

MODELLING THE FATE AND TRANSPORT OF MICROBIAL PATHOGENS AND RISK ANALYSIS UTILIZING FAECAL INDICATORS AT TEMBA CEMETERY, HAMMANSKRAAL,

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GEOL 8003A – MSc Dissertation

For the fulfilment of the Master of Science in Geology



31 January 2025

School of Geosciences
University of the Witwatersrand
Johannesburg, South Africa

DECLARATION

I declare that this research project “Modelling the Fate and Transport of Microbial Pathogens and Risk Analysis Utilizing Faecal Indicators at Temba Cemetery, Hammanskraal, South Africa” is my own, independent work. This research report is being submitted in partial fulfilment of the requirements for the degree, Master of Science (by research) in Geology at the University of the Witwatersrand, Johannesburg. It has not been submitted for degree awarding or examination purposes at any other university. All the sources I have used or quoted have been indicated and acknowledged by means of complete references.



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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to the Almighty God for granting me the strength, wisdom, and perseverance throughout this academic journey. Without His guidance and grace, none of this would have been possible.

I extend my heartfelt appreciation to my beloved wife, Rialivhuwa Maria Muravha, for her unwavering support, encouragement, and understanding during the demanding phases of fieldwork. Her belief in my capabilities and constant motivation played a pivotal role in my ability to persevere and complete this dissertation. To my son, Nungodzawe Innocent Muravha, I am grateful for your understanding and patience as I balanced the demands of academia with our precious quality time. Your support has been invaluable, and I am truly blessed to have you by my side.

I owe a debt of gratitude to my supervisor, Dr Khuliso Masindi, for his exceptional guidance, mentorship, and scholarly insights. His dedication to my academic development has been instrumental in shaping the quality of this dissertation.

I would like to acknowledge the generous support of Geo Pollution Technologies for their financial sponsorship, which played a crucial role in enabling me to complete my master's degree. Their commitment to fostering education and research is commendable, and I am grateful for the opportunity they provided. Special thanks are extended to Colette de Villiers and Vanessa Kubayi who helped with the compilation of research maps and to the Environmental Pollution Laboratory for their invaluable assistance in the analysis of my samples. Their expertise and resources significantly contributed to the scientific rigor of this research.

In conclusion, I express my gratitude to all those who have played a part, directly or indirectly, in the successful completion of this dissertation. Your support and contributions have been fundamental to this academic achievement.

ABSTRACT

The study conducted at Temba Cemetery in Hammanskraal, South Africa, sought to comprehend the complexities of microbial pathogen fate and transport within burial sites. Aiming to address environmental contamination and associated health risks, the investigation focused on modelling pathogen movement using faecal indicators, specifically *E. coli*. Real-time observations and assessments were possible due to Temba Cemetery's active use since the late 1960s, providing a dynamic research setting. The site visit identified significant factors impacting the study, such as waterlogged graves and notable groundwater seepage, influencing faecal indicator distribution and pathogen movement. Drilling operations established ten monitoring wells, crucial for assessing groundwater levels, hydraulic conductivity, and diverse testing protocols. Hydraulic tests unveiled variations in soil types, affecting pathogen migration rates, while groundwater flow calculations determined velocities across the cemetery. The geometric mean of hydraulic conductivity and groundwater flow velocity from bail tests was calculated to be 0.0528 and 3.4803 m/day, respectively. Water quality analyses identified elevated faecal coliform (i.e. 5 000 colonies/100 ml) and *E. coli* (i.e. 5 000 to 5 300 colonies/100 ml) counts in burial zones and stream, surpassing safety thresholds. Tracer tests informed a sophisticated Advection-Dispersion Equation (ADE) model using Sauty (1980) equation, refining pathogen transport simulations. Utilizing the breakthrough curves (BTC) for two tracer tests, longitudinal dispersivity of 5.1 and 2.3 m; velocities of 18 and 6 m/day and effective porosities of 0.02 and 0.05 were calculated from model fitting. However, discrepancies between simulated and observed velocities highlighted model limitations, necessitating continual refinement. Quantitative Microbial Risk Assessment (QMRA) indicated potential exposure routes, emphasizing the need for further investigation to mitigate health risks. Varied groundwater velocities highlighted the complex hydrogeological system's influence on pathogen transport. This investigation explained the challenges in predicting pathogen fate and transport, highlighting the need for continuous model refinement. Discrepancies identified emphasized the complexities in modelling pathogen movement, demanding ongoing model validation and refinement to improve accuracy. Recommendations include improved burial practices, community engagement, collaborative efforts, regular monitoring, and in-depth hydrogeological studies. These findings underscore the critical role of accurate modelling in

addressing health risks and guiding environmental health management within cemetery environments.

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CHAPTER 1: INTRODUCTION

1.1. Study Background

The predominant method of disposing of deceased bodies involves burial in soil, fostering interactions with the environment and facilitating the return of nutrients to the natural life cycle (Loefler, 2003). However, challenges arise when burial sites are situated in areas with unfavourable hydrogeological, geological, and climatic conditions where there is a risk of soil and groundwater contamination, and the decomposition process may be impeded, giving rise to various social, economic, and political issues (Oliveira et al., 2013). Key factors influencing the pollution potential of a burial ground include the depth of inhumation, geological formation, water table depth, inhumation density, soil type, and climate and these parameters play a crucial role in assessing the environmental impact of burial practices (Oliveira et al., 2013).

Cemeteries typically lack adequate regulations about engineering geological and hydrogeological evaluations due to their perception as low-risk sites for waste disposal (Dippenaar, 2014). This is due to several factors, including the gradual decomposition of human bodies and the short lifespan of bacteria outside the body; the well-structured water supply system which guarantees high-quality drinking water; and waste disposal sites and sewage contribute to more substantial contamination (DWA, 2010). Improperly situated or inadequately safeguarded cemeteries can present a considerable health concern for individuals because of the decomposition of buried human corpses, which generates substances like residues, particles, and disease-causing pathogens which could result into local epidemic diseases (Fisher and Croukamp, 1993; Dippenaar et al., 2018; and, Nguyen and Nguyen, 2018). Insufficient access to clean water and sanitation, especially in resource-poor communities heightens the risk of cholera outbreaks, as evidenced by recent events in Hammanskraal, South Africa (Obasa et al., 2023).

The risk of water contamination increases when burials are close to the water table or groundwater extraction points, as it reduces the time needed for waste degradation and pathogen purification (DWAF, 2004). Contamination can further escalate if corpses are directly buried in contact with groundwater, especially with a higher number of burials (Engelbrecht, 2000). To evaluate the risk of pathogen contamination in soil and groundwater, it is crucial to comprehend how pathogens are

transported and survive in the runoff water, through the shallow vadose zone, and groundwater environment (Bradford et al., 2013). This understanding helps in assessing the potential for pathogen migration and developing effective control measures (Bradford et al., 2013). These pathogens can enter the soil and groundwater through the decomposition of human remains and can persist in the environment for extended periods (Üçisik & Rushbrook, 1998). Climate change may alter waterborne pathogen distribution, requiring thorough assessment for effective health interventions (Sterk et al., 2013).

The complex behaviour of microorganisms in groundwater remains inadequately comprehended, primarily due to the complex interaction of biophysical and biochemical processes influencing their fate and transport (Haricombe, 2016). Beyond the movement of groundwater, various processes, including natural die-off, biofilm formation, and adsorption-desorption phenomena, exert considerable influence on the spatial and temporal distribution of microorganisms in groundwater (Taylor et al., 2004). While some investigation has been conducted on these processes in international literature such as Taylor et al. (2004), López-Falcón et al. (2008), Liu et al. (2020) and Saba et al. (2023), there exists a notable gap in local knowledge concerning the specific chemical, physical, and biological mechanisms governing the fate and transport of microorganisms in South African aquifers (Haricombe, 2016).

Temba Cemetery is a burial site located in the Tshwane municipality of South Africa, which serves as a final resting place for people from the surrounding areas. The cemetery has been in use for several years and is situated near residential areas, a wetland, and a river, which raises concerns about the potential risks associated with the disposal of human remains at this site. Even though several studies such as Dippenaar (2014) and Dippenaar et al. (2022), have investigated the microbial diversity at burial sites in different regions, there is limited research on the fate and transport of microbial pathogens and human health risk analysis. This research seeks to understand the fate and transport of microbial pathogens present in the cemetery environment utilizing a faecal indicator, and the study model and assesses the risks associated with these pathogens. This analysis provides valuable insights into the potential spread of microbial pathogens, allowing for a better understanding of the associated health risks and the development of effective mitigation strategies.

The presence of faecal contamination at Temba Cemetery lacks monitoring, and limited knowledge is available regarding the distribution of microbes in water resources at the site. In efforts to comprehend bacterial contamination in water, indicator organisms like faecal coliform and *E. coli* are commonly used to estimate concentrations of both pathogenic and non-pathogenic microorganisms (Motlagh and Yang, 2019). While *E. coli* does not exhibit a direct correlation with waterborne pathogens, it is widely utilized globally as an indicator of faecal contamination and this preference is attributed to the cost-effectiveness and time efficiency associated with measuring *E. coli* in comparison to other pathogenic microorganisms such as *Cryptosporidium* and Rotavirus (Iqbal & Hofstra, 2019). In this study, process-based analytical modelling is utilized to enhance the comprehension of the fate and transport of microbes in water resources. This approach serves as a cost-effective and efficient alternative to extended periods of sampling and expensive fate and transport modelling software.

1.2. The Research Problem

Burial sites are potential sources of microbial pathogens that can pose risks to public health and the environment (Franco et al., 2022). These risks are particularly significant in densely populated areas, where land for burial is limited, and the proximity of burial sites to water sources can increase the risk of contamination (Miller and Wiens, 2017; and Cabral, 2010).

Previous studies such as Dippenaar (2014); Masindi and Foteinis (2021); and Dippenaar et al. (2022), have investigated the microbial diversity at burial sites in different regions, but there is limited research on the fate and transport of microbial pathogens and human health risks in the South African geological environment. While the use of faecal indicators has been identified as a useful tool for assessing the potential risks associated with microbial pathogens in different environmental settings (Motlagh and Yang, 2019). According to the author's knowledge there is no available literature on the modelling of microbial transport and fate and the risk to the receptor in the Temba Cemetery, Hammanskraal area. The importance and originality of this study are that it provides new insights into the transport and fate of microbial pathogens in the Temba Cemetery, and the associated risk to the surrounding communities.

1.3. Study Objectives and Research Question

The main objective of this study is to investigate the fate and transport of microbial pathogens at Temba Cemetery and to quantify the risks associated with human remains disposal at this site utilizing faecal indicators. The specific objectives are:

- I. To assess the spatial distribution of faecal indicators in groundwater samples collected from Temba Cemetery and the surrounding areas.
- II. To investigate the influence of burial practices on the fate and transport of microbial pathogens in soil and water samples using the advection-dispersion equation or model.
- III. To quantify the risks associated with microbial pathogens at Temba Cemetery by using faecal indicators to estimate the concentration of indicator organisms and the likelihood of exposure.
- IV. To compare the risks associated with microbial pathogens at Temba Cemetery to those associated with other burial sites in the Tshwane municipality and other regions.

The outcome of this study provides important insights into the potential risks associated with human remains disposal at Temba Cemetery, if any, and inform policy decisions related to burial site management. Additionally, the findings of this study may have implications for the management of other burial sites in the Tshwane municipality and other regions.

The research questions for this study are:

- I. What is the spatial and temporal variation in faecal indicators and microbial pathogens at Temba Cemetery?
- II. What is the correlation between faecal indicators and microbial pathogens at Temba Cemetery?
- III. What are the implications of the findings for public health or surrounding communities?
- IV. What are the implications of the findings for and the environment?
- V. How do environmental factors such as soil type, topography, and hydrological conditions influence the transport of microbial pathogens from burial sites to groundwater sources?
- VI. What are the long-term implications of microbial pathogen contamination from burial sites on ecosystem health and biodiversity in the surrounding areas?

- VII. How can the findings of this study be integrated into existing burial site management practices to improve public health outcomes and minimize environmental impacts in not only Temba Cemetery but also other burial sites within the Tshwane municipality and beyond?
- VIII. What is the role of the Quantitative Microbial Risk Assessment (QMRA) in analysis of contamination risk emanating from burial sites?

1.4. Significance of the Study

This study addresses the potential risks associated with water contamination from cemeteries. By examining the fate and transport of microbial pathogens and conducting a risk analysis using faecal indicators, the study aims to provide valuable insights into the impact of cemetery activities on water quality, allowing for informed decision-making and the development of appropriate mitigation measures to protect the public health and the environment in the specific context of Temba Cemetery in Hammanskraal, South Africa.

The study outlined holds significant relevance to several Sustainable Development Goals (SDGs) as outlined in UN DESA (2023). By investigating the fate and transport of microbial pathogens and quantifying associated risks at Temba Cemetery, the research contributes to SDG 3 (Good Health and Well-being) by enhancing understanding of public health implications related to human remains disposal. Assessing water quality dynamics aligns with SDG 6 (Clean Water and Sanitation), while examining the impact on urban areas like Tshwane municipality supports SDG 11 (Sustainable Cities and Communities). Furthermore, the study's consideration of soil and ecosystem health contributes to SDG 15 (Life on Land). Through collaboration and knowledge-sharing, the research fosters partnerships for sustainable development, in line with SDG 17 (Partnerships for the Goals), ultimately advancing efforts to build resilient and inclusive societies.

The following chapter “Chapter 2” is the literature review chapter which provides an overview of existing research related to cemetery management, environmental impact studies, and the fate and transport of microbial pathogens from burial sites. By synthesizing and critically analysing prior studies, this chapter contextualizes the current research within the broader academic discourse. It

helps identify gaps in existing knowledge and justifies the need for the present study, creating a theoretical framework that informs subsequent chapters.

CHAPTER 2: LITERATURE REVIEW

Several studies such as Jonker and Olivier (2012), Oliveira et al. (2013), Żychowski and Bryndal (2015), have investigated the impact of cemeteries on human health and the environment as well as the microbial diversity and the fate and transport of microbial pathogens at burial sites in different regions. These studies have shown that the risk and transport of microbial pathogens in soil and water samples can vary depending on factors such as the type of burial site, the depth of burial, and the composition of the soil. To achieve the research objectives, it is imperative to formulate hypotheses based on a review of prior investigations related to groundwater contamination and transport mechanisms originating from burial sites. Special emphasis should be placed on understanding the dynamics of microbial pathogens within environmental systems, including the characteristics of these pathogens and the utilization of faecal indicators as essential tools for environmental monitoring. This involves a detailed examination of a specific type of faecal indicator available. Additionally, an in-depth exploration of diverse modelling approaches is necessary to establish a robust foundation.

The literature review should encompass a critical analysis of prior studies addressing microbial contamination in cemetery settings. Furthermore, it is essential to delve into the significance of risk analysis in the context of environmental microbiology. This exploration should conclude with a careful identification of existing gaps in the current scientific literature. This approach ensures that the subsequent research is firmly grounded in the existing body of knowledge, thereby enhancing its scientific rigor and relevance.

2.1. Microbial Pathogens in Environmental Systems

Cemeteries emerge as prominent sources of anthropogenic pollution and water contamination, extending their impact from urban settings to broader geographic areas and a consensus among researchers is that every cemetery poses a potential environmental hazard (Żychowski and Bryndal, 2015). During the decomposition of a human body, the resultant decomposed remains and their leachates contain microorganisms that have the potential to contaminate substrates, surface water, and groundwater (Nguyen and Nguyen, 2018). Healthy human and animal cadavers release various bacteria, including those categorized as total coliform bacteria such as *Escherichia*

coli, Enterobacter, Klebsiella, Citrobacter, Streptococcus faecalis, Clostridium perfringens, Clostridium welchii, and Salmonella typhi, along with human-hosted viruses like enterovirus (Dent et al., 2004; and Castro 2008). In many instances, environmental contamination arises from pathogenic intestinal bacteria, with Escherichia coli being a prominent example (Gleeson & Gray 2002). Microorganisms, including enduring ones like B. anthracis, variola virus, and Clostridium spp., can persist in the soil profile or groundwater under suitable environmental conditions for an extended period (Żychowski and Bryndal, 2015).

Diverse pathogens' influence on groundwater pollution at the local scale has been investigated through an examination of various environmental factors such as geological settings and substrate lithology, relief conditions, and the depth of the groundwater table, including its fluctuation (Gray et al., 1974; Martins et al., 1991; Almeida et al., 2006; and Żychowski, 2008). The spatial heterogeneity of groundwater contamination in the vicinity of cemeteries is often attributed to these factors (Morgan, 2004). A study conducted by Żychowski and Bryndal (2015) presented that in temperate climates, cemeteries have a modest influence on groundwater contamination by bacteria and viruses, with increased bacterial levels correlating with prolonged rainfall. This observation is exemplified by heightened counts of thermotolerant coliforms, faecal streptococci, and S. aureus in a Wolverhampton cemetery and nine cemeteries and mass graves in Poland (Żychowski and Bryndal, 2015).

Sterk et al. (2013) explained that climate change is expected to impact the spread of disease-causing agents in water used for drinking and recreational purposes, necessitating a thorough assessment of how climate change influences pathogen distribution in the environment and its potential repercussions on human health, to facilitate effective intervention strategies. Utilizing E. coli as an indicator of groundwater contamination, there are several factors that should be considered pertaining the survival and die-off rate of this indicator (Van Elsas et al., 2011).

2.1.1. Factors Affecting Survival of Escherichia coli (E. coli)

E. coli growth and survival in open settings depend on the availability of nutrients and energy, with fluctuations in environmental conditions influencing population dynamics and gene expression patterns, ultimately impacting its ability to endure and thrive (Van Elsas et al., 2011).

E. coli demonstrates varying capacities to persist in diverse open settings like soil, manure, and water (Jiang et al., 2002; Vital et al., 2008). Moreover, there's potential for migration between these habitats, for instance, *E. coli* might traverse from topsoil layers to groundwater, as evidenced in multiple studies (Mankin et al., 2007). Soil properties such as porosity, surface area, bulk density, and macropore structure play pivotal roles in the movement of infiltrating bacteria via sorption process and gravitational transport with water (Van Elsas et al., 1991). Contrary to common belief, *E. coli* O157:H7 can survive and even thrive in sterile freshwater with low carbon concentrations, challenging the notion that it would die off rapidly in severely carbon-limited environments (Vital et al., 2008).

Van Elsas et al. (2011) extensively studied *E. coli* survival, finding that resource availability, including carbon substrates, and environmental factors like temperature, pH, and water availability significantly impact its persistence. Fluctuating temperatures and soil acidity influence survival, with adaptations to nutrient scarcity and resistance mechanisms affecting its ability to withstand stressors (Van Elsas et al., 2011). Extreme water conditions, such as drought or flooding, also play a crucial role in *E. coli* physiology and survival, though its response in open settings warrants further investigation (Van Elsas et al., 2011).

2.1.2. *E. coli* Die Off Rate

A study by Brennan et al. (2010) showed that the significant presence of *E. coli* seeping from untreated soils, which hadn't received faecal material for over 9 years, suggests prolonged survival of *E. coli* in Irish soils, highlighting the importance of soil attributes affecting survival in addition to those affecting transportation when assessing potential risks. Sjogren (1994) studied how long *E. coli* bacteria can survive in soil and made charts that showed *E. coli* might last between about 1.7 to 2 years. Sjogren (1995) saw that a type of *E. coli* that can resist antibiotics stayed alive for 13 years in soil where they put a lot of it with a nutrient broth. Other studies, like the one by Jamieson et al. (2002), mostly found that *E. coli* lasts for about 2 to 4 months in soil. Ohtomo et al. (2004) discovered that *E. coli* could survive for some months in grassy soil, and Avery et al. (2004) found *E. coli* O157:H7 living for at least 8 weeks in pasture.

The behaviour of *E. coli* in natural conditions can be unpredictable, as suggested by Semenov et al. (2008). Despite being less favourable environments compared to the gut, *E. coli* has shown varied survival times—ranging from days under specific conditions of elevated temperature and limited nutrients to a year—in soil, manure, and water, as indicated by different research studies (Fukushima et al., 1999; Jiang et al., 2002).

2.2. Faecal Indicators as Tools for Environmental Monitoring

Untreated or minimally treated sewage or improperly sited cemeteries often contain faecal pollution, which poses risks to health, ecological balance, and economic stability and detecting faecal pollution serves the dual purpose of tracking faecal waste sources and identifying the presence of pathogens, enabling the assessment of potential health risks (Li et al., 2021). Standard water contamination indicators include total coliforms, comprising bacteria from the *Citrobacter*, *Klebsiella*, and *Enterobacter* groups, as well as faecal coliforms, thermotolerant coliforms (*E. coli*), *Streptococcus* (*S. faecalis*), and *Clostridium* (*C. perfringens*) (CETESB, 1996). Total coliforms play a crucial role in evaluating the effectiveness of water treatment for faecal waste removal and assessing the integrity of water distribution systems and their prevalence in water is indicative of potential faecal pollution, given their primary origin from the gastrointestinal tracts of humans and warm-blooded animals, including mammals and birds (Li et al., 2021).

Escherichia coli (*E. coli*) serves as a faecal indicator in adherence to drinking water regulations (Some et al., 2021; and U.S. EPA, 1985). This bacterium exhibits a robust association with faecal pollution, as it is consistently present in the faeces of warm-blooded animals, as well as a few reptiles, in substantial concentrations (Li et al., 2021). *E. coli* persists at detectable levels in water bodies affected by animal faecal pollution, encompassing sewage, rivers, lakes, groundwater, and coastal areas (Nowicki et al., 2021). Originally deemed exclusively of faecal origin, *E. coli*'s status as a faecal indicator is now complicated by the recognition of "naturalized" *E. coli*, which can endure and even replicate in non-enteric/non-faecal environments like soil, sediment, beaches, and aquatic plants (Li et al., 2021). While initial beliefs suggested poor survival and minimal multiplication of *E. coli* outside animal gastrointestinal tracts due to environmental disparities and stressors such as insufficient organic matter, sunlight exposure, and high salinity, prolonged

survival is observed at lower temperatures, with heightened replication occurring at higher temperatures in environments offering sufficient nutrients (Li et al., 2021).

A study by Cabral (2010) showed that various strains of *E. coli* associated with intestinal diseases have been categorized into at least six distinct groups. These groupings are determined based on epidemiological evidence, observable characteristics, clinical aspects of the diseases, and specific virulence factors and among these groups, enterohemorrhagic (EHEC, like O157), and enteroinvasive serotypes (EIEC, such as O124) hold significant importance (Cabral, 2010). These strains have the potential to spread through contaminated water sources (Cabral, 2010). A study by Leclerc et al. (2001) redefined coliform bacteria's roles and the significance of tests for total and faecal coliforms and highlighted *E. coli* as the sole reliable indicator of faecal pollution in environmental waters among Enterobacteriaceae, urging the abandonment of the traditional total coliform test. They emphasized the need for faecal coliform detection at 44.5°C and species-level identification to exclude false positives like *K. pneumoniae* (Leclerc et al., 2001).

Studies on pulp and paper mill effluents by Gauthier et al. (2000); and, Gauthier and Archibald (2001) question the efficacy of total and faecal coliform counts, as well as enterococcus counts, as indicators of faecal pollution. Across seven mills in Canada, they found these indicators present in various mill samples, but the majority of identified faecal coliforms were species like *K. pneumoniae*, *Raoultella terrigena*, and *Raoultella planticola*, with *E. coli* in the minority and *Salmonella* was absent in most samples tested (Gauthier et al., 2000). These studies suggest that relying on total and faecal coliforms or enterococci might not truly reflect faecal pollution in these systems, emphasizing the need to verify the identities of bacteria triggering positive test results (Gauthier and Archibald, 2001).

2.3. Fate and Transport Models for Microbial Pathogens

The movement of water within porous medium is governed by convection and dispersion, irrespective of the material being transported (Bear, 1972). Convection arises from the bulk flow of water, driven either by density differences, regional aquifer movement, or human-induced disruptions, typically through wells, while dispersion, on the other hand, stems from the irregular motion of water and at the pore scale, these irregularities arise from the tortuosity of flow paths,

while at a larger scale, they result from the presence of zones with varying permeabilities (Bear, 1972; and, Fried and Combarnous, 1971).

In the context of pollutant elements transported by water particles, Sauty (1980) highlighted that such as solutes, adhere to the same hydrodispersive framework and these elements undergo additional phenomena like sorption and chemical reactions, which typically impede their movement. While these processes can significantly alter the transfer dynamics, it is essential to recognize that the fundamental driving forces for displacement and dispersion still originate from the movement of water (Sauty, 1980). The intricacies introduced by sorption and chemical reactions may alter the pace of pollutant movement, but the foundational principles of water flow remain pivotal in dictating the overall transport behaviour within porous media (Sauty, 1980).

The complex interaction between microbial pathogens and surfaces in the environment plays a crucial role in various environmental processes such as how they are adsorbed to the surfaces, get released, clump together, and survive (Bradford et al., 2013). According to Bradford et al. (2013), these interactions depend on the unique characteristics of the pathogens, the surfaces they interact with, and the liquid environment they are in. Ginn et al. (2002) pointed out the challenges in finding clear connections between the properties of bacteria and how they move, especially when dealing with living microbes in groundwater, which is more complicated than dealing with lifeless particles.

In the realm of microbial movement, particularly in groundwater as studied by Flynn et al. (2004), things get more complicated because microbes are alive, and this liveliness brings in biological factors that make the movement of microbes more complex than non-living particles. Ginn et al. (2002) also highlighted that, unlike non-living particles, microbes not only go through physical and chemical changes but also undergo various strictly biological processes that strongly affect how they move. Understanding these complex interactions is crucial for studying how microbial pathogens move in groundwater, as it involves considering both the biological characteristics of the microbes and the physical and chemical factors that affect how they interact with the environment (Sauty, 1980). This combined approach is essential for improving our understanding of the complexities involved in the movement and survival of microbial pathogens in different

environmental settings, providing important insights for managing the environment and public health (Van Elsas et al., 2011).

According to Freeze and Cherry, (1979), understanding the parameters governing the convection and dispersion of water, constituting hydrodispersive transfer, is crucial for evaluating subsurface transport phenomena and these parameters, though not directly measurable, can be inferred through the behaviour of an ideal (i.e., nonreactive) tracer introduced into the aquifer. The mass transfer equation (1) below representing the dynamics of this process, includes several terms (Sauty, 1980):

$$\frac{\partial}{\partial t} \left(C + \frac{1-n}{n} F \right) = \nabla(D\nabla C) - u\nabla C + Dm\nabla^2 C - \lambda \left(C + \frac{1-n}{n} F \right) - OR \quad 1$$

Where on the left-hand side, storage is denoted, while on the right-hand side, the first term accounts for dispersion, the second for convection, the third for molecular diffusion, the fourth for radioactive decay, the fifth for adsorption, and OR represents other reactions (Sauty, 1980).

In instances of purely hydrodispersive transfer, which disregards reactions other than dispersion, convection, and molecular diffusion, the equation simplifies and given the swift flow in shallow aquifers, particularly susceptible to pollution, the kinematic dispersion components become prominent in comparison to molecular diffusion (Freeze and Cherry, 1979). Consequently, the mass transfer equation in this scenario is then expressed as in equation 2 and 3 from Sauty (1980):

$$\frac{\partial C}{\partial t} = \nabla(D\nabla C) - u\nabla C \quad 2$$

Thus

$$\frac{\partial C}{\partial t} = \alpha_L u \frac{\partial^2 C}{\partial x^2} - u \frac{\partial C}{\partial x} \quad 3$$

2.4. Studies Relevant to Cemetery Environments

Some of the investigation conducted on the microbial diversity and the fate and transport of microbial pathogens at burial sites includes the following:

2.4.1. Studies in South Africa

In the Western Cape Province, Engelbrecht (1993) conducted research on poorly located graves in cemeteries, which revealed significant pathogenic contamination in groundwater. The study area included sandy geological profiles, where twenty groundwater monitoring wells were installed within the cemetery zone, and two additional wells were located at distances of 50 meters and 500 meters (reference well) from the site to assess water quality (Engelbrecht, 1993). Monitoring of these wells showed the presence of pathogenic microorganisms such as *E. coli*, *S. faecalis*, *S. aureus*, heterotrophic bacteria, and faecal coliforms in wells located in sandy geological profiles (Engelbrecht, 1993).

Another study was conducted at Diteng teng Cemeteries in Tshwane, Gauteng Province, which revealed elevated levels of pathogenic contamination in monitoring wells located near the site at shallow sandy geological profiles and coastal zones (Tumagole, 2006). Groundwater levels in the Tshwane region rise during the rainy season, making the aquifer more susceptible to bacterial contamination from cemeteries (Tumagole, 2006). Tumagole (2006) also conducted a study at Harare's urban Granville cemetery in which total and faecal coliforms were found in groundwater. The study involved seven piezometers installed within the cemetery area and downstream of the site to monitor the presence of contaminants.

The ongoing COVID-19 crisis has raised concerns about the contamination of groundwater through mass burials, emphasizing the need to understand how burial practices impact viral spread (La Rosa et al., 2020). Factors like temperature sensitivity and vulnerability to chlorination affect the survival of SARS-CoV-2 in the environment, underlining the importance of temperature control (Naddeo and Liu, 2020). A study by Van Wyk, et al. (2022) elaborated that the COVID-19 pandemic has underscored the imperative for further investigation into the potential risks to both human health and the environment posed by mass burial practices for victims of the disease. Adjustments in policy and legislation are necessary to ensure safe burial practices, especially with varying burial methods due to the pandemic's demands (Van Wyk, et al., 2022). Research using surrogate viruses has demonstrated significant groundwater contamination from cemetery sites, particularly in specific geological settings (Casanova et al., 2009). It's essential to safeguard boreholes against pathogens through proper cemetery management, although viruses typically

cannot spread through the vadose zone on their own (Van Wyk, et al., 2022). Van Wyk, et al. (2022) recommended that future research should explore responses to mass fatalities from natural disasters and deepen understanding of microbial contaminant loading and groundwater flow patterns from cemeteries.

2.4.2. Studies in Europe

Bouwer (1978) conducted a study at a Berlin cemetery in West Germany, revealing that the abundance of pathogens in groundwater was at least sixty times higher than in natural water. However, the number of pathogens appeared to decrease rapidly when investigations were conducted about five meters away from the burial site (Bouwer, 1978).

Rodrigues & Pacheco (2003) conducted studies at three different cemeteries and found many pathogens in monitoring wells located within and around the graves. Pathogenic contamination was observed in all samples obtained from one of the research locations (the Querenc cemetery), which was situated in a karst hydrogeological environment (Rodrigues & Pacheco, 2003). Furthermore, pathogens such as *S. faecalis*, *Bacillus cereus*, *Clostridium perfringens*, *Staphylococcus aureus*, and thermotolerant coliforms were found in the groundwater environment during additional research conducted at Danescourt Cemetery in Wolverhampton, England (Rodrigues & Pacheco, 2003).

Zychowski (2009) investigated nine cemeteries in Poland and found pathogenic bacteria like *B. cereus*, *S. aureus*, *Staphylococcus* spp., *C. perfringens*, *S. faecalis*, and thermotolerant coliforms in groundwater monitoring wells installed within burial plots and downgradient from the cemetery.

2.4.3. Studies in Other Countries

Dent and Knight (1998) studied the permeable silty sands and clay of various Australian cities and discovered pathogenic organisms such as *Pseudomonas aeruginosa* and Faecal streptococci in insignificant amounts in various locations, along with varying amounts of coliforms and low counts of faecal coliforms and streptococci. The findings suggest that in some hydrogeological conditions, a variable number of coliforms may transfer into the groundwater (Dent and Knight, 1998). However, the studies found that Australian cemeteries have a lesser impact on groundwater

contamination (Dent and Knight, 1998). Dent (1995 and 2005) conducted two sets of experiments at the Botany cemetery in Sydney and found extremely low levels of bacteriological contamination such as total coliforms, *S. faecalis*, faecal coliforms, and *P. aeruginosa* in the groundwater. These bacteria were found in only four out of eleven boreholes, located along the line of water runoff, particularly underneath fresh burials (Dent, 1995 and Dent, 2005)

Wu et al. (2009) utilized *Escherichia coli* as a bacterial tracer to develop, calibrate, and validate a model for predicting the fate and transport of various pathogens at a watershed scale. The model aimed to encompass pathogens such as *Cryptosporidium*, *Giardia*, *Campylobacter*, and *E. coli* O157:H7 (Wu et al., 2009). To assess the changes in *E. coli* concentrations over time and space in the Blackstone River, a hydrologic model named WATFLOOD/SPL9 was employed (Wu et al., 2009). The model's accuracy in predicting the rapid increase in *E. coli* densities in the stream was significantly improved when sediment resuspension was considered, highlighting the crucial role of this process in the overall understanding of *E. coli* dynamics (Wu et al., 2009).

Wang et al. (2013) conducted laboratory and numerical studies to investigate the transport and fate of *Escherichia coli* D21g and coliphage 'X174 in saturated soils with the preferential flow. The experiments examined different solution ionic strength conditions (Wang et al., 2013). Results showed that higher solution ionic strength increased the retention of *E. coli* D21g and 'X174, with a greater impact on *E. coli* D21g in finer sand than in coarse sand (Wang et al., 2013). Numerical simulations effectively described the microbe transport behaviour (Wang et al., 2013). Preferential flow played a more significant role in the transport of *E. coli* D21g compared to 'X174, and cell retention was observed at the interface of the coarse-sand lens and fine-sand matrix (Wang et al., 2013). Decreasing solution ionic strength resulted in multiples breakthrough behaviour during cell release (Wang et al., 2013).

Despite the importance of understanding the fate and transport of microbial pathogens and the potential risks associated with human remains disposal at burial sites, there is limited research on these topics at Temba Cemetery. The use of faecal indicators to quantify the risks associated with human remains disposal at Temba Cemetery has not been explored. The outcomes of this study will provide important insights into the potential risks associated with human remains disposal at Temba Cemetery and inform policy decisions related to burial site management.

2.5. Risk Analysis in Environmental Microbiology

Quantitative Microbial Risk Assessment (QMRA), initially suggested in the 1990s to manage microbial risks in water treatment, has broadened the scope of risk assessment, extending from chemical hazards to include microbial safety in food, water, and environmental settings (He & Huang, 2020). Its fundamental objective is to gather the most reliable data to comprehend the potential consequences of exposure to microorganisms (Pepper et al., 2015). While officially structured in six steps, many studies typically follow a streamlined four-step process: (1) hazard identification, (2) exposure assessment, (3) dose-response analysis, and (4) risk characterization (Pepper et al., 2015; and, He & Huang, 2020).

2.5.1. Applications of Risk Analysis in Similar Studies

Numerous studies have utilized Quantitative Microbial Risk Assessment (QMRA) as a methodology, among them the works of Ahmed et al. (2020), Derx et al. (2022), and Burch et al. (2022).

Ahmed et al. (2020) conducted a QMRA to analyse drinking water quality in primary schools across Sindh, Pakistan, revealing significant contamination primarily from *Escherichia coli*, *Shigella* spp., *Salmonella* spp., and *Vibrio cholerae*. Regional differences showed higher infection risks in Southern Sindh, particularly in Karachi, emphasizing the urgent need for management plans to address waterborne diseases among schoolchildren (Ahmed et al., 2020).

When discussing microbial monitoring and risk assessment in porous aquifers, Derx et al. (2022) provide insights into current approaches from groundwater to drinking water. The study delves into the Dutch approach to QMRA for ensuring safe drinking water, mandated since 2005 to maintain a negligible risk of infection (less than 1 in 10,000 people yearly) from untreated water consumption (Derx et al., 2022). Using guidelines and computational tools, it evaluates pathogens in surface and vulnerable groundwater sources based on indicator organism reductions, employing complex formulas to estimate infection risks (Derx et al., 2022). Treatment barriers are crucial for surface water and susceptible groundwater, while protected groundwater focuses on maintaining safe distances from contamination sources (Derx et al., 2022). QMRA, repeated every four years, assesses vulnerability and protection zones, considering factors affecting pathogen survival (Derx

et al., 2022). Computational models aid in river microbial assessments and effective pathogen reduction strategies, contributing to proactive water safety management (Derx et al., 2022).

Burch et al. (2022) conducted a statewide QMRA in Minnesota, analysing waterborne pathogens in public water supply wells. Over a 2-year period, 964 water samples from 145 wells were collected to estimate infection risks associated with nine pathogens (Burch et al., 2022). The annual risk varied among well types, with noncommunity wells having the highest risk, surpassing the U.S. benchmark in 59% of well-years (Burch et al., 2022). *Cryptosporidium* was identified as the primary contributor to the annual risk, highlighting the importance of identifying wells vulnerable to *Cryptosporidium* contamination to effectively mitigate overall risk (Burch et al., 2022).

2.5.2. Integration of Risk Analysis in the Context of Temba Cemetery

Integrating risk analysis within the context of Temba Cemetery would involve an assessment of potential risks associated with waterborne pathogens in the vicinity. Utilizing quantitative microbial risk assessment (QMRA) techniques, like studies conducted in Minnesota by Burch et al. (2022), would enable an evaluation of infection risks linked to water sources around the cemetery. This approach involves collecting water samples from various sources in and around the cemetery area, conducting hazard identification, and assessing exposure levels to different waterborne pathogens (Burch et al., 2022). The findings from studies like the one conducted in Minnesota emphasize the importance of site-specific assessments, indicating the prevalence and extent of risks associated with several types of wells or water sources (Burch et al., 2022). In the case of Temba Cemetery, such analysis could aid in understanding the potential health hazards linked to water sources accessible to the community in the vicinity of the cemetery.

2.6. Research Gaps and Questions

Based on the extensive literature review, the proposed research topic, "Modelling the Fate and Transport of Microbial Pathogens and Risk Analysis Utilizing Faecal Indicators at Temba Cemetery, Hammanskraal, South Africa," emerges with several potential areas for investigation and unexplored gaps.

Firstly, the reviewed literature indicates a lack of research specifically addressing microbial dynamics at Temba Cemetery in Hammanskraal, South Africa. While numerous studies from different regions as review under section 3.4., emphasized potential risks posed by cemetery environments to groundwater and soil due to pathogenic contamination, there is a significant gap in understanding the specific types and abundance of microbial pathogens originating from human remains in this setting (Engelbrecht, 1993; Tumagole, 2006). Investigating these dynamics could provide insights into localized risks and transport mechanisms affecting the surrounding environment at Temba Cemetery. Additionally, while faecal indicators such as *Escherichia coli* have been extensively discussed as reliable tools for assessing water contamination and potential health risks (Li et al., 2021), their specific application for evaluating the risks associated with human remains disposal at Temba Cemetery remains unexplored.

Moreover, the literature emphasizes the need for developing site-specific fate and transport models for Temba Cemetery. Previous studies have highlighted the influence of diverse environmental factors on microbial transport, including soil composition, groundwater depth, and hydrogeological characteristics (Żychowski & Bryndal, 2015). Creating these models tailored to the specific conditions of Temba Cemetery would contribute to understanding pathogen movement and survival in this environment. Furthermore, integrating QMRA techniques within the context of Temba Cemetery is crucial. This approach involves hazard identification, exposure assessment, and risk characterization, aiming to quantify infection risks associated with waterborne pathogens prevalent in the vicinity (Burch et al., 2022; and Ahmed et al., 2020). Assessing these risks would enable the development of targeted interventions and management strategies to mitigate potential health hazards for the local population.

2.7. Review of Methods

The review of methods section within the literature review chapter encompasses an examination of the methodologies utilized in this research endeavor. Diverse tests were administered in the field to gather and quantify data, including percolation tests, bail tests, and tracer tests, all of which are integral components of the research methodology. Additionally, this section delves into the sampling techniques employed and provides an overview of the model validation techniques utilized, offering a summary of the research methodology.

2.7.1. Percolation Tests

Numerous assessments of field percolation tests have been conducted, primarily focusing on their limitations. Notable examples include studies by Bouma (1971), Elrick and Reynolds (1986), and Amoozegar (1997). This approach relies solely on a unit gradient, considering the gravitational potential gradient while disregarding gradients associated with pressure and matric potentials (Mulqueen & Rodgers, 2001). The matric potential arises from the cohesive forces between water molecules and the interactions between water and soil surfaces in unsaturated conditions (Mulqueen & Rodgers, 2001). This method offered a practical way to estimate soil permeability in the field, but accuracy can be influenced by factors such as hole size and soil heterogeneity (Kessler and Oosterbaan, 1974; and Dippenaar et al., 2014).

