side of the site, particularly within elevated topographical regions. These satellite-derived findings have prompted the identification and digital representation of these potential drainages, which are being integrated into the study. It is essential to highlight that further validation through comprehensive investigation is warranted to ensure the accuracy and reliability of these newly identified features. The spatial relationship between the Crocodile River and the digitised drainages is visually represented in Figure 21.

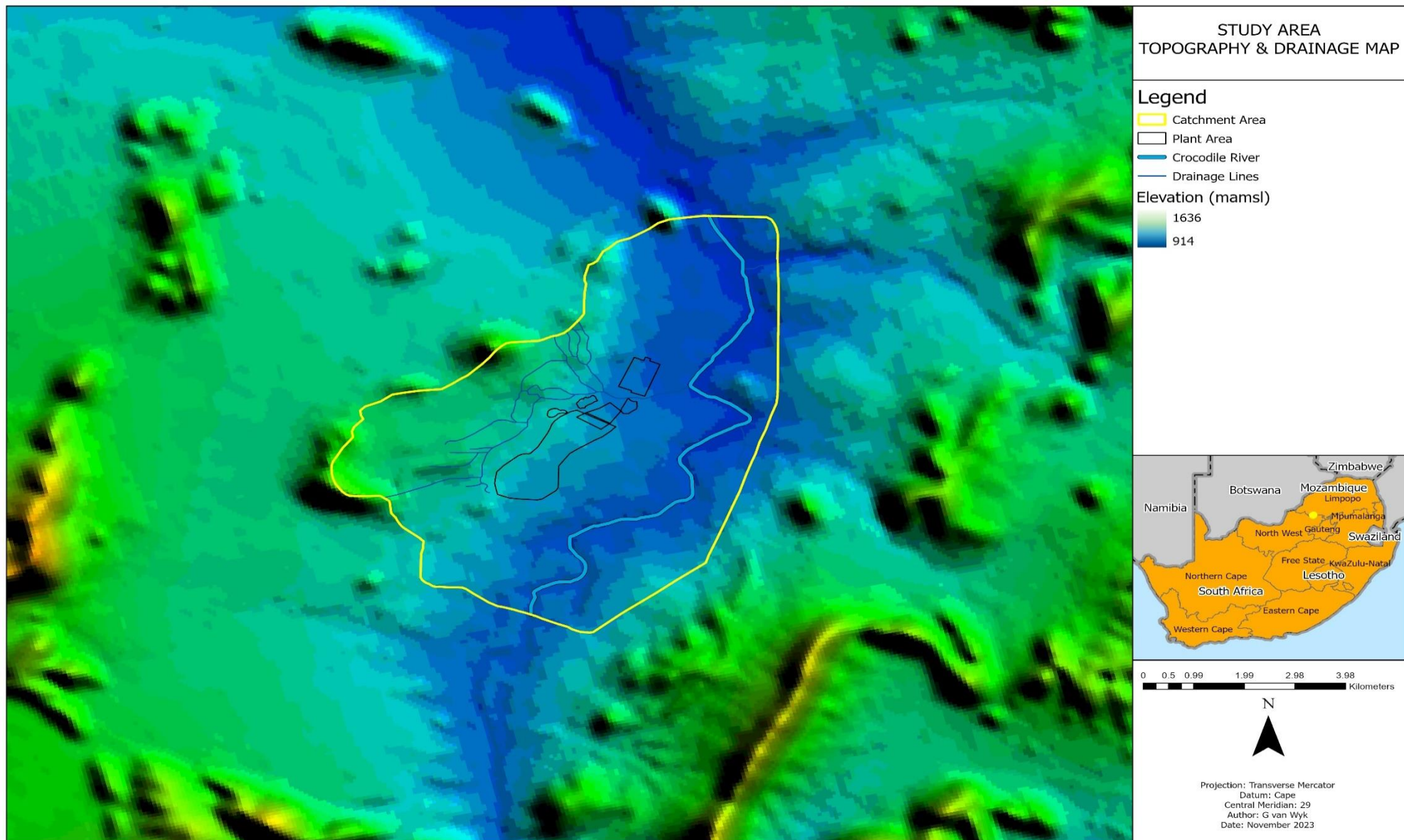


Figure 21: Study Area Drainage and Topography Map

4.2.4 GEOLOGICAL SETTING

Regionally the site is located inside Crocodile River fragment sediments. In this area, sediments of the Chuniespoort Group forms part of the Transvaal Sequence (dolomite, quartzite, shale, and banded ironstone) and outcrops over a large area that is known as the Crocodile River fragment. The Crocodile fragment is almost entirely encircled by granite of the Lebowa Granite Suite that is part of the Bushveld Igneous Complex (Hobbs *et al.*, 1987:35). Figure 22 shows the location of the Crocodile River fragment in relation to the Transvaal Sequence and Bushveld Complex.

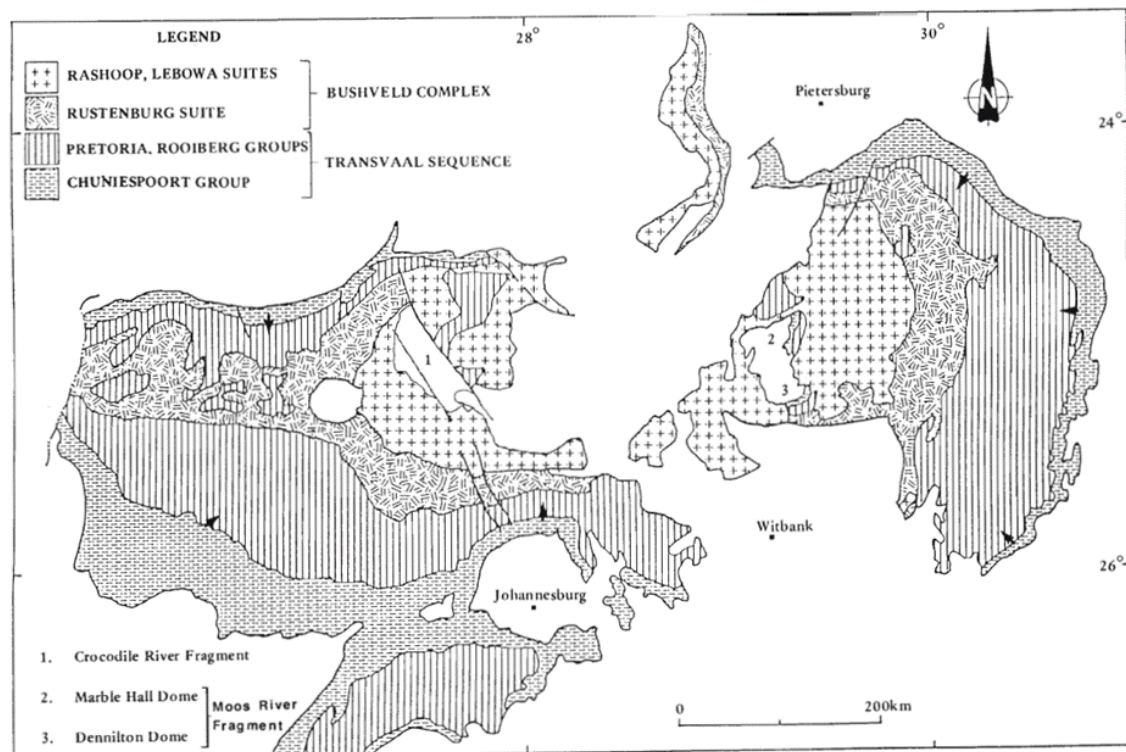


Figure 22: The geology of the Transvaal Basin, illustrating the location of the Crocodile River Fragment (1) in relation to the Transvaal Sequence and Bushveld Complex. Source: (Hartzer, 1989)

The geological landscape within the study area exhibits a diverse composition, predominantly characterised by limestone and dolomite formations, which are periodically interspersed with deposits of shale and quartzite. Towards the northeastern part of the study area, a notable geological feature emerges in the form of coarse-grained granite, originating from the Bushveld Igneous Complex. The geological makeup of the region further encompasses the presence of local fault zones and quartz veins, as depicted in Figure 23, indicating the complex nature of the terrain.

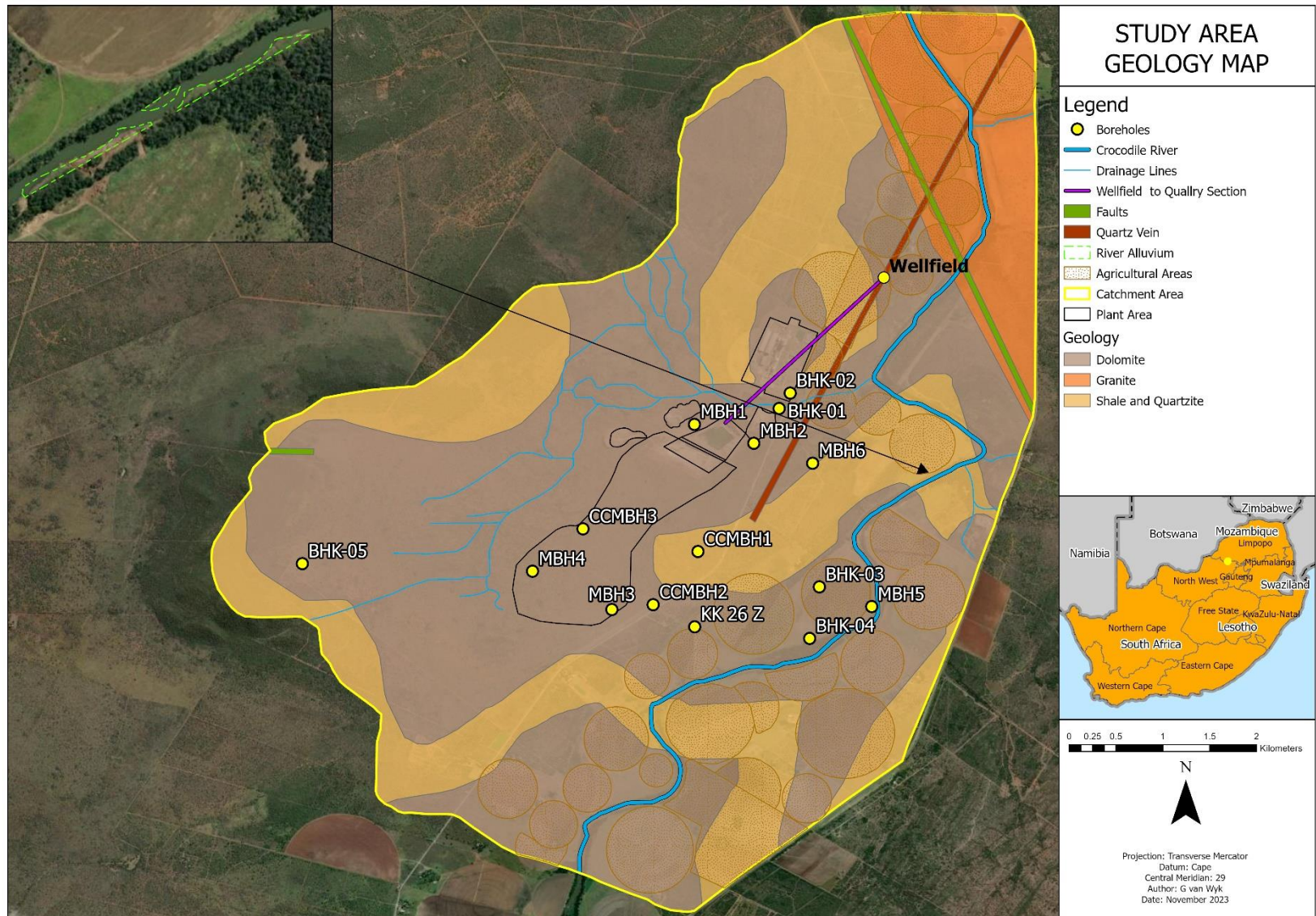


Figure 23: Geological Map of Study Area

4.2.5 HYDROGEOLOGICAL SETTING

In the hydrogeological setting of the study area, geohydrological maps revealed groundwater occurrence at a yield of 2 L/s. The region's geology significantly influences the distribution and movement of groundwater, making it a critical consideration for environmental and hydrogeological assessments. This occurrence of groundwater is influenced by the presence of two distinct aquifer systems, each with its own characteristics:

1. The primary aquifer system is located within the unconsolidated alluvial sediments along the Crocodile River's flood plains. These sediments serve as a vital reservoir for groundwater storage, playing a pivotal role in maintaining local water resources.
2. The secondary fractured rock aquifer system primarily consists of dolomite formations within the study area's boundaries. This fractured rock aquifer system serves as an additional source of groundwater, with water stored within the fractures and voids in the dolomite rock layers.

Understanding the presence and characteristics of these aquifer systems is essential for effective water resource management and groundwater utilisation within the study area.

Regarding recharge rates, calculations based on specific datasets reveal the following percentages of recharge relative to the total annual precipitation (GR11 – 16 mm/a, Vegter – 20 mm/a):

- GR11 (%) Recharge: 16 mm/a corresponds to 2.5% of the MAP.(Department of Water Affairs and Forestry, 2009);
- Vegter (%) Recharge: 20 mm/a corresponds to 3.1% of the MAP (Vegter,1995).

In addition, the regional groundwater levels have a strong correlation with surface topography as shown in Figure 24. This correlation indicates the presence of unconfined aquifers or the fact that the unconfined and deeper confined systems are hydraulically connected.

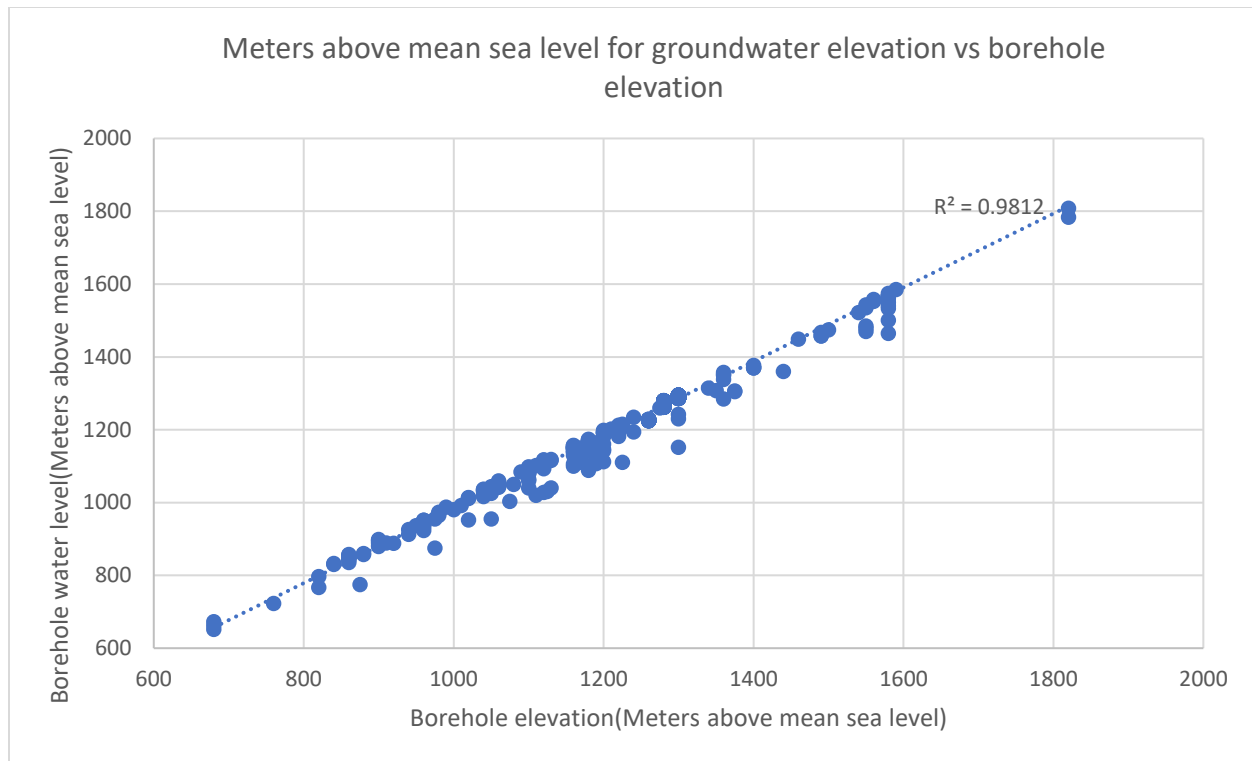


Figure 24: Water level and Topography correlation graph.

Making use of the high correlation between groundwater level and surface topography, Bayesian interpolation was applied to generate a groundwater level map based on available data. This groundwater level map, presenting the average static groundwater level is presented in Figure 25.

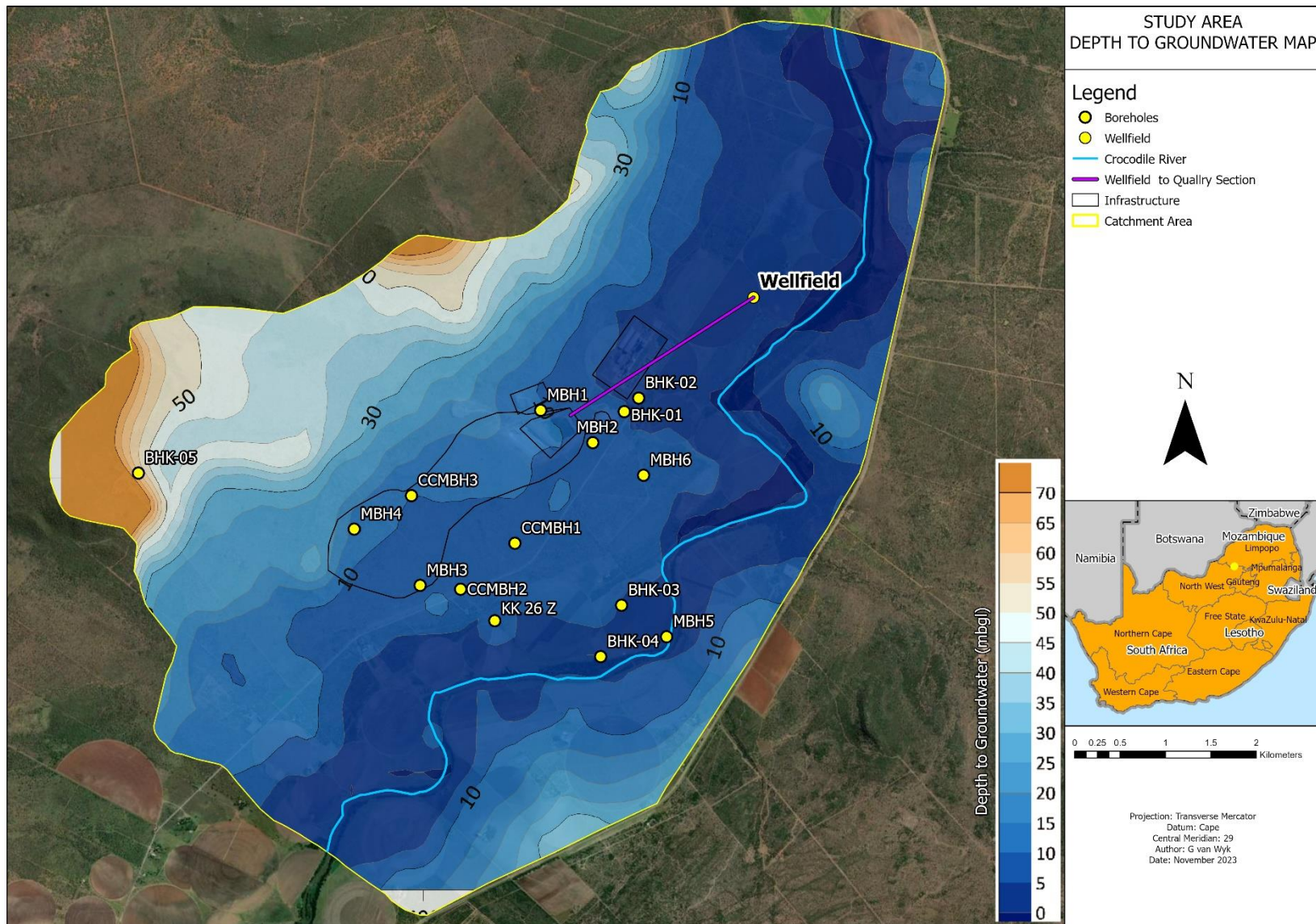


Figure 25: Study Area Depth to Groundwater Map

4.2.6 SOILS

Figure 26 displays a map illustrating the characteristics of the local soil media.

The soils in the study area, situated adjacent to the Crocodile river, exhibit various textures characterized by soil horizons. The predominant soil textures include Sa-SaLm, LmSa-SaLm, and SaCILm-Cl.

- Sa-SaLm: This indicates a sequence where the surface soil (A horizon) is sandy (Sa), transitioning to a subsurface horizon (Lm) with a mixture of sand (Sa) and loam (Lm) components. This composition suggests a well-draining soil profile at the surface.
- LmSa-SaLm: In this case, the surface soil is primarily loam (Lm) transitioning to a subsurface horizon that is a combination of sand (Sa) and loam (Lm). This texture profile may suggest a soil that retains more moisture compared to the Sa-SaLm profile due to the increased loam content.
- SaCILm-Cl: This texture sequence starts with a sandy surface soil (Sa), followed by a horizon with a mixture of clay (Cl) and loam (Lm) components. This indicates a transition towards heavier soil textures as you move deeper into the soil profile.

The proximity to the river suggests potential influences from river sediments, affecting the soil characteristics. Sandy textures often imply good drainage, while loam and clay components contribute to soil fertility and water retention. (Department of Water and Sanitation, 2023)

This textural information serves as a crucial element in determining the parameters for DRASTIC calculations.

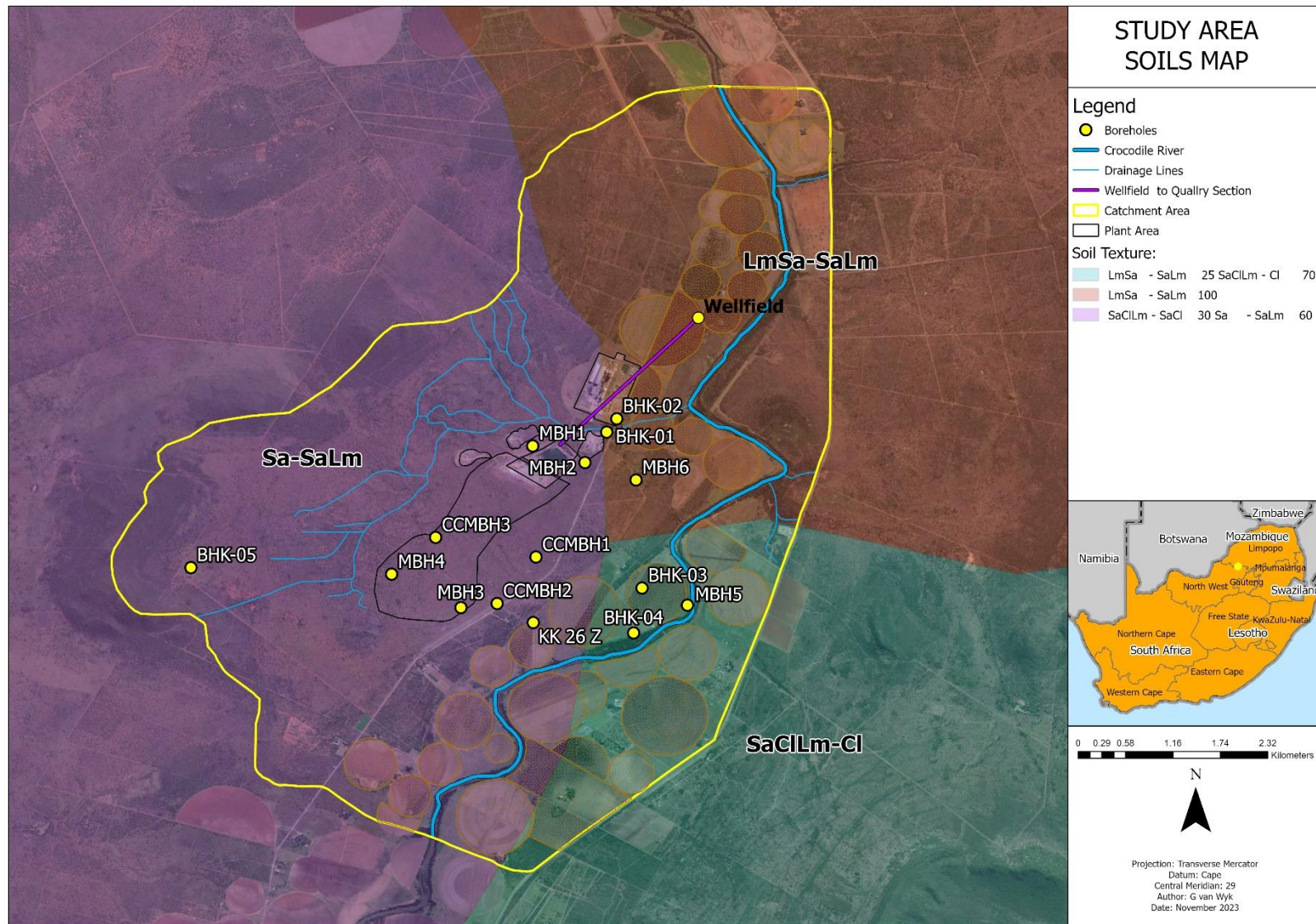


Figure 26: Study Areas Soil Media Map

4.3 DATA COLLECTION AND ANALYSIS

The effectiveness and reliability of the geohydrological risk assessment relies on the comprehensive collection and integration of diverse datasets. This section outlines the approach taken to acquire site-specific data required for an accurate understanding of the risk landscape within the Crocodile River farms area. Please refer to APPENDIX C and Figure 27 for the boreholes used in the study area, as well as the boreholes from the National Groundwater Archive (NGA).

To ensure the accuracy of the assessment, a dedicated site visit was conducted to collect essential geohydrological data. This endeavour yielded the following vital datasets:

- **Water Level Readings:** Multiple boreholes were instrumented to measure water levels, enabling the assessment of groundwater depth, as depicted in Figure 25
- **Historical Borehole Log Data Evaluation:** The historical borehole log data were scrutinised to ascertain aquifer media composition and thickness. Based on this available data, a conceptual model was developed, as illustrated in Figure 28. This conceptual model also indicates the scenario where the quarry pit has formed. For the purposes of this study, the assessment will focus on the assumed natural groundwater levels. This section refers specifically to the cross section, as it indicates the assumed natural groundwater level based on interpolation of data. The associated borehole log data is included in APPENDIX D.
- **Execution of pump tests:** Pump tests are instrumental in quantifying two fundamental parameters: Storativity and Transmissivity. These parameters play a paramount role in understanding the capacity of an aquifer to store and transmit groundwater, respectively. The results of the pump test are summarised in Table 5.
- **Water quality assessments:** Water quality assessments were conducted on boreholes in the vicinity of the mine area, shedding light on the potential impacts of mining activities. The water quality findings are detailed in Table 6. Notably, some elevated nitrate levels were detected, likely attributable to blasting activities occurring within the quarry.

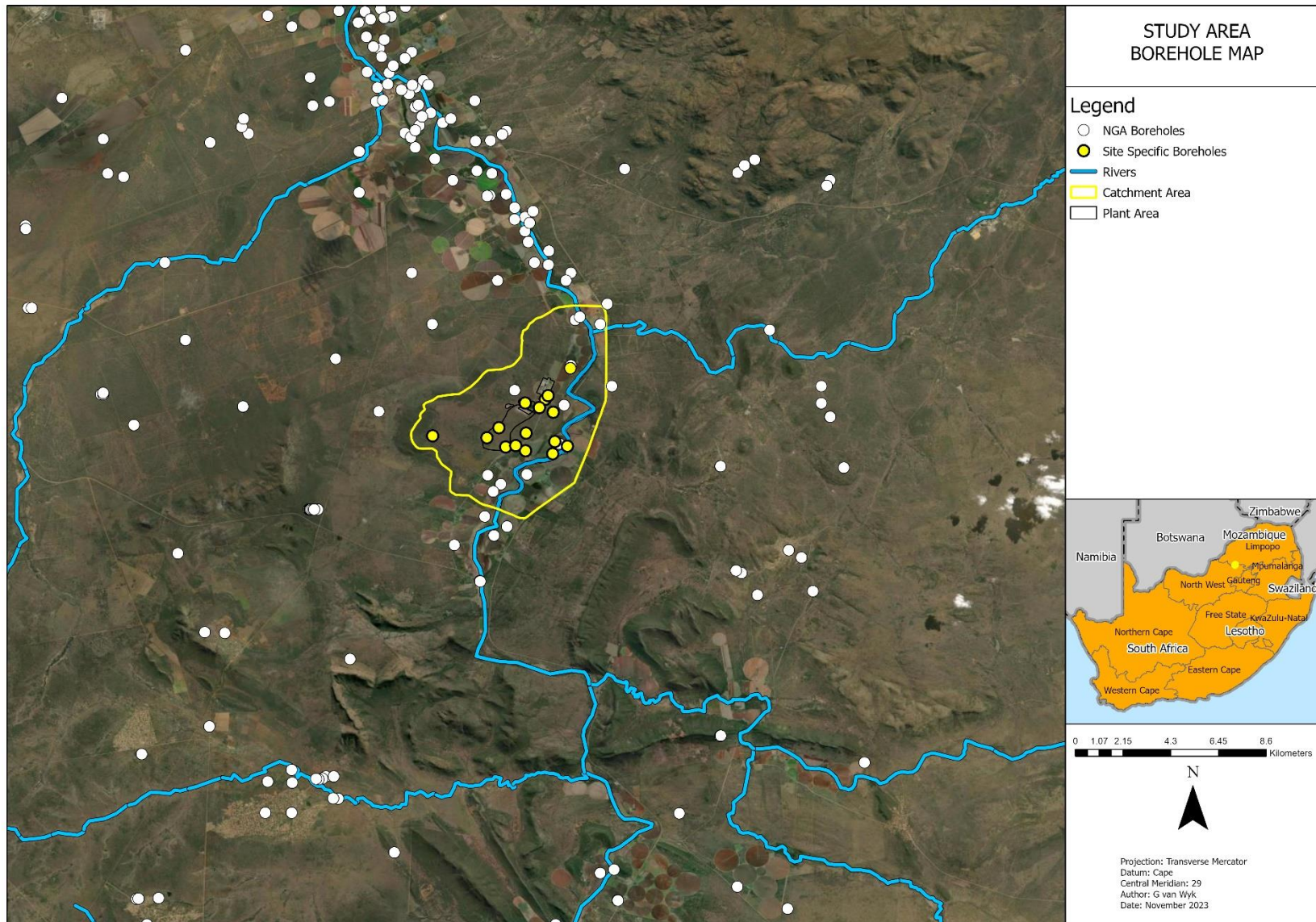


Figure 27: Borehole Map of Study Area

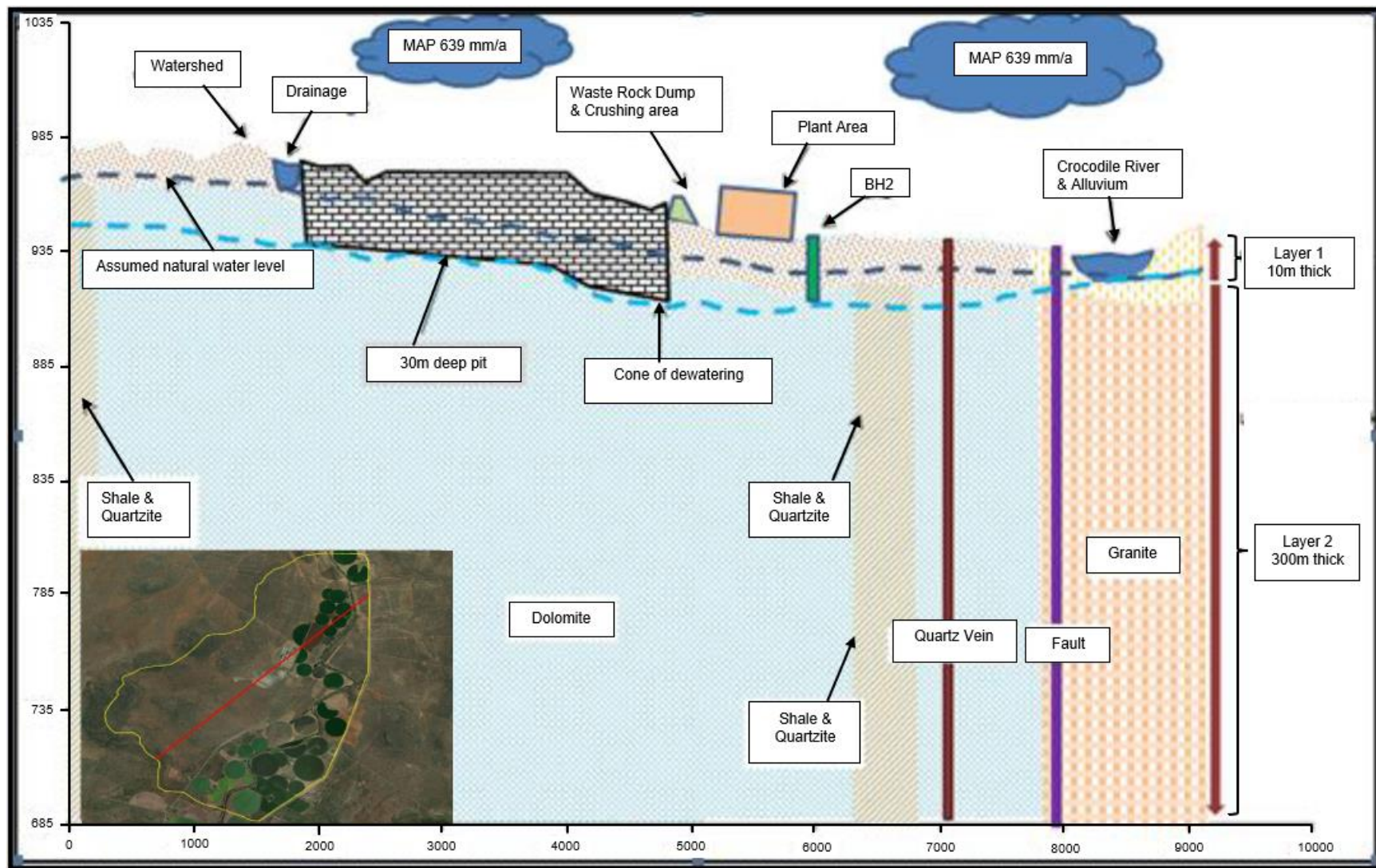


Figure 28: Study Area Conceptual Model

Table 5: Pump Test Results

Alluvial aquifer					
Borehole ID	Early T	Late T	Recovery T	Average T	Geometric mean
BH-K01	115	74.3	118	102.43	100.2742803
BH-K02	187	55	137	126.33	112.1092949
BH-K03	157	309	86.7	184.23	161.4206443
BH-K04	147	52.7	110	103.23	94.80695795
Fractured Rock aquifer					
BH-K05	2.4	47	17.6	22.33	12.56822429