2.7.2. Bail Tests

The bailer test drew inspiration from analogous examinations conducted during site investigations, although it was uncommon for these tests to be subjected to quantitative interpretation, as observed in the study by Brandon (1986). The bailer test is a unique type of examination to determine hydraulic properties of the soil and rock layers that is carried out manually using a simple tool known as a bailer, eliminating the need for a motorized pump, making it feasible for use in extremely remote locations or aquifers with low permeability; however, it's best suited for boreholes where the water level is relatively close to the surface, typically within 15 to 20 meters below ground, and might not yield accurate results in very permeable aquifers due to minimal drawdown and rapid recovery rates (ICRC, 2011). A bailer is a cheap, lengthy, tube-like container with a valve at its bottom, employed for extracting water, sand, mud, drilling debris, or oil from a well during the process of collecting groundwater samples (ICRC, 2011).

This test is specifically intended for application in smaller boreholes or wells with narrow diameters (Barker and Herbert, 1989). The reason for this preference is that, in the case of large-diameter-wells, the act of removing water using bails would not produce a significant shift in the water level (Macdonald et al., 2008). For assessing and analysing large-diameter-wells, it is advisable to rely on conventional techniques and methodologies, as exemplified by studies such as those conducted by Barker and Herbert (1989), Mace (1999) and Macdonald et al. (2008).

2.7.3. Tracer Tests

Tracer tests serve as invaluable tools for the examination of groundwater dynamics and the dispersion of contaminants, with a particular focus on their utility in karst landscapes (Goeppert and Goldscheider, 2008). In the realm of groundwater research, artificial tracers play a pivotal role in delineating recharge zones, elucidating flow patterns and velocities, and assessing the susceptibility of groundwater to contamination (Massei et al., 2006; Goldscheider, 2008). Additionally, tracer tests prove instrumental in characterizing transport phenomena in natural watercourses (Boulton et al., 2010; Lemke et al., 2013).

The interpretation of the complex data derived from tracer tests necessitates rigorous mathematical analysis (Kreft and Zuber, 1978). To this end, several mathematical models have been devised to estimate crucial transport parameters by examining the observed breakthrough curves (BTCs) (Sauty, 1980). Notable contributions in this field include models introduced by researchers like Kreft and Zuber (1978), Sauty (1980), Maloszewski et al. (1992), and Berkowitz et al. (2006). These models enhance our comprehension of the complex dynamics governing the movement of tracers in complex hydrogeological systems (Sauty, 1980).

According to Fernández-Garcia and Gómez-Hernández (2005) there are three distinct methods for analysing tracer field concentration data: (a) curve matching techniques, (b) the method of moments, and (c) model calibration. This research will focus on the first approach, where field data is adjusted to analytical or numerical model solutions, often presented as dimensionless type curves (as described by Sauty in 1980, Carrera and Walters in 1985, and Welty and Gelhar in 1994). Tracer test curve matching techniques should determine the dispersivity and effective porosity that will be used in the analytical model to evaluate the advection and dispersion processes which are responsible for contaminant spread and migration (Sauty, 1980).

2.7.4. Water sampling

Sampling guidelines, both local and international, were adhered to. Specifically, the “Groundwater Sampling – A guide for sampling methods” published by the Water Research Commission (Weaver et al., 2007) and Environmental Protection Agency (EPA) Standards were used as references (EPA, 2009).

2.7.5. Model Validation

Małłoszewski and Zuber (1992) examined the calibration and validation processes necessity for mathematical models utilized in analysing tracer experiments within groundwater contexts, using several case studies as examples. The study defined basic terms pertinent to groundwater tracing and highlights the challenges in calibration due to parameter interplay, leading to difficulties in validation (Małłoszewski and Zuber, 1992). Strategies to address these challenges, such as reducing fitting parameters through independent observations or multi-tracer experiments, are discussed, alongside the acknowledgment that achieving ideal validation is often impractical, necessitating the use of indirect validation methods (Małłoszewski and Zuber, 1992). A similar approach was employed in the current research to validate the model created.

2.7.6. Chloride Concentrations and EC values relationship

In the natural environment, chloride compounds are ubiquitously present, encompassing sodium chloride (NaCl), potassium chloride (KCl), and calcium chloride (CaCl₂) salts (Peinado Guevara et al., 2012). Chloride ions constitute the primary components in aquatic systems and saline soils, directly influencing EC values (Xu and Eckstein, 1997). As a result, a strong correlation can be observed between EC and chloride ion (Cl⁻) concentrations, a relationship reported by multiple researchers (Oteri, 1988; Hajrasuliha et al., 1991; Xu and Eckstein, 1997; McNeil and Cox, 2000; Abyaneh et al., 2005; Alhumoud et al., 2010; and Peinado Guevara et al., 2012).

Peinado Guevara et al. (2012) employed various regression models, including linear, polynomial, and potential regression, to establish the relationship between EC and Cl⁻ concentration. The linear regression model proposed in the study for 1358 samples of groundwater electrical conductivity and chloride concentrations closely resembled the results obtained by Abyaneh et al. (2005): $[Cl^-] = 9 \text{ EC}$ for $0.15 < EC < 39.9 \text{ dS m}^{-1}$. The relation obtained by Peinado Guevara et al. (2012) showed that $[Cl^-] = 9.22 \text{ EC}$, for $0.15 < EC < 95 \text{ dS m}^{-1}$ in the linear regression model. In contrast, for the 66 samples collected in the study area in 2008, a linear model $[Cl^-] = 4.928 \text{ EC}$, for $0.18 < EC < 8.08 \text{ dS m}^{-1}$, was found, which is consistent with the linear model proposed by Hajrasuliha et al. (1991): $[Cl^-] = 5.22 \text{ EC}$, for $EC = 16 \text{ dS m}^{-1}$.

The various models presented, linking water electrical conductivity to chloride concentration, exhibit a strong fit in the linear, polynomial, and potential models, with R-squared (R fit) values exceeding 0.94 (Peinado Guevara et al., 2012). Consequently, it is feasible to estimate chloride concentration using only the groundwater EC value and the gradient of the linear model for the $[\text{Cl}^-]$ versus EC relationship indicates that the gradient tends to increase as the chloride concentration rises (Peinado Guevara et al., 2012).

The following chapter “Chapter 3” is the case study description chapter which delves into the specific details of Temba Cemetery as a case study. It provides a historical background, emphasizes the cemetery's significance, and offers insights into the evolution of burial practices at the site. By thoroughly examining Temba Cemetery, this chapter establishes a solid foundation for the subsequent analysis of burial practices, hydrogeological conditions, and potential environmental risks.

CHAPTER 3: CASE STUDY DESCRIPTION

3.1. Site Description

A description of the regional area information is described under the headings below.

3.1.1. Site Location

The research site is situated in Hammanskraal, at the outskirts of Gauteng Province, South Africa and neighboured by a village of Kudube. The predominant languages spoken in the area is Northern Sotho and Setswana. The research site was established in the late 1960s and continues to be actively used for burials, making it a dynamic environment for research. The locality map of the research study area is presented in Figure 1 below.



Figure 1: Locality map of the research study area.

3.1.2. Climate and Drainage

The research area in Hammanskraal, South Africa, experiences a climate characterized by seasonal variations and typical of the region (Meteoblue, n.d.). It falls within a subtropical climate zone, with distinct wet and dry seasons and summer months, which typically span from October to March, bring warm to hot temperatures with the occasional occurrence of thunderstorms and heavy rainfall, while the winters, on the other hand, occur from April to September and are marked by mild and dry conditions, with cooler temperatures during the night (Meteoblue, n.d.). The climate in the region is influenced by the South African High, which can result in extended periods of drought during the winter months (Meteoblue, n.d.). The simulated historical climate for a research study area is illustrated in Figure 2 below.

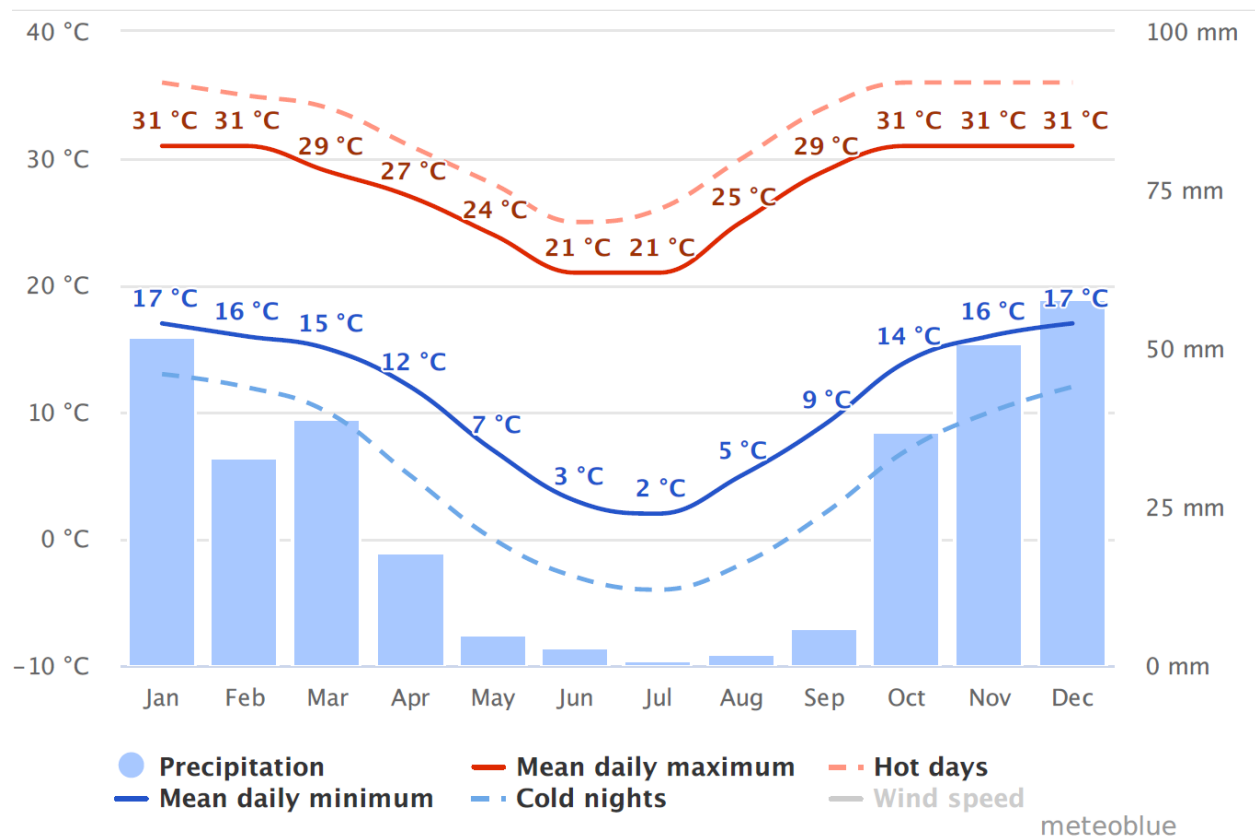


Figure 2: Simulated historical climate and weather for Hammanskraal (Meteoblue, n.d.)

The study area is situated in the Crocodile (west) and Marico Water Management Area (WMA 3) in the Apies area under quaternary catchment A23B. The water resource category of this catchment is categorized as good. In terms of drainage, the research area features a diverse hydrological landscape. The presence of the non-perennial stream the runs northwest to southeast through the

site and towards the Apies Rive and Kudube (Leeukraal) Dam located approximately 1.8 km east, adds a significant hydrological component to the region (DWS, 2012). The topographical presentation of the research study area is illustrated in Figure 3 below.

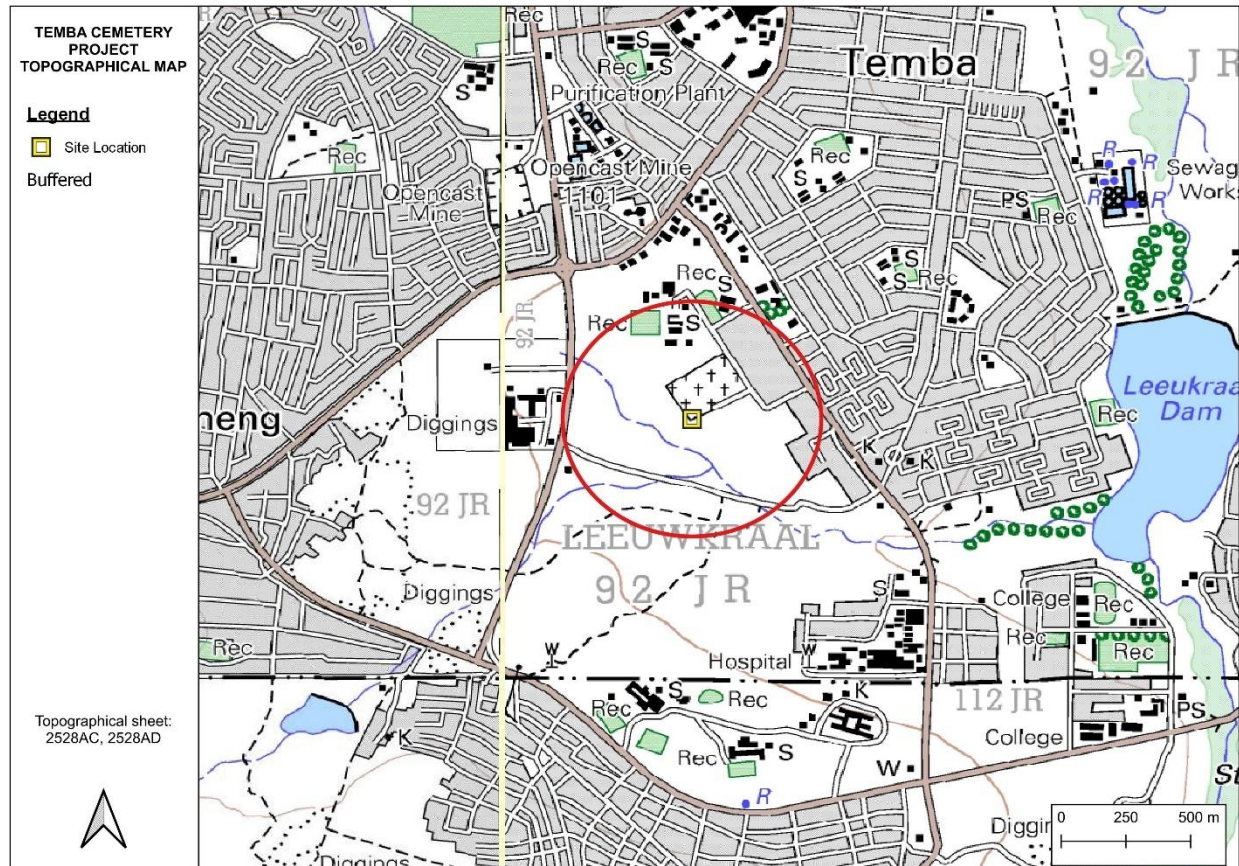


Figure 3: Topographical map of the research study area (2528AD, DWAF)

The presence of stream through the site can influence the drainage patterns and potentially serve as a conduit for waterborne transport of microbial contaminants. Additionally, the topography and land use practices in the area play a crucial role in shaping drainage pathways, affecting how water moves through the landscape. The presence of marshy areas and dense vegetation in certain sections of site further complicates drainage dynamics, potentially influencing the transport of pathogens and the distribution of faecal indicators within the research site. Understanding the interplay between the climate and drainage in this region is fundamental to comprehending the fate and transport of microbial pathogens and conducting accurate risk analysis.

3.1.3. Regional and Local Geology

The study area is located within the complex geological formations of the Karoo Supergroup, which was formed from the late Carboniferous to the middle Jurassic, accumulating to a thickness of approximately twelve kilometres in the southeastern portion of the Main Basin (Viljoen et al., 2010). This geological formation is composed of five distinct basins: the Main Basin, Springbok Flats Basin, Ellisras Basin, Tshipise Basin, and Tuli Basin, as indicated by Johnson et al. (2006). Specifically, the Springbok Flats Basin, covering an area of about 7200 square kilometres, exhibits sedimentary layers dipping toward the basin's centre and is bounded by a normal fault on its northern side (Figure 4) (Roberts, 1992). Furthermore, the basin is subdivided into two smaller sub-basins—the northeastern and southwestern sub-basins—by an east-west striking normal fault, as presented in a Figure 4 below by Viljoen et al. (2010).

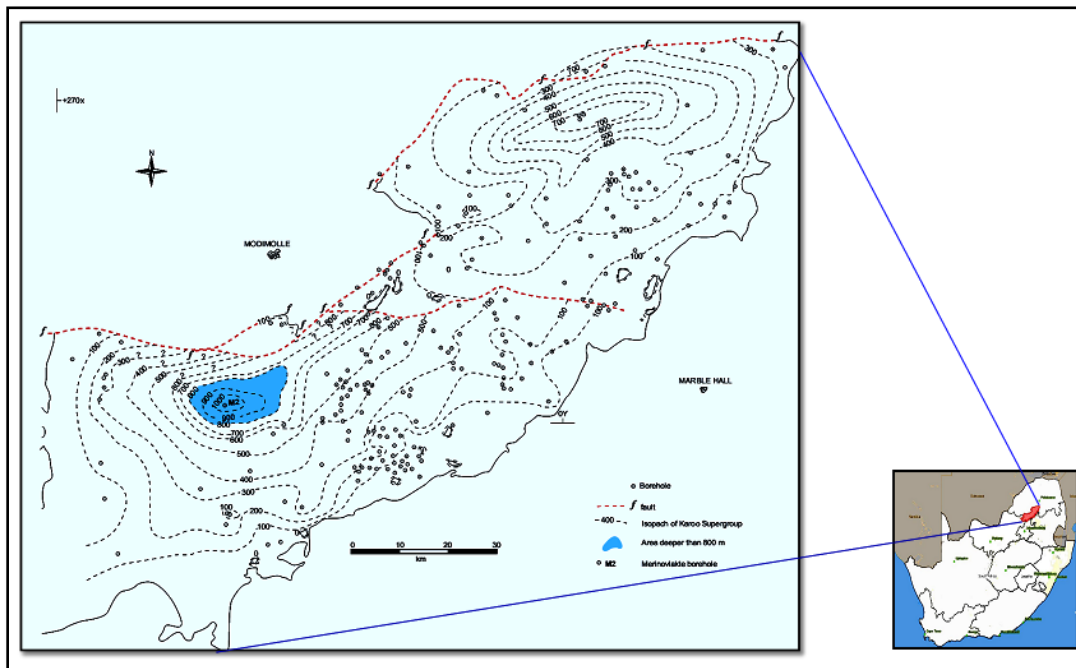


Figure 4: Isopach of the Karoo Strata thickness in the Springbok Flats Basin (after Roberts, 1992).

The north-eastern and the south-western sub-basins have thickness range of between 700-1 000 m and the north-eastern sub-basin covers an area of approximately 200 km². The north-eastern sub-basin forms part of the Eccra Group (Hammanskraal Formation). This sub-basin is characterised by sandstone with individual bed thickness range of approximately 1-4 m, see the stratigraphy in Figure 5 below (Viljoen et al., 2010).

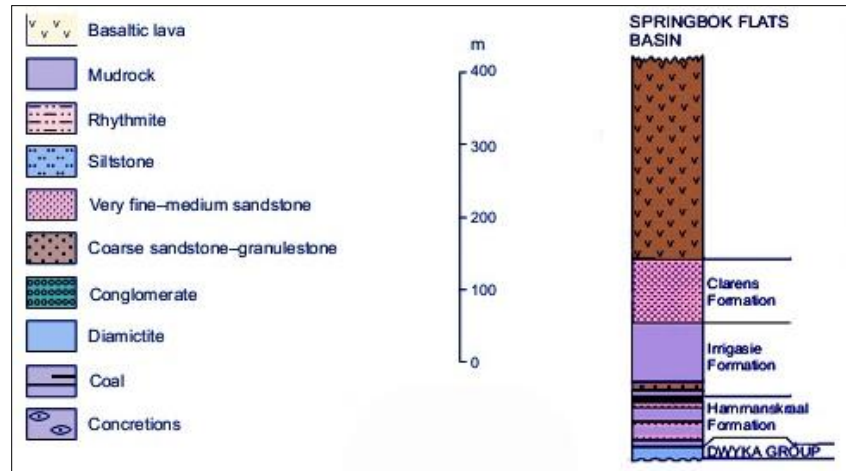


Figure 5: Stratigraphy of the Springbok Flats Basins (after Johnson et al., 2006).

The Hammanskraal Formation, which belongs to the Early Permian Gondwanan assemblage, comprises various rock types including mudrock, fine to medium sandstone, and coal, as detailed by Adendorff et al. (2003). This formation also contains carbonaceous shale and coal, which overlay beds of fine to very coarse-grained sandstones (2528, Pretoria). Within the 110-meter-thick layers of the Hammanskraal Formation, a mix of deltaic, fluvial, lacustrine, and peat deposits can be found, alongside conglomerate and rhythmite rocks, as described by Cole (2009). In the study area, the Springbok Flats Basin sequences overlay the site and encompass rock types ranging from coarse sandstone-granule stone to fine to medium sandstone and mudrock (Cole, 2009).

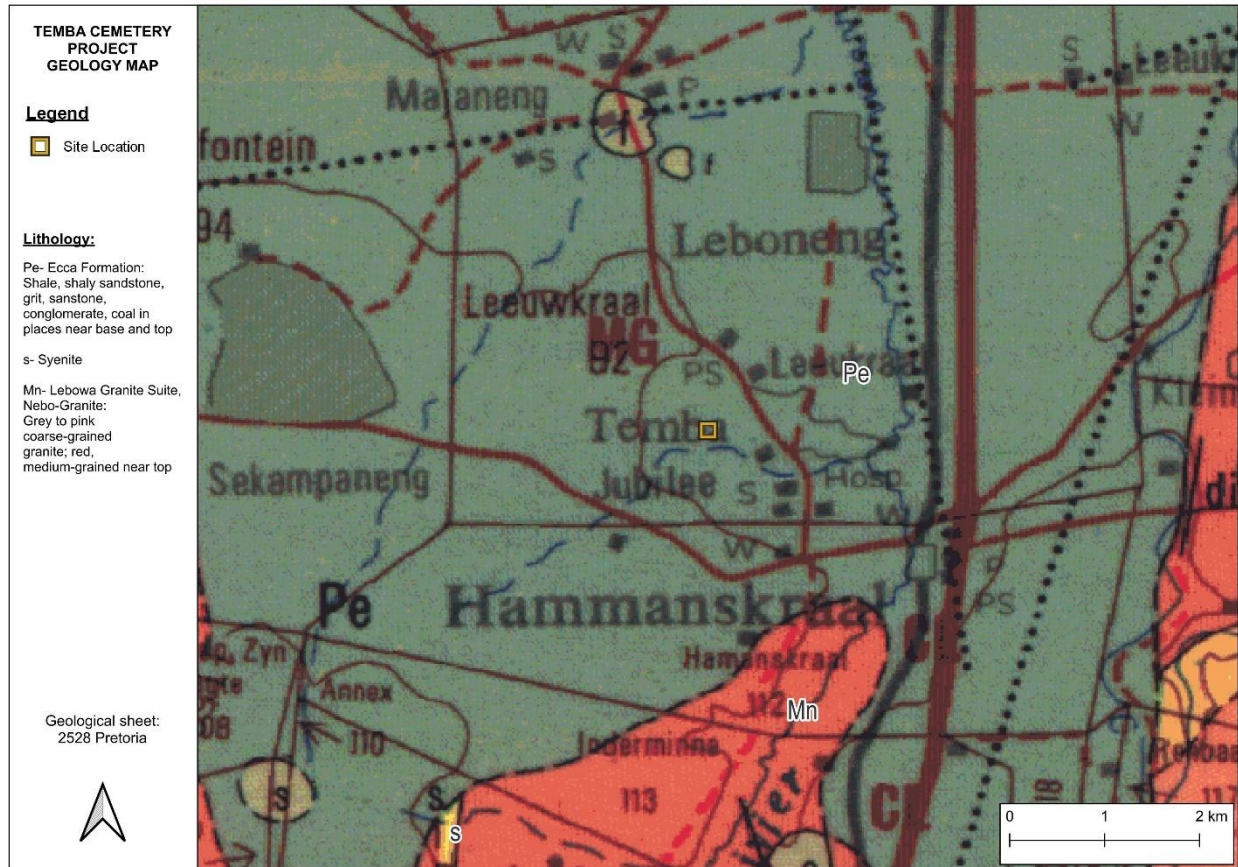


Figure 6: Geological map of the research area (2528, Pretoria)

According to the geological data provided by the 1:250,000 geological sheet 2528 Pretoria under Figure 6 above, the site is underlain by various materials from the Eccca Group within the Karoo sequence, including shale, shaly rock, sandstone, and conglomerate. Furthermore, during fieldwork, the in-situ soils found in previously excavated test pits, observed outcrops, and recently drilled monitoring wells exhibited characteristics such as residual gravelly silty sand with clay nodules in some areas and weathered sandstone bedrock. Quartz was identified as the predominant mineral grain in the soil from all test pits. The site was underlain by highly weathered and discoloured sandstone, which extended and covered the entire study area.

3.1.4. Local Hydrogeology

The investigation site is characterised by visible water seepages, wetland delineations and dense vegetation cover. Dippenaar et al. (2014) mentioned that Temba Cemetery represents a seasonal wetland intricately linked to a primary drainage channel. The imperative for establishing a cemetery outweighed the environmental risks, and the cemetery's development predated the

National Water Act (NWA), marking the inception of noteworthy enforcement efforts, particularly regarding wetlands (Dippenaar et al., 2014). The study area is characterized by minor class aquifer with moderate vulnerability and medium susceptibility (DWA, 2012 & 2013). This refers to the qualitative assessment of how susceptible a groundwater aquifer is to potential contamination from human activities (DWA, 2012 & 2013). It encompasses both the vulnerability of the aquifer, and the significance of the aquifer based on its classification (DWA, 2012 & 2013).

3.1.5. Burial Spatial Analysis

The study area within Temba Cemetery encompasses a total of 13,673 burials for adults and 4,695 burials for children, resulting in a cumulative total of 18,368 burials. The site exhibits an open field, while the residential area to the east is densely populated. The total land area under investigation covers approximately 207,705 square meters, with the southwestern portion characterized by dense vegetation and surface water bodies. The cemeteries within the site occupy an approximate area of 95,976 square meters. The graves within the study area are primarily located in the northern region.

3.2. Site Historical Data Review

The field work was previously carried out at Temba Cemetery by various researchers and comprised of various Geotechnical and Hydrogeological investigations (Dippenaar et al., 2014).

3.2.1. Information on Burial Practices

In this research, a critical aspect was to gain an understanding of burial practices, as these practices directly influenced the potential for the transmission of pathogens. To collect data on burial practices and historical records was utilized. Essential data elements included information about the depths at which burials occurred, and the frequency of burials was requested from the cemetery management and examined to extract information about the evolution of burial practices over time. In accordance with Chapter 2, Section 12(2) of the Cemeteries and Crematoria By-Law, it is stipulated that following the burial of a coffin, a minimum of 300 mm of soil must be placed over the coffin (RSA, 2004). Additionally, there should be a minimum distance of 1,200 mm of soil between the coffin of an adult and the surface of the ground, or a minimum of 900 mm of soil in the case of a child's coffin (RSA, 2004). It was observed that the burial practices at Temba Cemetery grave standards adhered to this By-Law, however, it was noted that certain burials occurred at depths that less than the requirements outlined in the By-Law, primarily because of shallow sandstone bedrock and the presence of a high-water table in the area (RSA, 2004).

Burial at Temba Cemetery commenced in the late 1960s and currently taking place with an average burial rate of approximately twenty graves per year. The research study area is divided into eight designated sections, denoted by letters A through H, P, and O.S. Each of these sections contains a specific quantity of buried corpses. Table 1 below gives information about the cemetery and the number of the buried corpses over time.

Table 1: The record of burials in Temba cemetery (adopted from Dippenaar et al., 2014).

Number of sections	Start year for burial	End year for burial	Total number of buried corpses	Adults or children
Section A	2002	2008	878	Adults
Section B	2002	2005	840	Adults
Section C	2002	2009	724	Adults
Section D	2003	2009	208	Adults
Section E	2006	2008	354	Adults
Section F1	2003	2008	380	Children
Section F2	2008	2009	37	Children
Section F3	2009	2012	112	Children
Section F4*	2010	Still in operation	48	Children
Section G	2008	2010	760	Adults
Section H	2005	2007	149	Adults
Section P1	2003	2005	135	Adults
Section O. S	1966	2005	9 625	Adults
Section O.S 2	1966	2004	4 118	Children

3.2.2. Characterization of Soil and Rock Properties

In June 2012, a total of seven test pits were excavated using a CASE tractor loader backhoe (TLB) at Temba Cemetery. This excavation method was employed to gather data about the physical characteristics of the soil and rock layers. The investigation was conducted in accordance with the

guidelines outlined in the site investigation code of practice as per SAICE (2010). Following the excavation of each test pit, a thorough soil profiling process was conducted, and detailed records were made of all geological conditions. Each vertical section of the soil profile was accurately described in terms of its moisture content, colour, consistency, structure, soil texture, and origin, in accordance with the MCCSSO standards (Dippenaar et al., 2014). The positions of the excavated test pits are illustrated in Figure 7 below.



Figure 7: Positions of excavated tests pits at the site area (Dippenaar et al., 2014).

Test pit method serves as a fundamental means of providing essential information about the soil profile, facilitating the recognition of geotechnical conditions in the area, and offering a quantitative assessment of material properties, as elucidated by Brink and Bruin (1990). From each of the seven test pits, soil samples were collected and strategically selected for the laboratory analysis for particle size distribution.

3.2.3. Soil Sampling

The soil samples obtained from the test pits underwent analysis to assess their particle size distribution and Atterberg limits. This analysis quantified the proportions of sand, silt, and clay within the soil, offering valuable information regarding its permeability and the potential for the

transport of pathogens. These soil samples were sent to Soillab (Pty) Ltd, an accredited laboratory adhering to the South African National Accreditation System (SANAS) standards and situated in Lynwood to determine the particle size distribution and Atterberg limits of the soil. This laboratory possessed the requisite proficiency and advanced equipment to conduct precise soil analyses (Dippenaar et al., 2014). Table 2 below provided a summary during the excavation of test pits on site.

Table 2: Field observation during test pits excavation at the study area (Dippenaar et al., 2014).

Test pits	Depth of Alluvium (mbgl)	Depth to Pebble Marker (mbgl)	Depth to Sandstone (mbgl)	Depth of Test pit (mbgl)	Soil Sampling Depth (mbgl)	Water Strike Depth (mbgl)
VT01	0.64	None	1.95	2.3	0.0 – 2.30	2.15
VT02	0.96	None	1.44	2.3	0.96 – 2.30	2.1
VT03	0.86	2.05	1.4	2.47	None	1.2
VT04	0.49	None	1.09	2.32	None	0.4
VT05	0.79	None	1.52	1.8	None	0.9
VT06	0.24	None	1.07	2.13	None	0.1
VT07	0.95	None	1.52	2.42	None	None
Notes: mbgl - Meters below ground level						

Understanding the soil characteristics, particularly the clay content and its swelling potential, is crucial when modelling the fate and transport of microbial pathogens at Temba Cemetery, Hammanskraal, South Africa. The Atterberg limits, specifically the plastic limit (PL) and plasticity index (PI), are instrumental in classifying soil and evaluating its plasticity concerning geotechnical parameters like compressibility, permeability, and shear strength (Casagrande, 1932). This knowledge is valuable in assessing the behaviour of soil regarding its ability to retain water and its cohesive properties (Casagrande, 1932). The plasticity index (PI) and liquid limit (LL) serve as indicators of the relative swell potential of clay soil (Bain, 1971). For instance, soils containing

more than 30% clay content and a PI exceeding 35% are considered active clays, while those with clay content and PI above 10% are labelled as inactive clays (Bain, 1971).

In the context of Temba Cemetery, the analysis of soil samples reveals liquid limits ranging from 46% to 65% and plasticity indexes between 20% and 30%. All samples exhibit plasticity indexes below 35%, indicating that the present clay minerals lack high activity or cohesion. For example, a specific soil sample from test pit (VT03) with a plasticity index of 30% indicates a cohesive sandy clay soil type. This understanding of soil characteristics, particularly clay-related properties, and their swell potential, provides crucial groundwork for modelling microbial pathogen fate and transport. It helps in assessing how soil properties might influence the movement and behaviour of microbial pathogens and faecal indicators within the cemetery environment, impacting risk analysis and strategies for management and mitigation. The soil samples collected from the test pits comprised of silts and clays based on the particle size distribution analysis.

The following chapter “Chapter 4” is the research methodology chapter it outlines how the multi-tiered approach, incorporating various methods and strategies, contributes to achieving the research objectives. It establishes the foundation for the entire dissertation by elucidating the systematic and rigorous approach adopted to investigate the fate and transport of microbial pathogens at Temba Cemetery.

CHAPTER 4: RESEARCH METHODOLOGY

This research methodology outlined the multi-tiered approach employed to model the fate and transport of microbial pathogens and conduct risk analysis using faecal indicators at Temba Cemetery in Hammanskraal, South Africa.

4.1. Introduction

The research methodology for this study was designed to investigate the fate and transport of microbial pathogens in the context of burial practices at Temba Cemetery in Hammanskraal, South Africa. The study aimed to evaluate the potential contamination of groundwater and surface water sources, assess the risks to human health, and provide recommendations for mitigating these risks effectively. The methodology employed a multi-tiered approach, integrating data collection, laboratory analysis, modelling, risk assessment, monitoring, adaptation, and reporting strategies. Research methodology flow chart for the research is presented under Figure 8 below.

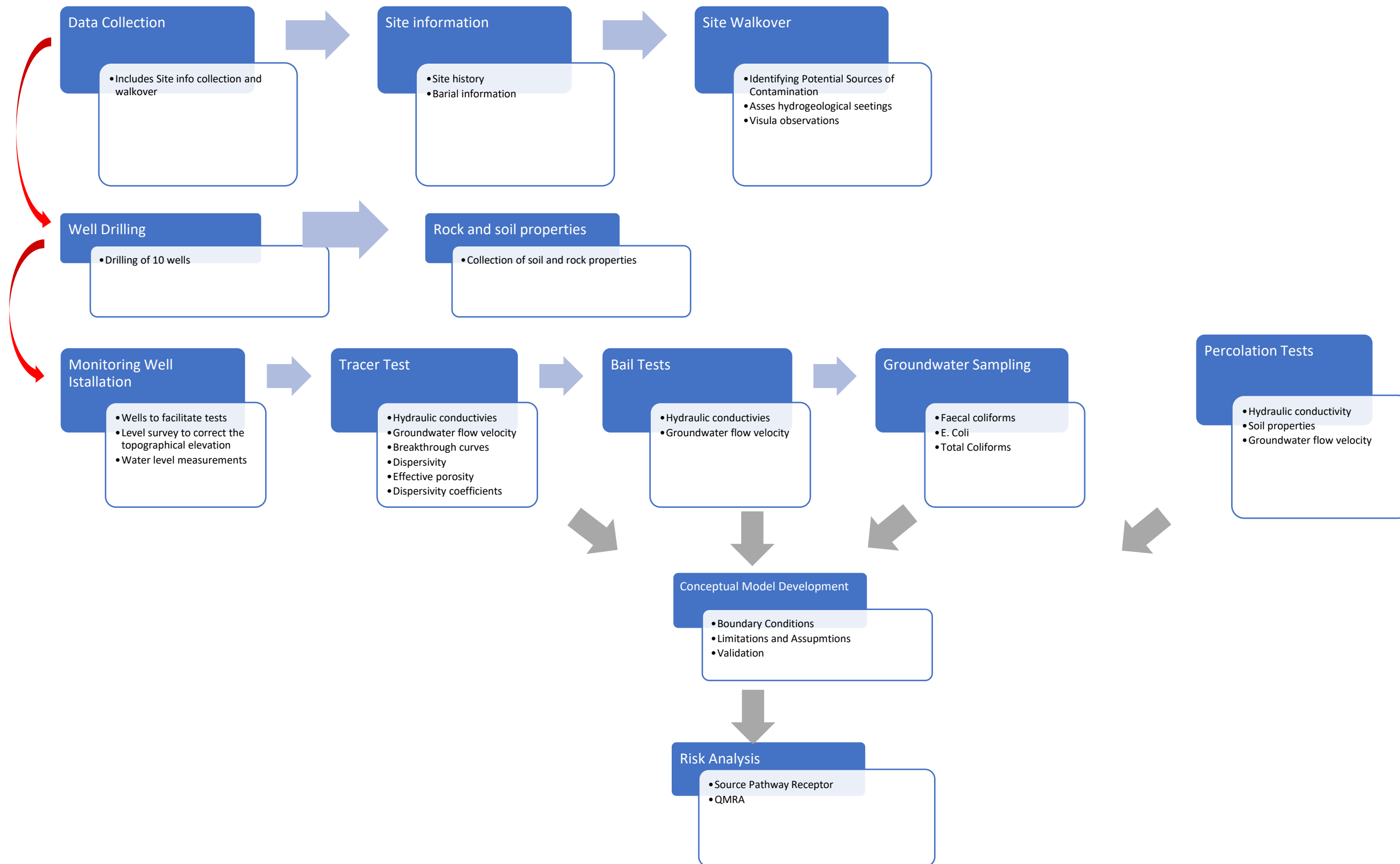


Figure 8: Research methodology flow chart for Temba Cemetery

4.2. Data Collection

4.2.1. Information on Burial Practices

Understanding burial practices was a crucial aspect of this research and data on burial practices were gathered through a request of historical records. Key information included burial depths, number of burials and burial frequency were gathered from the cemetery management. Groundwater hydrocensus survey data was collected in the cemetery's neighbouring properties to gather groundwater quality data at the points of receptor.

4.2.2. Site Visits

The site visits were conducted to gain a firsthand understanding of the cemetery's layout, environmental conditions, and potential sources of contamination. These visits served multiple purposes:

- i. **Identifying Potential Sources of Contamination:** Site visits allowed researcher to identify areas within the cemetery that may have posed a higher risk of contaminating groundwater and surface water.
- ii. **Assessing the Hydrogeological Setting:** Understanding the hydrogeological setting was essential for modelling pathogen transport. Researcher assessed factors such as groundwater depth, flow direction, and the presence of aquifers.
- iii. **Consolidating Climatic Data:** Historical climatic data, including effective rainfall in the study area, were consolidated. This data was crucial for understanding how climatic conditions may have influenced pathogen transport.

4.2.3. Site Walkover

In the context of examining the fate and movement of microbial pathogens near Temba Cemetery in Hammanskraal, South Africa, the preliminary site walkover serves as an opening phase of the research. This section focuses on the detailed observations made during the on-site walkover survey. By navigating the area surrounding the cemetery, a thorough visual examination was conducted to identify potential sources, pathways, and environmental factors influencing the transport of microbial pathogens. The goal was to detail and examine features such as land use

patterns, topography, drainage systems, and any observable human activities that could impact the movement of contaminants. This section provides an essential basis for subsequent analyses and modelling efforts aimed at understanding the complex dynamics of faecal indicators and microbial pathogen transport in the research study area. Field observations during site walkover are presented in the photos below.



Photo 1: View of grave located at waterlogged area



Photo 2: View of livestock observed on site



Photo 3: View of sewer utility hole observed on site



Photo 4: Precipitated salts observed on site

In July 2023, a site visit was conducted at the Temba Cemetery in Hammanskraal, South Africa, specifically aimed at conducting a walkover survey to gather pertinent environmental data crucial to the research. Observations revealed notable characteristics within the cemetery environment. Several graves were situated in waterlogged areas, while others remained inaccessible due to excessive groundwater seepage, impeding burial activities. Furthermore, the cemetery perimeter

was enclosed, yet the presence of cattle within the grounds was evident, leading to potential faecal contamination, particularly faecal coliforms, which could significantly influence the study's outcomes. Notably, the presence of six sewer utility holes linked to on-site ablution facilities raised concerns regarding the introduction of faecal coliforms into the research dataset, potentially skewing the findings. Additionally, the cemetery's south westerly region bordered a wetland and stream, with observed salt precipitations during the walkover survey, indicating potential environmental factors that could impact microbial transport and fate within the cemetery grounds.