Table 6: Water Quality Analysis Results

Site name	Date	HCO ₃	Ca	Cl	F	Mg	K	Na	SO ₄	NO ₃ -N	NH ₃ -N	NH ₄ -N	PO ₄	CO ₃	pH	EC	TDS
		mg/L CaCO ₃	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L N	mg/L	mg/L	mg/L CaCO ₃	pH	mS/m	mg/L
BHK-01	2020-12-14	185	126	173	0.403	29.3	10.8	91.7	111	10.8	<0.005	0.066	0.996	2.13	8.09	126	794
BHK-03	2020-06-18	515	231	372	0.34	52	2.2	240	281	14	<0.005	0.016	<0.005	1.3	7.41	252	1696
BHK-04	2020-09-21	547	224	437	0.33	96	3.5	174	254	12	<0.005	0.023	<0.005	7.2	8.14	244	1822
BHK-05	2020-12-14	227	342	337	0.30	43.0	3.66	30	286	11.80	<0.005	0.105	0.084	1.2	7.76	202	1206
KK26Z	2020-11-16	432	153	20	0.26	21.5	1.88	7	38	3.38	<0.005	0.048	<0.005	0.5	7.06	94	662
MBH1	2020-12-14	323	37	13	0.67	36.5	8.41	54	29	0.21	0.011	0.061	0.121	14.2	8.67	64	390
MBH2	2020-12-14	498	172	23	0.45	36.6	5.68	26	42	17.7	<0.005	0.064	0.071	1.3	7.44	119	696
MBH3	2020-12-14	357	207	56	0.41	20.5	4.21	10	63	30.4	<0.005	0.07	0.087	1.1	7.5	116	732
MBH4	2020-12-14	573	144	12	0.68	50	6.22	11	11	0.22	0.082	7.270	0.397	1.3	7.39	111	558
MBH5	2020-12-14	508	88	8	0.99	58	11.00	21	12.9	0.22	<0.005	0.127	0.052	1.3	7.44	98	584
MBH6	2020-12-14	412	16	400	0.32	158.0	2.89	96	9	0.22	0.087	1.720	0.049	4.9	8.1	190	1004
CCMBH1	2020-12-14	507	190	157	1.36	62	11.6	45	87	11.60	<0.005	0.212	0.049	0.4	6.92	167	1118
CCMBH2	2020-12-14	526	88	40.4	0.9	39.3	14.50	72.5	5	0.3	0.0	2.050	0.054	0.7	7.17	112	616
Wellfield	2020-12-14	504	170	167	1.26	52	12.6	55	77	11.10	<0.005	0.222	0.059	0.4	6.82	177	1113
<u>SANS 241 (2015) **</u>		<u>N/A</u>	<u>N/A</u>	<u>≤ 300</u>	<u>≤ 1.5</u>	<u>N/A</u>	<u>N/A</u>	<u>≤ 200</u>	<u>≤ 500</u>	<u>≤ 11</u>	<u>N/A</u>	<u>N/A</u>	<u>N/A</u>	<u>N/A</u>	<u>≥ 5; ≤ 9.7</u>	<u>≤ 170</u>	<u>≤ 1200</u>

In addition, supplementary data were obtained through thorough desktop studies, enhancing the assessment by considering the following factors:

- Distances between contamination sources and receptors were measured.
- Topography and slope angles were analysed using digital elevation models, as demonstrated in Figure 21.
- From the analysis of the topographical data, the resulting path profile is depicted in Figure 29.
- Recharge rates were obtained making use of national datasets as discussed in 4.2.5.

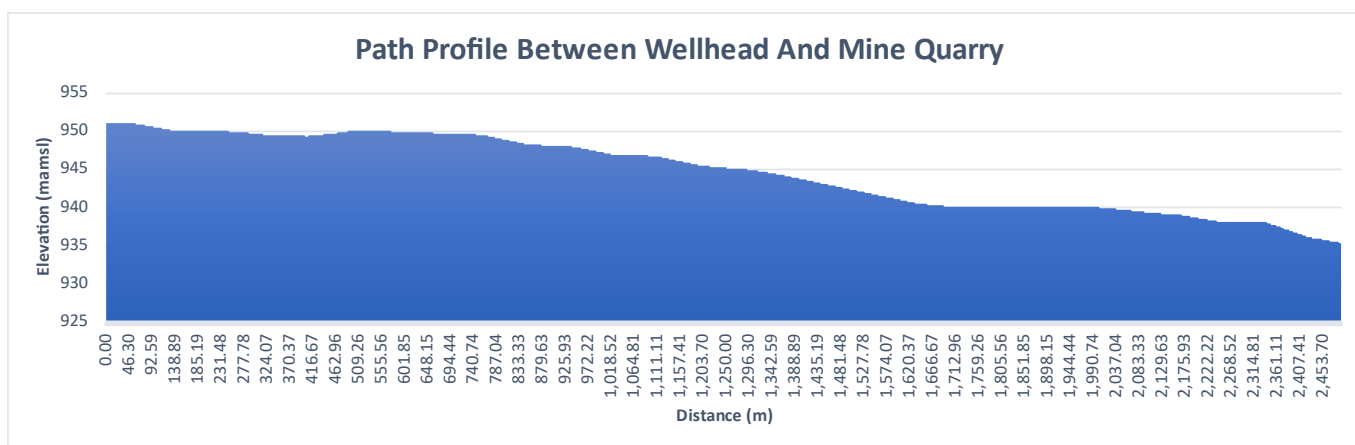


Figure 29: Path profile between quarry and wellhead

By collecting a wide range of geohydrological, meteorological, and mining-related data, this study aims to establish a solid foundation for the risk assessment.

5 RESULTS AND DISCUSSION

5.1 PREAMBLE

The formulated methodology in Chapter 3 was implemented in an Excel spreadsheet as a risk assessment tool (RAST). The information available for the case study area was applied to RAST to produce the associated risk assessment results. The remainder of this chapter will discuss the results of each risk category and then present the final overall risk assessment result.

5.2 TIER 1 – REGIONAL SCALE

The initial step of RAST is to select the quaternary catchment of interest. For the study area under consideration this is quaternary A42B and after the selection, RAST will show the baseline data available as presented in Figure 30. This baseline information includes:

- **Regional scale** (Catchment Area)
- **Hydrological/Geohydrological parameters** such as Mean Annual Runoff (MAR), Baseflow, Specific Yield and Recharge derived from the GRII and Vegter Datasets.
- **Drastic and DART indexes** are then calculated based on the GRII and Vegter Datasets.
- **The Special Report on Emissions Scenarios (SRES)** is a set of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) to explore diverse futures for greenhouse gas emissions and their potential climate impacts. South Africa's position in these scenarios was contingent on assumptions about global and regional factors within each storyline (Dennis et al., 2014).

Figure 30 displays the initial startup screen of the risk assessment support tool, serving as the inception point for the risk assessment. This screen provides users with baseline information about the study area in relation to the catchment in which it is situated.

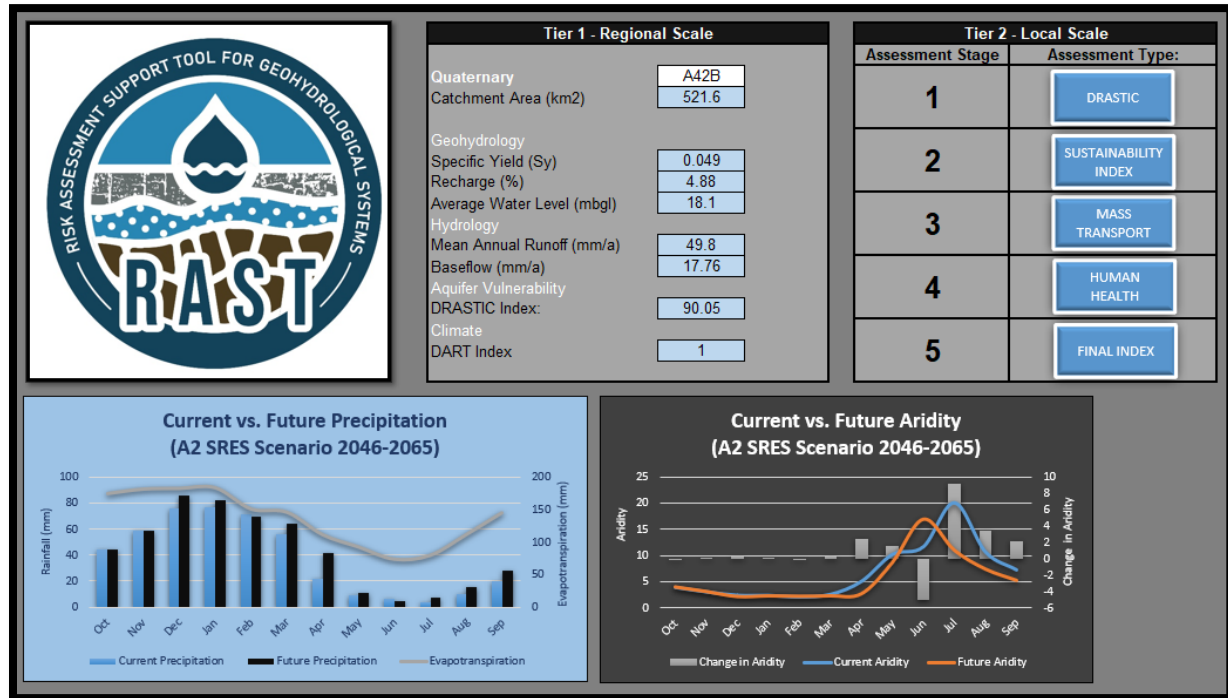


Figure 30: Case Study Baseline Information

From the baseline data it is clear that the 4.88% recharge differs from the 2.5% and 3.1% reported earlier in the GRII and Vegter datasets from Chapter 4.2.5. By selecting the Tier 2 assessment categories, local scale parameters gathered from the field testing can be entered into the system to reflect the study area.

5.3 TIER 2 – LOCAL SCALE

5.3.1 DRASTIC

From the starting point as shown in Figure 30, users can proceed to the initial assessment stage for the local scale, specifically the DRASTIC assessment. Based on the available data from the study area the model inputs shown in Figure 31 were derived from the collected data as well as desktop sources.

SITE SPECIFIC RATING	
Depth to groundwater (m)	9.1 - 12.1
Net Recharge (mm/a)	13 - 20
Aquifer media	Shale
Soil media	Loamy Sand
Topography/Slope (%)	0
Vadose zone media	Dolomite
Site specific Vulnerability Rating:	135
DRASTI Index:	High
Description:	Aquifer is highly sensitive to an imposed contaminant load that could affect groundwater quality

Figure 31: DRASTIC Assessment Outcome

The justification for the input parameters in Figure 31 is based on the following reasoning:

- Depth to Groundwater: 10 m, as derived from the information presented in Figure 25.
- Net Recharge: Estimated at 13-20 mm per annum, based on data from the GRII and Vegter Datasets.
- Aquifer Media: Identified as shale according to geological mapping and the conceptual model.
- Soil Media: Categorised as loamy sand.
- Topography: Recorded as 0, as the path profile analysis indicated a topography change of only 0.6% in the area.
- Vadose Zone Media: Delineated as dolomite in accordance with geological mapping.

The regional DRASTIC rating was reported as 90, while the site-specific evaluation yields a higher value of 135. This highlights an increased aquifer vulnerability compared to the catchment average when accounting for site-specific data. Multiple factors contribute to this disparity. Firstly, the shallower depth to groundwater compared to the catchment average increases the potential for contaminants to infiltrate groundwater sources (Almasri & Kaluarachchi, 2004:726). Secondly, the higher porosity in the soil media than the catchment norm enhances the susceptibility of the aquifer to contamination pathways (Kachanoski et al., 1984:211). Thirdly, the presence of dolomitic material in the vadose zone within the study area alters the percolation and attenuation processes, influencing groundwater vulnerability (Keller & Blanz, 1994:35). Additionally, discrepancies may arise due to the study area's proximity to the river, as quaternary data may not fully capture the influence of surface water-groundwater interactions on vulnerability assessments (Hossain & Rahman, 2015:98).

5.3.2 SUSTAINABILITY INDEX

The next step of the risk assessment is then to assess the sustainability index. In Figure 32, the depicted outcomes reveal that the Wellfield, previously highlighted in Figure 18 during evaluation, is presently being pumped at a sustainable rate, taking into account aquifer recharge. However, a crucial observation is the imperative recognition that the borehole is at a high risk of failure, standing at a 99% probability, as the drawdown has approached dangerously close to the critical water strike level.

Borehole Sustainability Risk:		
Cone of depression radius (r)	867.6	m
Transmissivity (T)	110	m ² /d
For how long has borehole been pumped (days)	365	
Pumping Time per day (hour)	1	
Elapsed time since start of pumping (t)	15.2	days
Storativity (S)	0.005	
Borehole Pump Rate (Q)	0.5	L/sec
	0.043	m ³ /day
Abstraction volume	0.66	m ³
Critical Water strike level (m)	70	m
Borehole Recharge		
Area	2365030.22	m ²
	2.37	km ²
Recharge for pumping period (m)	0.00	m
Recharge volume for area	2182	m ³
System Water Balance	2181.16	m ³
Pumping Sustainability Risk:	Sustainable	
Borehole Failure		
Radius r	0.08	m
Drawdown (s)	69.28	m
Borehole Failure Risk:	98.97%	

Figure 32: Sustainability Assessment Results

For the sustainability assessment the following inputs were used:

- Transmissivity – Based on the pumping test results.
- Elapsed time since start of pumping – the borehole is effectively pumped 1 hour daily for irrigation.
- Storativity – This component was determined at 0.005 based on the storage coefficient data from the available DART dataset as seen in APPENDIX A
- Borehole pumping was provided at 0.5 L/s by the farmer.
- Borehole critical water strike was provided by the farmer at 70 m, while the total depth of the borehole was documented as 75 m.

5.3.3 HUMAN HEALTH ASSESSMENT

After assessing sustainability, the next step in the risk assessment pertains to human health. Within the framework of this geohydrological risk assessment, it is crucial to determine the relationship between mass transport and human health risks. A particular emphasis is placed on identifying the representative concentration of the identified chemical of concern. The study employs the source-pathway-receptor concept to analyse chemical trajectories and assess potential health impacts.

5.3.3.1 MASS TRANSPORT

Given the availability of chemical concentration data from monitoring records, it is possible to calculate the concentration of the chemical of concern and subsequently compare it with the actual measured values to evaluate accuracy. In this particular instance, the concentration at the receptor, represented by the wellfield borehole downstream of the source (Crocodile Quarry, as shown in Figure 18), is calculated to be 10.64 mg/L of nitrate, as indicated in Figure 33. The water quality data presented in Table 6 reveals that nitrate levels range between 10 to 17 mg/L, confirming that the calculation method is performing as intended.

While nitrate is often associated with wastewater, its presence in groundwater can also be linked to mining activities, particularly in certain types of mining operations, where intensive blasting is required. Research by Smith et al. (2017:325) highlights that in limestone quarrying operations, blasting activities can release nitrate-rich minerals present in the geological formations, contributing to groundwater contamination. In this specific case study, the notable increase in nitrate levels observed in boreholes MBH2&3 (Table 6) aligns with the blasting activities and the expansion of the quarry pit. This correlation strongly suggests that these mining activities are likely the primary source of nitrate pollution in the area.

Constant Source		
Chemical Substance	Nitrate	
Receiver		
Concentration at Receiver at Specific Time - $C(x,t)$	10.64	mg/L
Time (t)	730	day(s)
Physical Properties		
Injection rate (Q)	10000	L/day
Dispersion coefficient (D)	50	
Distance between source and receiver (x)	400	m
Hydraulic Conductivity (K)	120	m/d
Hydraulic Gradient (i)	0.06	
Effective Porosity (ne)	0.20	
Seepage Velocity (v)	36	m/d

Figure 33: Constant Source Transport Assessment Results

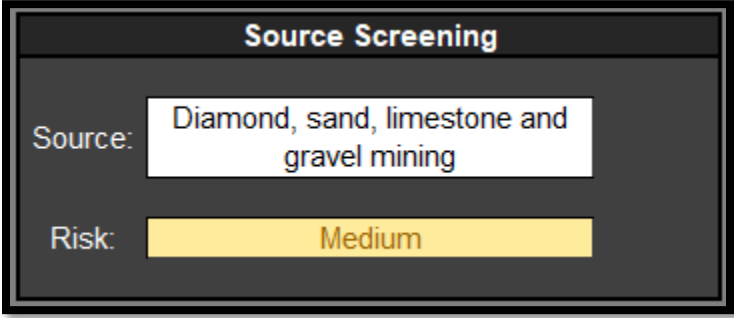
For the transport component of the assessment, the following key parameters were utilised:

- Injection Rate: An estimation of roughly 10,000 L/day. This parameter has a bit of uncertainty and may require sensitivity analysis to evaluate how changes in this input parameter affect the output of risk calculations.
- Dispersion Coefficient: Approximately 50. This parameter has a bit of uncertainty and may require sensitivity analysis to evaluate how changes in this input parameter affect the output of risk calculations.
- Distance between the source and the receiver: Value measured at 400 m as indicated in Figure 18.
- Time: Determined by the initiation of blasting at the mine quarry, which, in this instance, occurred two (2) years ago.
- Hydraulic Conductivity: This value was determined based in the pump test results presented in Table 5

- Hydraulic Gradient: This value was calculated through the path profile of Figure 29.
- Effective Porosity: This parameter was determined by assessing the aquifer media and the pumping tests from Table 5.

5.3.3.2 HUMAN HEALTH

By pinpointing the source of contamination, in this particular scenario, which stems from limestone mining for cement production, the user can establish a foundational risk assessment rating based on the activity responsible for the potential hazard, as illustrated in Figure 34.



The image shows a digital form titled "Source Screening". It has two main input fields. The first is labeled "Source:" and contains the text "Diamond, sand, limestone and gravel mining". The second is labeled "Risk:" and contains the text "Medium". The form has a dark grey background with white text for labels and a yellow background for the risk value.

Source Screening	
Source:	Diamond, sand, limestone and gravel mining
Risk:	Medium

Figure 34: Source Screening Assessment Results

In conducting the site-specific human health risk assessment, the majority of parameters have been derived from previous assessments. The sole variable introduced in this assessment pertains to the duration of exposure to the hazardous substance. In this instance, the estimated exposure duration is set at two (2) years (equivalent to 730 days). The outcome of the risk assessment indicates that the substance is non-carcinogenic, and the toxicity risk, based on the permissible reference dosage is estimated at 19% as calculated. This value remains within an acceptable range. Please refer to Figure 35 for further details.

Chemical analysis	
Chemical Substance	Nitrate
Exposure Pathway	Ingestion
Toxin Concentration (mg/L)	10.64
Exposure Duration (days)	730
Intake Rate (L/day)	2
Average bodyweight (kg)	70
Average Human Lifespan (years)	70
Dose(mg)	15533.30
Toxicity assessment	
Average daily dose (mg/kg/d)	0.30
Reference Dose (mg/kg/d)	1.6
Risk:	19.00%
Carcinogenic assessment	
Lifetime average daily dose	3.17
Cancer Potency Factor	
Risk:	Substance not carcinogenic

Figure 35: Health Assessment Results

5.4 COMPOSITE RISK RESULT

5.4.1 TIER 1 – RESULTS

Upon concluding the last aspect of the risk assessment, we are now positioned to analyse the final risk results. In this context, Figure 36 offers a summary of the outcomes pertaining to regional components. It is important to note that these results are derived from the best available data, despite the limitations in data availability.

Assessment Method	REGIONAL RESULTS		Next Steps/Comments
DRASTI	Regional DRASTI INDEX: Index Rating:	90.054 Medium	Aquifer has a moderate sensitivity to an imposed contaminant load that could affect groundwater quality
DART	DART Index	1	A positive value of the DART index indicates resistance to deterioration of groundwater resources due to climate change.
HEALTH	Source Based Screening Risk:	Medium	Source indicates a moderate risk of pollution in relation to the nature of the associated chemicals and quantity of waste produced.

Figure 36: Regional Risk Results

5.4.2 TIER 2 - RESULTS

When we scrutinise the site-specific results, we find a more precise dataset employed to yield an accurate outcome. The final Risk Index, in this case, reveals a 100% risk, primarily attributed to the lack of sustainability of the system, as determined during the sustainability assessment. It is crucial to acknowledge that if the system is unsustainable, it ultimately results in a 100% risk profile. Furthermore, the heightened aquifer vulnerability can be attributed to the proximity of the study area to the Crocodile River. The constant source transport calculation was cross-referenced with actual results, demonstrating a robust correlation, and affirming the accuracy of the methodology employed. In the context of the final health assessment, it is noteworthy that the hazardous substance is non-carcinogenic, and the toxicity risk registers at 19%, conforming to permissible reference dosage standards as indicated in Figure 37.

Assessment Method	SITE SPESIFIC RESULTS			Next Steps/Comments
DRASTI	Site spesific Vulnerability Rating:	135		Aquifer is highly sensitive to an imposed contaminant load that could affect groundwater quality
	DRASTI Index:	High		
SUSTAINABILITY INDEX	Pumping Sustainability Risk:	Sustainable		Decreasing the pumping rate of the borehole should increase the sustainability of the system and lower the risk of borehole failure.
	Borehole Failure Risk:	Not Sustainable		
	System Sustainability Risk:	System Will Fail		
DOMINICO 1D	Constant Source			
	Concentration at Receiver (Cx)	10.64	mg/L	
	Slug Injection			
	Concentration at Receiver at spesific time		g	
HEALTH	Toxicity Risk:	19.00%		Seek medical assistance if toxicity and/or carcinogenic risks exceed 50%
	Carcinogenic Risk:	Substance not carcinogenic		
FINAL RISK	100.00%			

Figure 37: Site Specific Risk Results

5.5 APPLICATION OF MITIGARION MEASURE

Based on the findings presented in Section 5.4, the model reveals that the borehole is extracting water at an unsustainable rate, with the drawdown just below the critical water strike (99%, as shown in Figure 32). The model suggests that mitigating this risk requires a reduction in the pumping rate. Following a reduction of 0.4 L/sec to achieve a more sustainable level, the associated risk has significantly decreased, aligning with the model's indication of 100% risk when the system is unsustainable (Figure 38).

Borehole Sustainability Risk:		
Cone of depression radius (r)	867.6	m
Transmissivity (T)	110	m ² /d
For how long has borehole been pumped (days)	365	
Pumping Time per day (hour)	1	
Elapsed time since start of pumping (t)	15.2	days
Storativity (S)	0.005	
Borehole Pump Rate (Q)	0.4	L/sec
	0.035	m ³ /day
Abstraction volume	0.53	m ³
Critical Water strike level (m)	70	m
Borehole Recharge		
Area	2365030.22	m ²
	2.37	km ²
Recharge for pumping period (m)	0.00	m
Recharge volume for area	2182	m ³
System Water Balance	2181.30	m ³
Pumping Sustainability Risk:	Sustainable	
Borehole Failure		
Radius r	0.08	m
Drawdown (s)	55.42	m
Borehole Failure Risk:	79.17%	

Figure 38: Borehole sustainability after mitigation measure has been applied.

Evaluating the comprehensive risk rating post-mitigation measures (refer to Figure 39), the model, now considering the system sustainable, conducts a toxicity assessment focusing on nitrates as the substance of concern. Since nitrates are non-carcinogenic and the toxicity assessment reveals their concentration is only 19% of the maximum allowable concentration determined by reference dosages, the overall risk for this system is deemed low.

Assessment Method	SITE SPECIFIC RESULTS			Next Steps/Comments
DRASTI	Site spesific Vulnerability Rating:	135		Aquifer is highly sensitive to an imposed contaminant load that could affect groundwater quality
	DRASTI Index:	High		
SUSTAINABILITY INDEX	Pumping Sustainability Risk:	Sustainable		System recharge and borehole puming rate is sustainable.
	Borehole Failure Risk:	Sustainable		
	System Sustainability Risk:	System is Sustainable		
DOMINICO 1D	Constant Source			
	Concentration at Receiver (Cx)	10.64	mg/L	
	Slug Injection			
	Concentration at Receiver at spesific time		g	
HEALTH	Toxicity Risk:	19.00%		Seek medical assistance if toxicity and/or carcinogenic risks exceed 50%
	Carcinogenic Risk:	Substance not carcinogenic		
FINAL RISK	10.00%			

Figure 39: Final Risk results after mitigation measures.

5.6 SUMMARY

In Chapter 5, the developed risk assessment methodology was applied to a South African case study, utilizing an Excel-based tool. The analysis commenced at a regional scale, integrating baseline data, hydrological parameters, and emissions scenarios. Tier 2 assessments were then conducted, focusing on the A42B quaternary catchment. This comprehensive evaluation examined aquifer vulnerability, sustainability, mass transport, and human health, with site-specific data providing crucial insights into groundwater contamination risks.

The findings of this study revealed a composite risk analysis indicating a 100% risk, predominantly attributed to sustainability issues, which underscored heightened aquifer vulnerability and assessed health risks associated with limestone mining (Smith & Jones, 2018:237). This evaluation emphasized the pivotal role of sustainability in mitigating groundwater pollution risks, particularly in areas susceptible to anthropogenic activities such as mining.

Furthermore, mitigation measures outlined in Section 5.4 addressed unsustainable borehole pumping by reducing the rate, thereby ensuring the system's sustainability (Figure 38). This reduction significantly decreased associated risks, as indicated by the findings of Brown *et al.* (2020:124), which highlighted the importance of implementing proactive measures to mitigate groundwater contamination risks.

Moreover, considering the toxicity assessment on nitrates, the results showed a low overall risk due to their non-carcinogenic nature and a concentration of only 19% of the maximum allowable level (Patel et al., 2019:345). This corroborates the risk assessment conducted in the study and supports the conclusion that while contamination exists, the level of risk posed by nitrates is relatively low.

These studies provide empirical evidence and validation for the model's findings, reinforcing the significance of sustainability measures and mitigation strategies in managing groundwater pollution risks associated with mining activities in South Africa.

6 CONCLUSIONS AND RECOMMENDATIONS

Groundwater pollution in South Africa presents a critical environmental challenge with profound implications for human health, the environment, and overall sustainability. As a vital resource supporting drinking water and agricultural irrigation for communities, the contamination of groundwater can lead to long-lasting and irreversible effects. The central issue lies in the uncertainty associated with predicting contaminant behaviour in the subsurface, necessitating the development of robust and adaptive risk assessment frameworks at both local and regional scales. These frameworks must be meticulously designed to consider the unique characteristics of the subsurface environment, accounting for variability in contaminant transport processes, and capable of seamlessly integrating new information and data, particularly concerning health risks. Emphasizing sustainability, the overarching aim of this research is to address groundwater pollution in South Africa by developing effective risk assessment frameworks that not only combat pollution but also exhibit flexibility and adaptability, contributing significantly to the sustainable use and management of this critical water resource.

The research aimed to achieve seven key objectives tailored to address groundwater pollution risks in South Africa. These objectives included a meticulous literature review, detailed development of a tiered risk assessment framework, strategic implementation of fuzzy logic for flexibility, identification of contamination hazards, creation of a data information system, construction of a practical Excel-based support tool, and a successful real-world case study demonstration. Each objective contributed to a comprehensive approach in mitigating uncertainties and showcasing the effectiveness of the risk assessment framework.

1. The first objective, focusing on conducting a literature review, was diligently achieved through a thorough exploration of existing studies and methodologies in Chapter 2. This comprehensive review specifically targeted methods to reduce uncertainty in risk assessments for groundwater pollution, with a keen eye on their applicability to South Africa's geohydrological systems.
2. For the second objective, the development of a tiered risk assessment framework was successfully addressed and detailed in Chapter 3 of the research. This framework, accommodating both basic and detailed analyses, was designed to address risks to human health and the environment, taking into consideration the unique geohydrological characteristics of South Africa.
3. The third objective, emphasizing flexibility and adaptability in the framework, was strategically achieved through the implementation of a fuzzy logic methodology, detailed

in Section 2.1.7. This approach ensured the seamless integration of emerging information into the risk assessment framework, thereby enhancing accuracy and minimizing uncertainties.

4. The fourth objective, focusing on the identification and evaluation of groundwater contamination hazards in South Africa, was meticulously addressed and documented in Section 2.2.3. The research involved a comprehensive exploration of various hazards, with a particular emphasis on categorization and prioritization to inform the risk assessment framework.
5. The fifth objective, involving the creation of a comprehensive data information system, was successfully executed through the development of an Excel-based support tool. This tool, detailed in Section 2.1.7, catalogued hazardous sources and substances within South Africa's primary sectors, providing a valuable resource for the risk assessment process.
6. For the sixth objective, the construction of the Excel-based support tool was achieved, facilitating the practical application of the risk assessment framework. This tool, detailed in Section 2.1.7, played a crucial role in calculating risk ratings and ensuring the effective implementation of the developed framework.
7. Finally, the seventh objective, which aimed to demonstrate the efficacy of the frameworks through a real-world case study in South Africa, was successfully accomplished. The research presented practical insights into assessing groundwater pollution risks, showcasing the effectiveness of the developed risk assessment framework in the Results and Discussion section.

The implementation of the risk assessment tool in the South African study area demonstrated its success in providing a detailed and nuanced analysis of groundwater pollution risks. By utilizing site-specific data, the tool offered a more accurate and tailored assessment, considering the unique hydrogeological characteristics of the A42B quaternary catchment. The preference for site-specific data over generalized information was evident in various assessments within Tier 2, such as the DRASTIC model, sustainability index, mass transport calculations, and human health risk assessment.

Working with site-specific data allowed for a more precise characterization of the aquifer's vulnerability, taking into account factors like depth to groundwater, net recharge, and geological media. The sustainability index, crucial for evaluating the long-term viability of the system, incorporated transmissivity, pumping rate, and critical water strike levels specific to the study

area. The mass transport assessment, examining the movement of contaminants, was enhanced by considering actual chemical concentration data from monitoring records. Additionally, the human health risk assessment benefitted from site-specific information, providing a more accurate understanding of exposure durations and potential hazards associated with local activities such as limestone mining.

In summary, the successful implementation of the risk assessment tool in the South African study area underscored the importance of using site-specific data. This approach not only enhanced the accuracy of risk evaluations but also ensured that the developed frameworks and conclusions were directly applicable and relevant to the unique conditions of the local hydrogeological setting, offering a valuable resource for informed decision-making in groundwater pollution management.

To enhance the effectiveness of the risk assessment tool for groundwater pollution, several recommendations can be considered:

1. Continuous Validation and Calibration:

Regularly validate and calibrate the risk assessment tool with up-to-date and real-time data to ensure its accuracy and relevance over time. This ongoing process will enhance the tool's reliability in reflecting current hydrogeological conditions.

2. Incorporate Advanced Modelling Techniques:

Explore the integration of advanced modelling techniques, such as machine learning algorithms, to improve the precision of predictions and accommodate the complexities inherent in groundwater pollution dynamics. Advanced modelling can provide a more nuanced understanding of contaminant transport processes.

3. User-Friendly Interface:

To optimize accessibility and usability, consider programming the risk assessment tool using Python. Crafting an intuitive platform in Python can broaden stakeholder engagement, including policymakers and local communities. This approach fosters a more inclusive and informed strategy for managing groundwater pollution.

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APPENDIX A

The DART Index

In analogy with the DRASTIC vulnerability index (Lynch et al., 1994), the DART methodology was developed (Dennis & Dennis). The parameters considered in the DART methodology are as follows:

D – Depth to water-level change

A – Aquifer type (storage coefficient)

R – Recharge

T – Transmissivity

The DRASTIC vulnerability index was developed to express aquifer vulnerability with reference to the threat of pollution. The DART methodology focuses more on typical parameters used in sustainability studies, but also indirectly accommodates the issue of quality due to the fact that the water quality is likely to deteriorate with a decline in water level over time as the salt load will concentrate. The availability of regional data to support the DART index was a major consideration in the selection of parameters.

The two static parameters of the DART index are the aquifer type (storage coefficient) and transmissivity as these relate to the geology. The geohydrological map of South Africa was used to classify these parameters for South Africa. The resulting storage coefficient and transmissivity maps are presented in Figure 40 and Figure 41 respectively.

The remaining parameters depth to water level change and recharge are considered dynamic parameters and are interrelated since the change in water level is calculated as follows:

$$\Delta Water Level = \frac{\Delta Recharge}{Storage Coefficient}$$

The static groundwater level at a specific point is then used as the depth reference. For the purpose of the index calculation, recharge is expressed as a function of slope and mean annual precipitation and the estimated recharge function is shown graphically in Figure 42.

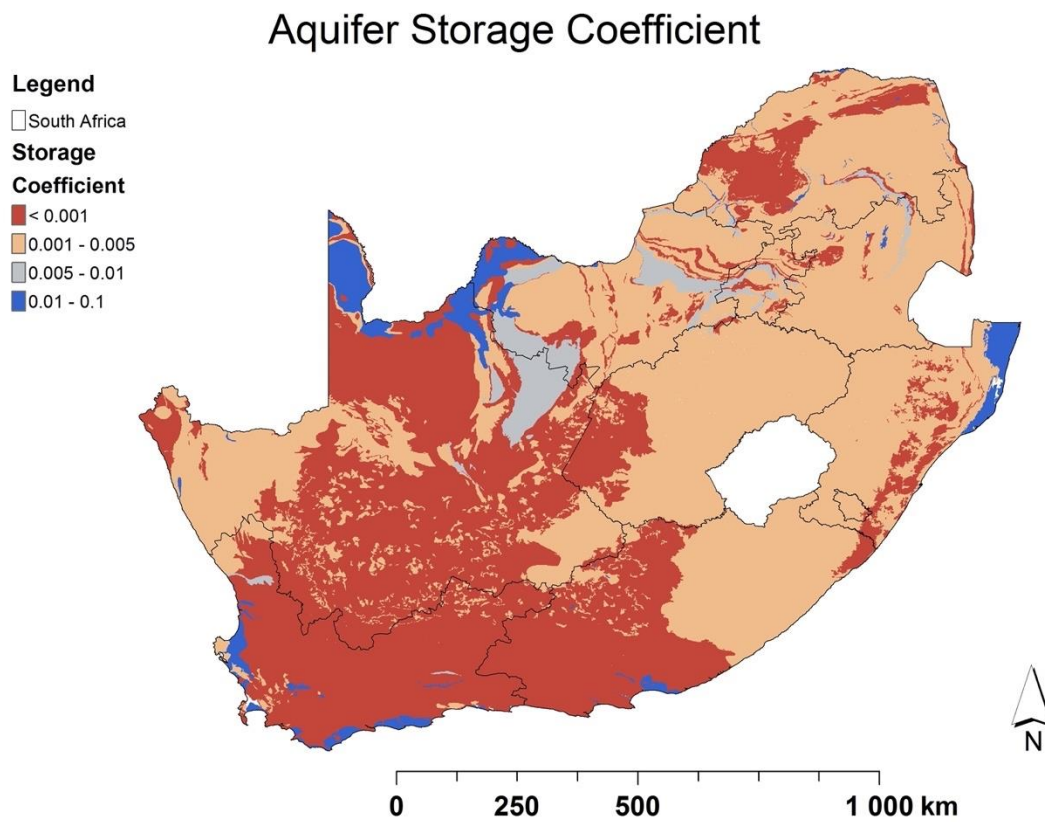


Figure 40: Aquifer type based on storage coefficient (Dennis & Dennis)