4.2.4. Groundwater Static Water Levels

A dip meter was used to measure groundwater static water levels at various points within the study area. These measurements provided critical data on groundwater depths.

4.2.5. Hydrogeological Data Collection

The hydrogeological characteristics of the study area were documented. This included information on soil and rock properties, groundwater vulnerability, source protection zones, and aquifer features. The following methods were employed:

4.2.5.1. Drilled Monitoring Wells

In August 2023, a rigorous drilling operation was conducted to establish ten monitoring wells (designated MW1 to MW10) using the hand auger drilling method. These wells were strategically positioned throughout the study area, covering locations upstream (upgradient), within the burial zone (source area), spanning the entire site, and downstream (downgradient). The primary objectives of these wells were to facilitate precise measurement of groundwater levels and to gather data for diverse testing and sampling protocols.

The depths of the installed monitoring wells ranged between 0.67 and 2.05 meters below ground level (mbgl). These depths were meticulously chosen to align with grave depths and were influenced by encountered geological formations. During the drilling process, groundwater presence was identified or encountered within depths ranging from 0.3 to 1.30 mbgl. Soil samples, collected at different depths, were characterized according to the guidelines stipulated by the

MCCSSO (Brink & Bruin, 2001) for thorough description and analysis. Field observations during monitoring well drilling is presented in the photos below.



Photo 5: Hand auger drilling of MW3



Photo 6: Geological log profile of MW3



Photo 7: Hand auger drilling of MW8



Photo 8: Geological log profile of MW8



Photo 9: View of MW10 after installation



Photo 10: View of MW2 after installation

Each auger-drilled hole was outfitted with a 63 mm outer diameter PVC perforated casing to establish a dedicated point for monitoring groundwater. The space surrounding these casings was filled with carefully washed and graded silica gravel to ensure optimal conditions. To prevent any surface run-off from infiltrating the wells, a precise concrete grout seal was applied to seal off these monitoring well installations. These wells construction was used to develop the well geological logs.

Ten monitoring wells (designated MW1 to MW10) were drilled and installed on and off site to facilitate precise measurement of groundwater levels and to gather data for diverse testing and sampling protocols. During the drilling process, groundwater presence was identified or encountered within depths ranging from 0.3 to 1.30 mbgl. These well constructions served as the basis for developing detailed geological logs, crucial for analysis and are included in Appendix I of this report. Observations and measurement during drilling of monitoring wells is presented in Table 3 below.

Table 3: Drilled monitoring wells observations

Monitoring Wells	X-Y Coordinates (degrees)		Elevation (mamsl)	Groundwater Strike Depth (mbgl)	Total Well Depth (mbgl)
	Southing	Easting			
MW1	25.39262	28.25545	1099	0.30	1.70
MW2	25.39385	28.25735	1098	0.30	1.90
MW3	25.39227	28.25816	1102	1.00	2.05
MW4	25.3931	28.25846	1098	1.00	1.50
MW5	25.39404	28.25871	1101	0.50	0.80
MW6	25.39388	28.25952	1102	1.30	1.30
MW7	25.39472	28.25889	1099	0.40	1.20
MW8	25.39383	28.25803	1099	0.50	1.00
MW9	25.3946	28.25797	1099	0.50	2.00
MW10	25.39422	28.25858	1099	0.55	0.67
BH1	25.39673	28.26328	1088	-	Unknown
Stream	25.39517	28.25785	1087	-	-
Notes:					
- = Could not measure					

The geological composition derived from the drilled soil cuttings consisted of silty sand and clay alluvium, transitioning to sandstone bedrock at greater depths. The site's elevation is approximately 1,099 meters above mean sea level (mamsl) and GPS coordinates, and elevation data for each well are presented in Table 3 above. The lithological observed during hand auger drilling makeup aligns closely with the broader regional geological formations delineated in geological mapping records. The elevation data exhibits a gentle hydraulic gradient of 0.0063 in a southward direction.

4.2.5.2. Characterization of Soil and Rock Properties

Site historical data for trial pits using a tractor loader backhoe (TLB), and current data for drilling of monitoring wells using a hand auger were consolidated. These methods provided information about the physical properties of the soil and rock layers, which influenced pathogen transport.

4.2.5.3. Groundwater Flow Analysis

Monitoring wells were used to determine the direction and velocity of groundwater flow. Data on groundwater monitoring wells was collected on-and off-site, as well as from boreholes discovered during the hydrocensus survey. A dumpy level was used to measure the relative heights of each installed well on-site. The measurements are accurate to 1 cm. These measurements are used to calculate the local groundwater flow direction on-site, by contouring these wells using recorded elevation meters above mean sea level (mamsl).

4.2.6. Hydraulic Property Quantification

Quantifying the hydraulic properties of the geology in the study area was vital for understanding how water moved through the subsurface. Several tests were performed to assess these properties:

4.2.6.1. Percolation Tests

Percolation test at Temba Cemetery was conducted to determine the permeability of the soil as permeability was a critical factor in understanding how pathogens may have moved through the soil in this research. The Temba Cemetery employed the traditional inverted auger hole method to evaluate the saturated hydraulic conductivity of the soil.

In this method, a hand auger was employed to drill a hole into the soil at the selected location, reaching a depth of 300 mm (Dippenaar et al., 2014). The diameter of the hole was 9.5 centimetres. After measuring the depth of the hole, it was thoroughly saturated with water by allowing the water to drain away completely three times before conducting the test (Dippenaar et al., 2014). Thereafter, the water level inside the hole was monitored as it gradually dropped due to percolation into the surrounding soil (Dippenaar et al., 2014). The time it took for the water level to drop a

certain distance was recorded, and the saturated hydraulic conductivity is calculated using Darcy's law (Dippenaar et al., 2014).

The experiments were conducted considering the soil's texture, and measurements were taken when the soil was fully saturated. The equation that describes the connection between the percolation test (PT) and the field saturated vertical hydraulic conductivity (Kfs) was as follows (Reynolds et al., 2015):

$$K_{fs} = \frac{\bar{C}_i a^2}{PT_i [2\bar{H}_i^2 + \bar{C}_i a^2 + \left(\frac{2\bar{H}_i}{\alpha^*}\right)]} \quad 4$$

Where:

- H = Mean water depth during a test
- a = the radius of the test pit
- α^* = the representative soil sorptive number, and
- C = is a shape function.

The data collected during percolation test was used to estimate the vertical hydraulic conductivity using the Porchet Method given by the following equation (Porchet, 1945):

$$K = \frac{V}{A.t} \quad 5$$

Where:

- K = Hydraulic conductivity (m/d)
- V = Volume of water that percolated through the soil (m^3)
- A = Area of the soil exposed to percolation (m^2), and
- t = Time over which the volume was measured (day).

4.2.6.2. Bail Tests

On 15 December 2023, a dumpy level was employed to measure the relative heights of each accessible monitoring well on-site. This approach aimed to quantify the hydraulic conductivity

(Kfs) of the underlying strata, providing a detailed understanding of how water moves through different soil types. The variability in hydraulic conductivity across diverse soil types, as determined through the bail tests and height measurements of monitoring wells, is instrumental in developing accurate models for predicting the movement of contaminants and microbial pathogens near the cemetery. This data forms a critical foundation for risk analysis related to faecal indicators, aiding in devising strategies to protect nearby water sources, and safeguarding the community's health. Understanding how water flows through these strata is pivotal in comprehending the potential pathways and risks associated with microbial pathogens in the vicinity.

Bail tests were performed on all monitoring wells which contained groundwater to assess the hydraulic properties of the soil and rock layers. These tests aimed to assess how easily water moves through the underlying strata, a crucial factor in understanding the fate and transport of microbial pathogens near Temba Cemetery in Hammanskraal, South Africa. The bail tests involved utilizing disposable bailers to extract water from the monitoring wells and create a negative displacement, inducing a hydraulic gradient towards the hole. This process allowed the measurement of how quickly the water level recovered, reflecting the hydraulic conductivity of the saturated zone.

The following procedures according to the ICRC (2011) and ASTM D4044-96 (2008) were followed to conduct field bail tests:

- An appropriate local reference point was selected, such as the top of the casing, as the baseline for all water level measurements, and determined the static water level. Ensured that the water level remains stable and motionless before commencing the test.
- During the bail test a disposable bailer was used to remove known quantity of water from the monitoring well and negatively displaced the water.
- Consequently, the water level in the well recovered, creating a hydraulic gradient towards the hole.
- A stopwatch was used to record the water level's reaction to the alteration in water level as well recovers. The frequency of measuring the water level during the test was adjusted based on the hydraulic conductivity of the material under examination.
- In the initial phases of the test, water level measurements were taken at frequent and closely timed intervals.

- Conducted manual water level measurements using a dip meter as frequently as practical until the water level has regained 60 to 80 percent of its initial level. As the test progressed and extended in duration, gradually extended the time intervals between measurements.
- After completing the test, an initial data analysis was performed on-site and assessed the test results based on the criteria outlined in the test method and the specified analysis procedure before concluding field operations.

The rate at which the water level recovers to its static state allows the calculation of the hydraulic conductivity of the saturated zone.

To analyse bail test data for unconfined aquifers using Hvorslev's method (1951), field measurements of recovery (m) and time (s) are taken during the test. These data points are converted into the dimensionless parameter H_t/H_0 where H_t represents the water level at time t and H_0 represents the initial water level immediately after bailing (Butler, 1998). The purpose of converting the data into this dimensionless ratio is to normalize the data, making it easier to compare the recovery curve across time (Butler, 1998). This method is applicable for slug or bail tests conducted in wells screened in unconfined aquifers (Heath, 2013).

The normalized data are then plotted on a semi-logarithmic scale to create a graph of H_t/H_0 versus time (Butler, 1998). This plot enables the identification of the time lag T_L , which corresponds to the time at which $H_t/H_0 = 0.37$ (Hvorslev, 1951). The time lag is critical for calculating hydraulic conductivity, as it reflects the rate at which the aquifer responds to the bail test (Hvorslev, 1951). The graphical method provides a simple yet effective means of visually analysing the recovery data (Hvorslev, 1951).

Once the time lag is determined, the hydraulic conductivity K is calculated using Hvorslev's method for unconfined conditions given by the following equation (Hvorslev, 1951):

$$K = \frac{r^2 \ln\left(\frac{L}{R}\right)}{2LT_L} \quad 6$$

where r is the effective radius of the well, L is the screen length, and R is the radius of the well including the gravel pack (Hvorslev, 1951). This equation accounts for the geometric properties

of the well and the aquifer system, providing a means to estimate hydraulic conductivity based on the time-lag data (Hvorslev, 1951). The Hvorslev method is particularly advantageous for bail test analysis in unconfined aquifers because it simplifies the process of estimating hydraulic conductivity with minimal data requirements and straightforward calculations (Fabbri et al., 2012). By plotting H_t/H_0 against time, it is possible to determine the aquifer's response to stress and calculate K effectively (Hvorslev, 1951). This methodology has been widely used and validated in hydrogeological studies, making it a reliable approach for analysing bail test data (MacDonald et al., 2008).

The Hvorslev Solution makes several simplifying assumptions (Hvorslev, 1951):

- The aquifer is vast and has no boundaries.
- The aquifer's properties are consistent throughout.
- The water table is flat before the test begins.
- Water is pumped or injected quickly, causing a sudden change in water level.
- The weight of the water and any resistance to flow are insignificant.
- The well goes all the way through the aquifer.
- The well is very thin.
- Water moves horizontally toward or away from the well.

The effective piezometer radius (r) was calculated using the following equation (Hvorslev, 1951):

$$r = \sqrt{r_i^2(1 - \eta_e) + \eta_e R^2} \quad 7$$

Where:

- r is the inside radius of the piezometer
- R is the Radius of the filter pack
- η_e is the filter pack effective porosity determined from Woessner and Poeter (2020)

4.2.6.3. Tracer Tests:

To understand the complex movement and behaviour of microbial pathogens at Temba Cemetery, tracer tests served as a fundamental component of the investigation. Sodium chloride (NaCl) was used as a tracer, to trace the pathways and movement of substances including pathogens in the groundwater. During these tests, careful measurements of electrical conductivity (EC) were taken at various stages, offering crucial insights into the transport mechanisms of contaminants. This section explores the methodologies and outcomes of these tracer tests, shedding light on how NaCl served as a tracer and the invaluable data derived from EC measurements. Through this rigorous approach, the research aims to enhance our understanding of how microbial pathogens move through the environment, aiding in risk analysis and the formulation of strong models for safeguarding community health in the vicinity of Temba Cemetery.

Sodium chloride (NaCl) was selected as the preferred tracer, with 2.0 kg of NaCl prepared and dissolved within twenty liters of water to create the tracer solution. The mixing process was conducted on-site, lasting for approximately 57 minutes. NaCl serves as an advantageous groundwater tracer for several reasons. Firstly, its non-toxic and environmentally gentle nature ensures minimal impact on ecosystems and human health, making it a safe choice for tracer studies. Additionally, its widespread availability and affordability render NaCl a practical option, facilitating extensive and cost-effective tracer tests. Tracer tests using sodium chloride (NaCl) were crucial in studying how microbial pathogens move at Temba Cemetery. They helped track the paths of substances, including pathogens, in the groundwater (Peinado Guevara et al., 2012). Measurements of electrical conductivity (EC) were carefully taken during these tests at various stages, giving valuable insights into how contaminants are transported. The EC measurements were converted to chloride (Cl^-) concentrations using a formula $[\text{Cl}^-] = 9.22 \text{ EC}$, for $0.15 < \text{EC} < 95 \text{ dS m}^{-1}$ in the linear regression model from Peinado Guevara et al. (2012).

Multi-well tracer tests were conducted as needed to determine the flow rates, aquifer hydraulic conductivity, effective porosity and dispersivity in the porous aquifer. These tests involved introducing a tracer substance into the groundwater and tracking its movement, similarly to Novakowski (1992), Novakowski et al. (1995), and Sauty (1980). The procedure for the test carried out is outlined below:

- To conduct this test, two boreholes are required within the same aquifer. One borehole is used for injecting a tracer, and the other is used to monitor the breakthrough of the tracer.
- The distance between these boreholes cannot be predetermined. A shorter distance results in a quicker test, but it also tests a smaller area. The time it takes for the tracer to travel depends on the velocity within the aquifer, typically ranging from 5 to 20 meters as a reference.
- The objective is to establish a steady-state flow between the two boreholes (creating a radial flow field) by abstracting water from the aquifer zone under investigation. This is achieved by continuously pumping water from the reception borehole at a constant discharge rate.
- The pump is positioned just below the top of the aquifer, usually around half a meter deep. There is no need to fully stress the borehole.
- Constant monitoring of the water levels in both the injection and reception boreholes is necessary to control the development of the radial flow field.
- Once a steady-state flow with a constant water level is achieved, the tracer test is initiated by injecting tracer material into the injection borehole.
- From the start of the injection, periodic measurements of tracer concentration are taken at predefined intervals in the water discharged from the reception borehole. These measurements continue until the breakthrough curve is observed, and the tracer's concentration returns to its initial background level.
- Throughout the test, ongoing measurements of water levels and discharge rates are maintained to ensure steady-state conditions.

Two wells, namely Injection Well 1 (IW1) and Observation Well 1 (OW1), were drilled at distances of 7.5 meters and five meters, respectively, from Abstraction Well (MW9). IW1 and OW1 were both drilled using the hand auger method, employing a 9.5 cm diameter, reaching depths of 1.03 meters and 1.11 meters below ground level (mbgl), respectively. MW9 served dual purposes as an abstraction well and a tracer monitoring well, housing a submersible pump installed at a depth of 1.55 mbgl. Groundwater extraction was conducted under steady-state conditions at a rate of 0.395 liters per minute, maintaining the water level in MW9 at 1.20 mbgl during pumping.

Notably, IW1 and OW1 lacked installation casings. Field observations during tracer test are presented in the photos below.



Photo 11: Experimental setup for tracer test



Photo 12: Connection between Abstraction well and flowthrough chamber



Photo 13: View of flowthrough chamber and water quality parameters

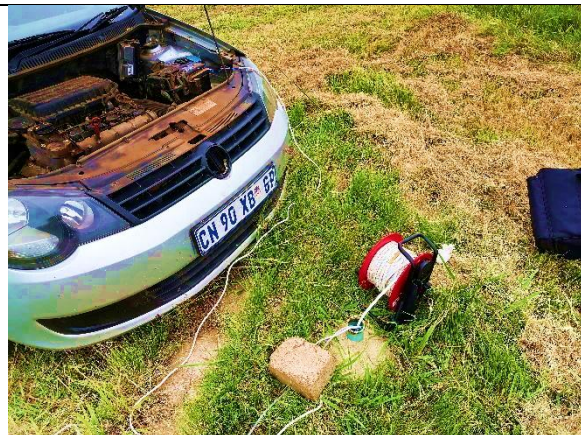


Photo 14: View of an abstraction borehole (MW9)

4.2.7. Soil and Water Sampling

The collection of soil and water samples was a fundamental component of this research. Samples were collected from various locations to assess the presence and concentration of microbial pathogens. The following methods were employed:

4.2.7.1. Soil Samples

Soil samples were historically collected from test pits on-site. These samples were analysed for particle size distribution, a key factor influencing soil permeability. Therefore, historical data from published articles at the study area were used.

4.2.7.2. Water Samples

Water samples were collected from relevant groundwater wells, and private water supply borehole in the vicinity of the cemetery. The sampling of groundwater and surface water for microbial analysis was conducted in strict adherence to local and international guidelines, specifically those outlined by the Water Research Commission (Weaver et al., 2007) and the Environmental Protection Agency (EPA, 2009). The primary objective of these guidelines was to ensure the collection of uncontaminated and representative samples for microbial analysis.

Prior to sampling, all equipment was thoroughly sterilized, and sterile gloves were used to minimize the risk of contamination (Weaver et al., 2007 and EPA, 2009). Groundwater wells were slowly purged using a clean bailer to avoid disturbing the microbial populations, while surface water samples were collected from approximately 15 cm below the water surface to prevent contamination from surface debris (Weaver et al., 2007 and EPA, 2009). After collection, samples were immediately placed in coolers with ice to maintain a temperature of approximately 4°C and were transported to the laboratory for analysis within 24 hours (Weaver et al., 2007 and EPA, 2009). No chemical preservatives were added to the samples to avoid interference with the microbial analysis. New clean bailers and sampling bottles were used for collection of each sample to avoid cross contamination.

Following each sampling event, all equipment was decontaminated using Alconox solution to prevent cross-contamination. Detailed field notes were recorded, and chain-of-custody forms were completed to document the handling of each sample from the field to the laboratory (Weaver et al., 2007 and EPA, 2009). By adhering to these guidelines, the successful collection of uncontaminated groundwater and surface water samples for microbial analysis was ensured, providing reliable data for assessing the microbial quality of the water sources.

4.2.7.3. Environmental Parameters

Environmental parameters such as temperature, pH, dissolved oxygen, and conductivity were recorded during sampling to provide additional context for water quality analysis. The methodology for collecting field environmental parameters such as temperature, pH, dissolved oxygen, and conductivity was rigorously applied using a calibrated water quality probe. Calibration of the probe followed the manufacturer's instructions and was performed prior to each field session to ensure sensor accuracy (U.S. Geological Survey, 2020). Once calibrated, the probe was carefully immersed in the sample and special care was taken to minimize disturbance to the sediment, which could potentially alter readings (U.S. Geological Survey, 2020). The probe was allowed to stabilize in the water for a few minutes before readings were taken, allowing the sensors to equilibrate with the environmental conditions, crucial for accurate temperature and dissolved oxygen measurements (U.S. Geological Survey, 2020).

Recordings of temperature, pH, dissolved oxygen, and conductivity were then taken in real-time. Consistency in the procedure of measurements was maintained when multiple samples were collected across the site, particularly for pH and dissolved oxygen, to ensure data comparability (Khan et al., 2023). Multiple measurements were taken at each sampling point to account for natural variability and strengthen the robustness of the data (Rousseeuw and Verboven, 2002). Each set of readings was meticulously logged alongside pertinent environmental metadata such as time of day, weather conditions, and GPS coordinates, enriching the contextual framework of the collected data (Woolf et al., 2023).

4.2.7.4. Water Quality Strips

Water quality strips were used in the field to record parameters such as total alkalinity, chlorine, nitrate, iron, carbonate root, nitrite, and sulphate. These parameters were essential for understanding the overall quality of the water samples collected. The field methodology for water sampling using water quality test strips can be outlined as follows:

The field measurement begins with the collection of water samples, which was conducted in clean, sterile containers to avoid contamination (U.S. Geological Survey, 2020). Each sample was labelled with relevant information, including the date, time, and location of collection, ensuring traceability and accuracy in the analysis (Woolf et al., 2023). Once the samples are collected, test

strip was used to measure the desired water quality parameters. Each strip is designed to change colour when exposed to specific chemicals in the water, providing a visual indication of concentration levels (Phukpattanachai et al., 2024). The strip was dipped into the water sample for the time ranging between 5 to 10 seconds, and then removed, allowing any excess water to drip off (Kim & Cho, 2022). The results were taken within the time frame, typically 30 to 60 seconds, to ensure accurate measurements (Silte, 2023).

The measurement of Total Alkalinity, Free Chlorine, Nitrate, and Nitrite using test strips is relatively straightforward. After dipping the strips into the water, the colours on the strips were compared against a colour chart provided by the manufacturer, which correlates the colour intensity with concentration levels (Kim & Cho, 2022). For Iron and Carbonate Root, the process was similar, though the strips required a slightly longer exposure to the sample, depending on the manufacturer's instructions (Spaanderman et al., 2014).

To ensure the reliability of the results, fresh test strips for each sample was used to avoid cross-contamination (Alketbi, 2024). Additionally, the calibration of test strips was verified periodically against known standards to maintain accuracy in long-term monitoring projects (Cheng and Zhu, 2005). The results were documented immediately in a field logbook with any deviations or unusual findings noted for further investigation (U.S. Geological Survey, 2014).

On 27 August, 4 November and 3 December 2023, water samples were collected from relevant groundwater wells, nearby stream, and private water supply borehole in the vicinity of the cemetery. Stringent sampling protocols, aligning with both local and international standards, were carefully followed throughout the sampling process. These references served as fundamental guidelines, ensuring the accuracy and reliability of the gathered water samples for analysis and assessment.

Groundwater samples were collected using bottom filling bailers with rope after purging. The samples were collected for E. Coli, Faecal coliforms, and Total Coliform analyses in a 500 ml plastic bottle for all the monitoring wells, stream, and a private borehole. The samples were kept cool, by using a cooler box with ice packs during the sampling event. Samples were then dispatched to the laboratory and analysed within 24 hours. A Chain of Custody (CoC) was

compiled as part of the quality process. All monitoring wells and a private borehole were found to be in good condition during the sampling process. Field observations during groundwater sampling are presented in the photos below.



Photo 15: View during groundwater sampling of MW9 on site.



Photo 16: Groundwater sampling by bailing method in MW2

4.3. Laboratory Analysis

Laboratory analysis was a critical component of this research, as it allowed for the precise measurement of microbial pathogens and other water quality parameters. The following laboratory tests were conducted:

4.3.1. Soil Analysis

Soil samples were historically collected from test pits and analysed for particle size distribution. The analysis determined the percentage of sand, silt, and clay in the soil, providing insights into its permeability and potential for pathogen transport. Historically collected soil samples were submitted to Soillab, a South African National Accreditation System (SANAS) Accredited Laboratory located in Lynwood. This laboratory had the necessary expertise and equipment to perform accurate soil analysis.

4.3.2. Water Analysis

Water samples collected from groundwater wells, surface water bodies, and springs underwent extensive analysis to assess their quality. The primary focus of the analysis was the presence of faecal indicators, particularly *Escherichia coli* (*E. coli*), using standard microbiological techniques. The collected water samples were submitted to the Environmental Pollution Laboratory, a South African National Accreditation System (SANAS) Accredited Laboratory located in Centurion. This laboratory specialized in water quality analysis and had the capacity to detect and quantify microbial pathogens. In addition to *E. coli* analysis, water samples were subjected to further water quality tests. These tests may have included the measurement of total coliforms and faecal coliforms. These parameters provided valuable information about the potential for pathogen contamination and water quality degradation.

4.4. Modelling the Fate and Transport of Microbial Pathogens

Modelling the fate and transport of microbial pathogens was a vital component of this research. It involved developing a conceptual model of the cemetery site and the surrounding hydrogeological system, creating mathematical equations to describe pathogen movement, incorporating relevant factors, and validating the model. This modelling process was crucial for understanding how pathogens may have moved through the environment and assessing the associated risks.

4.4.1. Conceptual Model Development

The first step in modelling the fate and transport of microbial pathogens was to create a conceptual model of the cemetery site and the surrounding hydrogeological system. This model served as a simplified representation of the real-world system and included key components and their interactions.

The conceptual model considered the following elements:

- The cemetery layout and burial areas.
- Soil and rock layers, including their permeability and hydraulic properties.
- Groundwater flow patterns, direction, and velocity.

- Hydrological parameters, such as effective rainfall.
- The presence of aquifers and their characteristics.
- Burial practices, including burial depths and liners.
- Environmental factors that may have affected pathogen transport.

The conceptual model provided a framework for developing mathematical equations that described the movement and dispersion of microbial pathogens within the system.

4.4.2. Mathematical Equations

Mathematical equations were essential for simulating the fate and transport of microbial pathogens. These equations were used based on the identified transport mechanisms and the data collected during fieldwork. Key factors that were taken into consideration when using the equations included:

- Burial practices: The depth of burials, the presence of liners, and other burial-related factors influenced pathogen release into the soil.
- Groundwater flow patterns: The direction and velocity of groundwater flow determined the potential pathways for pathogen transport.
- Hydrological parameters: Effective rainfall and other climatic conditions affected soil moisture levels and pathogen movement.
- Microbial die-off rates: The survival and persistence of microbial pathogens in the environment were considered in the equations.

The mathematical equations were used to simulate the movement and dispersion of microbial pathogens over time and distance. These equations were a fundamental component of the model used to assess pathogen fate and transport.

4.4.3. Model Validation

The accuracy and reliability of the model were critical for making informed assessments of pathogen transport and risks. To ensure the model's validity, it was rigorously validated using field observations and calibration techniques. Validation involved comparing the model's predictions

with real-world data collected from the study site. This data may have included measurements of groundwater levels, pathogen concentrations, and other relevant parameters. By comparing model outputs with observed data, researchers assessed how well the model represented the actual system. Calibration techniques may have been employed to adjust model parameters to improve its fit with observed data. This iterative process ensured that the model accurately reflected the complex interactions within the hydrogeological system and the behaviour of microbial pathogens.

4.5. Risk Analysis

The risk analysis phase of the study was pivotal for assessing the potential risks associated with the presence of microbial pathogens in groundwater and surface water sources. This assessment utilized a systematic approach to evaluate the level of risk to human health. The risk analysis process could be broken down into two key components.

4.5.1. Source Pathway Receptor (SPR) Approach

The Source Pathway Receptor (SPR) approach was a recognized method for assessing environmental risks as it has been used in Belle et al. (2023) and Waldschlaeger et al. (2020). In the context of this research, the SPR approach was employed to systematically evaluate the risks associated with microbial pathogens originating from burials at Temba Cemetery.

The SPR approach involved identifying three key elements:

1. **Source:** The source of contamination, in this case, the microbial pathogens, originated from the burial sites at Temba Cemetery.
2. **Pathway:** The pathway represented how the contaminants travelled from the source to the receptor. Pathways included groundwater flow, surface water runoff, and soil leaching.
3. **Receptor:** The receptor was the entity that may have been exposed to the contaminants. In this study, the receptors were human populations who may have encounter contaminated water sources.

By analysing these elements in conjunction with the model developed in earlier phases, researchers systematically assessed the risks posed by pathogen contamination.

4.5.2. Quantitative Microbial Risk Assessment (QMRA)

Quantitative Microbial Risk Assessment (QMRA) played a pivotal role in understanding the dynamics of microbial pathogens' fate and movement in environmental settings like the Temba Cemetery in Hammanskraal, South Africa. This model focused on explaining how faecal indicators, which serve as surrogates for pathogens, travel and persist in this environment. QMRA provided a structured framework for estimating the likelihood of exposure, infection, or health risks associated with the presence of these indicators. By employing hazard identification, exposure assessment, dose-response analysis, and risk characterization, this approach evaluates the potential impact of pathogens originating from the cemetery on the surrounding environment and public health (He & Huang, 2020). Through detailed simulations and empirical data, the model aims to quantify the probability of infection or illness caused by these pathogens, offering insights into strategies for risk mitigation and management at the cemetery site (He & Huang, 2020, and Pepper et al., 2015).

The following chapter “Chapter 5” is the results and interpretation chapter which focuses on the practical aspects of the research, Chapter 5 discusses the methods employed for data collection, including surveys, site visits, and hydrogeological data collection. The chapter emphasizes the importance of a sampling plan to ensure the reliability and representativeness of the gathered data. Furthermore, it interprets the collected data, providing a nuanced understanding of burial practices, environmental conditions, and potential sources of contamination at Temba Cemetery.

CHAPTER 5: RESULTS AND INTERPRETATION

This dissertation chapter systematically details the methodologies applied for data acquisition and analysis concerning the Temba Cemetery in Hammanskraal, South Africa. The methodologies encompass a range of hydrogeological techniques, including the installation of drilled monitoring wells to monitor groundwater dynamics, rigorous analysis of groundwater flow patterns, and precise quantification of hydraulic properties. Extensive percolation, bail, and tracer tests were executed to delineate crucial aspects of groundwater behaviour. Additionally, static water level observations and systematic groundwater sampling, coupled with an environmental parameter assessment via water quality strips and laboratory analysis, were conducted. This chapter concludes in a complex modelling framework to simulate the fate and movement of microbial pathogens. It involves the development of a robust conceptual model, delineation of assumptions and study limitations, definition of boundary conditions, the use of Sauty model (mathematical equation), and rigorous model validation procedures. The site map showing hydrogeological information and positions of drilled monitoring wells is presented in Figure 9 below.



Figure 9: Site layout map of the research study area.

5.1. Groundwater Static Water Levels

On 27 August and 4 November 2023, groundwater static water level (SWL) was measured in the monitoring drilled on site. A dip meter was used to measure groundwater static water levels at various points within the study area. These measurements provided critical data on groundwater depths and fluctuations over time as illustrated in Table 4 below. Hydrocensus survey was conducted in the vicinity of the study area and no additional private water supply boreholes were identified except BH1 located southeast of the study area (See Figure 9).

Table 4: Field measurement and observation during site visits

Sample ID	Sample Volume (ml)	Purged Volume (L)	Sampling Method	Static Water Level (mbgl)		Sample Description		
		27-Aug-23		27-Aug-23	4-Nov-23	27-Aug-23	4-Nov-23	3-Dec-23
MW1	500	50	Bailing	0.80	1.12	Light orange brown water	Light grey water	No sample collected
MW2		75		0.32	0.36	Orange brown water	Light brown water	
MW3		40		1.24	1.54		Orange brown water	
MW4		10		1.24	1.28		Orange brown water	
MW5		18		0.51	0.60		Orange brown water	
MW6		-		1.26	-	Little water to sample	Well dry at 1.30 mbgl	
MW7		38		0.36	0.44	Dark brown water	Clear water	
MW8		38		0.30	0.30	Light orange brown water	Clear water	
MW9		75		0.56	0.77	Light brown to murky water	Light brown water	
MW10		-		-	-	-	Well dry at 0.67 mbgl	
BH1	-	Tap	-	-	No sample collected	No sample collected	Clear water	
Stream	-	Grab	-	-			Light brown to murky water	
Notes:								
- = Could not measure								

The site visit was conducted during the dry (winter) and wet (summer) seasons. The SWL in August 2023 ranged between 0.30 and 1.26 meters below ground level (mbgl) while in November 2023 ranged between 0.30 and 1.54 mbgl. From Table 4 above, it is evident that shallower water levels were measured during winter seasons when compared to wet season. However, this might have resulted from lower precipitation (< 50 mm per month) in the region between April and October. Understanding these seasonal variations in groundwater levels is essential for comprehending the potential transport and distribution of microbial pathogens, particularly in proximity to Temba Cemetery. 2023.

The visible water seepage and logging conditions on the Temba Cemetery site are likely the result of perched aquifer conditions rather than groundwater discharge from deeper aquifers (Mitsch & Gosselink, 2015; Freeze & Cherry, 1979). Perched aquifers form when water is trapped above an impermeable layer such as clay or silt, creating a localized, shallow water table that is disconnected from the main aquifer (Mitsch & Gosselink, 2015; Freeze & Cherry, 1979). This type of aquifer can lead to surface waterlogging, particularly in areas where there is sufficient water infiltration from rainfall or surface water bodies (Fetter, 2001).

In this case, the presence of a perennial stream passing through the site suggests that water infiltration from surface sources is contributing to the perched water conditions. Rivers and streams can deposit fine-grained sediments over time, forming impermeable layers that trap water near the surface, leading to the formation of perched aquifers (Winter, 1999). The stream, along

with local precipitation, likely plays a significant role in recharging this perched system, which may explain the consistent wet areas observed on the site (Woessner, 2000). Moreover, the seasonal static water level (SWL) variations measured on-site, ranging between 0.30 and 1.54 mbgl, support the idea that the waterlogging is influenced by surface water sources rather than deep groundwater discharge (Boulton et al., 1998). These perched conditions can maintain a near-surface water table that sustains wetland areas or leads to localized waterlogging, especially in low-lying regions of the cemetery (Mitsch & Gosselink, 2015). In addition, a study by Vegter et al. (1995) in the study area revealed that the mean depth of the groundwater level in the deep aquifer ranges between 10 and 20 meters.

Therefore, it is likely that the water seepage and logging conditions at the cemetery are primarily due to perched aquifer conditions and surface water infiltration rather than the discharge of groundwater from deeper aquifers. The water seep conditions at the Temba Cemetery site appear to be influenced by a combination of factors, such as seasonal variations, nearby surface water body, and soil condition. Seasonal fluctuations are evident from the differences in SWL measurements between August 2023 and November 2023. In August (dry season), the SWL ranged between 0.30 and 1.26 meters below ground level (mbgl), while in November (wet season), the SWL ranged from 0.30 to 1.54 mbgl, showing some variability due to seasonal precipitation (Boulton et al., 1998; Mitsch & Gosselink, 2015).

The colour changes in the water samples also suggest seasonal influences on water seepage. For instance, water from MW1 shifted from light orange, brown in August to light grey in November, likely indicating changes in water quality due to increased surface water infiltration during the wet season (Winter, 1999; Woessner, 2000). Similarly, MW7 exhibited a shift from dark brown water in August to clear water in November, further supporting the influence of seasonal precipitation (Mitsch & Gosselink, 2015).

However, there is evidence of persistent perched water conditions contributing to water seepage throughout the year. For example, MW10 remained dry in both August and November, suggesting localized perched aquifer conditions that may limit water seepage in certain areas, regardless of the season (Fetter, 2001). Additionally, the presence of light brown to murky water in MW9 and consistent shallow SWLs in most wells across both seasons suggest that the perched aquifer

continues to maintain waterlogged conditions, particularly in areas with impermeable layers trapping water near the surface (Freeze & Cherry, 1979; Winter, 1999).

The shallow groundwater levels, waterlogging, and perched aquifer conditions directly affect the transport of microbial pathogens, groundwater contamination risk, and the persistence of faecal indicators. The shallow static water levels (SWLs), ranging from 0.30 to 1.54 meters below ground level (mbgl), indicate that microbial pathogens and faecal indicators can easily reach the shallow perched water table, facilitating contamination transport (Mitsch & Gosselink, 2015; Fetter, 2001). The consistently shallow SWLs, even during the dry season, suggest that pathogens are more likely to be transported through the saturated subsurface during rainfall events, when infiltration increases (Mitsch & Gosselink, 2015). The presence of a perched aquifer implies that this contamination is limited to the shallow groundwater system, isolating it from deeper aquifers (Winter, 1999).

5.2. Hydraulic Property Quantification

Quantifying the hydraulic properties of the geology in the study area was vital for understanding how water moved through the subsurface. Several tests were performed to assess these properties:

5.2.1. Percolation Tests

On 14 December 2023, percolation tests were conducted on site at four strategic locations targeting upgradient, burial area and down hydraulic gradient of the site. The percolation data is presented under Appendix II, while the calculated hydraulic conductivities are presented in Table 5 below. The provided table presents the results of percolation tests conducted at various locations, along with the calculated vertical hydraulic conductivities using the Porchet and Reynolds methods. The methodology and equations to calculate the conductivity using these two methods is summarised in Chapter 4. The data highlights the variability in soil type and its impact on hydraulic conductivity. The results of percolation tests provide data on the soil's hydraulic conductivity, which helps in building accurate models for predicting the movement of contaminants. Thus, aiding in evaluating the potential risk of microbial pathogens migrating from burial sites into the groundwater. This information is vital for developing robust models that simulate the pathways and behaviour of contaminants, assisting in risk analysis and informing

strategies for mitigating potential health hazards associated with faecal indicators near the cemetery.

Table 5: Percolation test results and calculated vertical hydraulic conductivities

Percolation Tests	X-Y Coordinates		Elevation (mamsl)	Soil type	Vertical Hydraulic Conductivity - Kfs (m/day) - Porchet Method (Porchet, 1945)	Vertical Hydraulic Conductivity - Kfs (m/day) - Reynolds et al., 2015
	Southing	Easting				
PT1	25.393	28.25871	1093	Gravelly silty SAND	0.2283	0.2923
PT2	25.39367	28.25989	1096	Gravelly fine SAND	0.1709	0.3058
PT3	25.39426	28.2581	1094	Silty SAND	0.1646	0.2236
PT4	25.3947	28.25798	1091	Clayey Silty SAND	0.0883	0.0689
Geometric Mean					0.1543	0.1926

A comparison of the hydraulic conductivities obtained by the Porchet and Reynolds methods reveals some discrepancies. For instance, at PT1 (Gravelly silty SAND), the Porchet method yielded a lower value (0.2283 m/day) compared to the Reynolds method (0.2923 m/day). This disparity can be attributed to the inherent differences in the methodologies themselves. The Porchet method is based on empirical correlations, while the Reynolds method involves a more rigorous analytical approach. The soil type plays a crucial role in determining hydraulic conductivity. As observed in the table, gravelly silty SAND exhibits higher hydraulic conductivities compared to silty SAND or clayey silty SAND. The presence of larger particles (gravel and sand) in the gravelly silty SAND allows for greater water flow, resulting in higher hydraulic conductivity. Conversely, finer-grained soils, such as clayey silty SAND, have lower hydraulic conductivities due to their smaller pore sizes and increased surface area for water retention.

The results from PT1 and PT2 suggests that these soil types allow water to move more easily, potentially influencing the transport of microbial pathogens and contaminants. While PT3 and PT4 soil types might restrict water movement more significantly, impacting how contaminants, including microbial pathogens, could spread through the soil. The percolation tests have estimated the soil permeability in the field; however, the difference in the hydraulic conductivity is mainly influenced by soil heterogeneity as explained in the previous scientific studies conducted by Kessler and Oosterbaan, (1974) and Dippenaar et al. (2014). The hydraulic conductivity of the soil

significantly influences the fate and transport of microbial pathogens. Higher hydraulic conductivities can facilitate the rapid movement of contaminants through the subsurface, increasing the potential for contamination of groundwater sources. In contrast, lower hydraulic conductivities can retard the movement of pathogens, reducing the risk of contamination.

The choice of method for estimating hydraulic conductivity can impact the accuracy of subsequent modelling efforts. The Porchet method, being empirical, may introduce some uncertainties, especially in soils with complex structures or unusual properties. The Reynolds method, on the other hand, is based on analytical principles and may provide more reliable estimates in certain scenarios. However, the specific applicability of each method depends on the characteristics of the study site and the objectives of the research. Given the demonstrated reliability of the Reynolds method and its incorporation of relevant parameters, it is deemed the more suitable choice for this research.

5.2.2. Bail Tests

The assessment of saturated hydraulic conductivity (K_f s) beneath the research site involved bail tests conducted across the monitoring wells. The bail test results for unconfined conditions were analysed using the Hvorslev's method (Hvorslev, 1951) to determine the hydraulic conductivities. The analysed data of the bail test results can be found in Table 6 below while the bail tests data and graphs are presented under Appendix III and the methodology and equations used are presented under Chapter 4. The data highlights the variability in hydraulic conductivity across different soil types and its potential implications for microbial pathogen transport.

The analysis from table below reveals a clear correlation between soil type and hydraulic conductivity. Silty CLAY and Sandy Silty CLAY generally exhibit lower hydraulic conductivities compared to Silty SAND, Fine SAND, and Gravelly silty SAND. This is due to the finer grain size and higher clay content in the former, which create a more restrictive environment for water flow. Conversely, coarser-grained soils with higher sand and gravel content allow for greater water movement, resulting in higher hydraulic conductivities. The Hvorslev method is a widely used approach for estimating hydraulic conductivity, it has certain limitations. The method assumes a homogeneous, isotropic aquifer, which may not always be the case in real-world scenarios.

Additionally, the accuracy of the results can be influenced by factors such as well construction, pumping rate, and the quality of the drawdown data.

Table 6: Bail test results and calculated hydraulic conductivities in the wells

Wells ID	Soil Type	Total Well depth (mbgl)	Depth To Screen (mbgl)	Screen Length (m)	SWL (mbgl)	Screen Open To Flow (m)	Time Lag - T_L (s)	Inside Radius of Well - r_i (m)	Radius of the Filter Pack - R (m)	Filter Pack Effective Porosity - η_e^*	Effective radius - r (m)	Hvorslev's Method - Hydraulic Conductivity - K (m/day)
MW1	Silty CLAY	1.7	0.6	1.1	0.28	1.1	2085	0.0275	0.0475	0.09	0.0299	0.0528
MW2	Silty CLAY	1.9	0.95	0.95	0.245	0.95	76	0.0275	0.0475	0.09	0.0299	1.5975
MW3	Sandy Silty CLAY	2.05	0.8	1.25	1.25	0.8	210	0.0275	0.0475	0.18	0.0320	0.7452
MW4	-	1.5	0.3	1.2	ND	ND	ND	0.0275	0.0475	ND	ND	ND
MW5	Silty SAND	0.8	0.2	0.6	0.44	0.36	79	0.0275	0.0475	0.25	0.0336	3.4803
MW6	-	1.3	0.5	0.8	ND	ND	ND	0.0275	0.0475	ND	ND	ND
MW7	Fine SAND	1.2	0.5	0.7	0.33	0.7	105	0.0275	0.0475	0.3	0.0347	1.9074
MW8	Gravelly silty SAND	1	0.4	0.6	0.22	0.6	98	0.0275	0.0475	0.35	0.0358	2.3874
MW9	Sandy CLAY	2	0.9	1.1	0.45	1.1	117	0.0275	0.0475	0.18	0.0320	1.0825
MW10	-	0.67	0.2	0.47	ND	ND	ND	0.0275	0.0475	ND	ND	ND
Geometric mean												1.0107
Notes												
ND - Not Determined												
* - Effective Porosity of sand from Woessner and Poeter (2020)												

Both bail and Percolation tests offered a direct assessment of how quickly water infiltrates the soil, providing values that represent the soil's inherent permeability. These tests indicated hydraulic conductivity values ranging from 0.0689 to 3.4803 m/day across various soil types. Wells with different soil types, such as silty sand, fine sand, gravelly silty sand, silty clay, sandy clay, among others, showcased varying hydraulic conductivity values, which might influence the potential transport rates of contaminants and microbial pathogens.

The hydraulic conductivity values obtained from both the percolation tests and bail tests provide complementary insights into the movement of water through different soil types surrounding the Temba Cemetery in Hammanskraal, South Africa. These values signify how readily water moves through specific soil types and aid in understanding the potential transport of microbial pathogens and contaminants. Like percolation tests, the bail tests have estimated the soil permeability in the field; however, the difference in the hydraulic conductivity is mainly influenced by soil heterogeneity as explained in the previous scientific studies conducted by Kessler and Oosterbaan, (1974) and Dippenaar et al. (2014).

Comparing the values obtained from both tests, similarities and differences emerge. In some cases, the hydraulic conductivity values are consistent between the two tests, indicating agreement in the soil's permeability assessments. For instance, similar hydraulic conductivity values for silty sand in both tests might suggest a consistent flow rate for water through this soil type. However, discrepancies might arise due to the varying methods employed in each test. Percolation tests assess overall soil permeability, while bail tests specifically target the saturated zone's conductivity. Therefore, variations in hydraulic conductivity values between the two tests might occur due to different depths of assessment, as percolation tests analyse general soil permeability, while bail tests focus on the saturated zone's behaviour. These tests collectively contribute valuable insights into the hydraulic conductivity of diverse soils, crucial for modelling the transport of contaminants and microbial pathogens near the cemetery and conducting risk analysis with faecal indicators.

5.2.3. Tracer Tests

On 15 December 2023, multi-well groundwater tracer tests were conducted to determine aquifer properties within the porous aquifer on-site and served vital roles in hydrogeology and environmental studies. These tests helped understand groundwater flow patterns, contaminant transport pathways, and aquifer properties. The results validated models, and provided essential data on flow velocity, dispersivity, and effective porosity using the Sauty model. Rigorous mathematical analysis was required to interpret the complex tracer test data and develop models enhancing our understanding of tracer movement in complex hydrogeological systems. Field trace testing map and experimental setup of tracer test at Temba Cemetery with respective distances to testing wells is illustrated in Figure 10 and Figure 11 below.

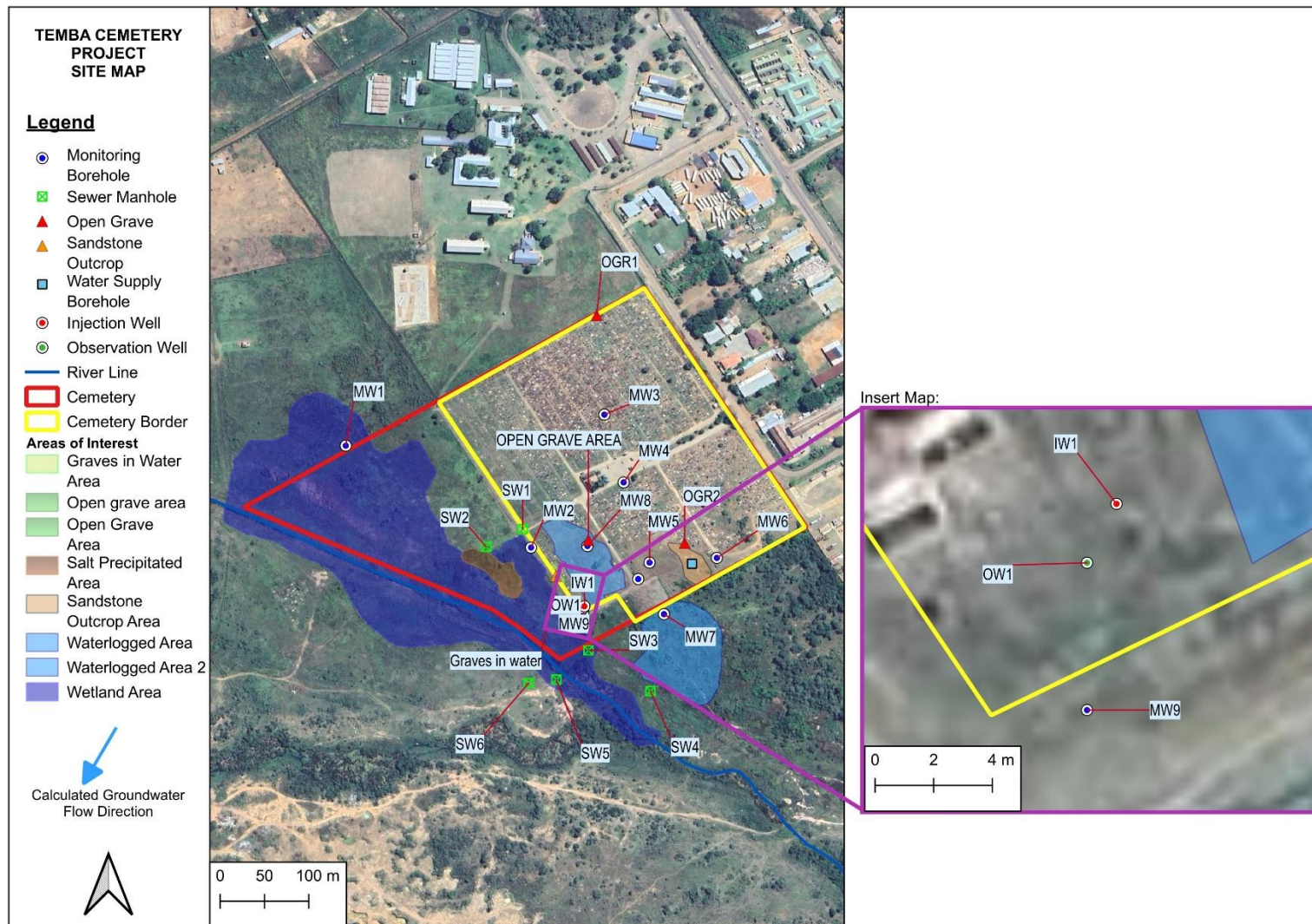


Figure 10: Trace testing well map at Temba Cemetery

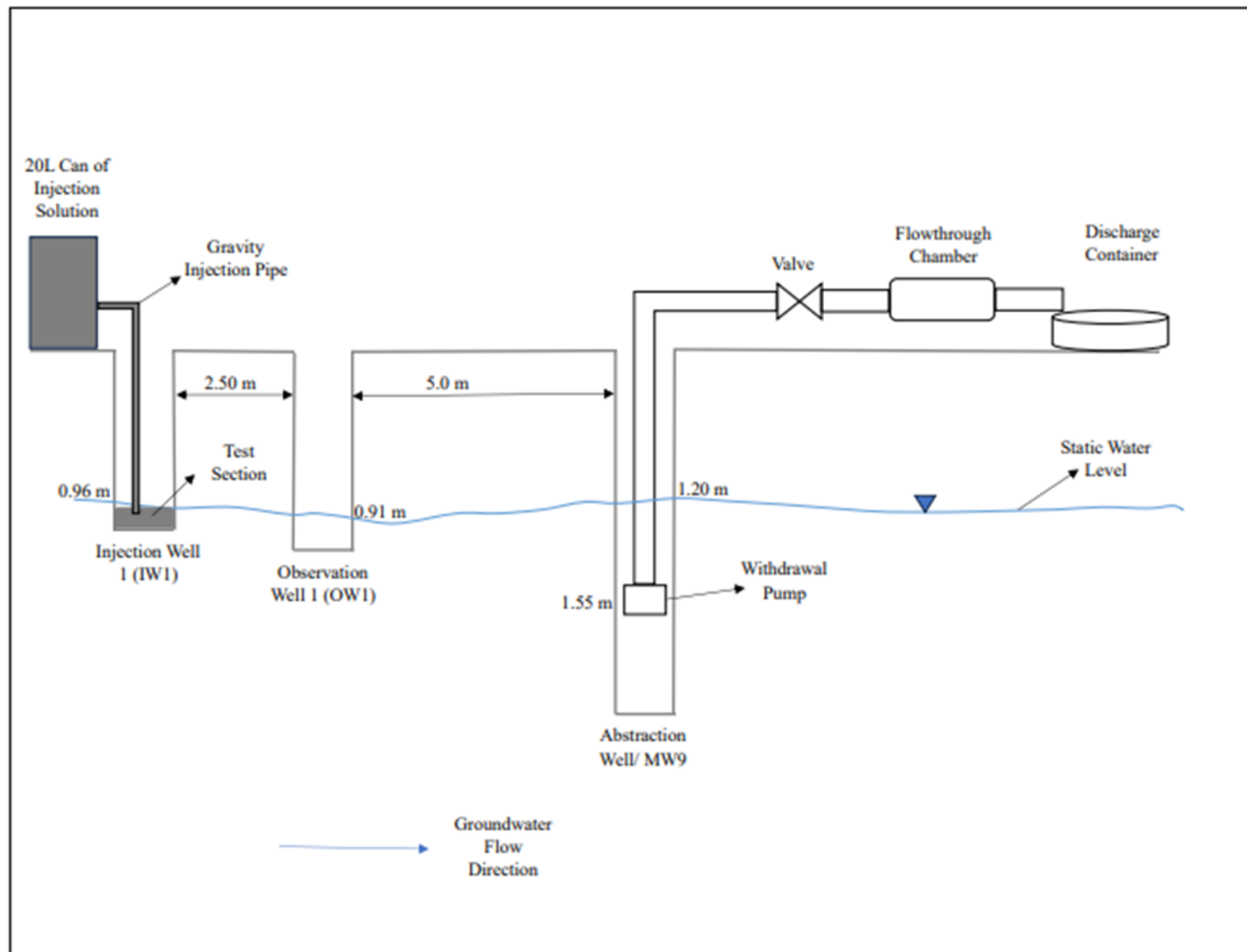


Figure 11: Experimental setup schematic diagram for tracer test at Temba Cemetery

Table 7: Field measurement of groundwater observations prior tracer test

Wells	SWL (mbgl)	Well Depth (mbgl)	Well diameter (cm)	X-Y Coordinates (degrees)		Pumping Rate (L/min)	Comments
				Southing	Easting		
IW1	0.96	1.03	9.5	25.39453	28.25798	-	No casing installed
OW1	0.91	1.11	9.5	25.39455	28.25797	-	No casing installed
MW9	1.1	1.87	9.5	25.3946	28.25797	0.395	Casing Installed
Notes: IW1 - Injection well 1 OW1 - Observation well 1 MW9 - Monitoring well 9/ Abstraction well mbgl - meters below ground level Pump was placed at depth of 1.55 mbgl							

The static water levels were measured at 0.96 meters for Injection well 1 (IW1), 0.91 meters for Observation well 1 (OW1), and 1.10 mbgl for Monitoring well 9/ Abstraction well (MW9). Initial field observations and water quality data prior groundwater tracer tests in IW1, OW1, MW9 are presented in Table 7 above and Table 8 below respectively.

Table 8: Field measurement of groundwater quality parameters prior tracer test

Wells	Water Quality Parameter					Test Stripes Water Quality Data						
	pH	Temperature (°C)	Salinity (ppm)	TDS (ppm)	EC (uS/cm)	Total Alkalinity (mg/l)	Free Chlorine (mg/l)	Total Chlorine (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Carbonate Root (mg/l)	Sulphate (mg/l)
IW1	6.62	28.7	499	713	1022	80	2	0	0	0	0	0
OW1	6.55	27.9	509	731	1048	40	0.5	0	0	0	20	0
MW9	6.79	28.1	574	818	1167	60	2	0	0	0	10	20
Tracer	8.88	27.3	90900	129857	45450	100	4	0	0	0	40	400
Test Sect	8.85	27.5	85600	122285	45800	100	3	0	0	0	40	300
Notes: 2 kg NaCl was used as a tracer Dissolved in 20 L of water to form a Tracer Solution Trace mixing time: 57 Minutes Trace Injection Time: 6 Minutes												

The concentrations of salinity, total dissolved solids (TDS) and levels of Electrical conductivity (EC) were measured from OW1 and MW9 during field tracer tests. These field measured results were plotted Figure 12 to Figure 14 below.

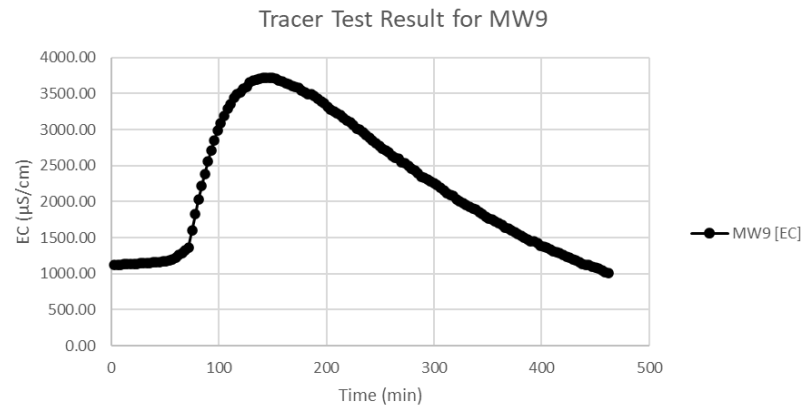


Figure 12: EC Tracer test results for MW9

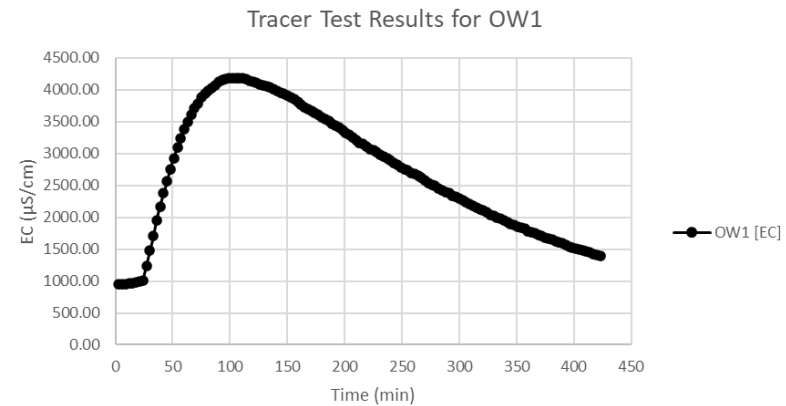


Figure 13: EC Tracer test results for OW1

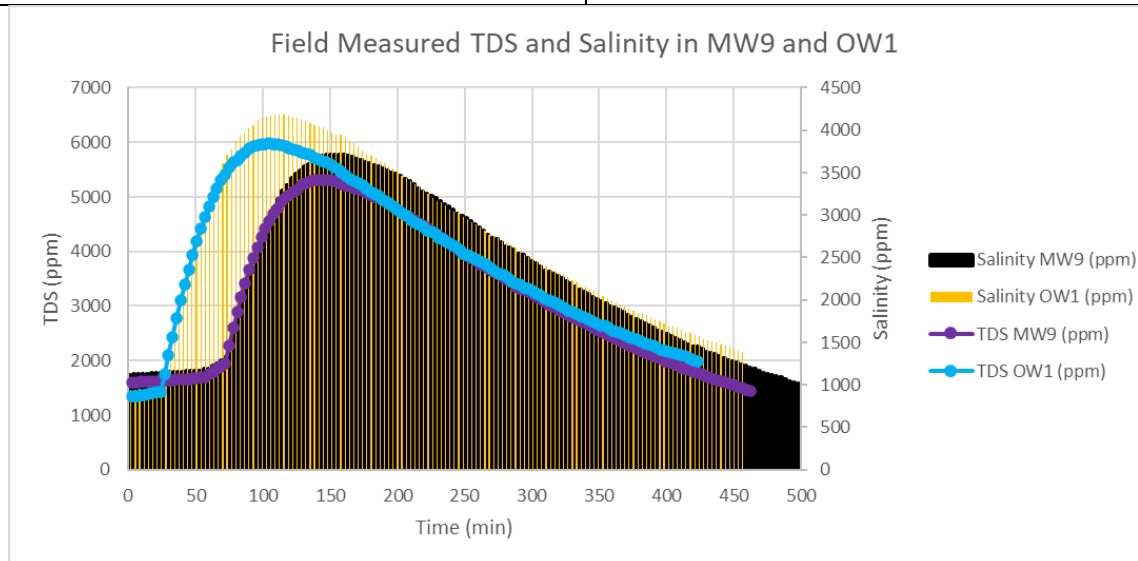


Figure 14: TDS and Salinity field measurement results for MW9 and OW1

5.3. Groundwater Flow Analysis

Monitoring wells served the purpose of assessing both the direction and velocity of groundwater movement. Information pertaining to groundwater monitoring was gathered from wells situated both on-site and off-site, including boreholes identified during the hydrocensus survey. Utilizing a dumpy level, the relative heights of each on-site well were carefully measured, ensuring precision to within 1 cm. These measurements play a crucial role in determining the local direction of groundwater flow on-site. By contouring these wells based on assumed elevation meters above mean sea level (mamsl), the data aids in calculating the direction of groundwater flow within the area under study.

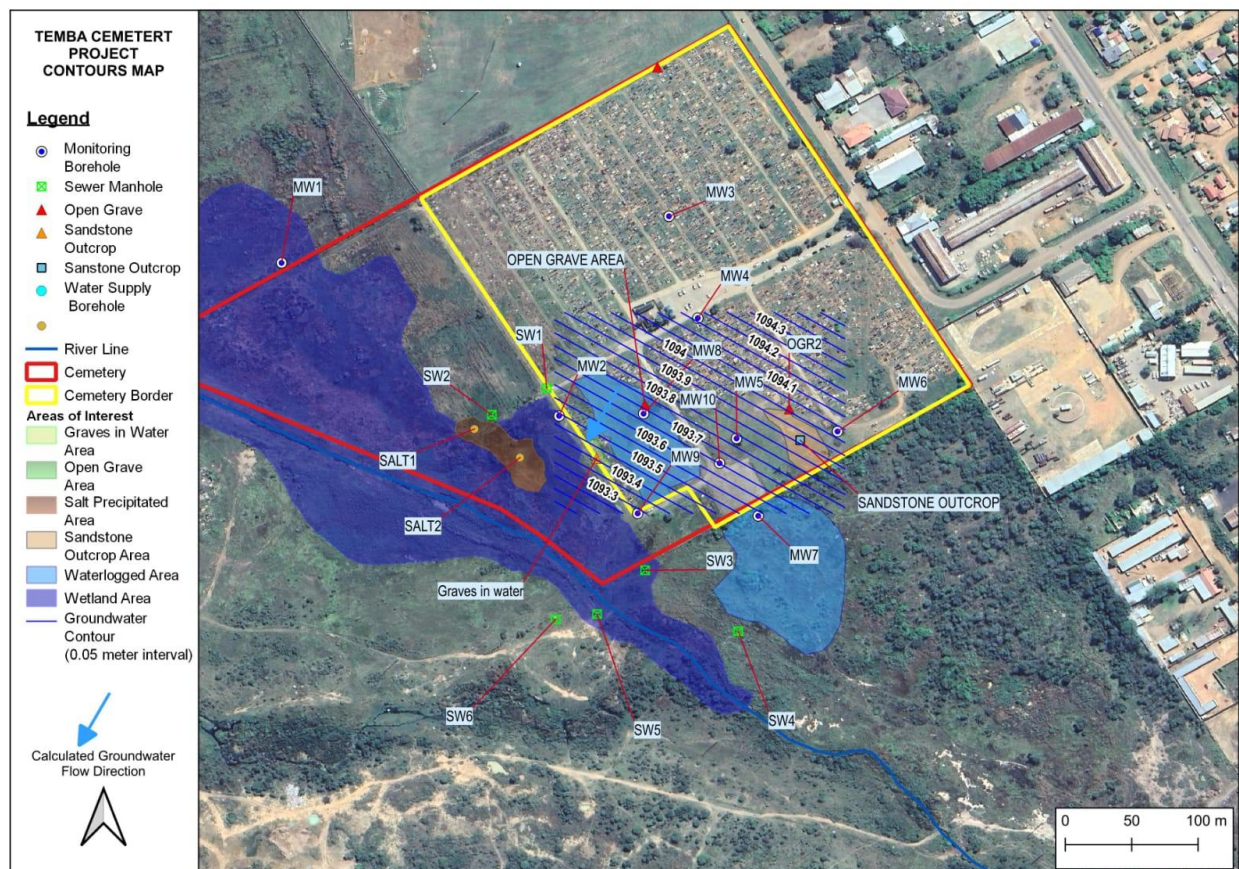


Figure 15: Groundwater contour map and flow direction.

The visual representations of groundwater contours are presented in Figure 15 above. Examination of geological profile logs from the monitoring wells established that the site primarily consists of

unconsolidated material in shallow layers, overlaying weathered sandstone bedrock. Given the calculated geometric mean of effective porosity (0.0316) from field tracer test data, saturated hydraulic conductivity (1.0107 m/day) using the Hvorslev method, and hydraulic gradient (0.0056) determined by the three-point method, the local groundwater flow velocity was estimated using Darcy's law as illustrated in equation 8 below given by Labaky et al. (2009):

$$v = \frac{K \cdot i}{\varphi} \quad 8$$

Table 9: Calculated groundwater flow velocities

Wells ID	Soil type	Hvorslev's Method - Hydraulic conductivity (m/day)	Effective Porosity %	Hydraulic gradient	Flow Velocity (m/day)
MW1	Silty CLAY	0.0528	0.0316	0.0033	0.0055
MW2	Silty CLAY	1.5975			0.1668
MW3	Sandy Silty CLAY	0.7452			0.0778
MW5	Silty SAND	3.4803			0.3635
MW7	Fine SAND	1.9074			0.1992
MW8	Gravelly silty SAND	2.3874			0.2493
MW9	Sandy CLAY	1.0825			0.1130
Geometric Mean		1.0107			0.1055

The provided table (Table 9) shows the results of hydraulic conductivity calculations using the Hvorslev method and the subsequent determination of groundwater flow velocities for various monitoring wells at the Temba Cemetery site. The data highlights the variability in flow velocities across different soil types and its implications for microbial pathogen transport. The analysis reveals a clear correlation between hydraulic conductivity and groundwater flow velocity. Wells with higher hydraulic conductivities, such as MW5 (Silty SAND) and MW8 (Gravelly silty SAND), exhibit correspondingly higher flow velocities. This is due to the greater permeability of these soils, which allows for more rapid water movement. Conversely, wells with lower hydraulic conductivities, such as MW1 (Silty CLAY) and MW2 (Silty CLAY), demonstrate slower flow velocities, reflecting the restrictive nature of these soil types.

5.4. Groundwater Sampling

The collection of groundwater samples was a fundamental component of this research. Samples were collected from various locations to assess the presence and concentration of microbial pathogens from groundwater monitoring wells, stream and off-site receptor. Field data of the static water level and other sampling observations are presented in Table 10 below.

5.4.1. Water Samples

On 27 August 2023, groundwater samples were collected from monitoring wells. Field observations during the water sampling event found the water to be brown and orange, without sewer odour. MW10 was found to be dry at a depth of 0.67 mbgl. A total of eight groundwater samples were collected and sent to a SANAS accredited Environmental Pollution Laboratory (Pty) Ltd located in Centurion.

On 4 November 2023, the site was revisited for follow-up additional groundwater sampling. Field observations during the water sampling event found the water to be clear, orange-brown, and grey, without sewer odour. MW10 was also found to be dry at a depth of 0.67 mbgl. A total of eight groundwater samples were collected and submitted to the laboratory.

The study was re-visited again on 3 December 2023 to collect water samples from the nearby receptors (i.e., stream and private borehole BH1). No groundwater samples were collected from the monitoring wells during this site visit.

5.4.2. Physicochemical Parameters

Physicochemical parameters of water such as temperature, pH, dissolved oxygen, and conductivity were recorded during sampling to provide additional context for water quality analysis as presented in Table 10 below.

Table 10: Field measurement of environmental parameters during groundwater sampling.

Sample ID	Static Water Level (mbgl)	Dissolved Oxygen (mg/l)	pH	Electrical Conductivity (µS/cm)	Temperature (°C)
MW1	1.12	0.22	6.34	3120	19.80
MW2	0.36	0.56	7.32	1142	20.40
MW3	1.54	0.08	6.00	3230	20.60
MW4	1.28	0.31	7.41	1134	21.00
MW5	0.60	0.50	6.78	766	19.40
MW6	Dry	-	-	-	-
MW7	0.44	0.33	6.78	764	19.50
MW8	0.30	0.39	6.76	1145	19.50
MW9	0.77	0.31	7.12	3800	20.90
MW10	Dry	-	-	-	-
BH1	-	-	7.36	1068	33.10
Stream	-	-	8.31	722	30.60
Notes: - = Could not measure					

The measurement of field parameters during sampling of monitoring wells, stream and private borehole provided the following information regarding the conditions in the aquifer on-site as illustrated in Table 10 above.

Dissolved Oxygen (DO): Dissolved oxygen plays a pivotal role as the primary electron acceptor used by microorganisms during substrate biodegradation. As aerobic heterotrophic organisms metabolize substrates, the concentration of dissolved oxygen diminishes (APHA, AWWA, & WEF, 2017). Khan et al. (2021) conducted a study exploring the relationship between water quality parameters and E. coli growth using Pearson's correlation analysis. They found a negative

correlation between increased dissolved oxygen levels and the survival of *E. coli* growth in an aeration pond. Measurements of dissolved oxygen (DO) in private boreholes, groundwater monitoring wells, and streams at Temba Cemetery fell between 0.08 and 0.56 mg/L, indicating low levels conducive to *E. coli* growth.

Temperature: Bacterial growth speed relies on temperature, with most vital bacterial species for breaking down substances thriving in groundwater temperatures from 10 to 45°C. Microbial activity tends to double for every 10°C increase. Atlas (1985) concluded that the highest degradation rates occurred in soil, marine, and freshwater environments at temperatures of 30–40°C, 20–30°C, and 15–20°C, respectively, noting that rates decline as temperature drops. Temperature readings in private boreholes, groundwater monitoring wells, and streams at Temba Cemetery varied between 19.40 and 33.10°C, falling within the range conducive to microbial activity.

pH: Extreme pH levels, below 5 or above 9, typically hinder microbial activity. The ideal pH range supporting microbial survival in groundwater varies based on substrate and microbial community. Studies suggest that a pH between 6.5 and 8.0 promotes microbial survival (Atlas, 1981 and Bassazin et al., 2014). Gomaa et al. (2022) investigated how spatial variations and hydrogeochemical factors affect bacteria in Saudi Arabia's hyper-arid groundwater. They emphasized pH's substantial influence on *E. coli*, highlighting the preference for a neutral pH for microbial growth. Coliform bacteria and *E. coli* particularly flourish in a pH range of 6–8, aligning with the pH levels observed (6.0 to 8.31) in the Temba Cemetery area, conducive to bacterial survival.

Electrical Conductivity (EC): Electrical conductivity measures a substance's ability to conduct electric charge. As per DWAF (1996), water with an electrical conductivity (EC) between 0 - 1500 µS/cm poses no health risks for human consumption, while levels between 1500 - 3000 µS/cm may taste salty, affect body salt balance, and display corrosive properties. Water exceeding 4500 µS/cm could taste excessively salty and bitter, be corrosive, and potentially lead to short-term health issues. Luo et al. (2019) found that higher conductivity and total dissolved solids (TDSs) in water positively correlated with bacterial density, indicating a potential for increased biofilm growth. However, He et al. (2007) observed that elevated conductivity, as seen in Southern

California's water stream, inhibited bacterial growth due to heightened salt concentration, suggesting a detrimental effect on microorganisms. The electrical conductivity values measured in various water sources at Temba Cemetery ranged from 722 to 3800 $\mu\text{S}/\text{cm}$, indicating a mixed range that encompasses both acceptable and unsuitable levels for human consumption and microbial survival.

5.5. Water Quality Strips Results

In the field, water quality strips were employed to measure various parameters, including total alkalinity, chlorine, nitrate, nitrite, iron, carbonate root, nitrite, and sulphate. These parameters are essential in understanding the quality of the gathered water samples, as detailed in Table 11 provided below, allowing for a thorough assessment of the water's characteristics and potential implications for its use and environmental impact. However, this information was only used as a support for groundwater environmental factors affecting the survival rates of pathogens.

The water quality assessment conducted has revealed notable findings, particularly concerning the sulphate levels in the groundwater. The sulphate concentration of 200 mg/l detected in both BH1 borehole and stream water are significantly elevated and raises concerns about the potential sources and implications of such levels. The detection of 200 mg/l of sulphate in BH1 borehole and stream water is higher than what is typically expected from natural sources. Sulphate naturally occurs in groundwater due to the dissolution of sulphate-bearing minerals like gypsum and anhydrite, with concentrations usually ranging from 0 to 150 mg/l depending on the geological setting (Freeze & Cherry, 1979; World Health Organization [WHO], 2017). Therefore, the elevated levels observed in this study suggest the possibility of external or anthropogenic sources contributing to the sulphate concentration (Rodriguez-Eugenio et al., 2018).

Considering the study location near a cemetery, potential anthropogenic sources of sulphate could include leachates from decomposing organic matter, including human remains. Cemeteries have been identified as potential sources of groundwater contamination due to the release of various decomposition by-products, such as sulphates, nitrates, and other compounds (Leonard, 2022). Additionally, the elevated sulphate levels might also result from agricultural runoff or other chemical applications in the surrounding area, contributing to the contamination (Sharma & Kumar, 2020).

The implications of these elevated sulphate levels are significant, particularly concerning the transport and fate of microbial pathogens. Sulphate-reducing bacteria (SRB), which thrive in high sulphate environments, can influence the survival and transport of pathogens in groundwater (Karna et al., 2018). The presence of sulphate can alter the redox conditions, which in turn impacts the mobility of microbial pathogens and affects overall water quality (Karna et al., 2018). Therefore, the high sulphate levels could have a direct impact on the microbial dynamics and the effectiveness of natural attenuation processes in the subsurface environment (Karna et al., 2018).

Moreover, the elevated sulphate concentrations, in conjunction with the study's focus on faecal indicators, raise concerns about potential faecal contamination in the groundwater. Sulphate levels could correlate with contamination from human activities, including the leaching of sewage or other waste materials, which could introduce microbial pathogens into the groundwater system (WHO, 2017). This connection emphasizes the need for a detailed risk analysis that considers both chemical and microbial indicators to assess the potential health risks associated with groundwater use in the study area.

It can be concluded that the elevated sulphate levels detected in BH1 borehole and stream water at Temba Cemetery suggest possible anthropogenic influences, likely related to cemetery activities or other nearby sources. These findings are critical for understanding the transport and fate of microbial pathogens in the area and underscore the need for further investigation. Additional chemical analysis, isotopic studies, and microbial assessments will be essential to confirm the source of the sulphate and its implications for water quality and public health.

Table 11: Field measurement of water quality stripes during groundwater sampling

Well ID	Total Alkalinity (mg/l)		Free Chlorine (mg/l)		Nitrate (mg/l)		Nitrite (mg/l)		Iron (mg/l)		Carbonate Root (mg/l)		Sulfate (mg/l)	
Date	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23	27-Aug-23	3-Dec-23
MW1	120	NM	0.5	NM	0	NM	0	NM	0	NM	40	NM	0	NM
MW2	120	NM	0.5	NM	0	NM	0	NM	0	NM	20	NM	0	NM
MW3	0	NM	0	NM	0	NM	0	NM	0	NM	0	NM	0	NM
MW4	180	NM	1	NM	0	NM	0	NM	0	NM	30	NM	0	NM
MW5	80	NM	0	NM	0	NM	0	NM	0	NM	20	NM	0	NM
MW6	0	NM	0	NM	0	NM	0	NM	0	NM	20	NM	0	NM
MW7	100	NM	0.5	NM	0	NM	0	NM	0	NM	20	NM	0	NM
MW8	60	NM	0	NM	0	NM	0	NM	0	NM	40	NM	0	NM
MW9	180	NM	0.5	NM	0	NM	0	NM	0	NM	20	NM	0	NM
MW10	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM	NM
BH1	NM	150	NM	3	NM	0	NM	0	NM	0	NM	80	NM	200
Stream	NM	0	NM	3	NM	0	NM	0	NM	0	NM	0	NM	200
Notes:														
NM - Not measured														

5.6. Laboratory Analysis

In the pursuit of understanding the dynamics surrounding the fate and transport of microbial pathogens at Temba Cemetery, an important aspect of this research involves laboratory analysis. The collected water samples, gathered from various sources such as monitoring wells, nearby streams, and a private borehole, were submitted to the laboratory for analysis of total coliforms, faecal coliforms, and *E. coli*. This analytical phase serves as a critical cornerstone to model the complex pathways and behaviours of microbial pathogens, allowing for a thorough risk analysis centered around faecal indicators within the studied area. Through these thorough laboratory investigations, the research goal is to untangle the complex relationship between environmental elements and the existence of microbes. This effort seeks to highlight potential health hazards while providing invaluable insights essential for protecting the well-being of the local community.

5.6.1. Water Analysis

Water samples obtained from various sources, including groundwater monitoring wells, surface water body (Stream), and a private borehole (BH1), underwent analysis to evaluate their quality. The main emphasis of this analysis centred on identifying faecal indicators, notably *Escherichia coli* (*E. coli*), utilizing standard methods in microbiology. The collected samples were sent to the Environmental Pollution Laboratory (EPL), an accredited facility under the South African National Accreditation System (SANAS) located in Centurion. This specialized laboratory was proficient in water quality assessment and possessed the capability to detect and quantify microbial pathogens. These parameters offered valuable insights into potential pathogen contamination and the overall degradation of water quality. The results of water laboratory analysis are summarized in Table 12 below, while the laboratory certificates are attached under Appendix IV.

From the results presented in Table 12 below it can be seen that 5000 colonies per 100 ml of faecal coliforms and *E. Coli* were only detected in MW7 located east of the cemetery. Furthermore, 5300 colonies per 100 ml of *E. Coli* were detected from the sample collected in the stream located downgradient and southeast of the cemetery. None of the *E. Coli* were detected in the receptor private borehole (i.e., BH1). Elevated count of total coliforms ranging between 500 and 478 000

colonies per 100 ml were detected in the monitoring wells on site with high colonies count detected from monitoring well located within the burial zones.

The colonies count detected in monitoring wells, a surface water body, and a private borehole were evaluated against the South African National Standard (SANS) 241, which establishes the minimum criteria for potable water safety concerning human consumption. Assessing the quality of drinking water is vital in ensuring its suitability for consumption and mitigating the transmission of waterborne diseases. The South African National Standard (SANS) 241:2015 sets forth specific limits and associated risks concerning household water. Parameters exceeding these thresholds may prompt acute or chronic health issues in individuals, posing immediate health risks if their concentrations surpass the numerical limits outlined in SANS 241. Deviations from these parameters may also indicate potential operational failures in maintaining water quality standards, thereby warranting assessments to ensure efficient treatment system operations and safeguard infrastructure integrity. Based on the results presented in Table 12 below, all elevated count of total coliforms detected in the monitoring wells exceeded the SANS 241 limits.

Table 12: Groundwater laboratory results

	MW1		MW2		MW3		MW4		MW5		MW7		MW8		MW9		BH1	Stream	SANS 241: Risk	SANS 241 Limits
Date	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	27-Aug-23	5-Nov-23	3-Dec-23	3-Dec-23		
Faecal Coliforms (colonies/100ml)	0	0	0	0	0	0	0	0	0	0	5000	0	0	0	0	0	NA	NA	Acute health	Not detected
E.coli (colonies/100ml)	0	0	0	0	0	0	0	0	0	0	5000	0	0	0	0	0	0	5300	Acute health	Not detected
Total Coliforms (colonies/100ml)	99400	221000	377000	570	10900	18600	478000	131000	40400	207000	270000	500	6160	4000	13200	1700	NA	NA	Operational	≤ 10
Notes:																				
NA: Not Analysed																				
Results in Red: SANS 241 Limits Exceeded																				

5.7. Modelling the Fate and Transport of Microbial Pathogens

Modelling the fate and transport of microbial pathogens was a vital component of this research. This section focused on deriving a conceptual model delineating the site at Temba Cemetery and its interconnected hydrogeological system. Using the Advection-Dispersion Equation (ADE) according to Sauty (1980) that illustrate pathogen movement and integration of significant factors, including assumptions and limitations, boundary conditions, and model validation, the research aimed to provide a robust conceptual model framework. This modelling endeavour was vital in solving the potential pathways through which pathogens migrate in the subsurface environment, enabling a thorough assessment of associated risks.