Transmissivity Map

Legend

□ South Africa

Transmissivity

m^2/d

0.25

0.26 - 1.5

1.51 - 6.25

6.26 - 17.5

17.51 - 25

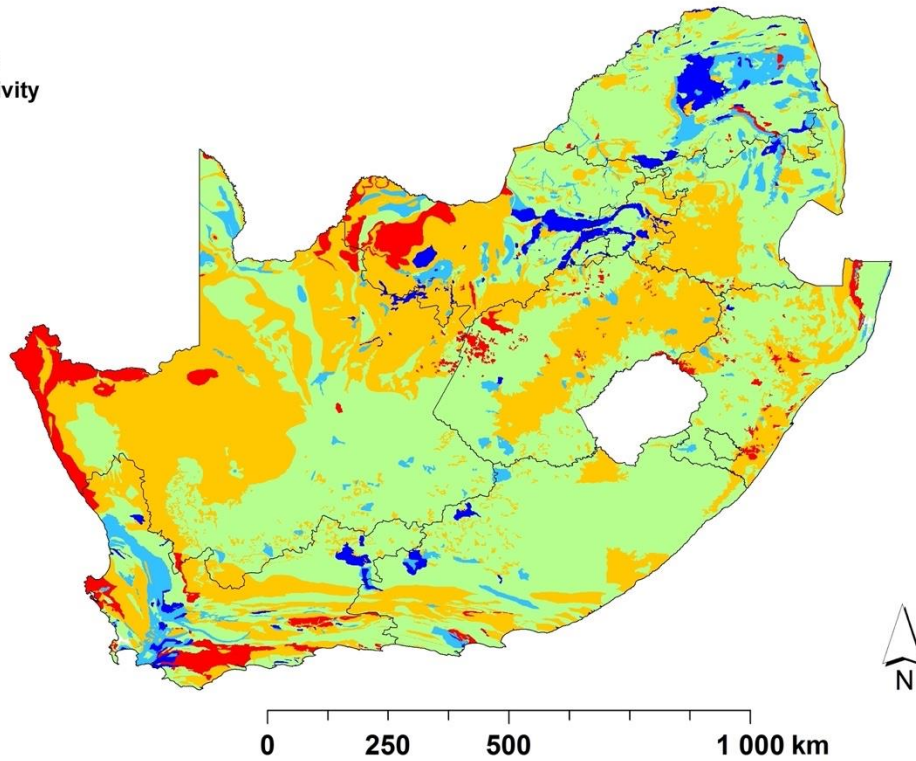


Figure 41: Transmissivity map (Dennis & Dennis)

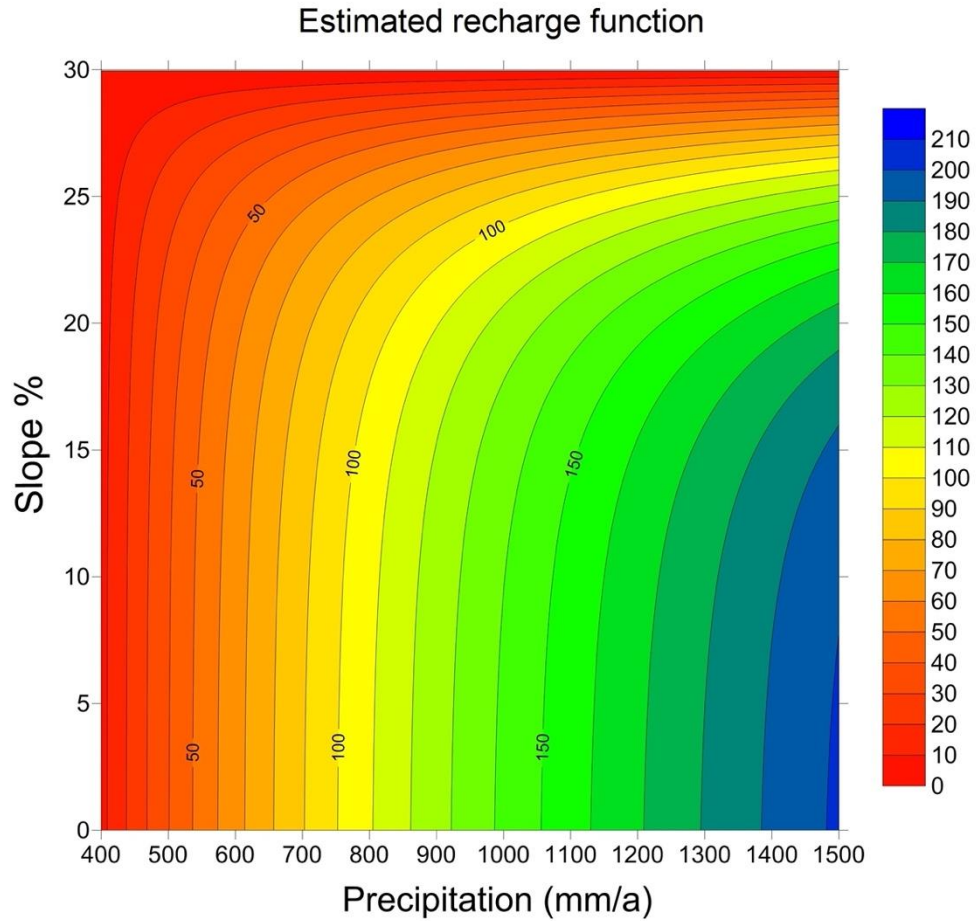


Figure 42: Estimated recharge function (Dennis & Dennis)

Finally, the DART index is calculated according to the rating and weight of each of the parameters in Table 7. The DART index has a maximum score of 10 where higher values represent more resilience to the climate change impacts driven by the change in rainfall.

Table 7: DART index rating and weighting table

Depth of Water Level Change (m)		Aquifer Type (Storage Coefficient)		Recharge (mm)		Transmissivity (m ² /d)	
65%		15%		15%		5%	
Range	Rating	Range	Rating	Range	Rating	Range	Rating
-5 - 0	0 - 10	0 - 0.1	0 - 10	0 - 10	0 - 10	0 - 25	0 - 10
Rating = (2*Range) + 10		Rating = 100 * Range		Rating = Range		Rating = 0.4 * Range	

APPENDIX B

1. Vulnerability (DRASTIC method)

Groundwater vulnerability was considered in terms of the DRASTIC method of assessment of the intrinsic vulnerability of an aquifer to contamination from the surface (Parsons & Conrad, 1998). The method considers the following factors which control the vulnerability of an aquifer to contamination from surface:

Parameter	Input dataset
Depth to water table (D)	126 263 groundwater levels from the NGDB (for 4 280 of these, the mean groundwater level was calculated from time-series data) were interpolated to a groundwater level grid.
Recharge (R)	Recharge calculated as part of GRAII-3 project.
Aquifer material (A)	1:1 million Geology from CGS
Soils (S)	WR90 soils data set
Topography and slope (T)	DWAF 20m DTM resampled to 1X1km
Impact of the vadose (unsaturated) zone (I)	1:1 million Geology from CGS
Hydraulic conductivity (C)	1:1 million Geology from CGS

The overall DRASTIC equation is shown below:

$$Pollution\ potential = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

Where: R = rating and w = weighting

The ratings and weights used were based on the categories and values defined by Parsons & Conrad (1998) and are shown below.

DRASTIC Ratings and Weights

Table 1.1 Depth to groundwater ratings used in the DRASTIC method

Range (m)	Rating
0 – 1.5	10
1.5 – 4.5	9
4.5 – 9.0	7
9.0 – 15.0	5
15.0 – 22.5	3
22.5 – 30.0	2
> 30	1
Weight	5

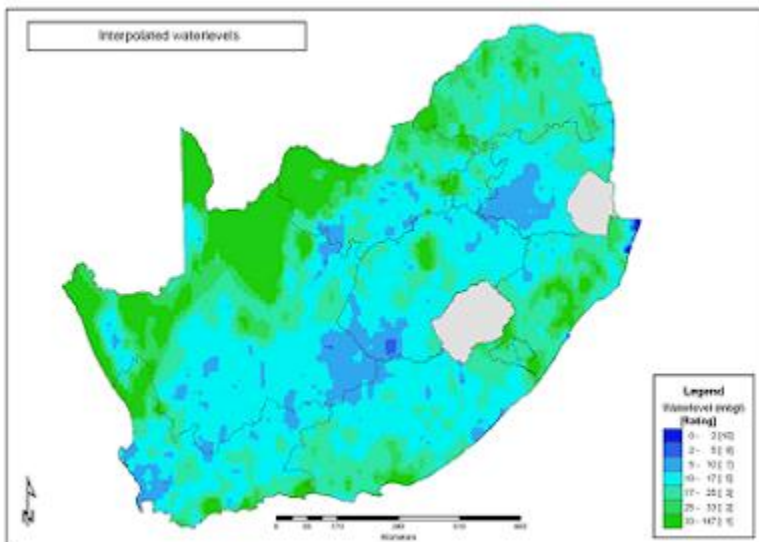


Figure 1.1 Interpolated waterlevels

Table 1.2 Recharge ratings used in the DRASTIC method

Range (mm)	Rating
0 – 50	1
50 – 100	3
100 – 175	6
175 – 250	8
> 250	9
Weight	4

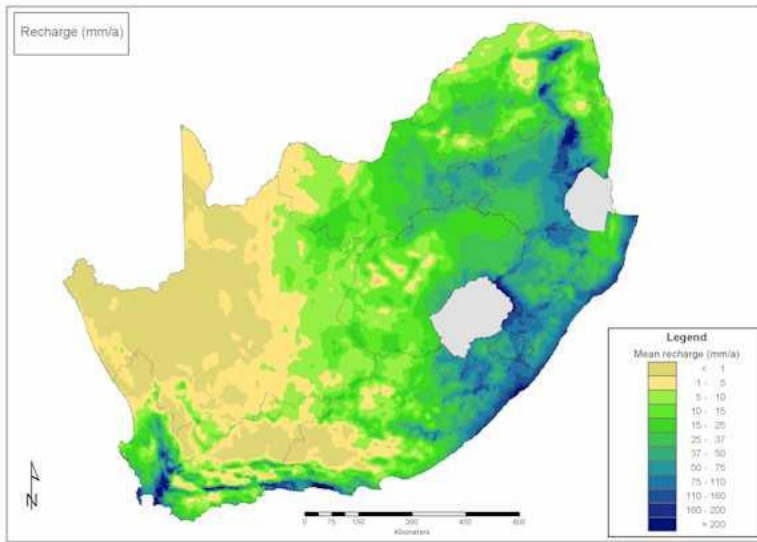


Figure 1.2 Recharge output from GRAII-3

Table 1.3 Topography (slope) ratings used in the DRASTIC method

Range (%)	Rating
<2	10
2 – 6	9
6 – 12	5
12 – 18	3
> 18	1
Weight	1

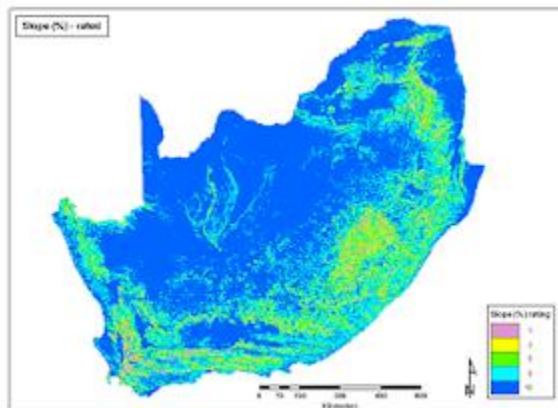


Figure 1.3 Slope

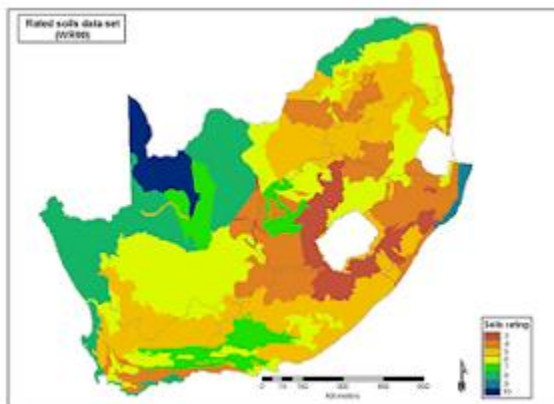


Figure 1.4 Soils

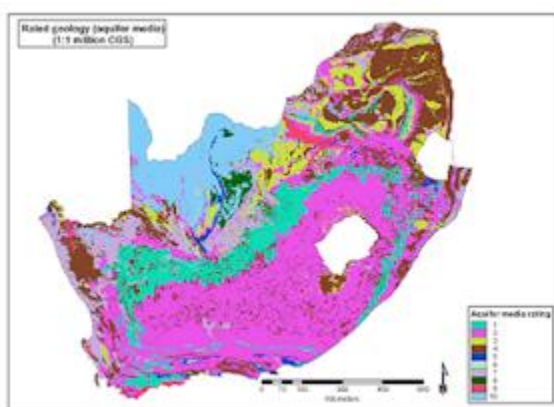


Figure 1.5 Geology – Aquifer media

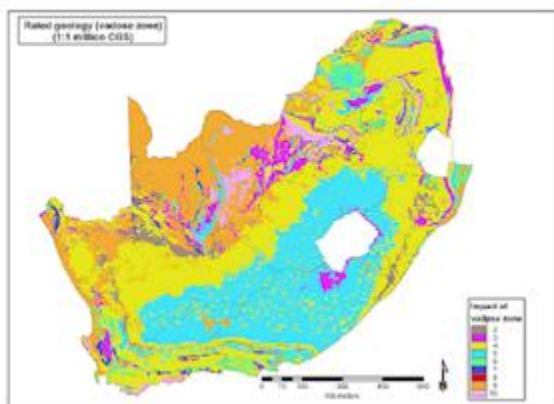


Figure 1.6 Geology – Impact of vadose zone

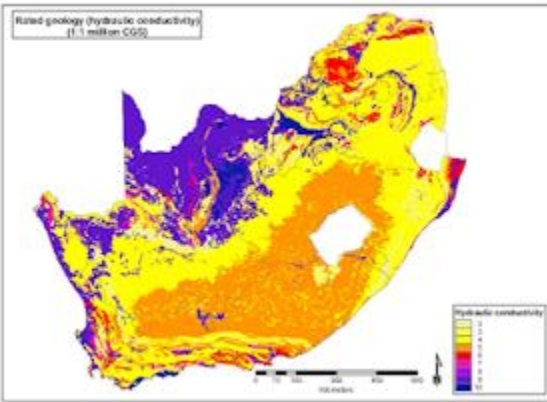


Figure 1.7 Geology – Hydraulic conductivity

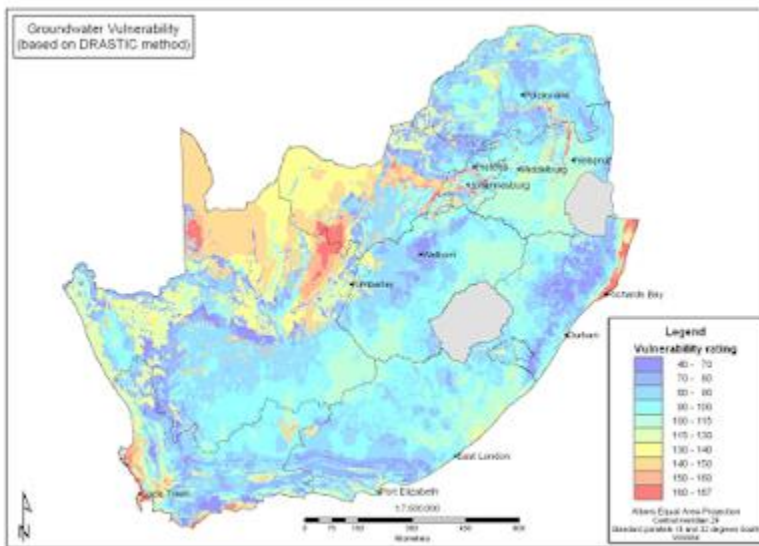


Figure 1.8 Overall DRASTIC

Table 1.4 Soils ratings used in the DRASTIC method

Soil type	Rating
LmSa - 60 SaLm - SaClLm 35	5
LmSa - SaLm 20 SaClLm - 70	5
LmSa - SaLm 20 SaClLm - 75	5
LmSa - SaLm 25 SaClLm - Cl 70	4
LmSa - SaLm 35 SaClLm - SaCl 60	3
LmSa - SaLm 40 SaClLm - SaCl 55	3
LmSa - SaLm 45 SaClLm - 50	4
LmSa - SaLm 50 SaClLm - SaCl 45	4
LmSa - SaLm 60 SaClLm - 30	5
LmSa - SaLm 60 SaClLm - SaCl 30	4
LmSa - SaLm 65 SaClLm - SaCl 25	5
LmSa - SaLm 70 SaCl - Cl 30	5
LmSa - SaLm 70 SaClLm - 30	5
LmSa - SaLm 80 SaClLm - 15	6
LmSa - SaLm 100	6
Sa - 80 SaClLm - SaCl 15	8
Sa - 90 LmSa - SaLm 10	9
Sa - 90 SaClLm - SaCl 10	9
Sa - 100	10
Sa - LmSa 20 SaLm - SaCl 75	4
Sa - LmSa 25 SaLm - SaClLm 70	6
Sa - LmSa 50 SaLm - SaClLm 45	6
Sa - LmSa 50 SaLm - SaClLm 50	6
Sa - LmSa 60 SaLm - 35	7
Sa - LmSa 70 SaLm - SaClLm 25	7
Sa - LmSa 70 SaLm - SaClLm 30	7
Sa - LmSa 80 SaLm - SaClLm 15	7
Sa - LmSa 100	8
Sa - SaLm 100	8
SaCl - 100	5
SaCl - Cl 100	4
SaClLm - 20 SaCl - Cl 75	4
SaClLm - 30 SaCl - 65	4
SaClLm - 30 SaCl - Cl 50	4
SaClLm - 30 SaCl - Cl 65	4
SaClLm - 50 SaCl - 40	5
SaClLm - 60 LmSa - SaLm 35	5
SaClLm - 70 SaCl - Cl 25	5
SaClLm - 80 SaCl - Cl 20	5
SaClLm - 100	5
SaClLm - SaCl 15 LmSa - SaLm 80	5
SaClLm - SaCl 30 Sa - SaLm 60	6
SaClLm - SaCl 65 SaLm - 30	4
SaClLm - SaCl 100	3
SaLm - 15 SaCl - Cl 80	4