The Advection-Dispersion Equation (ADE) model was originally developed by G.I. Taylor who introduced the concept of dispersion in fluid flow (Taylor, 1953). However, the ADE model as we know it today was further developed and refined by numerous scientists and engineers over the years and the ADE model is widely regarded as a robust framework for simulating solute transport as well as pathogen transport in groundwater (Foppen and Schijven, 2006 and, Camesano and Logan, 1998)). The ADE model was also refined by Sauty (1980) which combines advection and dispersion processes to describe the transport of solutes in groundwater. Advection refers to the bulk movement of solutes with groundwater flow, while dispersion accounts for the spreading of solutes due to variations in flow velocity within the porous medium (Bear, 1972). This model's ability to describe the movement of contaminants through porous media using both advection (transport via groundwater flow) and dispersion (spreading due to aquifer heterogeneity) makes it highly appropriate for the study of pathogen transport and other faecal indicators in aquifers (Sauty, 1980).

In the context of microbial pathogen transport, these mechanisms are critical for understanding how contaminants move through the aquifer over time and distance. According to Sauty (1980), the model assumes that contaminants are transported primarily through advection, with dispersion acting to spread the contaminant plume. This approach has been successfully applied in various studies of solute transport, including the movement of microbial pathogens such as *E. coli* (Foppen & Schijven, 2006). The utilization of Sauty's Advection-Dispersion Equation (ADE) model in the study is well-justified and supported by extensive literature as follows:

The ADE model has been widely used to simulate the transport of microbial pathogens in groundwater, including *E. coli*, viruses, and protozoa (Camesano & Logan, 1998, Saeed et al., 2000, and Foppen and Schijven, 2006). The transport of microbial pathogens in groundwater is often governed by advection and dispersion, as well as additional processes such as decay, inactivation, adsorption, and filtration (Schijven & Simunek, 2002). Although the ADE model was initially developed for chemical solutes, it can be modified to account for these microbial-specific processes, making it a suitable framework for pathogen transport simulation (Foppen and Schijven, 2006). For example, Saeed et al., 2000 applied the ADE model to simulate the transport of viruses in aquifers, incorporating virus inactivation and adsorption to account for microbial behaviour. Similarly, Foppen and Schijven (2006) modelled the transport of *E. coli* in riverbank filtration systems, demonstrating the applicability of the ADE model to microbial transport by incorporating attachment-detachment kinetics to simulate pathogen-sediment interactions.

In the case of microbial pathogens, such as *E. coli*, the ADE model can be modified by incorporating terms for biological decay, adsorption, and filtration to better reflect the fate of these organisms in groundwater (Camesano & Logan, 1998). For instance, Camesano and Logan (1998) successfully applied a modified ADE model to simulate the transport of bacteria in porous media, adjusting the model to account for microbial decay and filtration. These modifications are crucial in studies like the one at Temba Cemetery, where the fate of faecal indicators is influenced by both physical transport processes and biological inactivation. In similar studies, Saeed et al., (2000) used the ADE framework to predict the movement of viruses in sandy aquifers, modifying the model to include pathogen inactivation and adsorption rates. This approach would be particularly useful in the Temba Cemetery study, where burial practices may introduce microbial pathogens into the groundwater system, requiring an accurate representation of both transport and decay processes.

Numerous studies have successfully used the ADE model or its modified versions to simulate microbial transport in groundwater systems, for instance, Camesano and Logan (1998) demonstrated the applicability of the ADE model in bacterial transport by incorporating decay and filtration terms into the equation. Similarly, Saeed et al., (2000) used a modified ADE model to simulate virus transport in aquifers, accounting for virus inactivation and sorption to the aquifer

matrix. These studies highlight the flexibility of the ADE model in accommodating microbial-specific transport processes.

Additionally, Foppen and Schijven (2006) applied the ADE model to assess the movement of *E. coli* through porous media in riverbank filtration systems. Their study demonstrated that the model could predict the concentration of *E. coli* at various points in the aquifer, even after accounting for attachment to soil particles and biological decay (Foppen and Schijven, 2006). This is directly relevant to the study at Temba Cemetery, where microbial pathogens such as *E. coli* are expected to be transported through the aquifer and may interact with soil and sediment particles. Ginn et al. (2002) further supported the use of the ADE model in microbial transport studies, emphasizing the importance of accounting for both advection and dispersion, as well as additional processes such as microbial inactivation, in predicting contaminant movement in groundwater.

The use of the ADE model in microbial pathogen transport studies is critical for risk assessment and public health protection. The model's ability to predict the spatial and temporal distribution of pathogens in groundwater provides valuable insights into the potential contamination of drinking water sources (Saeed et al., 2000). At Temba Cemetery, where burial practices may introduce faecal pathogens into the aquifer, understanding the fate and transport of these pathogens is essential for assessing the risk to nearby communities that rely on groundwater for drinking water. Weaver et al. (2007) emphasized the importance of groundwater modelling in microbial risk assessment, particularly in areas where groundwater is used as a drinking water source. By applying the ADE model to predict pathogen concentrations at different points in the aquifer, researchers can assess the potential for groundwater contamination and develop strategies for mitigating public health risks.

The application of Sauty's ADE model in the study of microbial pathogen transport at Temba Cemetery is well-supported by both its theoretical foundation and successful application in similar studies. The model's ability to simulate advection and dispersion processes, while allowing for modifications to incorporate microbial-specific processes such as decay, adsorption, and filtration, makes it an appropriate and flexible tool for predicting the fate of faecal indicators in groundwater. Numerous studies, including those by Foppen and Schijven (2006), Saeed et al., (2000), and Camesano and Logan (1998), have demonstrated the ADE model's effectiveness in simulating

microbial transport, further validating its use in this research. The insights gained from using the ADE model at Temba Cemetery will contribute to a better understanding of microbial risk in groundwater and inform public health protection measures.

5.7.1. Assumptions and Limitations

To model the movement and potential risks posed by microbial pathogens at Temba Cemetery, the research framework relies on specific assumptions and acknowledges key limitations. Assumptions encompass the uniformity of soil properties, steady-state groundwater conditions, constant aquifer attributes, conservative pathogen behaviour, and limited human influence on pathogen transport. Conversely, limitations arise due to data constraints, the simplified nature of our model, inadequate consideration of site-specific factors, uncertainties in pathogen behaviours, and challenges associated with validating model predictions against real-world observations. Recognizing these assumptions and limitations is critical for interpreting our modelling outcomes and understanding the constraints in our microbial pathogen risk assessments within the Temba Cemetery environment.

5.7.1.1. Model Assumptions

The model assumes uniform soil properties, steady-state groundwater conditions, constant aquifer characteristics, conservative behaviour of pathogens, and limited human impact on pathogen transport.

- **Homogeneity of Soil Properties:** The model may assume uniformity or homogeneity in soil properties within specific layers or zones, simplifying the representation of soil characteristics. Even though the research study area is characterized by distinct types of soil texture such as silty clay and sand, it is assumed that the entire study area is characterized by this type of lithology.
- **Steady-State Conditions:** It might assume steady-state conditions for groundwater flow and pathogen transport, overlooking transient variations that could occur. The geometric mean of the hydraulic conductivity measured in the monitoring wells through bail tests and percolations tests were used, assuming that the entire study area is characterized by the same hydraulic conductivity. This assumption was also considered since the geological

lithology of the research does not extensively vary, and the site area is covered by sandstone bedrock.

- **Constant Aquifer Properties:** The model could assume constant properties for aquifers, isotropic single-layer aquifer, disregarding potential fluctuations or heterogeneity within aquifer systems. These properties include the effective porosity and dispersivity from the breakthrough curves.
- **Conservative Behaviour of Pathogens:** The model assumes conservative behaviour of microbial pathogens, neglecting transformation or decay mechanisms that might alter their movement.
- **Limited Impact of Human Activities:** Assumptions considers limited impact or influence from human activities on the movement of pathogens and groundwater dynamics in the vicinity of the cemetery.

5.7.1.2. Model Limitations

Model limitations arise from data availability, the simplified representation of the complex system, the inability to fully consider site-specific factors, uncertainties in pathogen behaviour, and challenges in validating model predictions against real-world observations.

- **Data Limitations:** The model's accuracy and reliability heavily rely on the availability and quality of input data, which might be limited or subject to uncertainties. These include slight inaccuracies in the measuring tolerances.
- **Simplification of Real-world Complexity:** The model's simplified representation of the complex hydrogeological system might overlook intricate details, leading to potential oversights or inaccuracies. The model does not account for molecular diffusion or any reactions during the pathogenic transport process. This includes the pathogen sorption mechanisms in the subsurface environment.
- **Inability to Account for Site-Specific Factors:** Model does not fully account for unique site-specific factors or localized variations that could significantly influence pathogen transport. This includes the pathogen transport mechanisms within the vadose zone; however, the model focuses on pathogen transport mechanisms within the saturated zone.

- **Uncertainties in Pathogen Behaviour:** Limitations arises from uncertainties surrounding the behaviour, persistence, and interactions of microbial pathogens within the environment. Sorption and diffusion mechanism in the subsurface environment is not accounted in the model. Other factors such as chemical reaction and environmental factors such as resource availability were neglected during the research study.
- **Model Validation Challenges:** Validation of the model's predictions against real-world observations might be challenging due to limitations in field data or the complexity of validating pathogen transport. However, the model was validated based on the test results obtained during field data collection on research site as well as published known data.

5.7.2. Boundary Conditions

In the exploration of microbial pathogen movement and the subsequent risk assessment with faecal indicators at Temba Cemetery in Hammanskraal, South Africa, delineating the specific boundary conditions within the research framework is paramount. These boundary conditions summarize geographical confines, hydrological features, soil and aquifer parameters, and human activities. Establishing these boundaries ensures an understanding of the environmental factors impacting pathogen fate and transport within the cemetery's vicinity, guiding the accuracy and applicability of the research modelling efforts.

5.7.2.1. Geographical Boundaries

Defining the geographical extent of the study area, outlining the specific boundaries within which the modelling is conducted, such as the cemetery's perimeters or surrounding hydrogeological features. These features are presented in Figure 9 and section 3.1.

5.7.2.2. Hydrological Boundaries

Defining boundaries related to hydrological features, such as groundwater recharge areas, surface water sources, and potential pathways for microbial pathogen transport within the hydrogeological system. These features are presented in Figure 9 and section 3.1.

5.7.2.3. Soil and Aquifer Boundaries

Identifying the spatial limits of soil layers and aquifers involved in the model, outlining the depths, extents, and properties of these geological elements crucial for pathogen transport. The site geology has been assessed from test pits and monitoring well geological logs as well as seepage depths encountered during excavation and drilling processes. The site geology provides crucial data such as soil texture to support the model. Aquifer information and characteristics were collected through various tests such as bail, percolation, and tracer tests.

5.7.2.4. Human Activities Boundaries

Incorporating boundaries related to human activities that might impact pathogen transport, including burial practices, land use patterns, and potential contamination sources within the vicinity of the cemetery. Human activities are evident in the research area in a form of sewer drainage system that runs across the site as well as cattle faeces which are penitential sources of faecal contamination. These features are presented in Figure 1 and section 4.2.

5.7.3. Mathematical Equations

Mathematical equations represent a crucial foundation in the analytical fate and transport modelling of microbial pathogens in the subsurface environment. These equations stand as the backbone, accurately created to simulate, and clarify the complex movement patterns of microbial pathogens within the research area. These equations compress the complicated influences shaping pathogen dispersion, incorporating crucial factors such as burial practices, groundwater dynamics, hydrological elements, and microbial behaviour. They serve as the base for an understanding of pathogen fate and transport, driving the subsequent risk analysis utilizing faecal indicators in this unique geographical and environmental setting. These equations were purpose-built to model how contaminants spread across time and space, forming a critical core of the model employed for evaluating their destiny and movement.

Understanding the factors controlling the movement and spread of water, specifically the hydrodispersive transfer, holds immense significance in assessing how substances travel below the surface. These factors, while not directly measurable, can be deduced by observing how an ideal

tracer behaves once introduced into the aquifer. The equation used to describe the dynamics of this process incorporates multiple elements. When focusing solely on hydrodispersive transfer, which excludes reactions beyond dispersion, convection, and molecular diffusion, the equation becomes simpler. In shallower aquifers where flow is rapid and pollution is a heightened concern, the components related to kinematic dispersion become more noticeable compared to molecular diffusion. By making assumptions that eliminate radioactive decay, sorption, and other reactions, these parameters are not considered in the overall equation (Sauty, 1980). Consequently, the instantaneous injection equation in this scenario is then expressed as (Sauty, 1980):

$$C_{(r,t)} = \left(\frac{\frac{m}{\omega}}{2(\pi DT)^{1/2}} \right) e^{-\left(\frac{(r-vt)^2}{4Dt} \right)} \quad 9$$

The equation can further be expressed as follows:

$$C_{(r,t)} = \left(\frac{\Delta M}{2Q\sqrt{\pi D_L t^3}} \right) \left[e^{-\left(\frac{(r-vt)^2}{4D_L t} \right)} \right] \quad 10$$

Where:

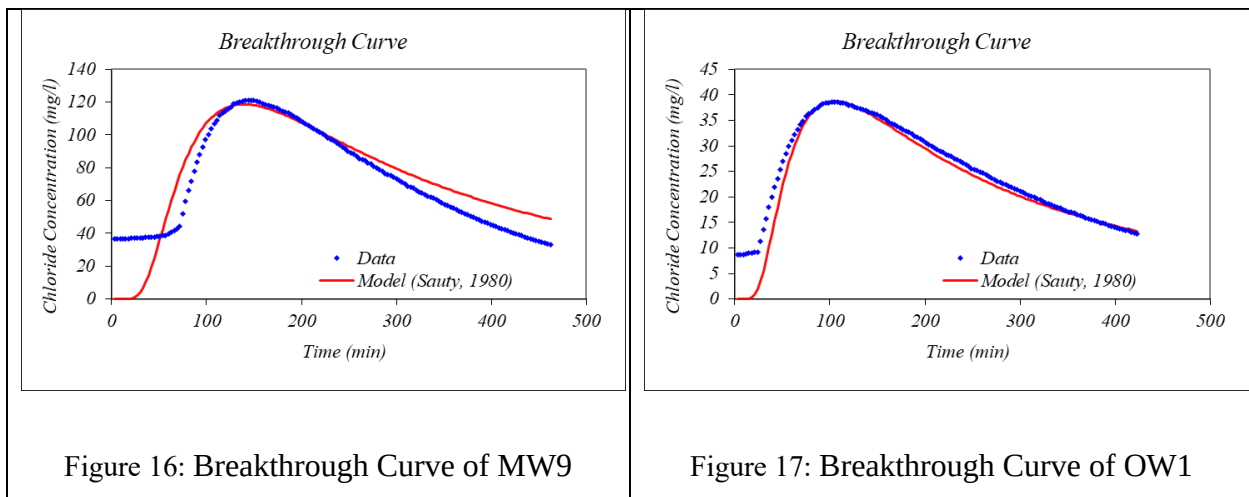
- ΔM is the injected mass of the tracer per unit section (Mass [m]/ Thickness [w])
- D_L is the longitudinal dispersion coefficient [m^2/day], $D_L = \alpha_L v$, α_L is the longitudinal dispersivity [m]
- v is groundwater velocity under forced gradient [m/day]
- Q is the pumping rate of the well [m^3/day]
- r is the radial distance [m] between the two boreholes

The groundwater velocity (v) and its dispersal characteristics (α_L) were approximated by analysing the tracer's breakthrough curve, employing the methodology outlined in Sauty's study from 1980. This solution by Sauty pertains to a pulse tracer test conducted within a single-layer aquifer that is both uniform and isotropic. In this scenario, the movement of substances is primarily influenced by the combined effects of advection and dispersion, with molecular diffusion being of negligible significance (Sauty, 1980). Sauty's model, as described by equation [10] above, serves as the governing framework of the model, and through a fitting process utilizing field data, critical parameters such as thickness, velocity, dispersivity, and effective porosity were determined. This

approach facilitated the estimation of these essential groundwater properties by aligning observed field data with the predictive capabilities of the Sauty model, allowing for a more understanding of aquifer behaviour.

5.7.4. Break Through Curves (BTC)

The Breakthrough Curves (BTC) compresses the dynamic representation of how microbial pathogens, along with faecal indicators, migrate through the subsurface environment around Temba Cemetery. These curves, derived from tracer tests and conductivity measurements, provide a visual representation of pathogen movement in the groundwater, offering critical insights into their behaviour and potential risks within this specific ecosystem. Breakthrough Curve for the abstraction and observation wells are illustrated in Figure 16 and Figure 17 below.



Breakthrough curves (BTC) stood as pivotal data points in determining crucial Sauty model parameters. Specifically, the peaks observed in the Breakthrough Curves (BTC) for monitoring well MW9 and observation well OW1 were distinctly significant. These peaks were notably attained within 144 and 105 minutes, exhibiting concentrations of 120.9268 and 135.9977 mg/l, respectively. These distinctive data points from the BTCs served as the basis for deriving and fitting the Sauty model parameters relevant to the transport dynamics of contaminants.

Table 13: The derived Sauty model fitting and field measured parameters.

Wells	Thickness (m)	Dispersivity Coefficient (DL) - (m)	Velocity (v) - (m/d)	Effective Porosity (ϵ) - (qf/vf)	Peak Time (t) - (min)	Peak Concentration (C) - (mg/l)	Injected Mass/Unit Section (ΔM)	Longitudinal Dispersivity (α_L) - (m ² /d)	Pumping Rate (Q) - (m ³ /d)	Radial Distance (r) - (m)
MW9	0.19	91.8	18	0.02	144	12.9268	10.5263	5.1	0.5688	7.5
OW1	2.03	13.8	6	0.05	105	135.9977	3.5088	2.3	0.5688	2.5

Table 13 above summarized the derived Sauty model fitting parameters attributed to MW9 and OW1. Leveraging the breakthrough curves enabled the estimation and subsequent fitting of critical parameters essential for the Sauty model. These parameters, including dispersivity, velocity, and effective porosity, play a pivotal role in characterizing the movement and behaviour of contaminants within the subsurface environment. The temporal and concentration-based understandings extracted from the BTCs facilitated an understanding, allowing the derivation of these parameters, crucial for accurately simulating the transport of microbial pathogens originating from the Temba Cemetery.

The utilization of breakthrough curves as a foundation for deriving the Sauty model parameters signifies a critical step in comprehending the intricate fate and transport mechanisms of microbial pathogens. By correlating temporal observations with concentration peaks within the BTCs, the study garnered essential insights, enabling the quantification of dispersivity, velocity, and effective porosity. These parameters serve as fundamental inputs into the Sauty model, enriching the understanding of contaminant transport dynamics, particularly originating from faecal indicators at the Temba Cemetery site in Hammanskraal, South Africa.

5.7.5. Conceptual Model Development

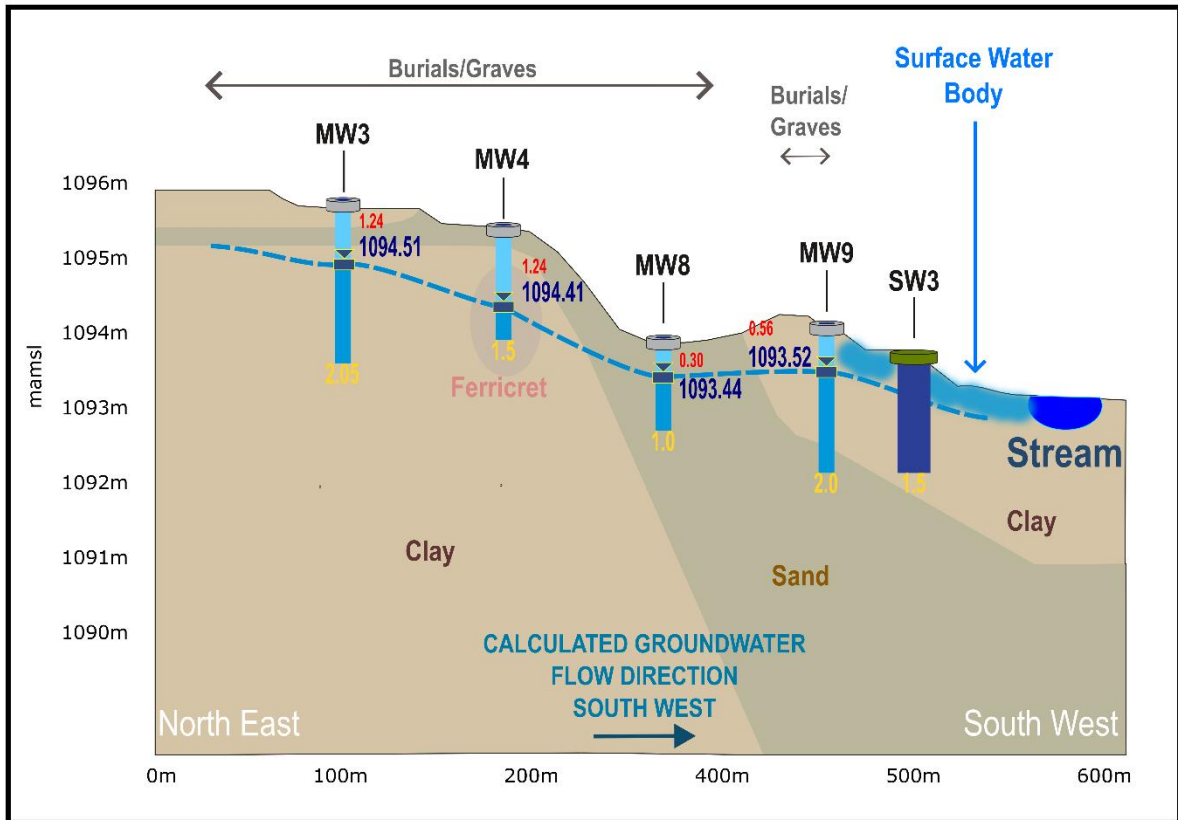
The initial step in modelling the movement and dispersion of microbial pathogens within the Temba Cemetery site and its surrounding hydrogeological system involved developing a conceptual model. This model served as a simplified representation of the real-world system, encompassing key elements and their interactions. It considered various critical factors, including the layout of the cemetery and burial areas, the properties of soil and rock layers such as permeability and hydraulic characteristics, the patterns of groundwater flow encompassing direction and velocity, hydrological parameters like effective rainfall, the presence of aquifers, burial practices including depths, and environmental factors impacting pathogen transport. This

conceptual model laid the foundation for creating mathematical equations that described how microbial pathogens move and disperse within this complex system.

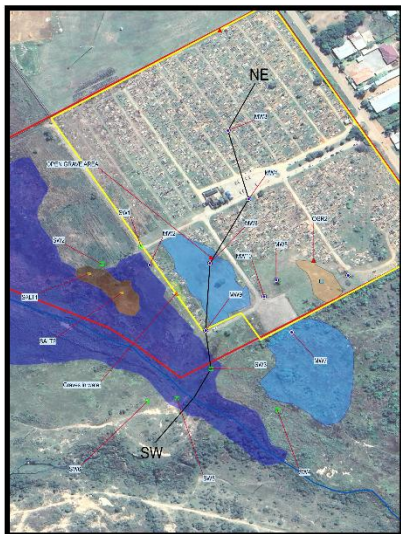
The Advection-Dispersion Equation (ADE) according to Sauty (1980) [equation 10] was used to predict the concentration of a tracer at a specific distance and time in a groundwater system using the given the parameters provided in Table 13. The ADE models integrate the fitted parameters along with other factors like topography, soil types, and hydrological conditions to simulate the movement of pathogens and predict how they spread through groundwater or surface water from the cemetery. Using the parameters presented in Table 13, the ADE model was used to predict the time it will take for concentrations to reach the receptors and severity of impact towards the receptor. The following input parameters were used for the ADE model by Sauty 1980 as summarized in the conceptual site modes (CSM) illustrated in Figure 16 and Figure 17 below:

- **Initial E. Coli concentration:** 5000 colonies/100 ml (concentration from source point acquired from the laboratory results of MW7)
- **Soil type:** Silty clayey sand (generic soil type of the study area)
- **Pathway:** Ingestion through groundwater
- **Groundwater receptor distance:** 450 meters from the point source (BH1)
- **Hydraulic conductivity of source point:** 1.0107 meters/day (Geometric mean of the hydraulic conductivities from bail tests)
- **Annual rainfall range:** 2 to 60 mm (from Meteoblue data)
- **Boundary conditions:** Study area covers 207,705 square meters, part of the site is a wetland, sewers, and cattle dung present at the point source.
- **Simulation durations:** 1 to 100 days
- **Desired concentration at the borehole receptor:** <10 colonies/100 ml

CONCEPTUAL SITE MODEL TEMBA CEMETERY PROJECT



LOCATION OF CROSS SECTION

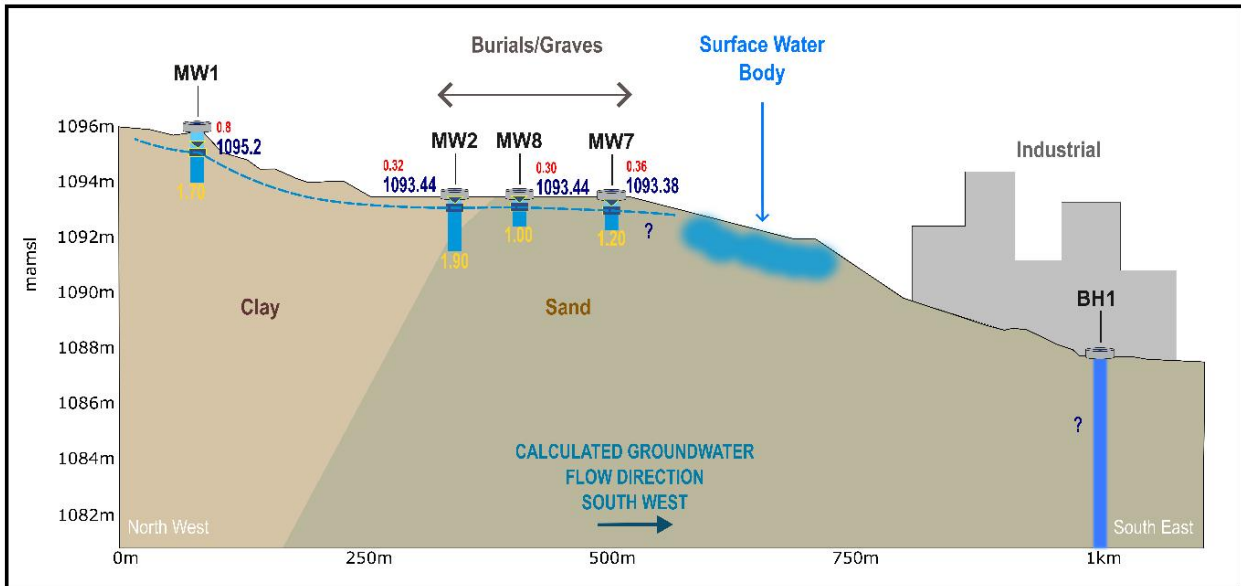


LEGEND

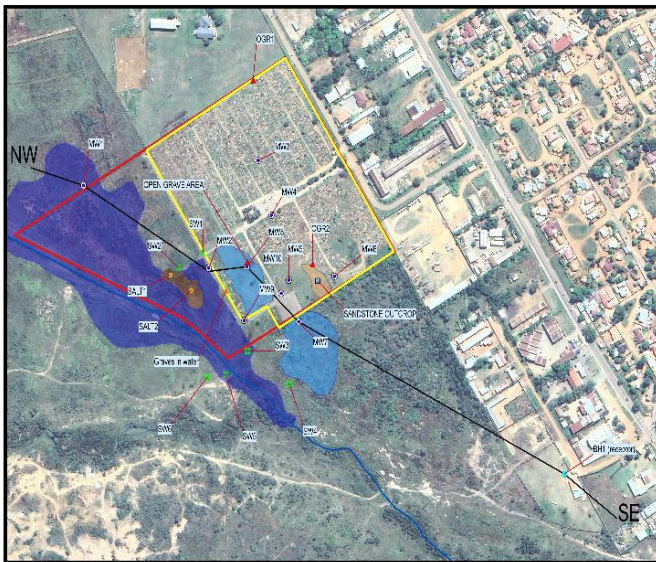
- 2 DEPTH IN MBGL
- 0.30 GROUNDWATER LEVEL IN MBGL
- 1093.44 GROUNDWATER LEVEL IN MAMSL
- GROUNDWATER LEVEL
- MW MONITORING WELL
- SW SEWER MANHOLE

Figure 18: Northeast-Southwest Conceptual Site Model

CONCEPTUAL SITE MODEL TEMBA CEMETERY PROJECT



LOCATION OF CROSS SECTION



LEGEND

2	DEPTH IN MBGL
0.30	GROUNDWATER LEVEL IN MBGL
1093.44	GROUNDWATER LEVEL IN MAMSL
	GROUNDWATER LEVEL
MW	MONITORING WELL
SW	SEWER MANHOLE

Figure 19: Northwest-Southeast Conceptual Site Model

Two distinct models were employed to simulate the spread of concentration gradients within the subsurface environment, directing towards a receptor (i.e., BH1) positioned 450 meters distant from the point source, indicated as the research site. The outcome results from the observation well (i.e., OW1) and abstraction well (i.e. MW9) were utilized in conjunction with Equation 10, known as the Sauty equation, across a time frame from 1 to 100 days to simulate pathogenic migration. This inclusive utilization of multiple models and data sources facilitated an assessment of the concentration dynamics, thus enhancing the accuracy and reliability of the generated simulations.

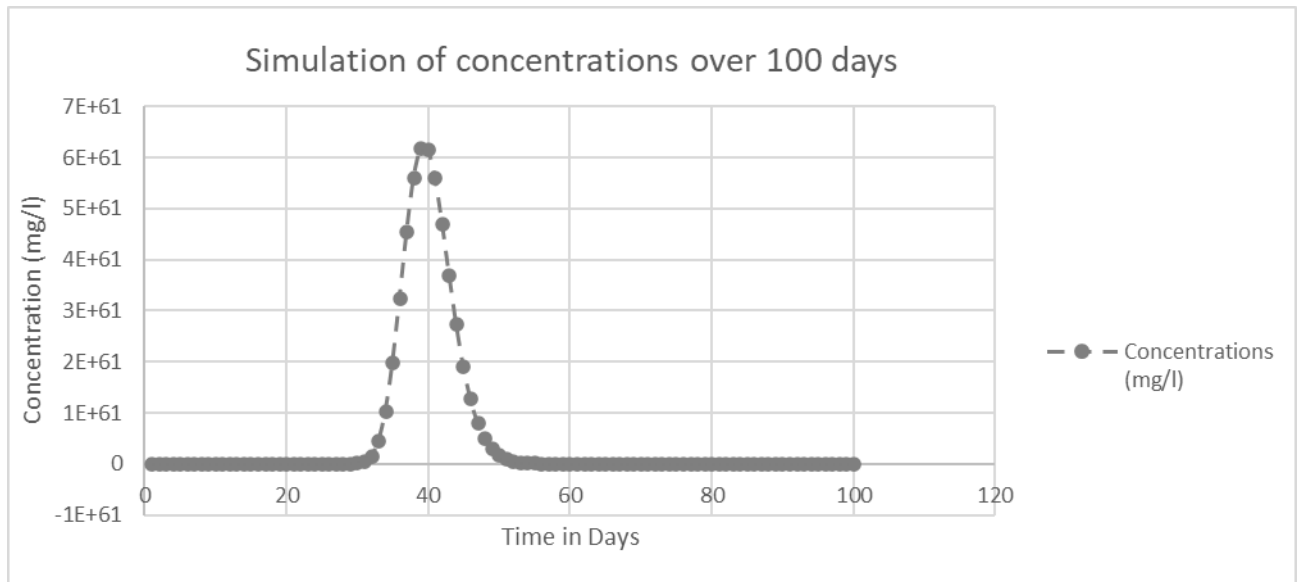


Figure 20: Simulation of concentration over 100 days utilizing OW1 results.

When utilizing OW1 data, the application of the Sauty Advection-Dispersion Equation (ADE) model to analyse the fate and movement of microbial pathogens, particularly in risk assessment via faecal indicators, yields valuable insights into the temporal dynamics of microbial concentration behaviours as illustrated in Figure 20 above.

At the beginning of the simulation (days 1 to 6), the concentrations remain consistently at 0 mg/l. This might indicate an initial period where the microbial pathogens are not significantly present or are present below the detectable limit and have not reached the receptor (i.e. BH1 located 450 m from point source). However, after day six, there is a daylight of concentration and a noticeable increase in concentration at the receptor. The concentration gradually rose from 2.4244E-231 mg/l to a peak of 6.17854E+61 mg/l at day 39, indicating an increase in microbial count over time.

Following the peak at day thirty-nine, the concentrations start to decrease gradually, suggesting a decline in the microbial population.

The initial period of low or undetectable concentrations represents a phase where microbial pathogens are transported to the receptor and the microbial risk to public health from the site is low. However, the subsequent increase in concentrations and their peak at day thirty-nine indicate a higher risk period, suggesting potential contamination or increased pathogen transport, posing a risk to the surrounding environment or potentially to individuals exposed to the water source. The subsequent decline in concentrations towards the end of the simulation suggests a reduction in the risk posed by microbial pathogens, potentially due to several factors like environmental conditions, die-off rate, natural attenuation processes, or interventions implemented to mitigate contamination.

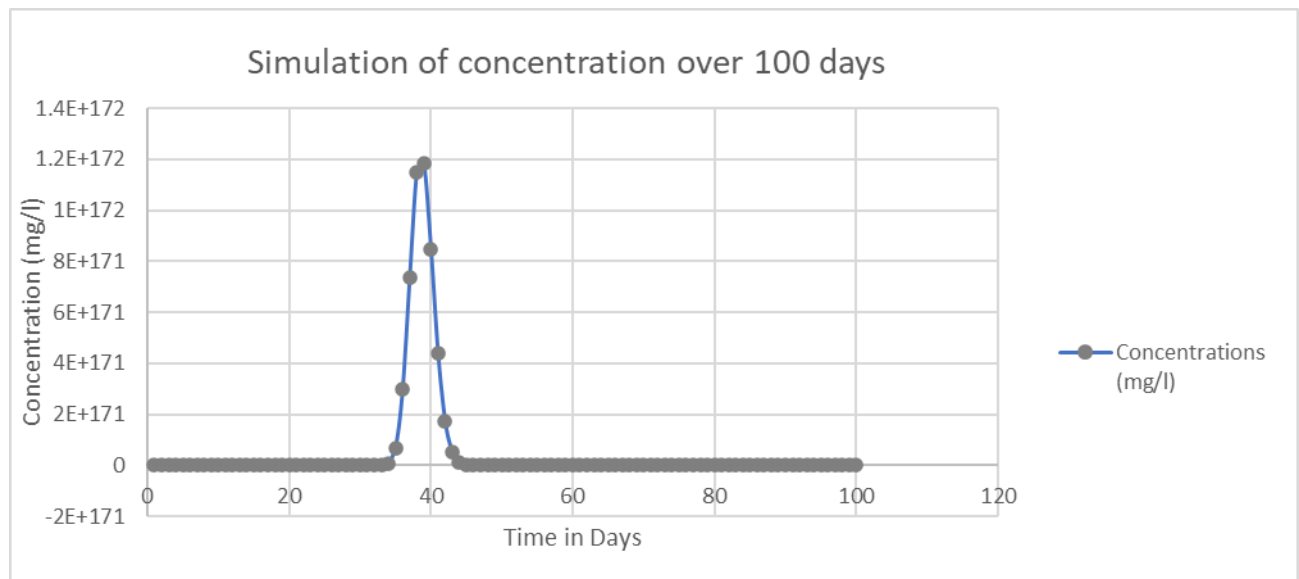


Figure 21: Simulation of concentrations over 100 days utilizing MW9 results.

Similarly, when utilizing MW9 data, the application of the Sauty Advection-Dispersion Equation (ADE) model to analyse the fate and movement of microbial pathogens, particularly in risk assessment via faecal indicators, yields valuable insights into the temporal dynamics of microbial concentration behaviours as illustrated in Figure 21 above.

In both simulations, at the initial stages (days 1 to 6), the concentrations of microbial pathogens remained consistently at zero in the OW1 and MW9 scenarios. Suggesting a phase that microbial

pathogen have not reached the receptor, and the pathogens were either absent or present at undetectable levels in the receptor during this period. From day seven onward, the concentrations start to exhibit variation between the OW1 and thereafter from day eleven in MW9 simulations. Like OW1, simulation for MW9 after day 10 there is a notable increase in concentrations, reaching a peak of 1.1825×10^{172} mg/l on day 39. A more abrupt rise was noted from MW9 when compared to the OW1 scenario. This increase suggests a potential risk of elevated pathogen presence over this time frame. Following the peak at day thirty-nine in both simulations, the concentrations start to decline gradually, demonstrating a reduction in the pathogen levels.

Comparing the two simulations, the differences in the rate of increase in the concentrations might suggest variations in transport mechanisms or factors influencing the movement and persistence of microbial pathogens between the observation well (OW1) and extraction wells (MW9). Furthermore, the difference in the fitted velocity parameter showed positive proportional correlation with the concentrations. These variations could be crucial in understanding the potential risk of pathogen transport and devising strategies for risk management and mitigation in the studied environment.

The outcomes of two computational simulations align with the findings reported in the investigation conducted by Wang et al. (2013), which examined the behaviour of *Escherichia coli* D21g and coliphage 'X174 within saturated soils featuring preferential flow. Wang et al. (2013) observed a more pronounced impact on *Escherichia coli* D21g in finer sand compared to coarse sand. In our current research, we have documented greater flow velocities and conductivity under saturated sand soil conditions. Dent and Knight (1998) explored permeable silty sands and clay in various Australian urban areas and detected insignificant levels of pathogenic organisms across different locations. Their findings indicate that under certain hydrogeological conditions, a variable quantity of coliforms might infiltrate groundwater. Our present investigation, akin to Dent and Knight's study, as well as the simulation models, indicates that under hydrogeological conditions characterized by silty sand and clay, a variable quantity of pathogens can indeed migrate into groundwater and subsequently reach receptors.

Nevertheless, environmental variables such as temperature, pH, and water availability exert considerable influence on pathogen persistence. These factors were meticulously assessed during

our study and were found to be conducive to pathogen survival (Van Elsas et al., 2011). While our model simulations project that contaminant concentrations would reach receptors within six to seven days, it is imperative to note that factors like sorption, chemical reactions, nutrients, and die-off rates were not factored into this transport model. These simulations incorporate the mechanisms of advection and dispersion in contaminant transport. However, various studies, such as those conducted by Sjogren (1994, 1995), have demonstrated that *E. coli* can persist in soil environments for up to 13 years when provided with nutrient broth. Conversely, studies by Jamieson et al. (2002), Ohtomo et al. (2004), and Avery et al. (2004) have suggested shorter survival times of 2 to 4 months for *E. coli*. Based on the outcomes of our model simulations in the present study, it is evident that pathogens could reach receptors in substantial quantities provided that other environmental conditions, such as nutrient availability, pH, temperature, and sorption, are conducive to their survival and transport.

5.7.6. Model Validation

Model validation is a critical step in assessing the accuracy and reliability of a simulation or predictive model. It involves comparing the model's predictions or outputs against observed or measured data to evaluate how well the model represents the real-world system it aims to simulate. This research investigates the movement of microbial pathogens at Temba Cemetery in Hammanskraal, South Africa, utilizing predictive models to understand their fate and transport. The section on model validation focuses on ensuring the accuracy and reliability of these models by comparing simulated pathogen concentrations from the Sauty ADE model against observed data collected at the research site. This validation process scrutinizes temporal trends, peaks, and declines in simulated concentrations to assess how well they align with actual observations. Any discrepancies found are thoroughly examined to identify potential limitations and areas for model enhancement. This validation process aims to strengthen the reliability of predictive models, providing critical insights into pathogen transport dynamics and guiding effective risk management strategies for the local community and surrounding environment. Model validation constitutes a detailed process essential to establish the precision and reliability of predictive models used in assessing microbial pathogen concentrations at Temba Cemetery. The evaluation comprises key components discussed below:

5.7.6.1. Comparing Simulated and Observed Data

To assess the model's accuracy and reliability, the simulated concentrations obtained from the Sauty model were validated against field-measured data. This validation process involved comparing the temporal trends and patterns exhibited by the simulated concentrations with those observed in the field. The field data used to calculate saturated hydraulic conductivities and groundwater flow velocities were incorporated into the validation process. By plotting the field-measured data as a function of concentration over time, it was possible to estimate the time required for the contaminant to reach the receptor borehole (BH1) located 450 meters from the site. The validation models, presented in Figure 22 and Figure 23, utilized the corrected groundwater velocity (0.1055 m/day) derived from field data to ensure accurate and reliable simulations. Table 14 provides the data used for these validation simulations.