SaLm - 20 SaCILm - SaCl 70	4
SaLm - 25 SaCILm - SaCl 70	4
SaLm - 35 SaCILm - SaCl 60	5
SaLm - 60 SaCILm - 40	6
SaLm - 60 SaCILm - SaCl 35	5
SaLm - 60 SaCILm - SaCl 40	5
SaLm - 100	6
SaLm - SaCILm 25 SaCILm - SaCl 70	4
SaLm - SaCILm 30 SaCILm - SaCl 65	4
SaLm - SaCILm 60 SaCl - Cl 30	4
SaLm - SaCILm 100	5
Weight	2

Table 1.5 Ratings used in the DRASTIC method based on underlying geology: aquifer media, impact of vadose zone and hydraulic conductivity

LABEL	LITHO_1	LITHO_2	LITHO_3	Aquifer media	Vadose Zone	Hyd_ Cond
Mpf	ALKALI-FELDSPAR SYENITE			2	3	3
Mj	AMPHIBOLITE	CALC-SILICATE ROCK		3	3	3
Ntu	AMPHIBOLITE	GNEISS	SCHIST	3	3	3
Rdo	AMPHIBOLITE	IRON FORMATION		3	3	3
Mha	ANDESITE	PYROCLASTIC		2	3	3
Mro	ANDESITE	DIORITE	PYROXENITE	2	3	3
Rd	ANDESITE	QUARTZ PORPHYRY	QUARTZITE	3	3	3
Rk	ANDESITE	TUFF		2	3	3
R-Vz	ANDESITE	DACITE	TUFF	2	3	3
Val	ANDESITE			3	3	3
Vh	ANDESITE			3	3	3
Vha	ANDESITE	TUFF	CONGLOMERATE	2	3	3
Vo	ANDESITE			3	3	3
Vri	ANDESITE	DACITE		3	3	3
Zme	ANORTHOSITE	SERPENTINITE	PYROXENITE	2	3	3
Cmk	ARENITE	CONGLOMERATE	SHALE	2	6	6
Dw	ARENITE	SHALE		2	5	5
Kma	ARENITE	CONGLOMERATE		3	6	6
Ks	ARENITE	MUDSTONE	SHALE	2	5	5
Ma	ARENITE	RUDITE	CONGLOMERATE	2	6	6
Mam	ARENITE	MUDSTONE		2	5	5
Mbl	ARENITE	RUDITE	CONGLOMERATE	2	6	6
Mc	ARENITE			4	6	6
Mf	ARENITE	BASALT		3	5	5
Mkr	ARENITE	QUARTZ PORPHYRY	BASALT	4	6	6
Mmb	ARENITE	SHALE	CONGLOMERATE	2	5	5
Mnz	ARENITE	SHALE	BASALT	2	5	5
Msm	ARENITE	CONGLOMERATE		3	6	6
Msw	ARENITE	TRACHYTOID		4	6	6
Mv	ARENITE	SHALE		2	5	5
Mwi	ARENITE	CONGLOMERATE		3	6	6
Mwy	ARENITE	CONGLOMERATE		3	6	6
Nf	ARENITE	CONGLOMERATE	SHALE	2	5	5
Nfi	ARENITE	SHALE		2	4	4
Nfl	ARENITE			4	6	6
Nh	ARENITE	DOLOMITE	DIAMICTITE	5	6	6
Nk	ARENITE	SHALE	CONGLOMERATE	2	4	4
Nkb	ARENITE	SHALE		2	4	4
Op	ARENITE	SHALE		2	4	4
Ope	ARENITE			4	6	6
O-S	ARENITE	SHALE		2	4	4
Pc	ARENITE	SHALE		2	4	4
Pko	ARENITE	SHALE		2	4	4

Pm	ARENITE	SHALE	COAL	2	4	4
Pr	ARENITE	SHALE		2	4	4
Pv	ARENITE	SHALE	COAL	2	4	4
Pwa	ARENITE	SHALE		2	4	4
Qb	ARENITE			4	6	6
Qpd	ARENITE	MUDSTONE	LIGNITE	2	5	5
Qs	ARENITE			4	6	6
Rw	ARENITE	SHALE		2	4	4
Sn	ARENITE	SHALE	TILLITE	2	4	4
T-Qn	ARENITE	SAND		5	6	6
TRc	ARENITE	SILTSTONE		3	5	5
TRm	ARENITE	MUDSTONE	SHALE	2	5	5
TRmc	ARENITE	MUDSTONE		2	5	5
TRnt	ARENITE			4	6	6
Vbt	ARENITE			4	6	6
Vhd	ARENITE	SILTSTONE	CONGLOMERATE	3	5	5
Vle	ARENITE	SHALE		2	4	4
Vlm	ARENITE	ARENITE	HORNFELS	4	6	6
Vlu	ARENITE	LIMESTONE		5	6	6
Vma	ARENITE			4	6	6
Vmg	ARENITE			4	6	6
Vrk	ARENITE			4	6	6
Vrw	ARENITE	ARENITE		4	6	6
Vsm	ARENITE	ANDESITE		4	6	6
Vst	ARENITE			4	6	6
Vsu	ARENITE			4	6	6
Zm	ARENITE	CONGLOMERATE	SHALE	2	5	5
Jdr	BASALT			4	3	3
Jl	BASALT			4	3	3
Jm	BASALT			4	3	3
Js	BASALT	TUFF	PYROCLASTIC BRECCIA	4	3	3
Ms	BASALT	QUARTZITE	CONGLOMERATE	4	3	3
Mt	BASALT	TUFF	ARENITE	4	3	3
Vdu	BASALT	ANDESITE		4	3	3
Zns	BASALT	ANDESITE	QUARTZITE	4	3	3
Mgn	CARBONATITE	PYROXENITE		5	9	9
Mno	CARBONATITE	SYENITE		5	9	9
Mtw	CARBONATITE			5	9	9
Mfr	CHARNOCKITE			3	3	3
Mst	CHARNOCKITE			3	3	3
Zk	CHERT	IRON FORMATION	SCHIST	3	10	10
Vc	CLINOPYROXENITE	HARZBURGITE	NORITE	3	4	4
Vvl	CLINOPYROXENITE	HARZBURGITE	NORITE	3	4	4
Vz	CLINOPYROXENITE	HARZBURGITE		3	4	4
Je	CONGLOMERATE	ARENITE		5	7	7
Kmb	CONGLOMERATE	ARENITE		5	7	7
Kmg	CONGLOMERATE	ARENITE		5	7	7
Nnt	CONGLOMERATE	MUDSTONE	LIMESTONE	4	6	6

Rka	CONGLOMERATE	SHALE		3	6	6
R-Vbo	CONGLOMERATE	QUARTZITE	SHALE	4	6	6
Zpr	CONGLOMERATE	LUTACEOUS ARENITE	LAVA	5	7	7
Nnu	DIAMICTITE	DOLOMITE	ARENITE	8	8	8
Vmk	DIAMICTITE	IRON FORMATION	ARENITE	7	7	7
Rro	DIORITE	GABBRO		4	3	3
Jd	DOLERITE			4	4	4
Vdi	DOLERITE			4	4	4
Vas	DOLOMITE	QUARTZITE		10	10	10
Vd	DOLOMITE	LIMESTONE	SHALE	7	9	9
Vgh	DOLOMITE	LIMESTONE	CHERT	8	10	10
Vm	DOLOMITE	CHERT		9	10	10
Vsc	DOLOMITE	SHALE		7	9	9
Vvo	DOLOMITE	IRON FORMATION	LAVA	9	10	10
Mka	DUNITE	PYROXENITE	NORITE	3	4	4
Z-Rm	DUNITE	HARZBURGITE	PYROXENITE	3	4	4
Mri	GABBRO	WEHLRITE	GRANITE	3	4	4
Nma	GABBRO	NORITE		3	4	4
Nmb	GABBRO	NORITE	PYROXENITE	3	4	4
Nti	GABBRO			3	4	4
Rmd	GABBRO	NORITE	PYROXENITE	3	4	4
Ru	GABBRO	GABBRO	GRANITE	3	4	4
Vbi	GABBRO			3	4	4
Vds	GABBRO	NORITE		3	4	4
Vmgr	GABBRO	NORITE		3	4	4
Vmn	GABBRO			3	4	4
Vpy	GABBRO	NORITE		3	4	4
Vrs	GABBRO	DIORITE		3	4	4
Vvi	GABBRO	ANORTHOSITE		3	4	4
MB	GNEISS	GRANITE		4	4	4
Mbt	GNEISS	QUARTZITE	SCHIST	3	4	4
Mga	GNEISS			4	4	4
Mgl	GNEISS			4	4	4
Mgo	GNEISS	QUARTZITE	SCHIST	3	4	4
Mh	GNEISS	METAMORPHIC		4	4	4
Mho	GNEISS			4	4	4
Mli	GNEISS			4	4	4
Mva	GNEISS			4	4	4
Nmp	GNEISS	GRANULITE		4	4	4
Nng	GNEISS			4	4	4
Rbu	GNEISS			4	4	4
Rdr	GNEISS			4	4	4
Rho	GNEISS	MIGMATITE		4	4	4
Zb	GNEISS			4	4	4
ZC	GNEISS			4	4	4
ZD	GNEISS			4	4	4
Zgo	GNEISS	GRANITE		4	4	4
Zhh	GNEISS	MIGMATITE	GRANODIORITE	4	4	4

Zma	GNEISS	QUARTZITE	PELITE	4	4	4
Zs	GNEISS			4	4	4
Mbi	GRANITE			4	4	4
Mbk	GRANITE			4	4	4
Mee	GRANITE	GNEISS		4	4	4
Mje	GRANITE			4	4	4
Mke	GRANITE			4	4	4
Mle	GRANITE			4	4	4
Mnr	GRANITE			4	4	4
Mpa	GRANITE			4	4	4
Msc	GRANITE			4	4	4
Msp	GRANITE	GNEISS		4	4	4
Mup	GRANITE			4	4	4
Mwt	GRANITE			4	4	4
N-Cma	GRANITE			4	4	4
N-Cmak	GRANITE			4	4	4
Nd	GRANITE			4	4	4
Nl	GRANITE			4	4	4
RB	GRANITE			4	4	4
Rga	GRANITE	QUARTZ PORPHYRY		4	4	4
Rha	GRANITE			4	4	4
Rsa	GRANITE			4	4	4
Rsk	GRANITE			4	4	4
R-VA	GRANITE			4	4	4
R-Vb	GRANITE			4	4	4
R-Vh	GRANITE			4	4	4
R-Vl	GRANITE			4	4	4
R-Vm	GRANITE			4	4	4
R-Vma	GRANITE	CHARNOCKITE		4	4	4
R-Vmh	GRANITE			4	4	4
R-Vmo	GRANITE			4	4	4
R-Vms	GRANITE			4	4	4
R-Vmt	GRANITE			4	4	4
R-Vp	GRANITE			4	4	4
R-Vs	GRANITE			4	4	4
R-Vsa	GRANITE			4	4	4
R-Vsh	GRANITE			4	4	4
R-Vt	GRANITE			4	4	4
R-Vu	GRANITE			4	4	4
VA	GRANITE			4	4	4
VB	GRANITE			4	4	4
Vme	GRANITE			4	4	4
Vmpg	GRANITE			4	4	4
Vra	GRANITE			4	4	4
ZA	GRANITE	GNEISS		4	4	4
ZB	GRANITE			4	4	4
Zka	GRANITE			4	4	4
Zne	GRANITE	MIGMATITE		4	4	4

Mau	GRANITOID			4	4	4
Mna	GRANITOID			4	4	4
Mcن	GRANODIORITE	GRANITE	QUARTZ MONZONITE	4	4	4
Mda	GRANODIORITE			4	4	4
Mvi	GRANODIORITE	QUARTZ MONZONITE		4	4	4
VC	GRANODIORITE			4	4	4
Zda	GRANODIORITE			4	4	4
Zh	GRANODIORITE			4	4	4
Jt	GRANOPHYRE			4	4	4
Nbi	GREENSTONE			3	3	3
Zn	GREENSTONE	AMPHIBOLITE	GRANULITE	3	3	3
Mlo	HARZBURGITE	NORITE	GABBRO	3	3	3
Vho	HORNFELS	QUARTZITE	LIMESTONE	5	3	3
Vn	HORNFELS	ARENITE	ARENITE	4	3	3
Vve	HORNFELS			4	3	3
R-Vhe	IGNIMBRITE	TUFF	PYROCLASTIC	4	3	3
Va	IRON FORMATION			5	5	5
Vla	IRON FORMATION			5	5	5
Vp	IRON FORMATION	SHALE		4	4	4
Mgr	KINZIGITE			3	3	3
Mto	KINZIGITE			3	3	3
Md	LAVA	TUFF	METAMORPHIC	3	4	4
Mk	LAVA	TUFF	CONGLOMERATE	3	4	4
Mku	LAVA	PYROCLASTIC	CARBONATITE	3	4	4
Mo	LAVA	GNEISS		3	4	4
Mpl	LAVA	TUFF		3	4	4
Vde	LAVA	TUFF	SCHIST	3	4	4
Zg	LAVA	SCHIST		3	4	4
Zgi	LAVA	SCHIST		3	4	4
Zl	LAVA			3	4	4
Zmu	LAVA			3	4	4
Zo	LAVA	PYROCLASTIC		3	4	4
Zp	LAVA	QUARTZITE	CONGLOMERATE	3	4	4
Zr	LAVA	TUFF		3	4	4
Ki	LIMESTONE			10	10	10
Kmz	LIMESTONE	CLAY		9	9	9
Nga	LIMESTONE	PHYLLITE	RUDITE	10	10	10
Nsc	LIMESTONE	SHALE		9	9	9
T-Qa	LIMESTONE	CLAY	CONGLOMERATE	9	9	9
T-Qb	LIMESTONE	ARENITE	CONGLOMERATE	9	10	10
Mm	LUTACEOUS ARENITE	QUARTZITE	CONGLOMERATE	7	7	7
Nbr	LUTACEOUS ARENITE			7	7	7
Nmo	LUTACEOUS ARENITE	SHALE	LIMESTONE	7	7	7
Rt	LUTACEOUS ARENITE	CONGLOMERATE		7	7	7
Zf	LUTACEOUS ARENITE	VOLCANIC ROCKS		7	7	7
Nmz	MARBLE	DOLOMITE	GRANULITE	7	7	7
Zgu	MARBLE	CALC-SILICATE ROCK	GNEISS	7	7	7
MI	METAMORPHIC			3	4	4

Z	MIGMATITE	GNEISS	ULTRAMAFIC ROCKS	3	4	4
J-K	MUDSTONE	ARENITE	CONGLOMERATE	2	5	5
Pa	MUDSTONE	ARENITE		2	5	5
Pem	MUDSTONE	SHALE	ARENITE	2	4	4
P-TRi	MUDSTONE	ARENITE		2	5	5
TRb	MUDSTONE			2	5	5
TRe	MUDSTONE	ARENITE		2	5	5
TRny	MUDSTONE	ARENITE		2	5	5
TRt	MUDSTONE	ARENITE		2	5	5
Vk	MUDSTONE	IRON FORMATION		2	5	5
MA	NORITE	EPIDIORITE		3	4	4
Vdr	NORITE	PYROXENITE	ANORTHOSITE	3	4	4
Vsl	NORITE	PYROXENITE	ANORTHOSITE	3	4	4
Nhl	OLIVINE GABBRO	GABBRO		3	4	4
Ntr	PERIDOTITE	PYROXENITE	GABBRO	3	3	3
Mz	PHYLLITE	QUARTZITE	GREENSTONE	2	3	3
Nm	PHYLLITE	LUTACEOUS ARENITE	CONGLOMERATE	2	3	3
Np	PHYLLITE	LUTACEOUS ARENITE	LIMESTONE	2	3	3
Npo	PHYLLITE	LUTACEOUS ARENITE	LIMESTONE	2	3	3
My	PYROCLASTIC	CARBONATITE		4	9	9
Jp	PYROCLASTIC BRECCIA	TUFF		4	9	9
Ksu	PYROCLASTIC BRECCIA	TUFF	TRACHYTOID	4	9	9
Mkk	PYROXENITE	SERPENTINITE		3	4	4
V-Mp	PYROXENITE	DUNITE	CARBONATITE	3	4	4
Rmp	QUARTZ MONZONITE			3	4	4
Rkr	QUARTZ PORPHYRY	RHYOLITE	TRACHYTOID	4	5	5
Rm	QUARTZ PORPHYRY			4	5	5
R-Va	QUARTZ PORPHYRY	TUFF		4	5	5
R-Vr	QUARTZ PORPHYRY			4	5	5
Vgl	QUARTZ PORPHYRY	CONGLOMERATE	ARENITE	4	5	5
Mbr	QUARTZITE	SHALE	ARENITE	6	6	6
Mge	QUARTZITE	CALC-SILICATE ROCK		7	7	7
Mkh	QUARTZITE	SCHIST		6	7	7
Mko	QUARTZITE	CONGLOMERATE		6	7	7
Mr	QUARTZITE			7	7	7
Mu	QUARTZITE	SCHIST		6	7	7
Nka	QUARTZITE	PHYLLITE	SCHIST	6	7	7
Nku	QUARTZITE			7	7	7
Ns	QUARTZITE	ARENITE	DOLOMITE	7	7	7
Rg	QUARTZITE	SHALE		5	6	6
Rjo	QUARTZITE	CONGLOMERATE	SHALE	5	7	7
Rmz	QUARTZITE	SHALE	HORNFELS	5	6	6
Vbr	QUARTZITE	CONGLOMERATE	SHALE	5	7	7
Vda	QUARTZITE			7	7	7
Vdw	QUARTZITE	SILTSTONE	CONGLOMERATE	6	7	7
Vg	QUARTZITE	SHALE	LAVA	5	6	6
VI	QUARTZITE	ARENITE		7	7	7
Zmo	QUARTZITE	GNEISS		7	7	7

Zw	QUARTZITE	CONGLOMERATE	SCHIST	6	7	7
Jb	RHYOLITE	SYENITE	BASALT	4	4	4
Jj	RHYOLITE			4	4	4
Vdm	RHYOLITE	PYROCLASTIC		4	4	4
Vkw	RHYOLITE			4	4	4
Vro	RHYOLITE			4	4	4
Vse	RHYOLITE			4	4	4
Vsh	RHYOLITE			4	4	4
Mss	RUDITE	CONGLOMERATE	ARENITE	3	3	3
Qm	SAND			10	9	9
T-Qk	SAND	LIMESTONE		10	9	9
Mb	SCHIST	CONGLOMERATE	QUARTZITE	2	3	3
Me	SCHIST	GNEISS	QUARTZITE	2	3	3
Mg	SCHIST	QUARTZITE	LAVA	2	3	3
Msr	SCHIST	GNEISS	KINZIGITE	2	3	3
Nbe	SCHIST	LUTACEOUS ARENITE	LIMESTONE	3	3	3
Ng	SCHIST	ANDESITE	BASALT	2	3	3
NgI	SCHIST	LIMESTONE	DOLOMITE	4	3	3
Nho	SCHIST	GNEISS	ARENITE	2	3	3
Nkl	SCHIST			3	3	3
Nmf	SCHIST			3	3	3
No	SCHIST	PHYLLITE	DOLOMITE	4	3	3
Npr	SCHIST	PHYLLITE		3	3	3
Vdg	SCHIST	QUARTZITE	AMPHIBOLITE	4	3	3
Nv	SEDIMENTARY			7	9	9
Q	SEDIMENTARY	SAND	CALCRETE	7	9	9
Nml	SERPENTINITE	GABBRO		2	3	3
Nsi	SERPENTINITE			2	3	3
Db	SHALE			1	4	4
Dbi	SHALE	SILTSTONE	ARENITE	1	4	4
Dc	SHALE	ARENITE		2	4	4
DI	SHALE	ARENITE	DIAMICTITE	2	4	4
Dt	SHALE	SILTSTONE	ARENITE	2	4	4
Nkn	SHALE	SILTSTONE	ARENITE	2	4	4
Nt	SHALE	LUTACEOUS ARENITE	QUARTZITE	2	4	4
Pe	SHALE			1	4	4
Pf	SHALE			1	4	4
Pk	SHALE			1	4	4
Pp	SHALE			1	4	4
Ppr	SHALE			1	4	4
Ppw	SHALE			1	4	4
Ps	SHALE	ARENITE		2	4	4
Pt	SHALE			1	4	4
P-TR	SHALE	ARENITE	MUDSTONE	2	4	4
P-TRsk	SHALE	MUDSTONE	ARENITE	1	4	4
Pvo	SHALE			1	4	4
Pw	SHALE			1	4	4
Rh	SHALE	QUARTZITE		2	4	4

Rj	SHALE	QUARTZITE	LAVA	2	4	4
Vga	SHALE	QUARTZITE	CONGLOMERATE	2	4	4
Vlo	SHALE	ARENITE	CONGLOMERATE	2	4	4
Vmt	SHALE			1	4	4
Vrt	SHALE	ARENITE		2	4	4
Vry	SHALE	ARENITE		2	4	4
Vs	SHALE			1	4	4
Vsi	SHALE			1	4	4
Vt	SHALE	ARENITE		2	4	4
Vw	SHALE	ARENITE	CONGLOMERATE	2	4	4
Tg	SILCRETE			2	3	3
Vvs	SILICICLASTIC			2	3	3
Kz	SILTSTONE	ARENITE	CONGLOMERATE	2	5	5
Tu	SILTSTONE	LIMESTONE	LIMESTONE	5	5	5
Vv	SILTSTONE	SHALE	ARENITE	2	4	4
Vbl	SLATE	ANDESITE	QUARTZITE	2	3	3
Mpi	SYENITE	ALKALI-FELDSPAR SYENITE	ANDESITE	4	4	4
Mps	SYENITE			4	4	4
Msi	SYENITE	ALKALI-FELDSPAR SYENITE	CARBONATITE	4	4	4
Nke	SYENITE	GRANITE		3	4	4
Nr	SYENITE	GRANITE		3	4	4
Rbo	SYENITE			4	4	4
VD	SYENITE			4	4	4
Vmd	SYENITE			4	4	4
Vsa	SYENITE	GRANITE		3	4	4
C-Pd	TILLITE	ARENITE	MUDSTONE	2	2	2
Nko	TONALITE			3	4	4
Rc	TONALITE			3	4	4
Ra	TUFF			4	5	5
R-Vha	TUFF	ANDESITE	CHERT	4	5	5
Vvg	TUFF	PYROCLASTIC BRECCIA		7	7	7
Z-R	ULTRAMAFIC ROCKS			3	3	3
Mw	VOLCANIC ROCKS			4	4	4
R-Vso	VOLCANIC ROCKS			4	4	4
Vb	VOLCANIC ROCKS	ARENITE		4	4	4
Weight				3	5	3

APPENDIX C

Study Area Boreholes

Borehole Coordinates					
Name	X	Y	Z	WL (mbgl)	WL (mamsl)
BHK-01	27.54581	-24.9887	947	8.72	938.28
BHK-02	27.54689	-24.9872	946	8.54	937.46
BHK-03	27.54967	-25.0058	943	12.26	930.74
BHK-04	27.54874	-25.0107	945	8.91	936.09
BHK-05	27.50011	-25.0036	1012	54.68	957.32
KK 26 Z	27.53772	-25.0096	944	9.74	934.26
MBH1	27.53769	-24.9902	956	19.23	936.77
MBH2	27.5434	-24.992	950	8.43	941.57
MBH3	27.52977	-25.008	952	3.89	948.11
MBH4	27.52218	-25.0043	967	16.88	950.12
MBH5	27.55468	-25.0077	943	10.17	932.83
MBH6	27.54902	-24.9939	949	11.58	937.42
CCMBH1	27.53803	-25.0024	953	11.05	941.95
CCMBH2	27.53375	-25.0075	951	4.01	946.99
CCMBH3	27.52701	-25.0002	968	9.26	958.74
Wellfield	27.54967	-25.0058	943	12.26	930.74

Regional Boreholes (NGA)

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2426CB00019	27.45	-	1060	43.28	1016.72
2426CB00020	27.45028	-	1060	30.48	1029.52
2426CB00021	27.45056	-	1060	25.91	1034.09
2426CB00022	27.45083	-	1060	34.14	1025.86
2426CB00026	27.45333	-	1060	15.24	1044.76
2426CB00028	27.45361	-	1060	12.19	1047.81
2426CB00030	27.45167	-	1060	15.24	1044.76
2426CB00032	27.45222	-	1060	13.72	1046.28
2427BD00001	27.49328	-	920	8.023240741	911.9767593
2427CD00001	27.42342	-	920	13.34484848	906.6551515
2427CD00002	27.43414	-	920	8.391288889	911.6087111

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.7979			
		-			
2427CD00003	27.43392	24.7994	920	11.53708861	908.4629114
		-			
2427CD00004	27.48008	24.8191	920	13.61235023	906.3876498
		-			
2427CD00005	27.48425	24.8539	920	10.2791573	909.7208427
		-			
2427CD00015	27.49644	24.8595	930	11.57037037	918.4296296
		-			
2427CD00018	27.49936	24.8727	940	10.34823529	929.6517647
		-			
2427CD00019	27.45914	24.8148	920	11.70424242	908.2957576
		-			
2427CD00020	27.45069	24.8245	920	5.900178571	914.0998214
		-			
2427CD00022	27.45397	24.8164	920	17.24222222	902.7577778
		-			
2427CD00023	27.48426	24.8539	920	8.87238806	911.1276119
		-			
2427CD00024	27.41	24.8847	980	19.838	960.162
		-			
2427CD00025	27.36667	24.8833	1000	29.52533001	970.47467
		-			
2427CD00032	27.36583	24.9867	1040	30	1010
		-			
2427CD00033	27.33527	24.9183	1010	20	990
2427CD00037	27.50833	-24.9	1020	38	982
		-			
2427CD00046	27.375	24.8986	1000	78	922
		-			
2427CD00084	27.33639	24.9517	1030	15.24	1014.76
		-			
2427CD00111	27.36669	24.9867	1040	27.43	1012.57
		-			
2427CD00112	27.3667	24.9867	1040	54.86	985.14
		-			
2427CD00115	27.33528	24.9197	1010	35.05	974.95
		-			
2427CD00123	27.33536	24.9197	1010	26.52	983.48
		-			
2427CD00125	27.33538	24.9197	1010	34.44	975.56
		-			
2427CD00129	27.42335	24.9917	1040	40	1000
2427CD00130	27.42336	-	1040	50	990

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.9917			
		-			
2427CD00132	27.37916	24.9992	1060	60	1000
2427CD00134	27.31444	-24.89	1010	30	980
		-			
2427CD00142	27.44306	24.8378	930	2.44	927.56
		-			
2427CD00145	27.44307	24.8378	930	30.48	899.52
		-			
2427CD00146	27.44308	24.8378	930	14.63	915.37
		-			
2427CD00147	27.44309	24.8378	930	15	915
		-			
2427CD00148	27.4431	24.8378	930	27.13	902.87
		-			
2427CD00149	27.44307	24.8378	930	25.3	904.7
		-			
2427CD00150	27.44307	24.8378	930	14.63	915.37
		-			
2427CD00151	27.44307	24.8378	930	15.24	914.76
		-			
2427CD00152	27.44307	24.8378	930	24.38	905.62
		-			
2427CD00154	27.48334	24.8333	920	31	889
		-			
2427CD00156	27.48336	24.8334	920	15	905
		-			
2427CD00158	27.47833	24.9936	1010	61	949
		-			
2427CD00159	27.47834	24.9936	1010	33	977
		-			
2427CD00160	27.49166	24.9375	970	30	940
		-			
2427CD00163	27.43333	24.8333	940	50	890
		-			
2427CD00166	27.48336	24.8334	920	12	908
		-			
2427CD00169	27.36667	24.9861	1040	42	998
		-			
2427CD00170	27.48333	24.8337	920	13.72	906.28
		-			
2427CD00171	27.48334	24.8336	920	13.72	906.28
		-			
2427CD00172	27.48335	24.8336	920	14.33	905.67
2427CD00173	27.48332	-	920	9.14	910.86

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.8336			
2427CD00174	27.48331	- 24.8336	920	14.02	905.98
2427CD00175	27.4833	- 24.8336	920	30.48	889.52
2427CD00177	27.48337	- 24.8336	920	21.34	898.66
2427CD00178	27.48338	- 24.8336	920	10.67	909.33
2427CD00179	27.48339	- 24.8336	920	17.07	902.93
2427CD00182	27.47836	- 24.9936	1010	51.82	958.18
2427CD00184	27.47838	- 24.9936	1010	47.24	962.76
2427CD00186	27.44311	- 24.8378	930	22.25	907.75
2427CD00199	27.40003	- 24.8472	950	44.5	905.5
2427CD00200	27.40004	- 24.8473	950	29.26	920.74
2427CD00201	27.40006	- 24.8473	950	26.82	923.18
2427CD00202	27.40007	- 24.8473	950	24.99	925.01
2427CD00204	27.39166	- 24.9333	990	9.14	980.86
2427CD00205	27.39167	- 24.9333	990	12.19	977.81
2427CD00206	27.39168	- 24.9334	990	14.02	975.98
2427CD00207	27.39169	- 24.9334	990	15.24	974.76
2427CD00208	27.3917	- 24.9334	990	26.52	963.48
2427CD00210	27.41667	- 24.7917	920	42.37	877.63
2427CD00211	27.41668	- 24.7917	920	18.29	901.71
2427CD00214	27.46089	- 24.9723	1020	48.77	971.23
2427CD00216	27.46087	- 24.9723	1020	45.11	974.89
2427CD00217	27.46086	- 24.9723	1020	54.86	965.14

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2427CD00221	27.40008	-	1010	43.89	966.11
2427CD00222	27.40007	-	1010	51.21	958.79
2427CD00224	27.40005	-	1010	42.8	967.2
2427CD00226	27.40003	-	1010	59.4	950.6
2427CD00228	27.40001	-	1010	60.96	949.04
2427CD00229	27.4	-	1010	48	962
2427CD00247	27.42337	-	1040	31	1009
2427CD00250	27.3378	-	1030	75	955
2427CD00253	27.47037	-	940	39	901
2427CD00254	27.47036	-	940	37	903
2427CD00256	27.47034	-	940	39	901
2427CD00258	27.47032	-	940	57.61	882.39
2427CD00259	27.47031	-	940	27.43	912.57
2427CD00261	27.47029	-	940	35.05	904.95
2427CD00262	27.47028	-	940	36.88	903.12
2427CD00264	27.35004	-	1000	22.56	977.44
2427CD00266	27.35002	-	1000	20.42	979.58
2427CD00267	27.35001	-	1000	25.91	974.09
2427CD00268	27.35	-	1000	27.43	972.57
2427CD00271	27.45835	-	950	18.29	931.71
2427CD00272	27.47723	-	920	24.38	895.62
2427CD00273	27.45836	-	950	21.34	928.66
2427CD00277	27.42557	-	960	51.51	908.49

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.8811			
		-			
2427CD00278	27.42278	24.8783	960	54.86	905.14
		-			
2427CD00279	27.42279	24.8783	960	15.54	944.46
2427CD00281	27.42362	-24.875	960	60.35	899.65
2427CD00282	27.42363	-24.875	960	67.06	892.94
		-			
2427CD00287	27.36862	24.8972	990	33.53	956.47
2427CD00293	27.47033	-24.905	960	19.2	940.8
		-			
2427CD00294	27.46092	24.9723	1020	44.2	975.8
		-			
2427CD00295	27.45167	24.8697	920	12.79	907.21
		-			
2427CD00296	27.48889	24.8808	930	14.15	915.85
		-			
2427CD00297	27.47778	24.8625	920	7.03	912.97
		-			
2427CD00298	27.47361	24.8561	920	8.34	911.66
		-			
2427CD00299	27.48194	24.8611	920	8.66	911.34
2427CD00300	27.49056	-24.865	920	7.78	912.22
		-			
2427CD00301	27.49139	24.8825	920	8.12	911.88
		-			
2427CD00302	27.49306	24.8867	930	15.68	914.32
		-			
2427CD00303	27.49472	24.8778	920	8.42	911.58
		-			
2427CD00304	27.49583	24.8742	920	9.22	910.78
		-			
2427CD00305	27.49194	24.8614	920	6.8	913.2
		-			
2427CD00306	27.49306	24.8797	920	8.65	911.35
		-			
2427CD00307	27.4875	24.8633	920	6.59	913.41
		-			
2427CD00308	27.48	24.8675	930	16.4	913.6
		-			
2427CD00309	27.49306	24.8703	920	8.32	911.68
		-			
2427CD00310	27.49444	24.8694	920	8.49	911.51
2427CD00311	27.47278	-	920	7.03	912.97

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.8317			
		-			
2427CD00312	27.48917	24.8297	930	21.72	908.28
		-			
2427CD00313	27.49167	24.8481	930	15.24	914.76
		-			
2427CD00314	27.4825	24.8564	920	8.7	911.3
		-			
2427CD00315	27.48889	24.8506	930	13.39	916.61
		-			
2427CD00316	27.47861	24.8467	930	12.9	917.1
		-			
2427CD00317	27.47333	24.8419	920	12.03	907.97
		-			
2427CD00318	27.47611	24.8458	920	12.76	907.24
2427CD00319	27.47944	-24.85	930	12.63	917.37
		-			
2427CD00320	27.48056	24.8431	930	13.59	916.41
		-			
2427CD00321	27.47444	24.8228	920	3.76	916.24
		-			
2427CD00322	27.47778	24.8203	930	12.39	917.61
		-			
2427CD00323	27.47917	24.8306	930	11.76	918.24
		-			
2427CD00324	27.47917	24.8306	920	12.39	907.61
		-			
2427CD00325	27.47	24.8361	920	7.72	912.28
		-			
2427CD00326	27.475	24.8347	920	8.42	911.58
		-			
2427CD00327	27.48056	24.8342	920	6.41	913.59
		-			
2427CD00328	27.49833	24.8614	920	7.28875	912.71125
		-			
2427CD00329	27.48417	24.8536	920	10.13490909	909.8650909
		-			
2427CD00330	27.46722	24.8225	910	11.09	898.91
		-			
2427CD00331	27.46639	24.8256	910	11.12	898.88
		-			
2427CD00332	27.45333	24.8222	910	6.88	903.12
		-			
2427CD00333	27.46222	24.8314	910	9.79	900.21
2427CD00334	27.45583	-	910	8.22	901.78