Table 14: Data used to validate the model simulations.

Wells	Field Calculated Velocity (v) - (m/d)	Injected Mass/Unit Section (ΔM)	Longitudinal Dispersivity (α_L) - (m^2/d)	Pumping Rate (Q) - (m^3/d)	Radial Distance (r) - (m)	Simulation Period (Years)
MW9	0.1055	10.5263	5.1	0.5688	450	30
OW1	0.1055	3.5088	2.3	0.5688	450	30

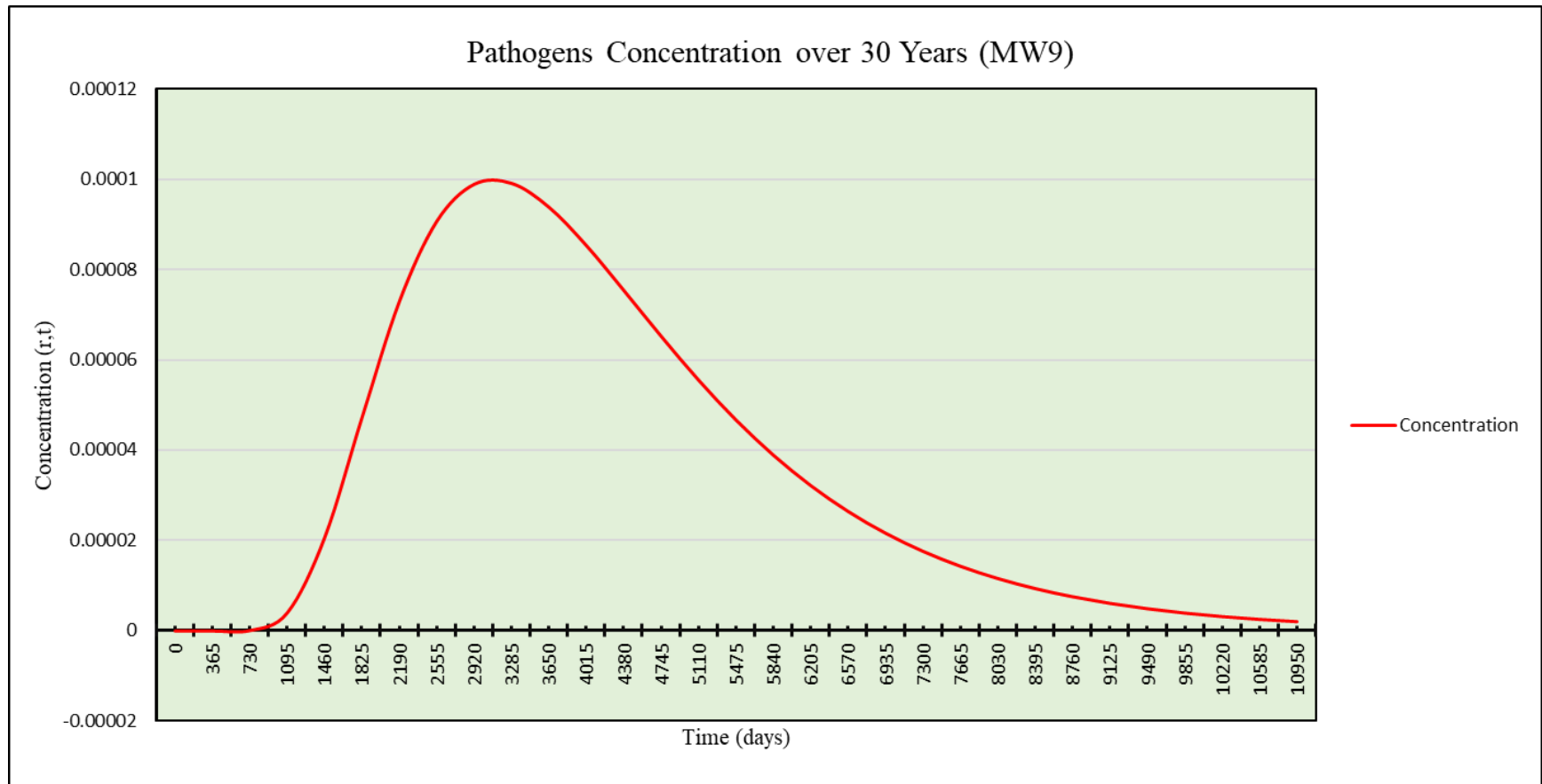


Figure 22: Validation of pathogen concentrations over 30 years utilizing MW9.

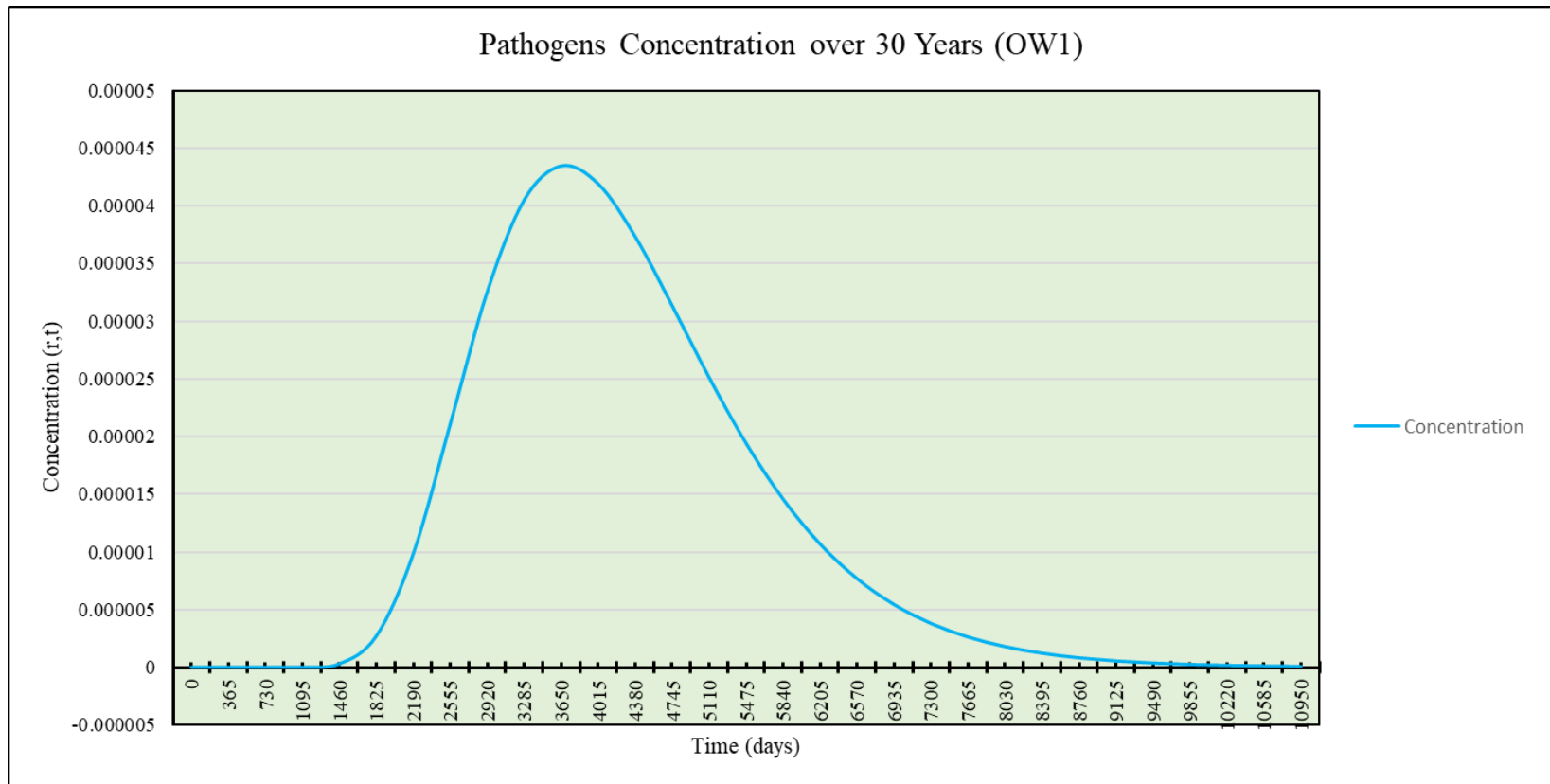


Figure 23: Validation of pathogen concentrations over 30 years utilizing OW1.

The plots above show the simulated concentration of pathogens over a period of 30 years when utilizing MW9 and OW1 data as the source points. The concentration increases gradually over time, reaching a peak and starting to decline in a manner comparable to the model simulations for both conditions of MW9 and OW1. This behaviour can be explained by the transport dynamics of the injected tracer, which disperses and spreads over time due to both advection (groundwater velocity) and dispersion (longitudinal dispersion coefficient). Initially, the concentration increases as the plume travels through the aquifer, but as the distance grows and dispersion dominates, the concentration starts to decrease.

The simulation results over a 30-year period, as illustrated in the concentration versus time graphs above, reflect the behaviour of pathogen transport in groundwater under the influence of advection and dispersion. The following is a detailed explanation of the observed trends in the concentration profile:

Early Time Behaviour (MW9: 0 – 730 days and OW1: 0 – 1 227 days)

In the initial stages of the simulation, there is a slow and gradual increase in concentration. This phase is dominated by the time lag required for the injected mass (ΔM) to travel through the aquifer to the observation point (450 meters from the injection point). During this time, the concentration remains low because the distance between the injection point and the well allows time for dispersive spreading of the pathogen plume. Pathogens are being transported through the aquifer mainly by advection (groundwater velocity, v) and longitudinal dispersion (D_L).

Intermediate Time Behaviour (MW9: 730 – 3 102 days and OW1: 1 227 – 3 650 days)

After approximately 730 days in MW9 and 1 227 days in OW1, the concentration starts to increase more rapidly. This marks the period when the bulk of the injected mass reaches abstraction well. Advection carries the pathogens more effectively towards the well, causing an increase in concentration. Longitudinal dispersion causes the plume to spread, but the mass transfer in this period is largely controlled by advection.

At around 3 102 days (8.5 years) in MW9 and 3 650 days (10 years) in OW1, the concentration reaches its peaks. These peaks represent the maximum concentration observed at the radial

distance of 450 meters. The peak occurs when the rate of mass transport by advection outweighs the dispersive spreading, concentrating the pathogens at the abstraction well.

Late Time Behaviour (After 3 102 days in MW9 and 3 650 days in OW1)

Following the peak concentrations, there is a gradual decline in concentration. This phase occurs due to Longitudinal dispersion becoming the dominant process. As time progresses, the mass of pathogens spreads out over a larger volume of the aquifer, reducing the concentration at the observation point. Dilution effects also contribute to the decline in concentration, as the injected mass continues to move further away from the injection point. As the injected mass is transported further, the number of pathogens reaching the abstraction point decreases with time because of decreasing mass flux.

Comparing model and validation results

Both model and validation simulation show similar behaviour of concentrations transport over time where concentration increases gradually over time, reaching a peak and starting to decline. However, the concentrations of the models relatively increase rapidly in both conditions (i.e., MW9 and OW1) in less than 15 days and peak at day 39 and thereby rapidly decline. On the other hand, the model validation simulations shows that concentrations take greater time to reach the receptor (≥ 2 years) and even longer time to peak (> 8 years) and thereby gradually declines over time.

These differences can be explained by the following key processes influencing the results:

- **Advection (Groundwater Velocity):** The groundwater velocity determines how quickly the mass is transported from the injection point to the well. A faster velocity determined by the model resulted in a more rapid concentration rise and a sooner peak which is not the real representation of the field conditions. Very lower velocities were determined from the field conditions and the validation simulations show that the detected velocity by the model should be corrected to mimic the field conditions.
- **Longitudinal Dispersion:** The longitudinal dispersion coefficient, $D_L = 5.1 \text{ m}^2/\text{day}$, influences how the pathogen plume spreads as it moves through the aquifer. Higher

dispersion values would cause more spreading and lower peak concentrations, while lower dispersion would result in a more concentrated plume.

- **Pumping Rate (Q):** The pumping rate $Q = 0.5688 \text{ m}^3/\text{day}$ represents the rate at which water is extracted from the well, influencing how quickly the contaminated groundwater reaches the well. A higher pumping rate would likely cause faster mass transport, potentially causing the peak to occur sooner.

5.7.6.2. Identifying Discrepancies and Limitations

Identification of discrepancies and limitations plays a vital role in understanding the model's performance. Investigation into discrepancies, particularly during critical periods, and identification of model limitations, be it simplifications, assumptions, or missing parameters, offers valuable insights into potential areas for refinement and enhancement. Slight discrepancy was obtained in the calculation of hydraulic conductivity when comparing the results obtained from bail and percolation tests. The significant variation of the modelled velocity and the field calculated groundwater velocity from bail test conductivity leads to varied results for pathogen to reach the abstraction point (BH1). Limitations and assumptions of the model were precisely elaborated under section 5.7.1.

5.7.6.3. Conclusion and Recommendations

The model validation at Temba Cemetery revealed both strengths and areas for improvement in understanding microbial pathogen transport in the groundwater system. Identifying discrepancies, like variations in hydraulic conductivity from different test methods, highlighted the need for precise parameter selection. Acknowledging limitations and assumptions emphasized the necessity for continuous refinement. Recommendations include parameter fine-modification based on observed discrepancies, reassessment of model assumptions, and a call for ongoing validation to enhance the model's accuracy for informed decision-making in environmental management and public health planning in the Temba Cemetery region.

The following chapter “Chapter 6” is the risk analysis chapter which outlines the risk analysis methodology, detailing the systematic approach used to quantify and evaluate the potential risks to human health posed by microbial pathogens. The discussion includes the Source Pathway

Receptor (SPR) approach, risk metrics calculation, and the comparison of results with established guidelines. This chapter plays a crucial role in bridging data collection and interpretation with the overarching goal of assessing and mitigating risks associated with burial practices.

CHAPTER 6: RISK ANALYSIS

The risk analysis phase of the study is a critical examination to assess the potential risks associated with the presence of microbial pathogens in groundwater and surface water sources. This section undertakes a systematic methodology aimed at evaluating the level of risk posed to human health. The risk analysis process is broken down into two key components, namely, the Source Pathway Receptor (SPR) approach and the Quantitative Microbial Risk Assessment (QMRA). The SPR approach serves as a foundational background, accurately analysing various components that contribute to the spread of microbial pathogens. It thoroughly examines the origins of these pathogens (sources), their pathways of travel through the environment, and the ultimate points where humans or other receptors might come into contact. However, the QMRA establishes a strong analytical tool that, based on the SPR methodology, quantifies the probabilities and potential consequences of human exposure to these pathogens. Together, these approaches enable an understanding and quantification of the risks linked with the presence of microbial pathogens in the studied water sources at Temba Cemetery, providing crucial insights for effective risk management and public health strategies.

6.1. Source Pathway Receptor (SPR) Approach

The SPR approach serves as a critical tool for evaluating environmental risks linked to microbial pathogens emanating from burial sites. This approach systematically breaks down the potential hazards by first identifying three crucial components.

6.1.1. Source of Concern

The "Source of Concern" categorically identifies the origins of contamination. At Temba Cemetery, the primary sources come from burial grounds, comprising decomposing organic matter, waste, and soil hosting microbial pathogens. Secondary sources encompass contaminated groundwater and surface runoff during rainfall, carrying contaminants into nearby water bodies, and aerosols liberated during decomposition or soil disturbance.

6.1.2. Pathway of Contamination

The "Pathway of Contamination" delineates how these contaminants navigate from source to receptor. Soil contamination pathways involve percolation, where pathogens seep into the soil and potentially infiltrate groundwater. Surface runoff during precipitation also aids in contaminant transport. Meanwhile, groundwater contamination pathways encompass percolation directly into groundwater or through preferential flow pathways. The research pathway will focus on groundwater as a preferential pathway of concern.

6.1.3. Receptor at Risk

The "Receptor at Risk" identifies individuals vulnerable to contamination. The human population, notably the local community and cemetery workers, stands as primary receptors potentially exposed to contaminated water sources. Additionally, environmental receptors comprise local ecosystems such as aquatic systems, vegetation, and wildlife that might be adversely impacted. The prominent receptor used for this research was groundwater users in the surrounding community.

6.2. Quantitative Microbial Risk Assessment

Quantitative Microbial Risk Assessment (QMRA) is a methodology aimed at measuring the probability of infection, illness, or mortality arising from microbial pathogens (Pepper et al., 2015). This chapter provides an in-depth exploration of risk assessment, which involves determining the likelihood of events occurring. It thoroughly covers various aspects such as hazard identification, exposure assessment, evaluating the relationship between the dose of exposure and the response in terms of illness, and finally, characterizing the risk posed by the microorganism. This phase involves assessing the potential impact of the microorganism, addressing uncertainties, and formulating strategies for risk projection and management. Moreover, the chapter illuminates its concepts through case studies and specific models used in microbial risk assessment to offer a grasp of how risk calculations are conducted in practical scenarios.

The tabulated QMRA below succinctly outlines the components and their role in understanding the fate of microbial pathogens from the Temba Cemetery and assessing the associated health risks.

Table 15: Tabulated breakdown of the QMRA for Temba Cemetery

QMRA Components	Description
Hazard Identification	Identification of potential microbial pathogens and faecal indicators present in the Temba Cemetery environment.
Exposure Assessment	Quantification of exposure pathways and routes through which individuals might encounter these microbial contaminants.
Dose-Response Analysis	Assessment of the relationship between the level of exposure to the pathogens and the likelihood of infection, illness, or mortality.
Risk Characterization	Estimation of the potential health risks posed by the presence of these pathogens, incorporating uncertainties and risk projection.
Simulation and Empirical Data	Utilization of detailed simulations and empirical data to quantify the probability of infection or illness, aiding in risk management.

6.2.1. Hazard Identification

This involves identifying and characterizing potential microbial pathogens and faecal indicators present in the environment of Temba Cemetery. It requires surveillance and sampling of the cemetery grounds, water sources, and surrounding areas to identify specific pathogens and indicator organisms, such as *E. coli* or other potential disease-causing microbes associated with human waste. Groundwater samples were collected on-site and off-site from installed monitoring wells and MW7 presented *E. coli* colonies count of 5 000. Since the *E. coli* colonies count was detected in MW7, therefore, groundwater around this well was considered as an identified hazard. No soil samples were collected for analyses of microbial pathogens during the study. The stream sample presented *E. coli* colonies count of 5 300 and was considered as an identified hazard.

6.2.2. Exposure Assessment

This step quantifies the pathways and routes through which individuals might encounter the identified microbial contaminants. This includes assessing potential exposure routes such as direct contact with contaminated soil, ingestion of contaminated water, or inhalation of aerosolized particles carrying pathogens from disturbed soil during activities like burial processes or

maintenance. The identified exposure pathway for microbial risk assessment at Temba Cemetery are as follows:

- Contaminated soil; and
- Ingestion of contaminated water

6.2.3. Dose-Response Analysis

Dose-response analysis aims to determine the relationship between the level of exposure to the identified pathogens and the likelihood of infection, illness, or mortality in individuals exposed. It involves extrapolating data from known dose-response relationships for various pathogens to estimate the probability and severity of health outcomes associated with exposure. However, during this step, the South African National Standard (SANS) 241 were used as a benchmark outlining the minimal requisites for safe drinking water intended for human consumption as opposed to extrapolating data from known dose-response. The counts of colonies identified in monitoring wells, a surface water body, and a private borehole screened against the South African National Standard (SANS) 241. All total coliform counts detected in the monitoring wells exceeded the prescribed limits outlined in SANS 241 as illustrated in Table 12. The SANS 241 limits set out for the total coliforms is ≤ 10 colonies per 100 ml.

6.2.4. Risk Characterization

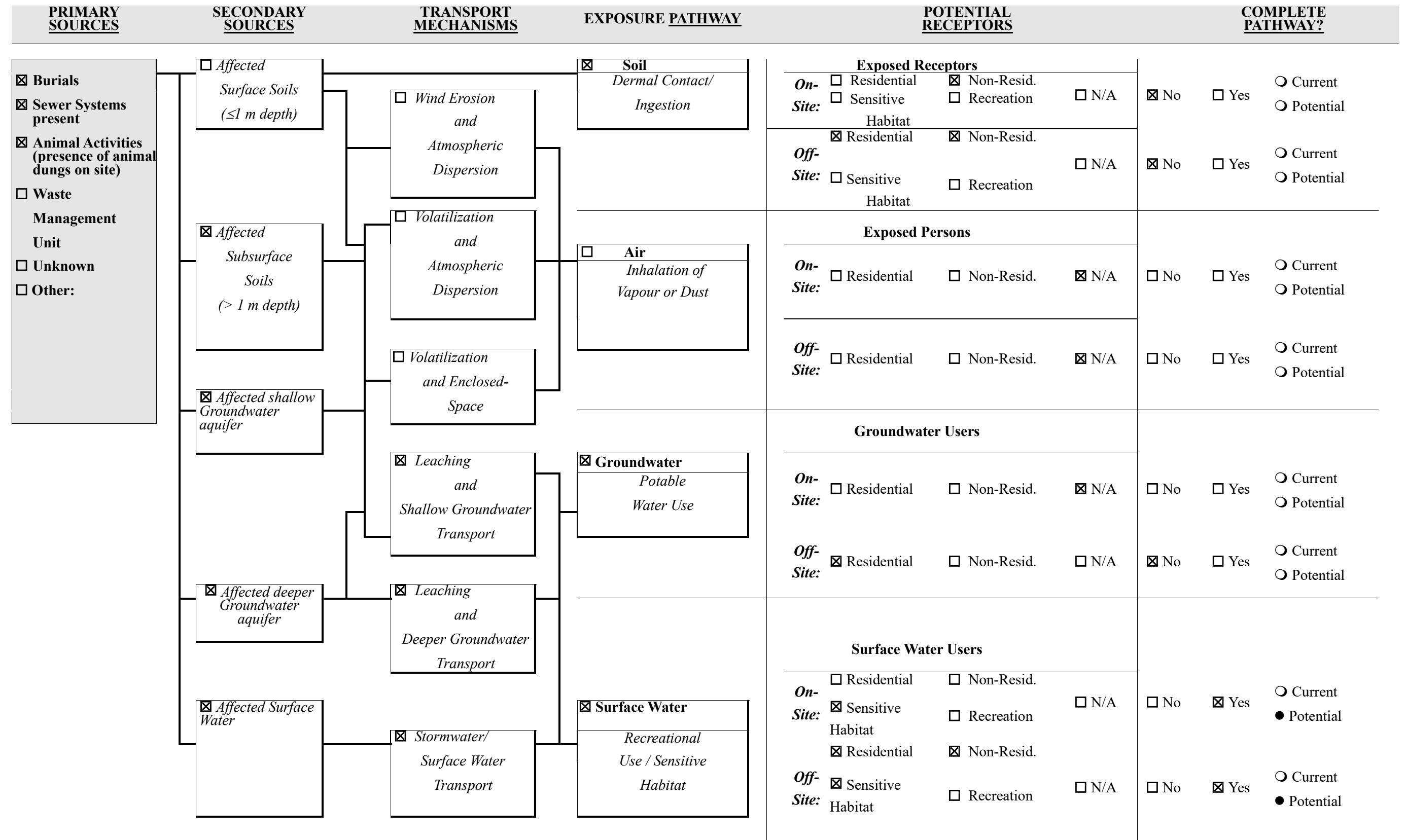
This step involves estimating the potential health risks posed by the presence of identified pathogens and faecal indicators in the cemetery environment. It integrates data from hazard identification, exposure assessment, and dose-response analysis to quantify the overall risk of infection, illness, or mortality. Uncertainties in data and variability in exposure scenarios are considered in this stage. Based on the laboratory analysis presented in Table 12, it is evident that none of the E. Coli colonies count were detected at the receptor (i.e., BH1). Therefore, it can be concluded that the potential risk posed by pathogens utilizing E. Coli as a prominent indicator can be considered low at this stage. In addition, the water present at the receptor (i.e., BH1) is currently not used for consumption; therefore, this further reduces the risk of exposure to waterborne pathogen through ingestion.

6.2.5. Simulation and Empirical Data

Utilizing simulation models based on empirical data aids in quantifying the probability of infection or illness. By incorporating various exposure scenarios, demographic data, and environmental factors, these simulations enable risk managers to predict the potential health risks associated with various levels of exposure to the identified microbial contaminants. This step contributes to informed decision-making regarding risk management strategies.

Two simulation models were developed utilizing refined parameter data obtained from the Sauty model fitting. These simulations aimed to assess the movement of pathogens towards the receptor (BH1), situated 450 meters from the primary source (Temba Cemetery). Figure 20 and Figure 21 depict the two models, revealing the potential migration of pathogens through groundwater to reach the receptor within the 100-day simulated period. However, the laboratory results at the receptor borehole showed that zero colonies per 100 ml of *E. coli* was present in the water sample. The human health risk analysis, depicted in the baseline exposure flowchart (Table 16), indicates no current risk posed by the site to groundwater users in the nearby area based on current laboratory findings. However, potential risks emerge through dermal contact and surface water ingestion, especially considering the *E. Coli* counts from the stream sample. Given that the stream is presently utilized by the local livestock, further investigations are required to better understand and address this potential risk.

Table 16: Conceptual Site Model (CSM) baseline exposure flowchart



The following chapter “Chapter 7” is the research synthesis chapter which is dedicated to the analysis of research results, Chapter 7 identifies areas of elevated risk and factors contributing to pathogen transport. It engages in a research synthesis, linking the obtained results with the initially set research objectives. The chapter critically evaluates the success of the study in addressing the research problem and presents a detailed interpretation of the findings.

CHAPTER 7: RESEARCH SYNTHESIS

The thorough study conducted at Temba Cemetery aimed to understand the complex dynamics of microbial pathogen fate and transport within the cemetery environment. The focus was on modelling the movement of these pathogens using faecal indicators, specifically *E. coli*, aiming to solve the complexities of environmental contamination and the associated health risks. Temba Cemetery, established in the late 1960s and still actively used for burials, provided a dynamic setting for this scientific investigation, making real-time observations and assessments possible.

During the site visit, several crucial characteristics were observed that revealed critical factors influencing the outcomes of the study. Waterlogged graves and significant groundwater seepage were observed, potentially impacting the distribution of faecal indicators and pathogen movement within the cemetery subsurface environment. Furthermore, the presence of cattle and sewer utility holes heightened concerns about potential faecal contamination, significantly impacting the research outcomes. These initial observations set the stage for further investigations into the burial practices' influence and potential sources of environmental contamination.

Drilling operation established ten (10) monitoring wells at strategic locations across the cemetery. These wells provided essential data for assessing groundwater levels, hydraulic conductivity, and facilitating varied testing protocols. Hydraulic tests, including percolation, bail, and tracer tests, were conducted to determine the permeability of different soil types within the cemetery. These tests were instrumental in understanding how groundwater flowed within the site and the potential paths for pathogen migration. For instance, the percolation test revealed that gravelly silty sand and gravelly fine sand exhibited higher hydraulic conductivity (0.2923 and 0.3058 m/day), suggesting faster water movement. In contrast, silty sand and clayey silty sand showed lower values (0.2236 and 0.0689 m/day), indicating restricted flow that might affect pathogen dispersal. On the other hand, geometric mean of hydraulic conductivity of 1.0107 m/day was acquired from the calculated bail test results. These field measured conductivities provide crucial data used in refining the models and the risk analysis of the research.

The data obtained from the hydraulic tests allowed for detailed groundwater flow calculations. This assessment helped in determining the velocities at which groundwater flowed through

different areas of the cemetery. Groundwater velocities were calculated and ranged between 0.0055 and 0.3635 m/day. Variations in velocities highlighted the heterogeneous nature of the hydrogeological system, influencing the potential movement of microbial pathogens. These values were crucial in constructing a conceptual site model, aiding in the understanding of how contaminants might spread within the cemetery environment.

Water quality analyses revealed elevated levels of faecal coliforms and *E. coli* counts in monitoring wells located within the burial zones and stream located in the vicinity of burial zones. These counts exceeded safety thresholds outlined by regulatory standards (South African National Standard - SANS 241) for potable water. However, the absence of *E. coli* in specific areas, such as a private borehole and other monitoring wells located within the burial zones, indicated spatial variability in contamination levels across different sampling points. This variability suggested localized factors influencing contamination patterns within the cemetery.

Tracer test using NaCl was conducted at the research site and EC levels were measured at the observation (OW1) and abstraction wells. These EC values were converted to concentrations using the relation obtained by Peinado Guevara et al. (2012) which showed that $[Cl^-] = 9.22 \text{ EC}$, for $0.15 < EC < 95 \text{ dS m}^{-1}$ in the linear regression model. These concentrations were used to model pathogen movement, using sophisticated analytical fate and transport model, particularly the Advection-Dispersion Equation (ADE) model by Sauty (1980), was employed. Breakthrough Curves (BTCs) derived from observation and abstraction wells served as crucial data points to refine these models.

BTCs analysis revealed distinctive peaks at MW9 and OW1 within 144 and 105 minutes, essential for deriving Sauty model parameters. Utilizing the NaCl concentration data, the Sauty model calculated fitting parameters such as dispersivity coefficients of 91.8 and 13.8 m² per day, velocities of 18 and 6 m per day, and effective porosities of 0.02 and 0.05, in MW9 and OW1, respectively. The BTCs provided insights into the movement and behaviour of pathogens within the groundwater system. However, discrepancies between simulated and observed data highlighted limitations in the models' predictive capabilities. Two simulation models were applied to MW9 and OW1 data to show microbial fate and transport utilizing results obtained from tracer test

concentrations. Both scenarios exhibited an initial absence of concentrations, followed by a gradual increase and subsequent decline in concentrations over time.

The validation of models involved comparing model simulation and validation simulations using data obtained from field measurements. The simulation results indicate that both the model and validation simulations exhibit a similar pattern of concentration transport, with a gradual increase, followed by a peak, and subsequent decline. However, a notable difference lies in the timing of these events. The model simulations predict a rapid increase and peak within 15 days, while the validation simulations show a significantly slower progression, with peaks occurring after 8 years.

These discrepancies can be attributed to several factors. The groundwater velocity, as determined by the model, is likely overestimated, leading to a faster-than-real concentration rise and earlier peak. Field conditions suggest a much lower velocity, which aligns better with the observed slower transport in the validation simulations. Additionally, the longitudinal dispersion coefficient, may influence the spreading of the pathogen plume. A higher dispersion coefficient could result in a broader, less concentrated plume, potentially delaying the arrival of the peak concentration at the well. The pumping rate, while relatively low, may also contribute to the transport dynamics. A higher pumping rate could accelerate the movement of contaminants towards the well, potentially influencing the timing of the peak concentration.

Quantitative Microbial Risk Assessment (QMRA) methodologies were employed to quantify the potential risks associated with microbial pathogens. While indicating low immediate health risks to groundwater users based on laboratory findings, the assessment highlighted potential exposure routes through dermal contact and surface water ingestion. These findings emphasized the necessity for further investigations to mitigate potential health risks posed by microbial pathogens in the environment.

The assessment of groundwater velocities across the cemetery revealed substantial variations in flow rates. Variability in velocities indicated diverse paths for pathogen migration and contamination dispersion within the cemetery. These findings highlighted the need for a detailed understanding of hydrogeological factors influencing groundwater movement and contaminant transport. The assessment of groundwater flow dynamics at Temba Cemetery involved complex

calculations derived from hydraulic tests and monitoring well data. These calculations aimed to ascertain the velocities at which groundwater moved through distinct areas of the cemetery, crucial for understanding pathogen migration patterns. Hydraulic conductivity values obtained from percolation and bail tests facilitated the calculation of groundwater flow rates. Variations in these rates across different soil types highlighted the heterogeneous nature of the hydrogeological system within the cemetery. This heterogeneity significantly influences the movement of microbial pathogens and contaminants.

Two simulation models were generated using the advection and dispersion equation to model the transport of contaminant toward the off-site receptor. Comparison of two simulations suggests variations in transport mechanisms or factors affecting microbial pathogen movement between observation and extraction wells. Differences in fitted velocity parameters show proportional correlation with concentrations, crucial for understanding pathogen transport risks and devising mitigation strategies. Results align with Wang et al.'s (2013) study on *Escherichia coli* D21g and coliphage 'X174 behaviour in saturated soils with preferential flow. Greater flow velocities and conductivity observed in saturated sand soil conditions.

Dent and Knight (1998) found insignificant pathogenic organism levels in permeable silty sands and clay in Australian urban areas, indicating variable coliform infiltration under specific hydrogeological conditions. Our investigation, like Dent and Knight's, suggests variable pathogen migration into groundwater in silty sand and clay hydrogeological conditions. Environmental factors like temperature, pH, and water availability influence pathogen persistence, with our study confirming conducive conditions for survival (Van Elsas et al., 2011). Although our simulations predict contaminant reaching receptors within six to seven days, factors like sorption, chemical reactions, and die-off rates were not considered. Studies show varied *E. coli* survival times, indicating pathogens could reach receptors under favourable environmental conditions. Our simulations highlight potential pathogen transport to receptors if conducive environmental conditions persist.

In summary, the detailed analysis of model results provided insights into the complexities of predicting pathogen fate and transport. While models such as the ADE models offered valuable simulations of pathogen movement, discrepancies between predicted and observed values

underscored the challenges in accurately capturing real-world scenarios. These discrepancies reinforced the importance of continual refinement and validation of models to improve their accuracy and reliability. The validation process involved a meticulous comparison between simulated data derived from fate and transport models and real-world observations obtained through field measurements. This rigorous assessment aimed to ensure the accuracy and reliability of the models in predicting pathogen transport and associated risks. Discrepancies identified between simulated data and observed values underscored the complexity inherent in modelling pathogen movement within the cemetery environment. For instance, discrepancies between predicted and observed concentrations of faecal indicators, such as *E. coli*, raised concerns about the models' predictive capabilities.

These discrepancies emphasized the need for continual refinement and validation of models to address underlying complexities and improve their accuracy. Factors contributing to these disparities, such as preferential flow paths or heterogeneities in the subsurface, required further exploration and incorporation into model refinements. By addressing these discrepancies and continuously validating the models against observed data, researchers aimed to enhance the reliability of predictions, supporting more effective risk assessments and mitigation strategies. Expanding on these methodologies offers a deeper understanding of the intricate processes involved in assessing microbial pathogen fate and transport at Temba Cemetery. It also highlights the critical role of accurate modelling in addressing potential health risks and guiding environmental health management strategies within cemetery environments.

The conceptual site model, constructed based on data gathered from various assessments, served as a foundation for understanding contaminant pathways and risks within the cemetery environment. The identification of potential exposure routes through modelling and assessments allowed for the formulation of effective risk mitigation strategies. Recommendations were made to refine modelling approaches, enhance monitoring initiatives, and engage the community in efforts to safeguard environmental health.

The last chapter synthesizes the entire dissertation by summarizing key findings, offering conclusive remarks, and presenting practical recommendations. It reflects on the research journey, reiterates the significance of the study, and suggests avenues for future research. This chapter

provides closure to the dissertation by encapsulating the study's contributions and implications for cemetery management and environmental health.

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

The research undertaken at Temba Cemetery in Hammanskraal, South Africa, stands as a robust investigation that has uncovered vital insights into the complex dynamics governing the fate and transportation of microbial pathogens arising from burial practices. This investigation, thoroughly supported with specific objectives, comprised of various hydrogeological tests, modelling applications, and risk quantification. Through a complex approach, the research has explained potential threats posed to both groundwater and surface water sources, highlighting the critical connections between burial practices and environmental health.

The thorough investigation at Temba Cemetery was conducted on a determined scientific approach, aiming not only to explain the complexities of microbial pathogen movement but also to pave the way for actionable insights that protect the environmental integrity and public health of the surrounding community. This chapter consolidates the findings and recommendations from the investigation, drawing from observed evidence, advanced analyses, and a strong commitment to improving environmental health management practices. The discoveries made through this research act as a guide, steering discussions toward proactive actions and well-thought-out interventions. These strategies aim to reduce risks and ensure the ongoing health of the environment and the surrounding community.

8.1. Recommendations for Mitigation

Building upon these findings, a set of recommendations was formulated to mitigate the identified risks and safeguard both the environment and the health of the community surrounding Temba Cemetery.

8.1.1. Implementing Improved Burial Practices

Developing and enforcing guidelines for safer burial practices is essential to mitigate pathogen contamination from burials. By specifying optimal burial depths and advocating the use of liners, the potential for pathogen migration can be significantly minimized. Guidelines can outline specific burial depths suitable for reducing pathogen transport, considering factors like soil

characteristics and hydrogeological conditions. By enforcing these depths, the potential for pathogens to reach groundwater sources can be reduced, thereby protecting water quality.

Additionally, advocating for the use of liners during burials can function as a protective barrier against pathogen infiltration into the soil and groundwater. These liners can serve as an effective means to contain pathogens within the burial site, preventing their movement into the surrounding environment. Implementing these practices would require collaboration between cemetery management, relevant authorities, and burial site stakeholders. Public awareness campaigns, training sessions, and regular inspections can aid in ensuring compliance with these guidelines. Continuous education and reinforcement of these practices would be pivotal in minimizing the environmental impact of burials on water quality in and around Temba Cemetery.

8.1.2. Community Engagement and Awareness

Engaging and educating the local community about proper burial practices and water quality monitoring is paramount for development of shared responsibility for environmental health. Through community engagement initiatives, residents can understand the direct link between burial practices, groundwater contamination, and their overall wellbeing. Education programs should be designed to inform community members about the implications of improper burial practices on groundwater quality and public health. This includes emphasizing the significance of adhering to recommended burial depths, the use of liners, and the potential risks associated with untreated water sources.

Interactive workshops, seminars, and outreach campaigns conducted in collaboration with community leaders, local health authorities, and educational institutions can effectively disseminate information. These initiatives should be tailored to resonate with the cultural context and values of the local population to ensure receptivity and active participation. Furthermore, empowering community members to actively participate in monitoring efforts, such as reporting observations or assisting in sample collection, can strengthen community ownership and vigilance over environmental health issues. By creating a sense of shared responsibility, community engagement can be a catalyst for sustainable changes in burial practices and environmental stewardship.

8.1.3. Collaborative Efforts

Establishing partnerships between research institutions, local authorities, and environmental agencies is essential for the effective implementation and compliance with mitigation strategies. Collaborative efforts can combine expertise, resources, and governance structures to address the complex challenges posed by microbial pathogen contamination. Research institutions can contribute by providing scientific expertise, conducting studies, and refining predictive models to guide mitigation strategies. Local authorities and environmental agencies play a crucial role in policy implementation, enforcement, and community outreach, ensuring that mitigation measures align with regulatory standards and are effectively communicated to stakeholders.

8.1.4. Regular Monitoring and Continual Research

Establishing a systematic routine for monitoring water quality, encompassing both groundwater and surface water, is vital for timely risk detection and safeguarding the community's water supply. This involves regular sampling and analysis of water from numerous points in and around the cemetery, assessing parameters like faecal coliforms, *E. coli*, nitrates, pH levels, and other relevant contaminants to identify any deviations from safe standards. A well-structured monitoring program would strategically position monitoring wells and sampling points across the cemetery, facilitating real-time data collection, analysis, and efficient reporting mechanisms to enable swift responses to any water quality deviations.

Engaging local communities in these initiatives can instil a sense of responsibility for their water supply's safety and encourage ownership. Continual commitment to research, ongoing monitoring efforts, and model refinements are vital to adapt to changing environmental conditions and enhance predictive accuracy. Sustaining these initiatives demands dedicated resource allocation to maintain monitoring programs, conduct field investigations, and analyse collected data, allowing for the identification of emerging trends, changes in pathogen behaviour, and variations in groundwater quality over time.