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		24.8167			
		-			
2427CD00335	27.46361	24.8236	910	10.61	899.39
2427CD00336	27.4625	-24.82	910	8.16	901.84
		-			
2427CD00337	27.4589	24.8217	910	7.49	902.51
2427CD00338	27.4694	-24.825	910	7.73	902.27
		-			
2427CD00339	27.46417	24.8272	910	11.36	898.64
		-			
2427CD00350	27.43944	24.8072	920	7.7	912.3
		-			
2427CD00351	27.435	24.8003	920	6.46	913.54
		-			
2427CD00352	27.43528	24.7994	920	6.15	913.85
		-			
2427CD00353	27.43361	24.8114	930	14.07	915.93
		-			
2427CD00354	27.43417	24.7967	920	8.72	911.28
2427CD00355	27.43611	-24.8	920	7.02	912.98
2427CD00356	27.43333	-24.795	920	7.69	912.31
		-			
2427CD00357	27.44861	24.8083	920	8.37	911.63
		-			
2427CD00358	27.45278	24.8086	920	3.01	916.99
		-			
2427CD00359	27.45278	24.8106	920	7.68	912.32
		-			
2427CD00360	27.43528	24.7942	920	8.259787234	911.7402128
		-			
2427CD00361	27.42694	24.7964	920	10.51088889	909.4891111
		-			
2427CD00362	27.44444	24.7919	920	10.1	909.9
		-			
2427CD00363	27.43861	24.7889	920	7.62	912.38
		-			
2427CD00364	27.45056	24.8028	920	7.76	912.24
		-			
2427CD00366	27.45111	24.7967	920	8.133513514	911.8664865
2427CD00367	27.53	-24.88	960	8.19	951.81
		-			
2427CD00369	27.48417	24.8536	920	7.84	912.16
		-			
2427CD00370	27.49194	24.8614	930	5.16	924.84

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2427DC00001	27.50106	-	940	6.250774648	933.7492254
2427DC00002	27.52331	-	940	8.302488889	931.6975111
2427DC00003	27.54694	-	940	5.888181818	934.1118182
2427DC00004	27.53751	-	940	8.343	931.657
2427DC00006	27.55792	-	930	58.36458564	871.6354144
2427DC00007	27.5	-	1000	11.05679933	988.9432007
2427DC00009	27.55972	-	930	8.74	921.26
2427DC00010	27.52639	-	960	25	935
2427DC00013	27.63666	-	1000	24	976
2427DC00026	27.66111	-24.9	1040	5.18	1034.82
2427DC00027	27.65972	-	1040	5	1035
2427DC00028	27.57778	-	1020	26.52	993.48
2427DC00029	27.57779	-	1020	30.78	989.22
2427DC00033	27.57783	-	1020	39.62	980.38
2427DC00034	27.57784	-	1020	30.48	989.52
2427DC00036	27.57786	-	1020	35.05	984.95
2427DC00038	27.57788	-	1020	50.29	969.71
2427DC00040	27.5779	-	1020	12.19	1007.81
2427DC00042	27.57792	-	1020	30.48	989.52
2427DC00043	27.57793	-	1020	13.72	1006.28
2427DC00044	27.52833	-	940	60	880
2427DC00049	27.55417	-	1120	49.38	1070.62
2427DC00050	27.55418	-	1120	33.22	1086.78

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2427DC00051	27.55419	-	1120	73.76	1046.24
2427DC00055	27.55556	-	1100	3.05	1096.95
2427DC00058	27.55694	-	1060	53.04	1006.96
2427DC00060	27.55696	-	1060	27.43	1032.57
2427DC00061	27.57278	-	940	21	919
2427DC00062	27.57279	-	940	31	909
2427DC00065	27.62363	-24.897	1140	10.97	1129.03
2427DC00068	27.6264	-	1140	9.14	1130.86
2427DC00069	27.63056	-	1200	1.83	1198.17
2427DC00070	27.65756	-	1060	16.76	1043.24
2427DC00071	27.65755	-	1060	24.38	1035.62
2427DC00072	27.66111	-	1080	6.1	1073.9
2427DC00074	27.66113	-	1080	6.1	1073.9
2427DC00076	27.6575	-	1040	18.59	1021.41
2427DC00080	27.57083	-24.95	960	18.29	941.71
2427DC00081	27.56367	-	1240	48.77	1191.23
2427DC00082	27.56367	-	1240	27.43	1212.57
2427DC00083	27.54694	-	930	3.08	926.92
2427DC00084	27.54695	-	930	2.99	927.01
2427DC00085	27.52222	-	930	6.08	923.92
2427DC00086	27.45055	-	920	8.11	911.89
2427DC00087	27.5375	-24.915	930	8.14	921.86
2427DC00088	27.53944	-	930	9.43	920.57
2427DC00089	27.54722	-	930	12.48	917.52

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2427DC00090	27.54083	-	940	10.17	929.83
2427DC00091	27.51806	-	930	12.88	917.12
2427DC00092	27.52417	-	930	12.05	917.95
2427DC00093	27.53333	-	930	11.86	918.14
2427DC00094	27.53	-	930	7.392352941	922.6076471
2427DC00095	27.51722	-	920	5.97	914.03
2427DC00096	27.50417	-	920	6.31	913.69
2427DC00097	27.5075	-24.875	930	8.81	921.19
2427DC00098	27.52361	-	940	16	924
2427DC00099	27.5175	-	930	9.67	920.33
2427DC00100	27.53333	-	930	13.26	916.74
2427DC00101	27.55611	-24.975	940	12.21	927.79
2427DC00102	27.54139	-	930	3.62	926.38
2427DC00103	27.53889	-24.925	930	12.46	917.54
2427DC00104	27.56806	-	940	10.03	929.97
2427DC00105	27.55611	-	930	4.82	925.18
2427DC00106	27.55417	-	930	1.66	928.34
2427DC00107	27.53333	-24.985	940	12.9	927.1
2427DC00108	27.55333	-	940	13.27	926.73
2527AB00005	27.39695	-	1120	15	1105
2527AB00006	27.38028	-	1040	42.92	997.08
2527AB00008	27.4667	-	1200	47.24	1152.76
2527AB00012	27.46669	-	1200	9.14	1190.86
2527AB00013	27.46667	-	1200	36.58	1163.42

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2527AB00014	27.4667	- 25.0939	1200	32.92	1167.08
2527AB00015	27.46667	- 25.0939	1200	42.67	1157.33
2527AB00016	27.46671	- 25.0939	1200	30.48	1169.52
2527AB00020	27.40781	-25.083	1131	7.86	1123.14
2527AB00022	27.38914	- 25.1907	1126	41	1085
2527AB00024	27.48458	- 25.1723	1030	43.68	986.32
2527AB00025	27.41597	- 25.0834	1100	31.5	1068.5
2527AB00027	27.3823	- 25.1324	1090	0.58	1089.42
2527AB00029	27.43338	- 25.1436	1020	21.51	998.49
2527AB00031	27.44303	- 25.1388	1030	23.4125	1006.5875
2527AB00032	27.45692	- 25.1415	1030	31.16666667	998.8333333
2527AB00033	27.46191	- 25.1505	1020	19.71	1000.29
2527AB00034	27.4433	-25.144	1030	32.8075	997.1925
2527AB00035	27.46015	- 25.1415	1030	30.315	999.685
2527AB00036	27.45993	- 25.1504	1020	39.2925	980.7075
2527AB00037	27.44309	- 25.1562	1040	29.86666667	1010.133333
2527AB00038	27.45544	- 25.1424	1020	31.17	988.83
2527AB00039	27.45395	- 25.1426	1020	28.29	991.71
2527AB00040	27.43243	- 25.1562	1040	36.768	1003.232
2527AB00041	27.45296	- 25.1424	1020	35.26857143	984.7314286
2527AB00042	27.38442	- 25.2014	1130	33.056	1096.944
2527AB00043	27.40975	- 25.1212	1059	26.72	1032.28
2527AB00195	27.38096	-25.191	1340	45.9308	1294.0692
2527BA00001	27.52122	- 25.0362	940	6.133053435	933.8669466

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2527BA00002	27.56806	- 25.1806	960	10.75571429	949.2442857
2527BA00003	27.57361	- 25.1792	960	9.904042553	950.0959574
2527BA00004	27.51931	- 25.0623	940	5.670829493	934.3291705
2527BA00007	27.575	- 25.1917	960	27.43	932.57
2527BA00008	27.57501	- 25.1917	960	25.29	934.71
2527BA00009	27.66667	- 25.0164	1120	30	1090
2527BA00010	27.66667	- 25.0164	1120	20	1100
2527BA00013	27.66669	- 25.0164	1120	15	1105
2527BA00015	27.6667	- 25.0164	1120	20	1100
2527BA00016	27.61667	- 25.0158	1020	42	978
2527BA00021	27.61667	- 25.0159	1020	30	990
2527BA00022	27.6167	- 25.0158	1020	20	1000
2527BA00023	27.61667	- 25.0159	1020	20	1000
2527BA00024	27.61671	- 25.0158	1020	80	940
2527BA00027	27.675	- 25.1358	960	32	928
2527BA00028	27.67501	- 25.1358	960	20.73	939.27
2527BA00029	27.675	- 25.1358	960	27.43	932.57
2527BA00031	27.675	- 25.1359	960	62.18	897.82
2527BA00037	27.675	- 25.1359	960	24.38	935.62
2527BA00038	27.67506	- 25.1358	960	30.48	929.52
2527BA00040	27.67507	- 25.1358	960	16.76	943.24
2527BA00042	27.6	- 25.1564	960	30.48	929.52
2527BA00052	27.61667	-25.125	1120	30	1090

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
2527BA00053	27.61667	-25.125	1100	30	1070
2527BA00054	27.61668	-25.125	1100	28.96	1071.04
2527BA00056	27.61669	-25.125	1100	8.84	1091.16
2527BA00057	27.61667	-25.125	1100	21.34	1078.66
2527BA00058	27.6167	-25.125	1100	14.33	1085.67
2527BA00060	27.61671	-25.125	1100	60.96	1039.04
2527BA00062	27.61672	-25.125	1100	64.92	1035.08
2527BA00063	27.61667	-	1100	21.34	1078.66
2527BA00064	27.61673	-25.125	1100	21.34	1078.66
2527BA00065	27.61667	-	1100	15.24	1084.76
2527BA00066	27.575	-	960	17.37	942.63
2527BA00067	27.61674	-25.125	1100	7.01	1092.99
2527BA00069	27.61675	-25.125	1100	10.97	1089.03
2527BA00070	27.61667	-	1100	11.89	1088.11
2527BA00071	27.61676	-25.125	1100	25.91	1074.09
2527BA00075	27.61678	-25.125	1100	36.58	1063.42
2527BA00076	27.61667	-	1100	54.86	1045.14
2527BA00077	27.61679	-25.125	1100	18.29	1081.71
2527BA00078	27.61667	-	1100	12.19	1087.81
2527BA00079	27.6168	-25.125	1100	24.38	1075.62
2527BA00080	27.61667	-	1100	6.1	1093.9
2527BA00082	27.61667	-	1100	33.83	1066.17
2527BA00084	27.61667	-	1100	9.14	1090.86
2527BA00086	27.61667	-	1100	37.49	1062.51
2527BA00087	27.61684	-25.125	1100	10.36	1089.64
2527BA00088	27.61667	-	1100	13.72	1086.28
2527BA00089	27.61685	-25.125	1100	14.02	1085.98
2527BA00090	27.61667	-	1100	7.01	1092.99
2527BA00091	27.61686	-25.125	1100	25.91	1074.09
2527BA00107	27.57501	-	960	25.91	934.09

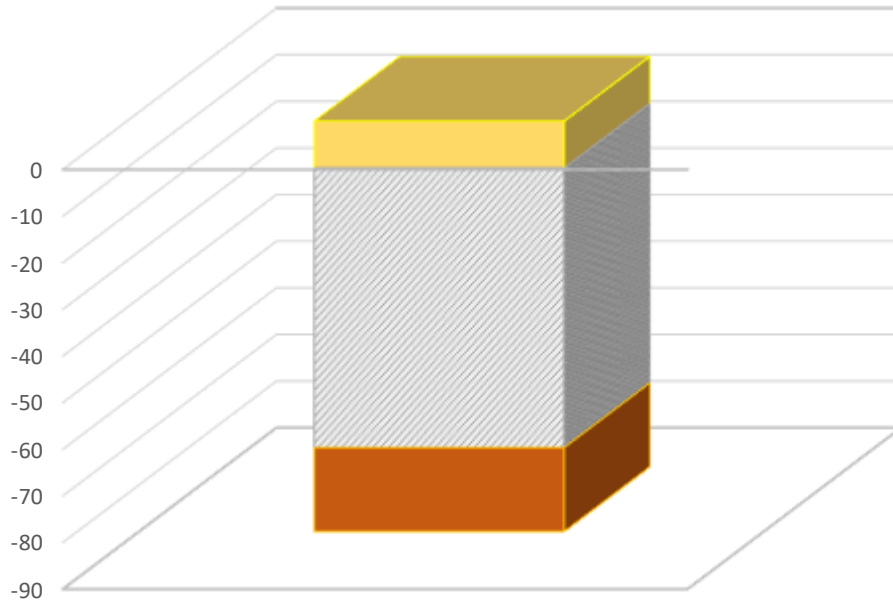
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2527BA00108	27.575	- 25.1917	960	27.13	932.87
2527BA00109	27.57502	- 25.1917	960	45.72	914.28
2527BA00110	27.575	- 25.1916	960	60.96	899.04
2527BA00111	27.57503	- 25.1916	960	35.97	924.03
2527BA00112	27.575	- 25.1916	960	39.62	920.38
2527BA00113	27.57504	- 25.1916	960	35.36	924.64
2527BA00114	27.575	- 25.1916	960	26.21	933.79
2527BA00115	27.57505	- 25.1917	960	12.19	947.81
2527BA00116	27.575	- 25.1917	960	27.43	932.57
2527BA00117	27.57506	- 25.1917	960	30.48	929.52
2527BA00118	27.57501	- 25.1917	960	30.48	929.52
2527BA00120	27.575	- 25.1917	960	32	928
2527BA00121	27.57508	- 25.1917	960	19.81	940.19
2527BA00122	27.57505	- 25.1917	960	30.48	929.52
2527BA00123	27.57509	- 25.1917	960	24.38	935.62
2527BA00124	27.575	- 25.1917	960	18.29	941.71
2527BA00125	27.5751	- 25.1917	960	12.19	947.81
2527BA00126	27.575	- 25.1917	960	20.12	939.88
2527BA00127	27.57511	- 25.1916	960	33.53	926.47
2527BA00129	27.57512	- 25.1917	960	33.53	926.47
2527BA00130	27.575	- 25.1916	960	13.12	946.88
2527BA00131	27.57513	- 25.1917	960	46.63	913.37
2527BA00133	27.57514	-	960	20.73	939.27

NAME	Xcoord	Ycoord	Zcoord	AvgOfWaterLevel m	Wlvl (mamsl)
		25.1917			
2527BA00134	27.55	- 25.2014	980	32	948
2527BA00135	27.57515	- 25.1916	960	42.67	917.33
2527BA00137	27.57516	- 25.1917	960	30.48	929.52
2527BA00160	27.62361	- 25.1861	980	31.7	948.3
2527BA00171	27.64432	- 25.0498	1060	38.49333333	1021.506667
2527BA00172	27.64948	- 25.0528	1050	25.64285714	1024.357143
2527BA00183	27.63172	-25.068	1000	30.895	969.105
2527BA00184	27.62524	-25.059	1030	41.08833333	988.9116667
2527BA00185	27.53028	- 25.0403	950	16.9	933.1
2527BA00186	27.53833	- 25.0192	940	9.29	930.71
2527BA00187	27.525	- 25.0439	940	9.78	930.22
2527BA00188	27.5225	- 25.0194	950	15.76	934.24
2527BA00189	27.52778	- 25.0231	940	7.79	932.21
2527BA00190	27.52472	- 25.0261	940	7.23	932.77
2527BA00191	27.55139	- 25.0067	940	8.99	931.01
2527BA00192	27.50889	- 25.0478	960	25.77	934.23
2527BA00193	27.65416	- 25.0664	1060	33	1027
2527BA00194	27.51944	- 25.0625	930	3.32	926.68
2527BA00198	27.64388	-25.195	1300	30.5	1269.5
2527BA00202	27.62305	- 25.0581	1040	35.5	1004.5

APPENDIX D

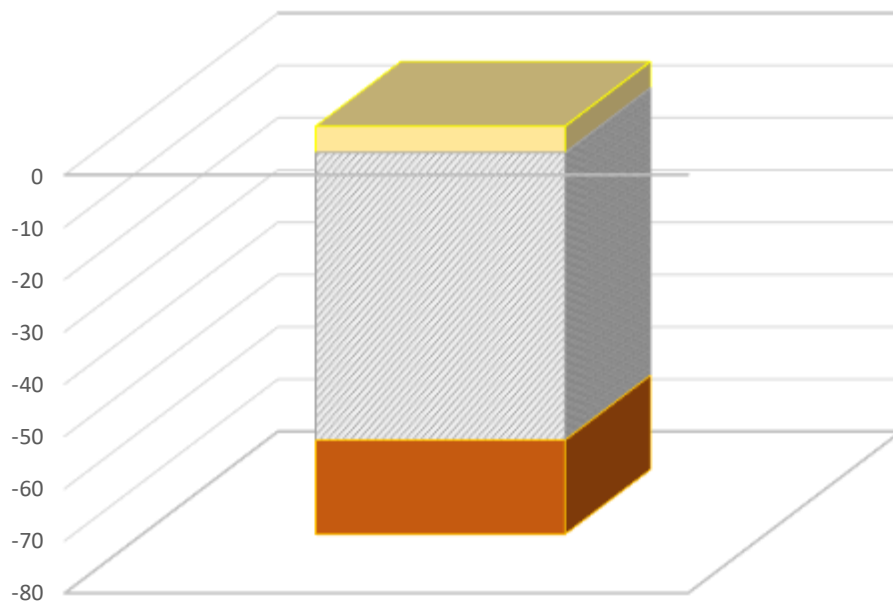
MBH 6 BOREHOLE LOG

Loam Sand Dolomite Fractured Dolomite



BHK -03 BOREHOLE LOG

Loam Sand Dolomite Fractured Dolomite



CCBH1 BOREHOLE LOG

Loam Sand Shale & Quartzite Dolomite