8.1.5. In-depth Hydrogeological Studies

Conducting in-depth hydrogeological studies is crucial to resolve the complex details of how groundwater flows within the cemetery environment. By researching deeper into the hydrogeological system, the complexities of groundwater movement can be uncovered, including pathways where water flows preferentially, mechanisms that recharge the water sources, and the impact of geological formations. These hydrogeological investigations would comprise detailed geological mapping, advanced geophysical surveys, and advanced hydrological modelling. Through these studies, researchers can gain insights into how groundwater flow changes over space and time. This understanding would help identify areas more susceptible to increased migration of pathogens and higher risks of contamination.

Incorporating advanced modelling techniques is critical for improving the accuracy of pathogen migration and contamination models. These advanced models should encompass the heterogeneous subsurface, specialized flow paths, and intricate interactions among environmental factors influencing pathogen movement. Utilizing state-of-the-art algorithms, machine learning, and three-dimensional simulations allows for a more precise representation of pathogen dispersion patterns, considering complex underground structures and hydrogeological variations. Integrating real-time monitoring data into these models enhances their predictive accuracy, and continual refinement based on updated information ensures their reliability in forecasting pathogen transport across diverse environmental scenarios. Understanding these intricate hydrogeological details is vital in refining predictive models, allowing for more precise simulations of how pathogens move. Detailed studies could reveal potential barriers or conduits that influence the pathways pathogens take, leading to more accurate risk assessments and targeted strategies to mitigate contamination.

In concluding the extensive research conducted at Temba Cemetery, the findings provide an essential foundation for informed decision-making and proactive measures in mitigating potential health risks linked to microbial pathogens. The continual refinement and validation of models, alongside proactive community engagement, strategic collaborations, and sustained research endeavours, emerge as necessary components in ensuring effective environmental health management within cemetery environments. These measures stand as imperative safeguards for

public health and the surrounding ecosystem, addressing the complex challenges posed by pathogen migration within such environments.

The research also serves as a cornerstone for comprehending and proactively managing the risks associated with microbial pathogens originating from burial sites. Through the interpretation of research outcomes and the formulation of mitigation recommendations, this study lays the foundation for safeguarding environmental health and ensuring the well-being of the surrounding community. Continued research efforts, complemented by the implementation of recommended strategies, play an essential role in effectively managing and mitigating potential risks posed by microbial pathogens.

8.2. Limitations of the Research Study

The research study was limited by several factors that hindered the thorough investigation of the aquifer system and the potential impact of pathogenic contaminants. One significant limitation was the inability to definitively determine if the perched aquifer on-site and surface water bodies are linked to the deep aquifer from which BH1 draws water. This uncertainty made it difficult to confidently attribute the detected concentrations at the receptor borehole to the interaction between these aquifers. Furthermore, the lack of water level data, construction details, and geological information for BH1 and other nearby boreholes prevented a thorough understanding of the deeper aquifer's characteristics, hindering comparisons with the perched aquifer conditions on-site. The absence of a deeper borehole on-site also precluded direct assessment of pathogenic impact conditions and testing of the deeper aquifer.

Anthropogenic impacts, such as stream pollution, were not fully evaluated due to the limited scope of the tracer test and the lack of long-term monitoring data. The high *E. coli* count in the stream sample indicated potential pollution risks, but further investigation was needed to assess their impact on the aquifer. The tracer test was confined to a single area, limiting the ability to thoroughly evaluate pathogen transport characteristics across the site. Additional tests from various areas would have provided more robust data and increased confidence in the results. The absence of long-term monitoring data also prevented the analysis of water level fluctuations and

bacterial count trends over time, hindering the evaluation of seasonal and climatic impacts on pathogen concentrations.

The limitations of the model stem from various factors, including data availability, the simplified representation of the complex system, and uncertainties in pathogen behaviour. The model's inability to fully consider site-specific factors and challenges in validating its predictions against real-world observations because of insufficient long monitoring data also contribute to its limitations. Uncertainties in pathogen behaviour arise due to the lack of measured about their persistence, interactions, and sorption and diffusion mechanisms within the subsurface environment. Additionally, the model neglects chemical reactions as per the assumptions and environmental factors such as resource availability could not be measured. While the model was validated using field data, challenges in validating its predictions against real-world observations persist due to limitations in field data and the complexity of validating pathogen transport as some of the analysed bacterial counts during some seasons were 0 colonies/100ml. Furthermore, the model assumes conservative behaviour of microbial pathogens, neglecting potential transformation (growth) or decay mechanisms that could affect their movement.

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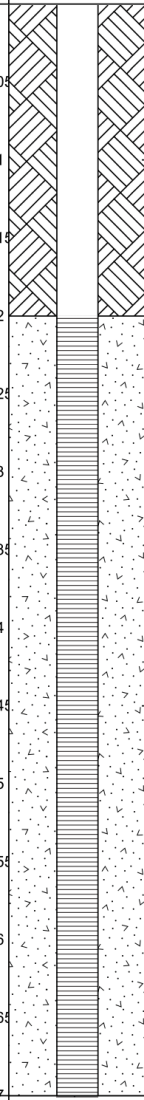
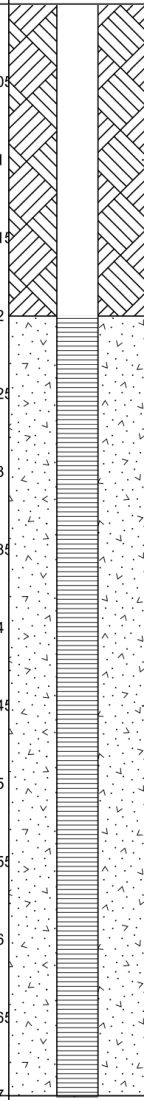
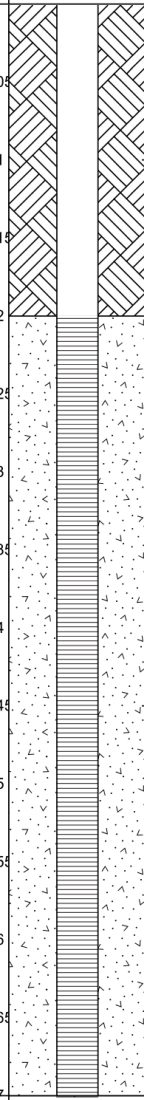
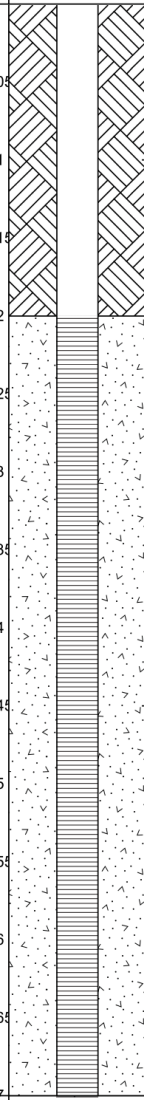
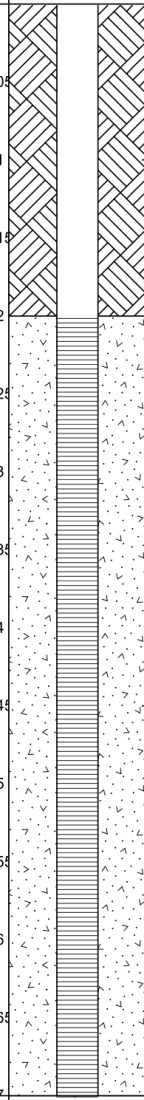
Zychowski, J. (2009). Impact of selected graves and mass burial sites from WW 1 and 2 on the presence of bacterium in groundwaters. In M. Ziulkiewicz (Ed.), *State and Anthropogenic Changes of Water Quality in Poland* (pp. 131–142). University of Łódź, Łódź.

Żychowski, J., & Bryndal, T. (2015). Impact of cemeteries on groundwater contamination by bacteria and viruses – a review. *Journal of Water and Health*, 13(2), 285–301. <https://doi.org/10.2166/wh.2014.119>.

Appendix I: Geological and Test Pits Logs



GROUNDWATER WELL LOG MW10

PROJECT NUMBER 2789481		DRILLING DATE 09 August 2023		COORDINATES -25.39422, 28.25858										
PROJECT NAME Temba Cemetery		TOTAL DEPTH 0.67m		COORD SYS										
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION										
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1099										
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC										
COMMENTS				LOGGED BY Elia Muravha										
				CHECKED BY Elia Muravha										
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description					
0.03		Hand Auger Drilling	No soil samples collected	NA			M	Loose	SILTY SAND: Greyish dark brown loose gravelly SILTY SAND with plant roots, Alluvium					
0.1														
0.13														
0.2									SILTY SAND: Greyish dark brown loose gravelly SILTY SAND, Alluvium					
0.25														
0.3													W	Medium dense
0.33														
0.4														
0.43														
0.5														
0.55														
0.6														
0.63														
0.65														
0.7														
									Termination Depth at:0.7 m due to Sandstone bedrock					



GROUNDWATER WELL LOG MW9

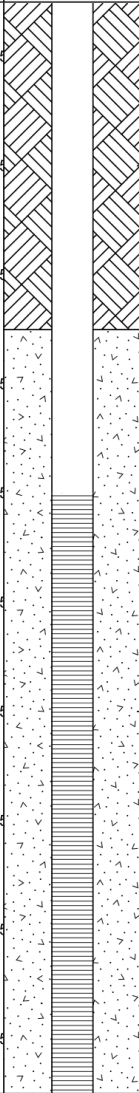
PROJECT NUMBER 2789481 PROJECT NAME Temba Cemetery CLIENT WITS ADDRESS Johannesburg Campus LICENCE NO.			DRILLING DATE 09 August 2023 TOTAL DEPTH 2.0m DIAMETER 9.5 cm CASING uPVC SCREEN uPVC Factory Slotted			COORDINATES -25.3946, 28.25797 COORD SYS COMPLETION SURFACE ELEVATION 1099 WELL TOC				
COMMENTS						LOGGED BY Elia Muravha CHECKED BY Elia Muravha				
Depth (m)	Well Diagram		Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.1	 concrete cement grout		Hand Auger Drilling	No soil samples collected	NA			VM	Soft	SANDY CLAY: Dark greyish-brown soft SANDY CLAY with plant roots, Alluvium
0.2									Firm	SANDY CLAY: Dark greyish-brown blotched orange firm to stiff silty SANDY CLAY, Alluvium
0.3										
0.4	 filter pack							W	Stiff	SILTY CLAY: Light gre blotched dark grey and orange stiff SILTY CLAY, Alluvium
0.5										
0.6										
0.7										
0.8										
0.9										
1.0										
1.1										
1.2										
1.3										
1.4										
1.5									Dense	GRAVELLY SAND: Light gre blotched orange dense clayey GRAVELLY SAND with cobbles, Residual soil
1.6										
1.7										
1.8										
1.9										
2.0										Termination Depth at:2.0 m due to Sandstone bedrock

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GROUNDWATER WELL LOG MW8

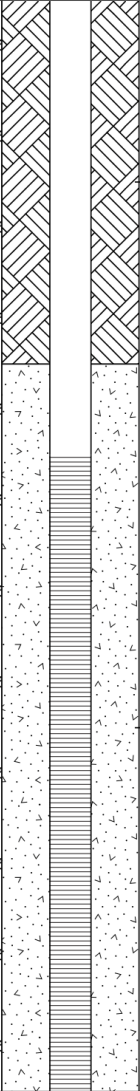
PROJECT NUMBER 2789481		DRILLING DATE 09 August 2023		COORDINATES -25.39383, 28.25803						
PROJECT NAME Temba Cemetery		TOTAL DEPTH 1.0m		COORD SYS						
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION						
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1099						
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC						
COMMENTS				LOGGED BY Elia Muravha						
				CHECKED BY Elia Muravha						
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description	
0.00	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA			VM	Loose	SILTY SAND: Dark greyish-brown mottled dark red loose fine SILTY SAND with plant roots, Alluvium	
0.10										
0.20										
0.30							M		SILTY SAND: Dark brown mottled grey loose fine SILTY SAND, Residual soil	
0.40										
0.50							W		Very Loose	GRAVELLY SAND: Dark orange-brown very loose silty GRAVELLY SAND with cobbles, Residual soil
0.60										
0.70										
0.80										
0.90										
1.00								Termination Depth at: 1.0 m due to Sandstone bedrock		

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GROUNDWATER WELL LOG MW7

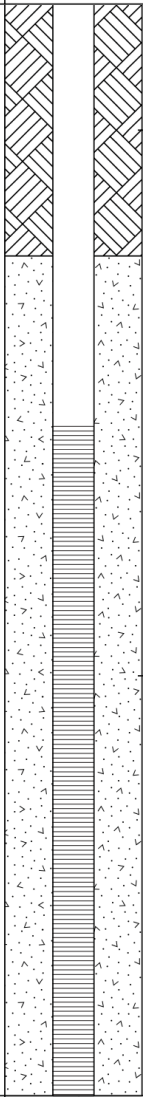
PROJECT NUMBER 2789481 PROJECT NAME Temba Cemetery CLIENT WITS ADDRESS Johannesburg Campus LICENCE NO.		DRILLING DATE 09 August 2023 TOTAL DEPTH 1.2m DIAMETER 9.5 cm CASING uPVC SCREEN uPVC Factory Slotted		COORDINATES -25.39472, 28.25889 COORD SYS COMPLETION SURFACE ELEVATION 1099 WELL TOC					
COMMENTS				LOGGED BY Elia Muravha CHECKED BY Elia Muravha					
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.05	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA			M	Very loose	SAND: Dark greyish-brown blotched orange very loose fine SAND with plant roots, Alluvium
0.1									
0.15									
0.2									
0.25									
0.3									
0.35									
0.4									
0.45									
0.5									
0.55									
0.6									
0.65									
0.7									
0.75									
0.8									
0.85									
0.9									
0.95									
1									
1.05									
1.1									
1.15									
1.2									
1.25									
									Termination Depth at:1.2 m due to Sandstone bedrock and collapsable sands

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GROUNDWATER WELL LOG MW6

PROJECT NUMBER 2789481		DRILLING DATE 10 August 2023		COORDINATES -25.39388, 28.25952					
PROJECT NAME Temba Cemetery		TOTAL DEPTH 1.3m		COORD SYS					
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION					
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1102					
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC					
COMMENTS				LOGGED BY Elia Muravha					
				CHECKED BY Elia Muravha					
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.1	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA			M	Med dense	SILTY SAND: Orange-brown medium dense SILTY SAND with cobbles, Alluvium
0.2									Very dense
0.3									
0.4									
0.5									
0.6									
0.7									
0.8									
0.9									
1.0									
1.1							W		SAND: Orange-brown very dense SAND (completely weathered Sandstone), Residual soil
1.2									
1.3									Termination Depth at: 1.3 m due to Sandstone bedrock

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GROUNDWATER WELL LOG MW5

PROJECT NUMBER 2789481		DRILLING DATE 09 August 2023		COORDINATES -25.39404, 28.25871					
PROJECT NAME Temba Cemetery		TOTAL DEPTH 0.8m		COORD SYS					
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION					
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1101					
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC					
COMMENTS				LOGGED BY Elia Muravha					
				CHECKED BY Elia Muravha					
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.05	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA			M	Loose	SILTY SAND: Dark greyish-brown blotched red loose SILTY FINE SAND with plant roots, Alluvium
0.1									SILTY SAND: Dark greyish-brown blotched red loose SILTY FINE SAND, Alluvium
0.15									
0.2									
0.25									
0.3									
0.35									
0.4									
0.45									
0.5									
0.55							W	Med dense	SAND: Reddish brown mottled dark orange medium dense SAND (completely weathered Sandstone), Residual soil
0.6									SAND: Reddish brown mottled dark orange medium dense SAND (completely weathered Sandstone), Residual soil with cobbles
0.65									
0.7									
0.75									
0.8									Termination Depth at: 0.8 m due to Sandstone bedrock

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GROUNDWATER WELL LOG MW4

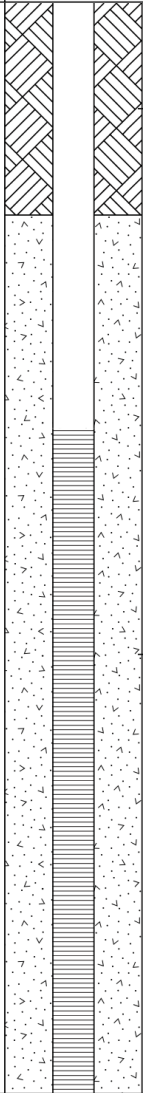
PROJECT NUMBER 2789481		DRILLING DATE 10 August 2023		COORDINATES -25.39310, 28.25846												
PROJECT NAME Temba Cemetery		TOTAL DEPTH 1.5		COORD SYS												
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION												
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1098												
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC												
COMMENTS				LOGGED BY Elia Muravha												
				CHECKED BY Elia Muravha												
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description							
0.1	 concrete cement grout	Hand Auger Drilling	No soil samples collected	NA			M	Dense	CLAY SAND: Dark orange-brown dense CLAY SAND, Alluvium							
0.2																
0.3																
0.4																
0.5																
0.6																
0.7																
0.8																
0.9																
1																
1.1																
1.2																
1.3																
1.4																
1.5																

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GROUNDWATER WELL LOG MW3

PROJECT NUMBER 2789481		DRILLING DATE 10 August 2023		COORDINATES -25.39227, 28.25816					
PROJECT NAME Temba Cemetery		TOTAL DEPTH 2.05		COORD SYS					
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION					
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1102					
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC					
COMMENTS				LOGGED BY Elia Muravha					
				CHECKED BY Elia Muravha					
Depth (m)	Well Diagram	Drilling Method	Samples and Groundwater strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.1	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA			M	Dense	SILTY CLAY: Orange-brown dense clayey SILTY SAND, Alluvium
0.2									
0.3							VM	Dense	CLAY SAND: Reddish dark orange-brown dense CLAYEY SAND, Alluvium
0.4									
0.5							W	Stiff	SILTY CLAY: Orange-brown mottled grey stiff sandy SILTY CLAY, Alluvium
0.6									
0.7									
0.8									
0.9									
1.0									
1.1									
1.2									
1.3	Very stiff		SILTY CLAY: Light orange-brown streaked yellow and red very stiff SILTY CLAY, Alluvium						
1.4									
1.5									
1.6									
1.7									
1.8									
1.9									
2.0									
2.1	Termination Depth at: 2.05 m due to Sandstone bedrock								

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GROUNDWATER WELL LOG MW2

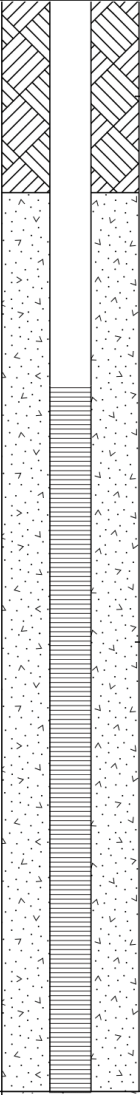
PROJECT NUMBER 2789481		DRILLING DATE 19 August 2023		COORDINATES -25.39385, 28.25735											
PROJECT NAME Temba Cemetery		TOTAL DEPTH 1.9		COORD SYS											
CLIENT WITS		DIAMETER 9.5 cm		COMPLETION											
ADDRESS Johannesburg Campus		CASING uPVC		SURFACE ELEVATION 1098											
LICENCE NO.		SCREEN uPVC Factory Slotted		WELL TOC											
COMMENTS				LOGGED BY Elia Muravha											
				CHECKED BY Elia Muravha											
Depth (m)	Well Diagram	Drilling Method	Samples & Groundwater Strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description						
0.1	 concrete cement grout filter pack	Hand Auger Drilling	No soil samples collected	NA	 1 2		W	Firm	SILTY CLAY: Grey mottled brown firm SILTY CLAY with plant roots, Alluvium						
0.2															
0.3														Firm	SILTY CLAY: Dark grey mottled brown firm SILTY CLAY, Alluvium
0.4															
0.5														Stiff	SILTY CLAY: Dark orange-brown mottled grey stiff SILTY CLAY, Alluvium
0.6															
0.7															
0.8															
0.9															
1															Stiff
1.1															
1.2															
1.3															
1.4															
1.5															
1.6								Dense	CLAYEY GRAVELLY SAND: Orange-brown dense CLAYEY GRAVELLY SAND, Residual soil						
1.7															
1.8															
1.9									Termination Depth at: 1.9 m due to Sandstone bedrock						

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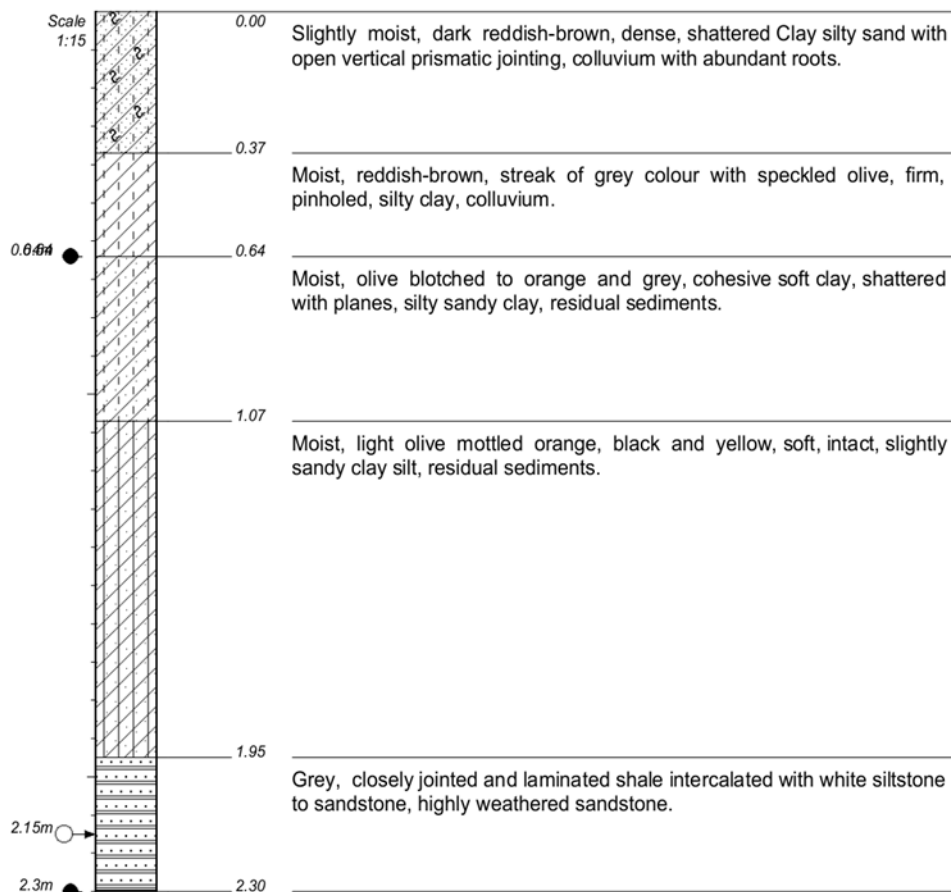


GROUNDWATER WELL LOG MW1

PROJECT NUMBER 2789481 PROJECT NAME Temba Cemetery CLIENT WITS ADDRESS Johannesburg Campus LICENCE NO.			DRILLING DATE 10 August 2023 TOTAL DEPTH 1.7 DIAMETER 9.5 cm CASING uPVC SCREEN uPVC Factory Slotted			COORDINATES -25.39262, 28.25545 COORD SYS COMPLETION SURFACE ELEVATION 1099 WELL TOC				
COMMENTS Off-site to the north						LOGGED BY Elia Muravha CHECKED BY Elia Muravha				
Depth (m)	Well Diagram		Drilling Method	Samples & Groundwater Strike	Sample Type	SWLs & Water bearing zone	Graphic Log	Moisture	Consistency	Material Description
0.1	 concrete cement grout		Hand Auger Drilling	No soil samples collected	NA		D	Firm	SILTY CLAY: Dark greyish brown firm SILTY CLAY, Alluvium	
0.2									SILTY CLAY: Dark grey mottled orange-brown stiff SILTY CLAY, Alluvium	
0.3										
0.4	 filter pack						W	Stiff	SILTY CLAY: Dark grey mottled orange-brown stiff SILTY CLAY, Alluvium	
0.5									SILTY CLAY: Orange-brown mottled grey stiff SILTY CLAY, Alluvium	
0.6										
0.7										
0.8	 filter pack						D		SILTY CLAY: Orange-brown mottled grey stiff SILTY CLAY, Alluvium	
0.9									SILTY CLAY: Yellowish-brown blotched grey stiff SILTY CLAY, with pebbles at 0.7 m, Alluvium	
1.0										
1.1										
1.2										
1.3	 filter pack						D		SILTY CLAY: Yellowish-brown blotched grey stiff SILTY CLAY, with pebbles at 0.7 m, Alluvium	
1.4									Termination Depth at: 1.7 m due to Sandstone bedrock	
1.5										
1.6										
1.7										

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NOTES

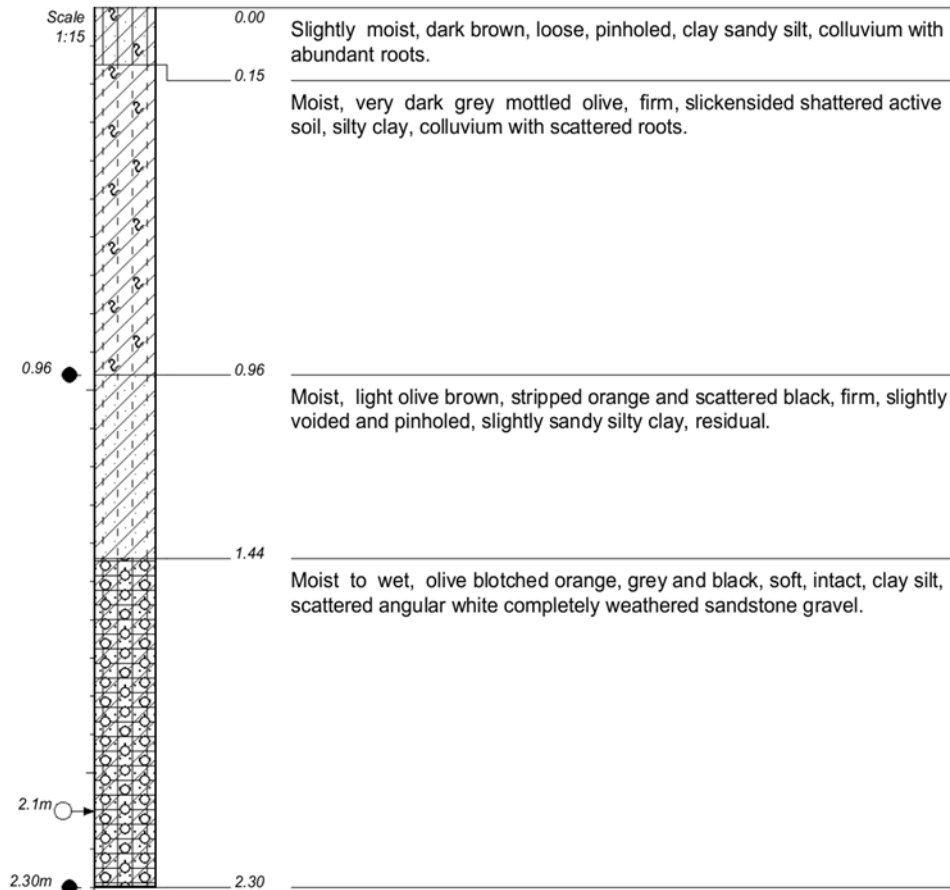
- 1) Final depth at 2.3m.
- 2) Groundwater seepage at 2.15m.
- 3) Soil samples at depth: 0.0 to 0.64m and 0.64 to 2.3m (Reddish soils from first two layers combined and green soils from lower horizons combined).

CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomu
PROFIED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION : Vertical
DIAM :
DATE :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT01



NOTES

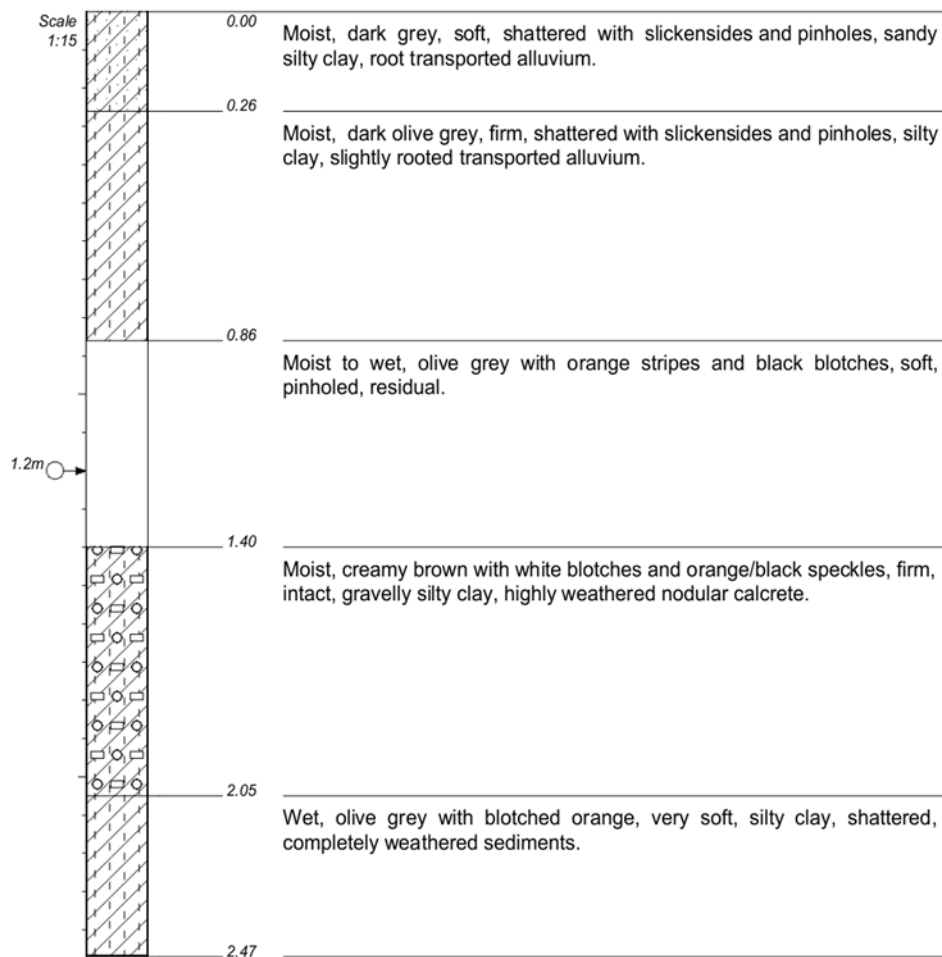
- 1) Final depth at 2.30m.
- 2) Groundwater seepage at 2.1m.
- 3) Soil samples at depth: 0.96 to 2.30m (all black layers we re sampled).

CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomu
PROFILED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION :
DIAM :
DATE :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT02



NOTES

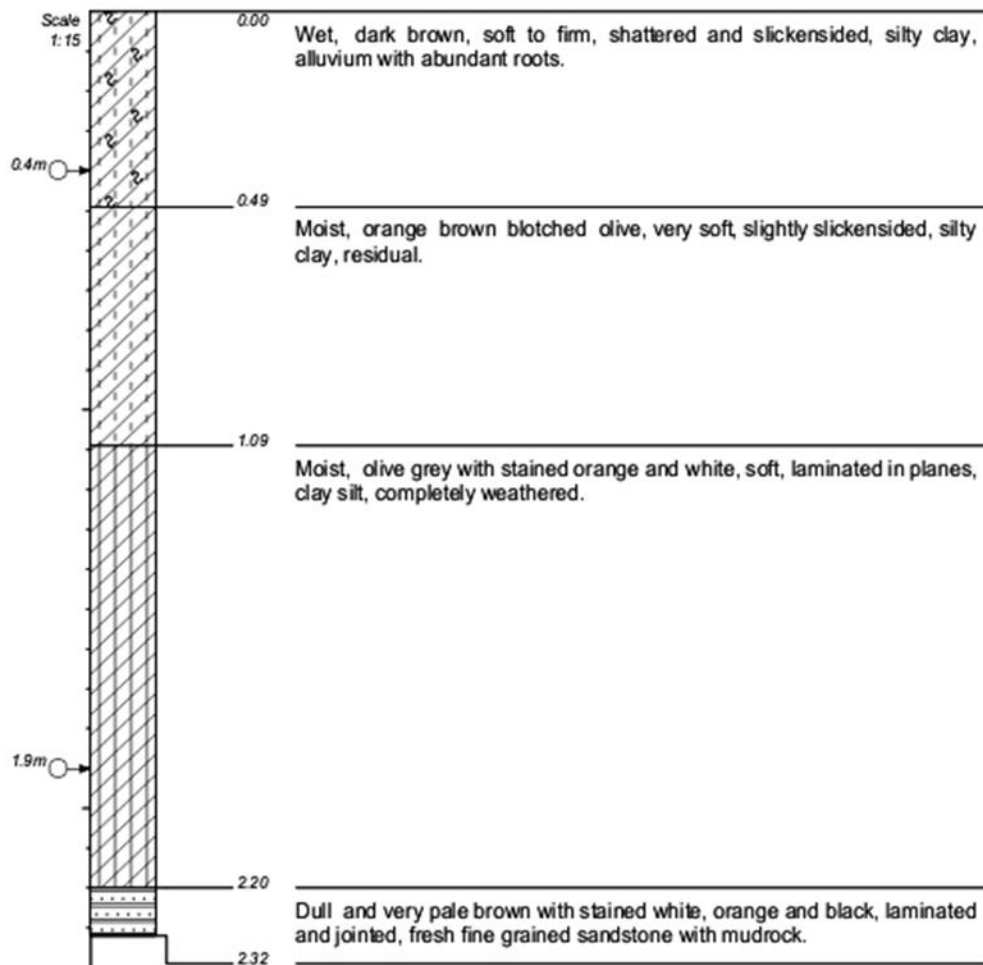
- 1) Final depth at 2.47m.
- 2) Groundwater seepage at 1.2m (slow seepage at this depth and below).
- 3) No soil samples taken.

CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomu
PROFILED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION :
DIAM :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

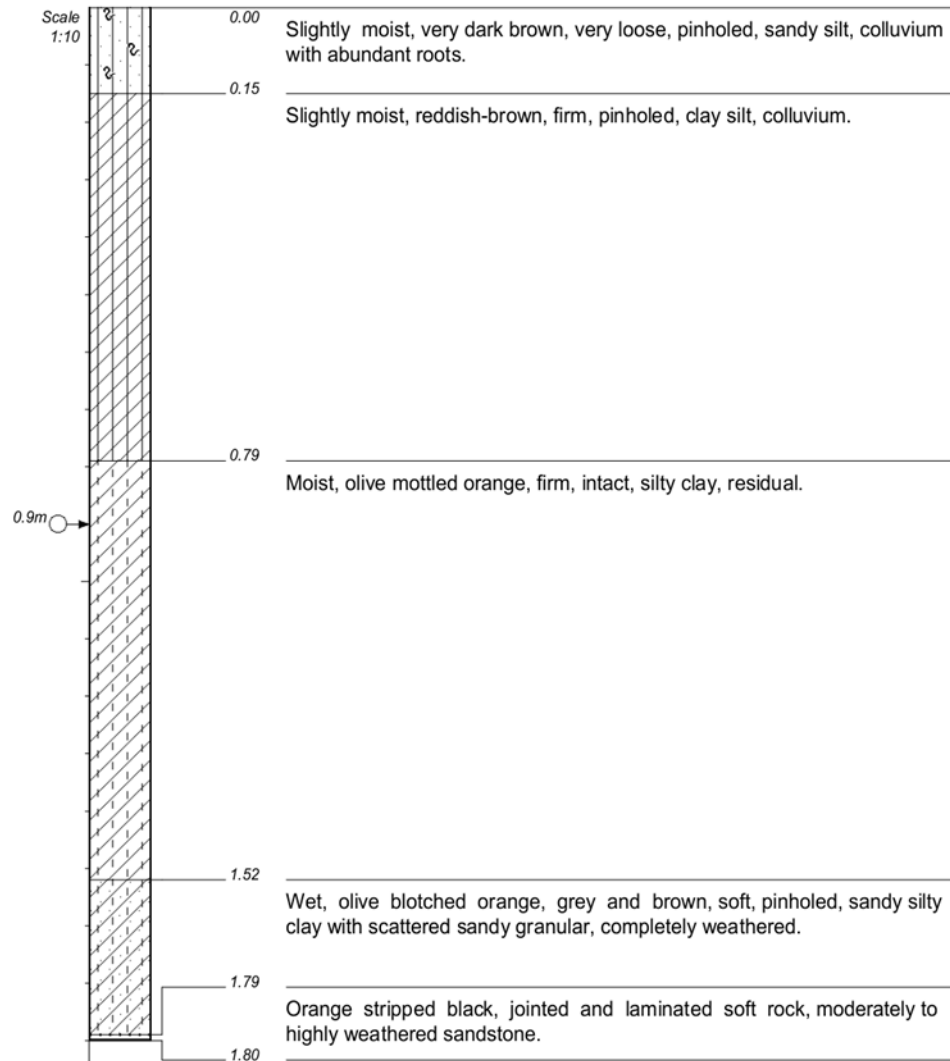
ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT03



NOTES

- 1) Final depth at 2.32m.
- 2) Slow groundwater seepage in the black layer at depth 0.4m and also at 1.9m.
- 3) No soil samples taken.



NOTES

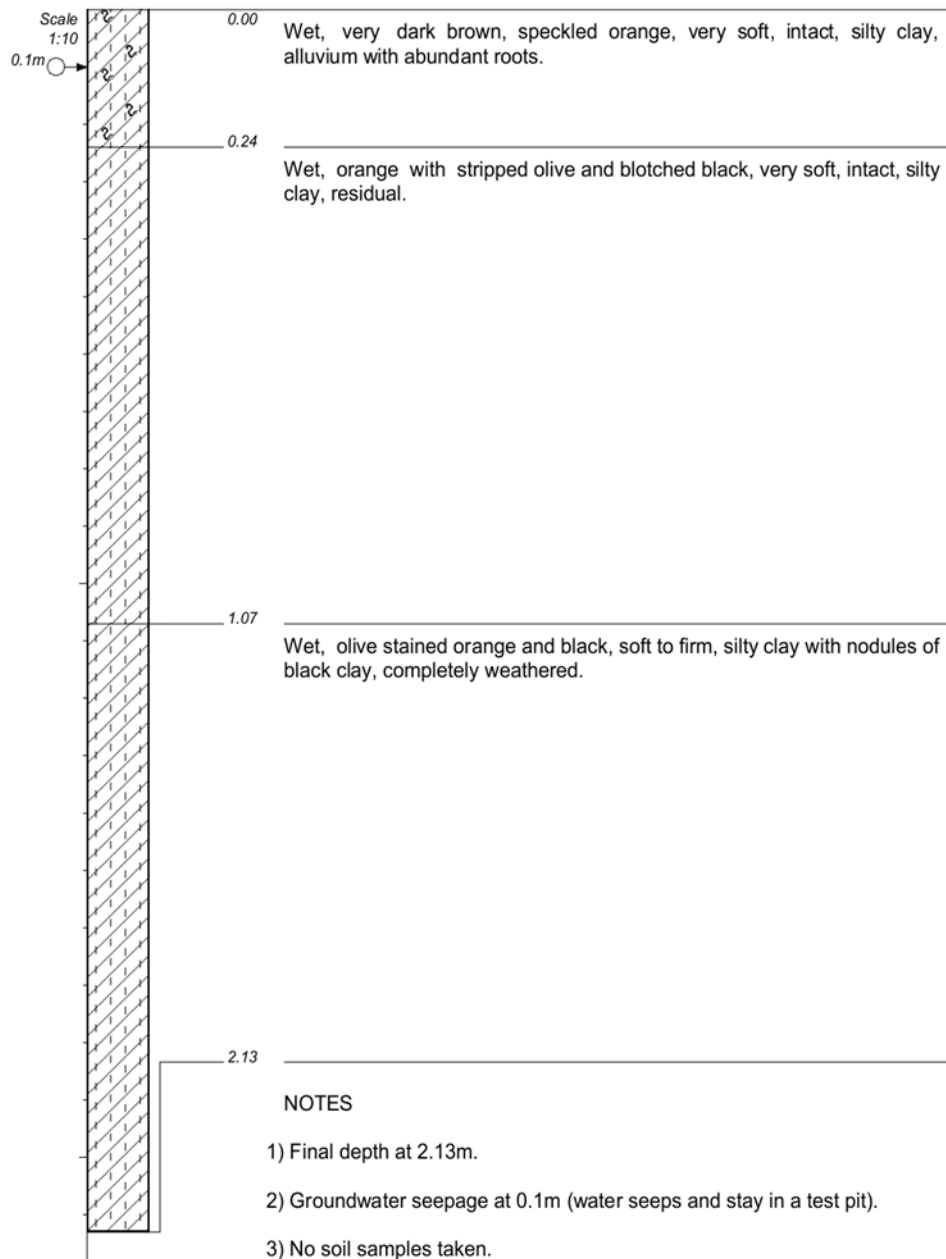
- 1) Final depth at ± 1.8 m.
- 2) Groundwater seepage at 0.9m.
- 3) No soil samples taken.

CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomu
PROFILED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION :
DIAM :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT05

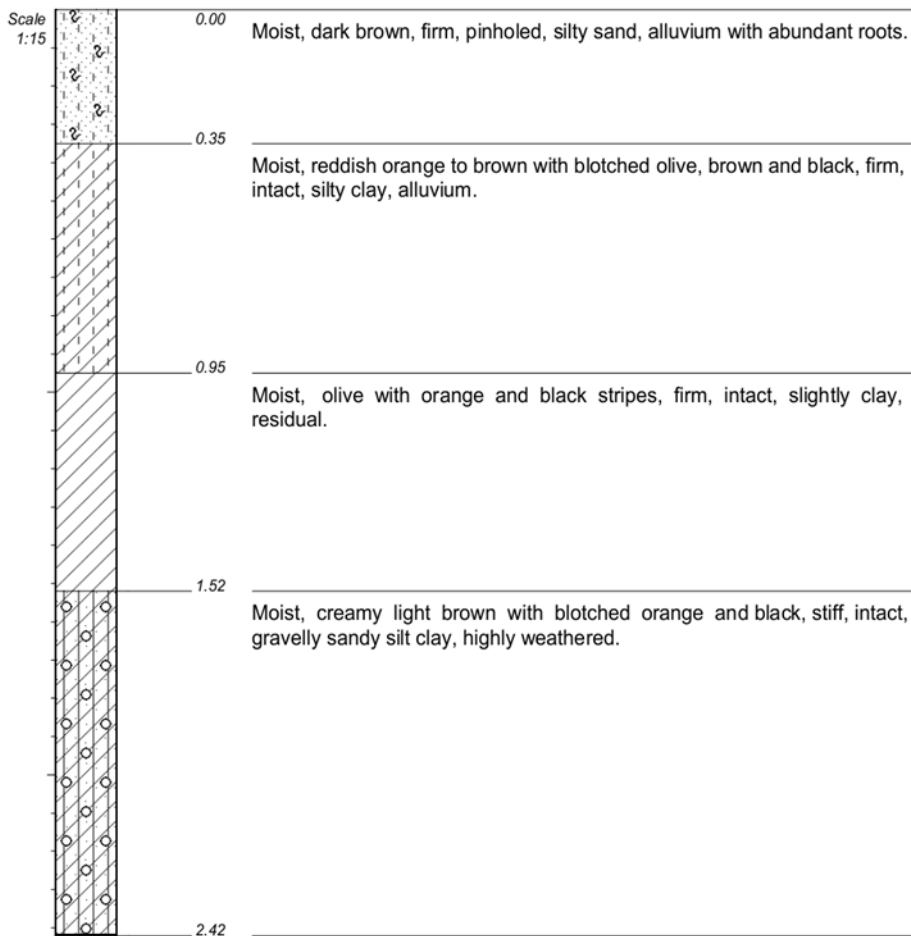


CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomo
PROFILED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION :
DIAM :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT06



NOTES

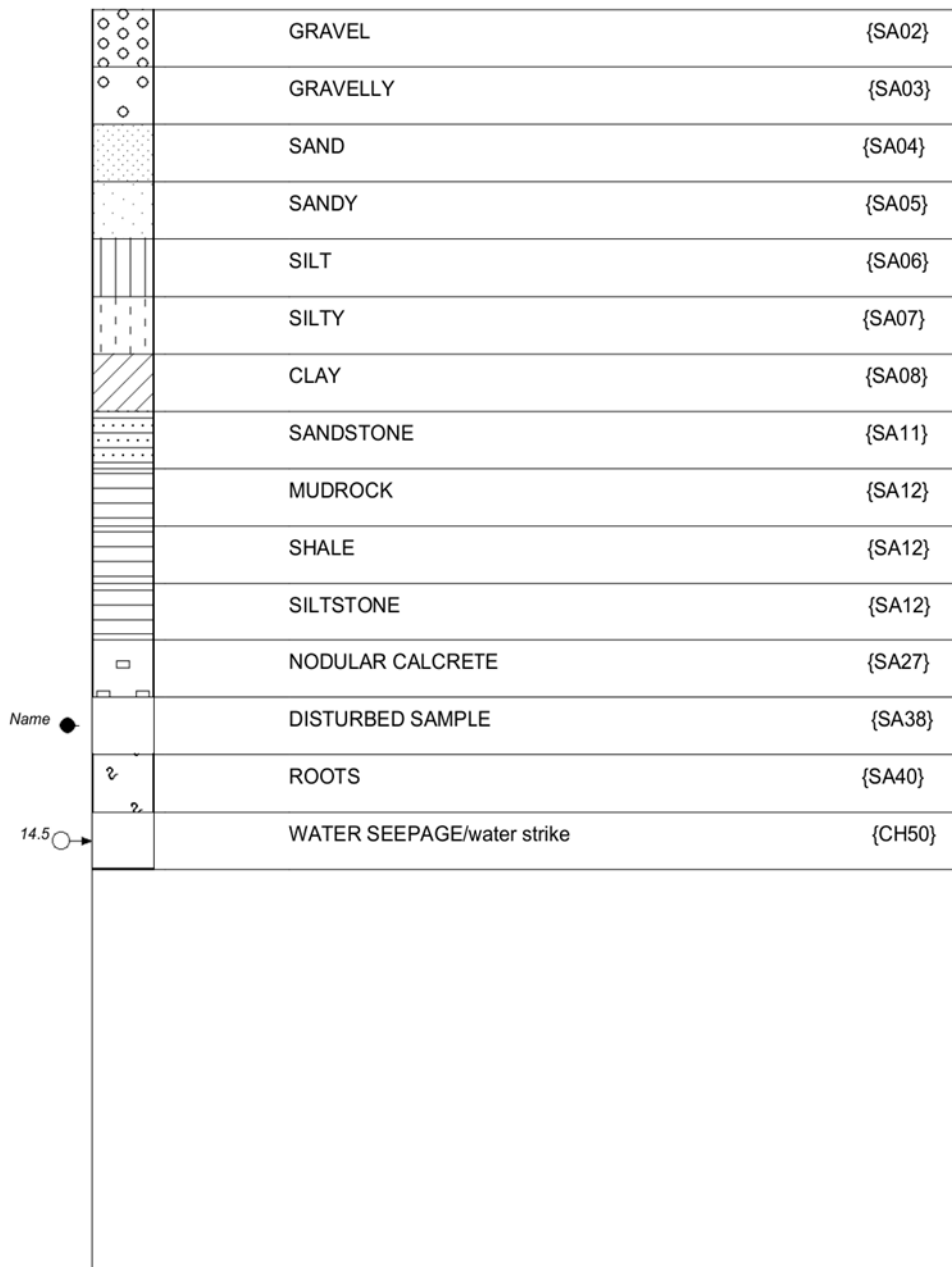
- 1) Final depth at 2.42m.
- 2) No groundwater seepage.
- 3) No soil samples taken.
- 4) Pebbles and minor cobbles of sandstone in the last layer.

CONTRACTOR :
MACHINE : TLB
DRILLED BY : Thomas Kgomu
PROFILED BY : Muravha SE
TYPE SET BY :
SETUP FILE : STANDARD.SET

INCLINATION :
DIAM :
DATE : 2012/08/06
DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

HOLE No: VT07



CONTRACTOR :
MACHINE :
DRILLED BY :
PROFILED BY :

TYPE SET BY :
SETUP FILE : STANDARD.SET

D095 University of Pretoria

INCLINATION :
DIAM :
DATE :
DATE :

DATE : 20/09/2012 15:00
TEXT : ..esktop\Tembatestpits.txt

ELEVATION :
X-COORD :
Y-COORD :

LEGEND
SUMMARY OF SYMBOLS

dotPLOT 7004 PBpH67

Appendix II: Percolation Test Data

Location:	Temba Cemetery (PT1)					
Date:	14-Dec-23					
Weather:	Sunny					
Analyst:	Elia Muravha					
Borehole radius (cm):	9.5					
Soil class:	Default					
Measurement	Start depth of water (cm)	End depth of water (cm)	Start time (*decimal min)	End time (*decimal min)	Perc test result (min/cm)	K _{fs} (mm/hr)
1	30	20	0.0	22.0	2.2	15.3
2	20	10	22.0	80.0	5.8	9.4
3	10	5	80.0	126.0	9.2	9.9
4	5	0	126.0	176.0	10.0	15.5

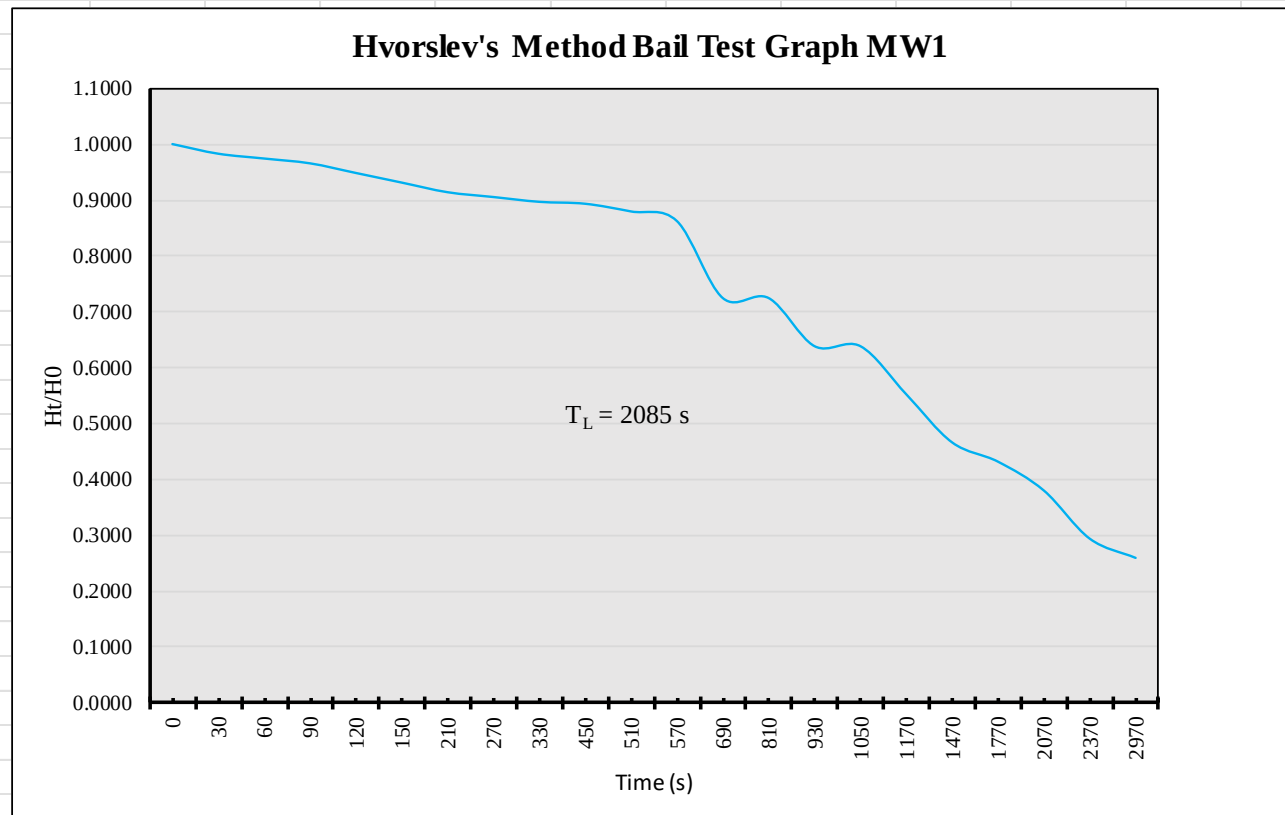
Location:	Temba Cemetery (PT2)					
Date:	14-Dec-23					
Weather:	Sunny					
Analyst:	Elia Muravha					
Borehole radius (cm):	9.5					
Soil class:	Weak capillarity					
Measurement	Start depth of water (cm)	End depth of water (cm)	Start time (*decimal min)	End time (*decimal min)	Perc test result (min/cm)	K _{fs} (mm/hr)
1	30	20	0.0	6.1	0.6	65.9
2	20	10	5.0	25.6	2.1	33.7
3	10	8	25.6	48.6	11.5	9.7
4	8	5	48.6	78.6	10.0	14.4
5	5	4	78.6	111.5	32.9	5.6
6	4	3.5	111.5	148.0	73.0	2.8
7	3.5	1.5	148.0	189.1	20.5	12.2
8	1.5	0	189.1	235.1	30.7	11.6

Location:	Temba Cemetery (PT3)					
Date:	14-Dec-23					
Weather:	Sunny					
Analyst:	Elia Muravha					
Borehole radius (cm):	9.5					
Soil class:	Default					
Measurement	Start depth of water (cm)	End depth of water (cm)	Start time (*decimal min)	End time (*decimal min)	Perc test result (min/cm)	K _{fs} (mm/hr)
1	30	23	0.0	5.3	0.8	42.0
2	23	20	5.3	17.7	4.1	9.5
3	20	17	17.7	37.9	6.8	6.7
4	17	14.5	37.9	65.4	11.0	4.7
5	14.5	11	65.4	99.3	9.7	6.4
6	11	5.5	99.3	163.3	11.6	7.3
7	5.5	0	163.3	244.1	14.7	10.2

Location:	Temba Cemetery (PT4)					
Date:	14-Dec-23					
Weather:	Sunny					
Analyst:	Elia Muravha					
Borehole radius (cm):	9.5					
Soil class:	Strong capillarity					
Measurement	Start depth of water (cm)	End depth of water (cm)	Start time (*decimal min)	End time (*decimal min)	Perc test result (min/cm)	K _{fs} (mm/hr)
1	30	23	0.0	18.0	2.6	8.6
2	23	20	18.0	42.0	8.0	3.3
3	20	16.5	42.0	110.0	19.4	1.5
4	16.5	14	110.0	150.0	16.0	2.1
5	14	10	150.0	240.0	22.5	1.8
6	10	5	240.0	347.0	21.4	2.5
7	5	0	347.0	455.0	21.6	3.9

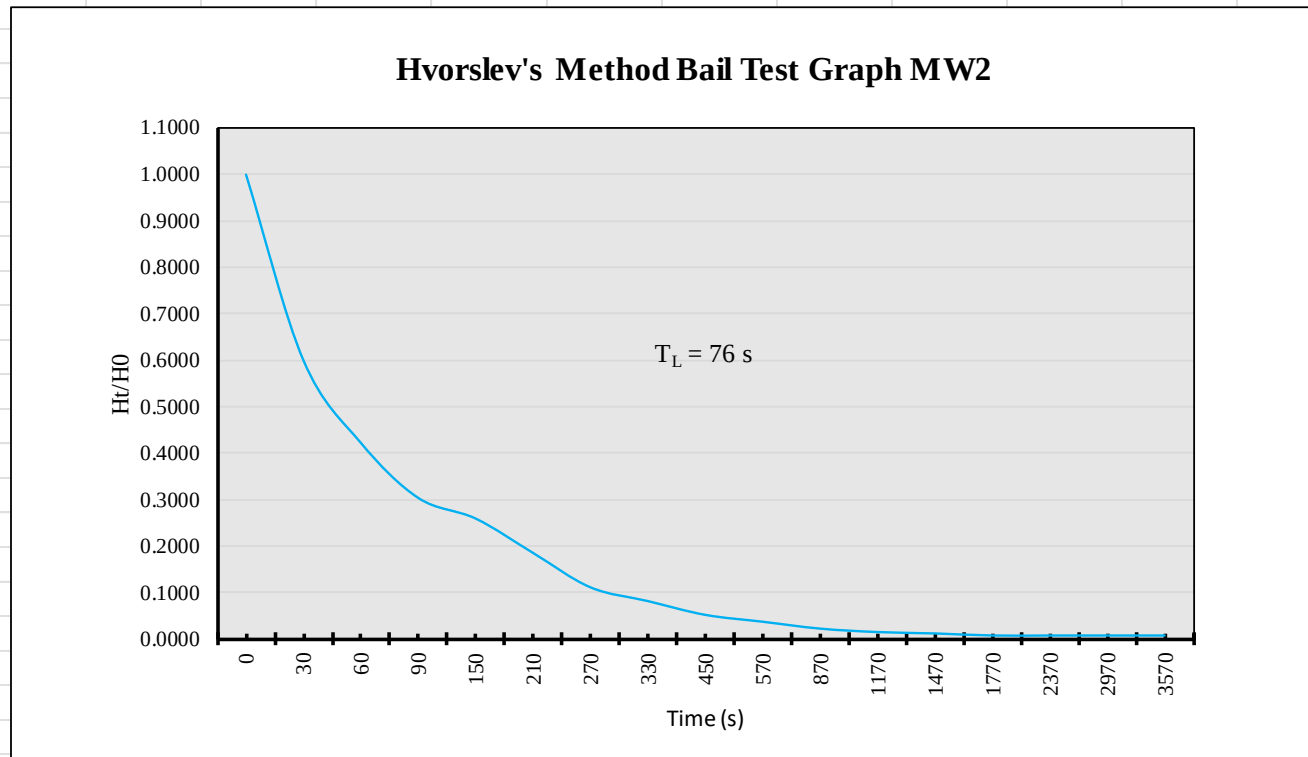
Appendix III: Hvorslev's Method Bail Test Results

t(s)	h(m)	ht/h0
0	0.58	1.0000
30	0.57	0.9828
60	0.565	0.9741
90	0.56	0.9655
120	0.55	0.9483
150	0.54	0.9310
210	0.53	0.9138
270	0.525	0.9052
330	0.52	0.8966
450	0.518	0.8931
510	0.51	0.8793
570	0.5	0.8621
690	0.42	0.7241
810	0.42	0.7241
930	0.37	0.6379
1050	0.37	0.6379
1170	0.32	0.5517
1470	0.27	0.4655
1770	0.25	0.4310
2070	0.22	0.3793
2370	0.17	0.2931
2970	0.15	0.2586



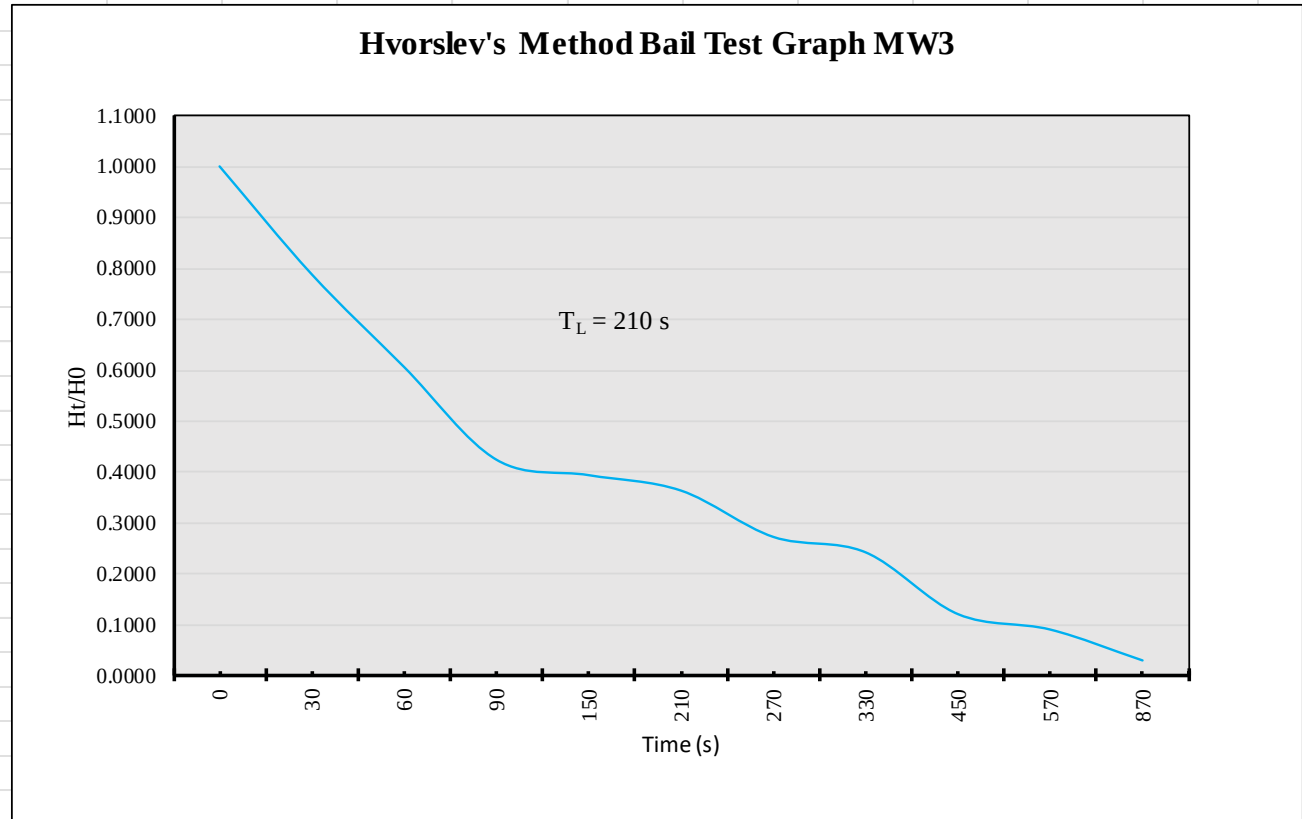
Hvorslev's Method Bail Test Graph MW2

t(s)	h(m)	ht/h0
0	0.675	1.0000
30	0.405	0.6000
60	0.285	0.4222
90	0.205	0.3037
150	0.175	0.2593
210	0.125	0.1852
270	0.075	0.1111
330	0.055	0.0815
450	0.035	0.0519
570	0.025	0.0370
870	0.015	0.0222
1170	0.01	0.0148
1470	0.008	0.0119
1770	0.005	0.0074
2370	0.005	0.0074
2970	0.005	0.0074
3570	0.005	0.0074



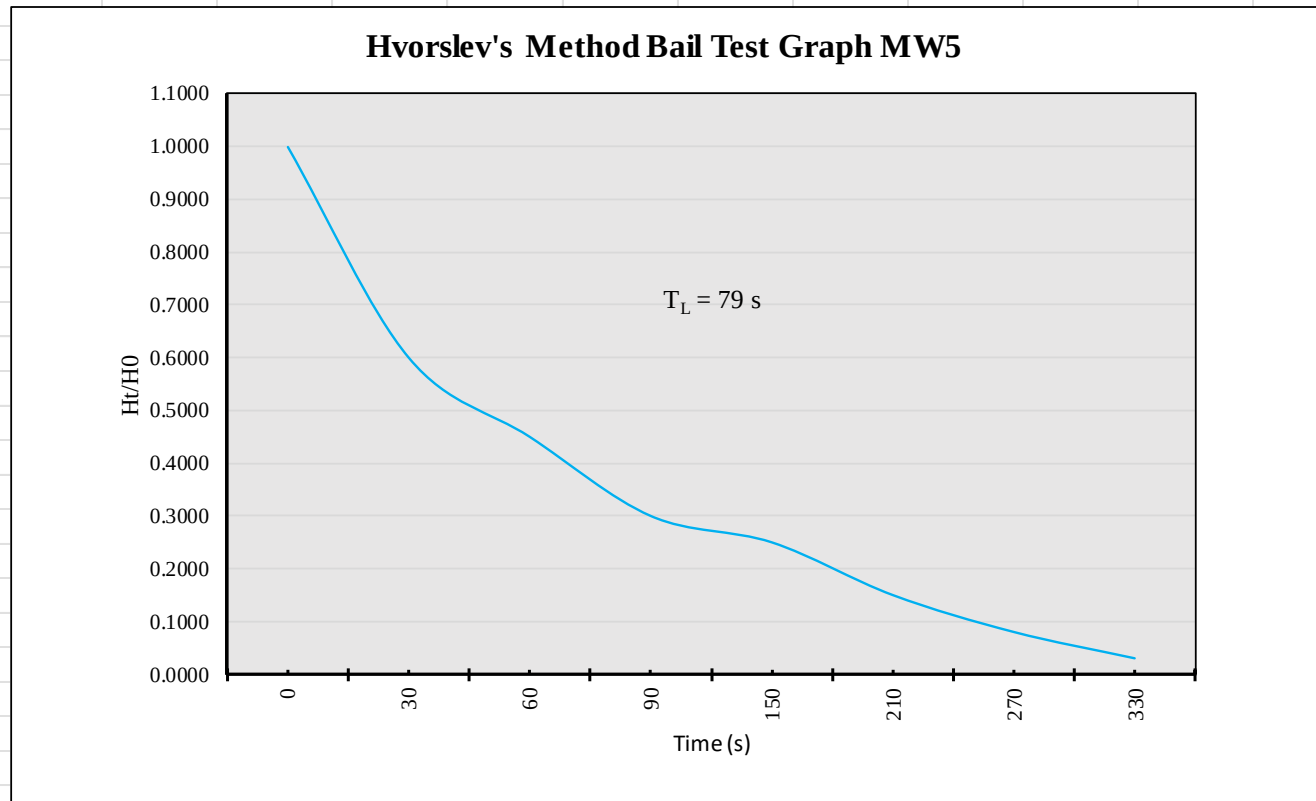
Hvorslev's Method Bail Test Graph MW3

t(s)	h(m)	ht/h0
0	0.165	1.0000
30	0.13	0.7879
60	0.1	0.6061
90	0.07	0.4242
150	0.065	0.3939
210	0.06	0.3636
270	0.045	0.2727
330	0.04	0.2424
450	0.02	0.1212
570	0.015	0.0909
870	0.005	0.0303



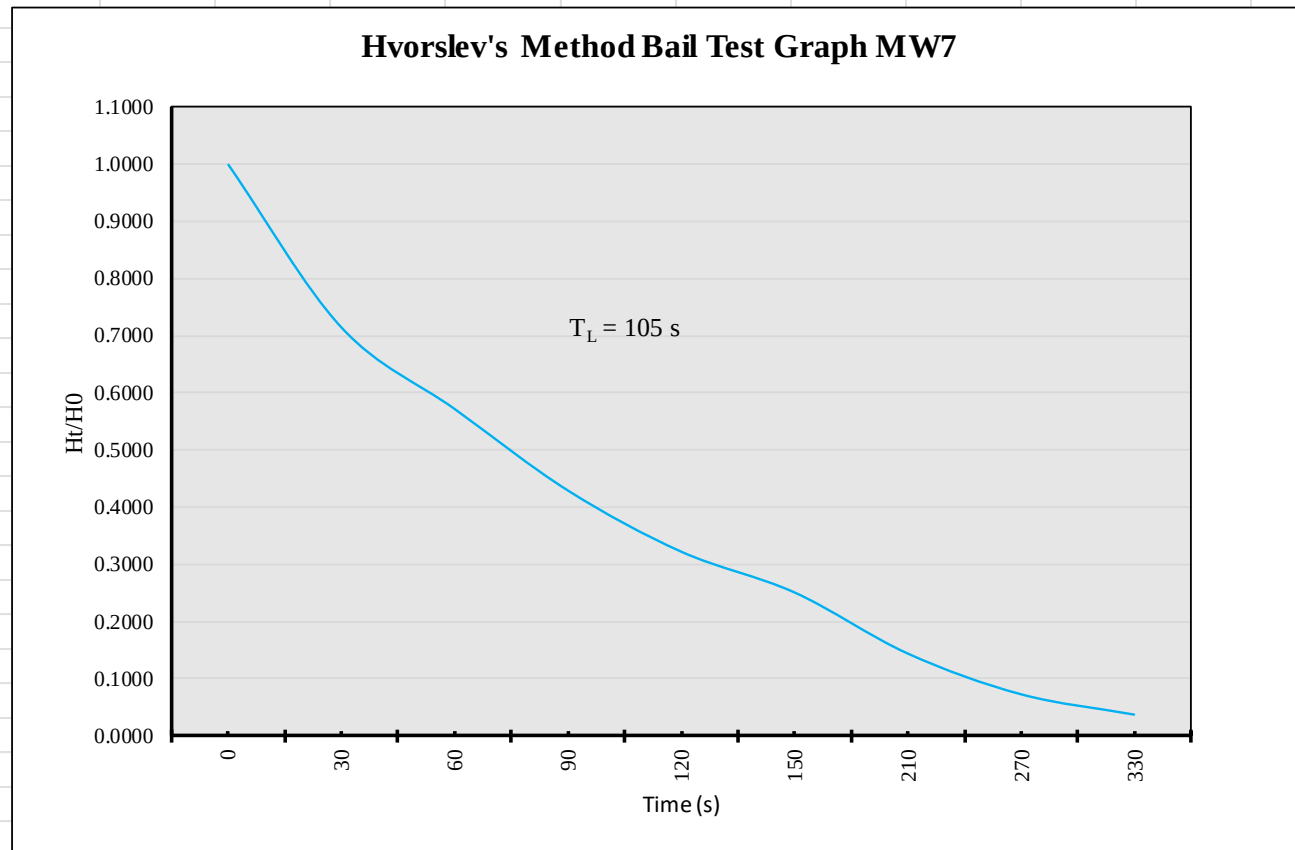
Hvorslev's Method Bail Test Graph MW5

t(s)	h(m)	ht/h0
0	0.1	1.0000
30	0.06	0.6000
60	0.045	0.4500
90	0.03	0.3000
150	0.025	0.2500
210	0.015	0.1500
270	0.008	0.0800
330	0.003	0.0300



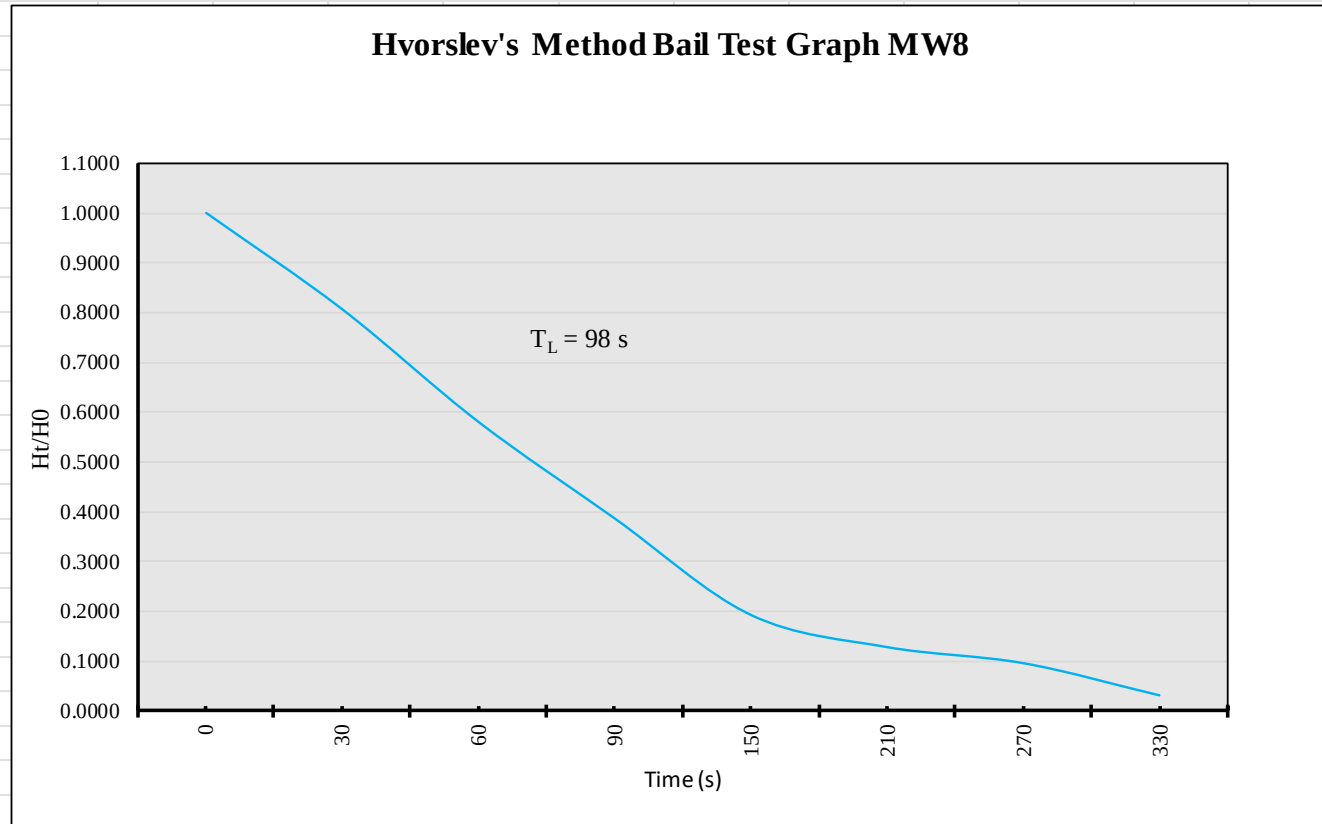
Hvorslev's Method Bail Test Graph MW7

t(s)	h(m)	ht/h0
0	0.28	1.0000
30	0.2	0.7143
60	0.16	0.5714
90	0.12	0.4286
120	0.09	0.3214
150	0.07	0.2500
210	0.04	0.1429
270	0.02	0.0714
330	0.01	0.0357



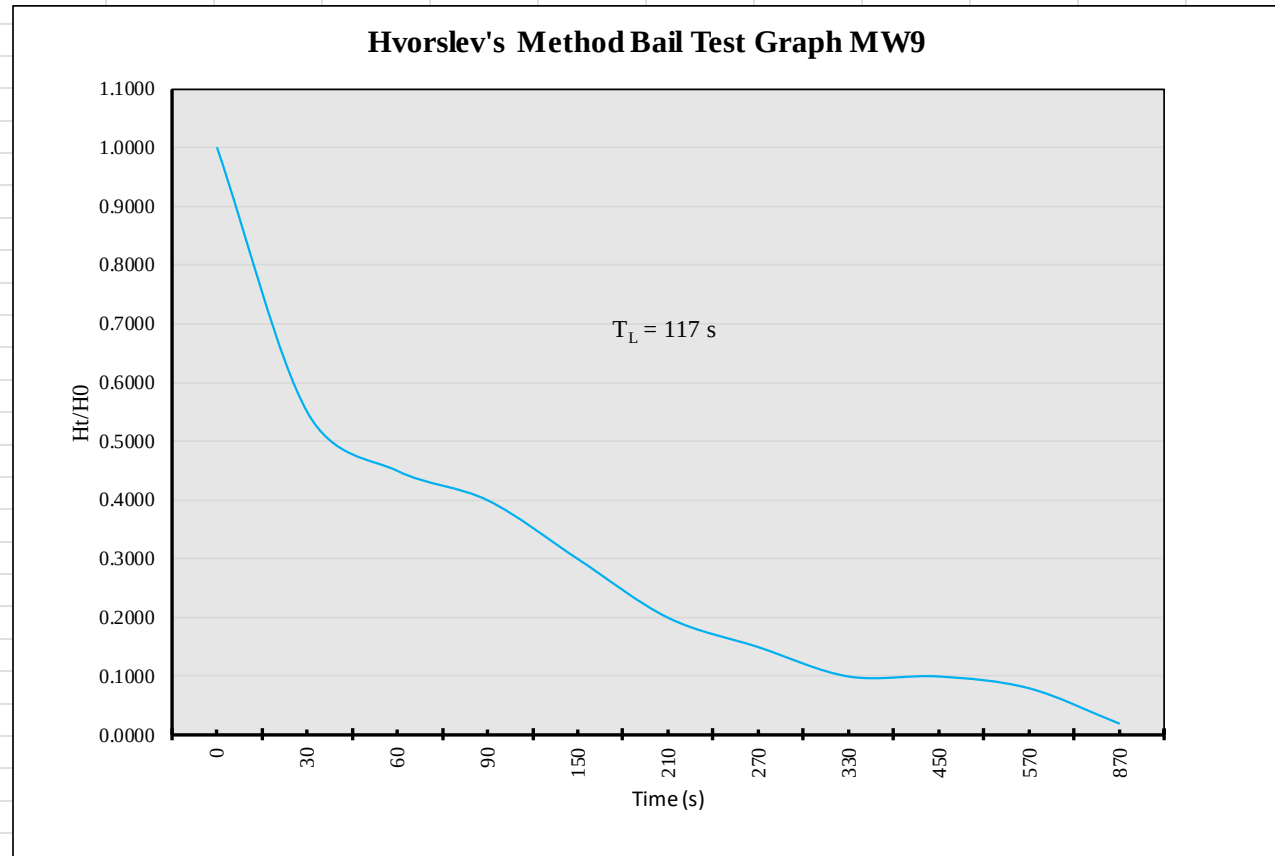
Hvorslev's Method Bail Test Graph MW8

t(s)	h(m)	ht/h0
0	0.31	1.0000
30	0.25	0.8065
60	0.18	0.5806
90	0.12	0.3871
150	0.06	0.1935
210	0.04	0.1290
270	0.03	0.0968
330	0.01	0.0323



Hvorslev's Method Bail Test Graph MW9

t(s)	h(m)	ht/h0
0	0.1	1.0000
30	0.055	0.5500
60	0.045	0.4500
90	0.04	0.4000
150	0.03	0.3000
210	0.02	0.2000
270	0.015	0.1500
330	0.01	0.1000
450	0.01	0.1000
570	0.008	0.0800
870	0.002	0.0200



Appendix IV: Laboratory Test Report



TEST REPORT

48064A

Client and Project Information

Client: Geo Pollution Technologies
Address: 20814 Mamelodi East
Bufferzone
0122

Attention: Elia Muravha
Tel: (081) 443-1539
Email: elia@gptglobal.com

Project number: N/A
Project name: Themba Cemetery

Sample Information

Matrix: Water
Units: mg/l [ppm] (unless stated elsewhere)
Container: Plastic

Date Received: 2023/12/04
Date Analysed: 2023/12/05
Date Issued: 2023/12/11

SAMPLE ID	E.coli (colonies/100ml)*
BH1	0
Stream	5300

Disclaimers

- 1) The results only relate to the test items provided, in the condition as received.
- 2) This report may not be reproduced, except in full, without the prior written approval of the laboratory.
- 3) Parameters marked " * " are not included in the SANAS Schedule of Accreditation for this laboratory.
- 4) A = Concentration outside calibration range, ** = Outsourced analysis, UTD = Unable to Determine, ND = Not Detected.
- 5) Methods: EPL-WL-001 (Conductivity), EPL-WL-002 (Alkalinity), EPL-WL-003 (pH), EPL-WL-004 (TDS), EPL-WL-005 (Anions by IC), EPL-WL-006 (Cations by IC), EPL-WL-007 (Metals), EPL-WL-008 (Cr(VI)), EPL-WL-009 (TOC), EPL-WL-010 (Hg by DMA), EPL-WL-011 (Anions by Discrete Analyser).
- 6) Uncertainty of measurement for all methods included in the SANAS Schedule of Accreditation is available on request.

Miche Kannemeyer
Authorised Signatory

Page 1 of 1

TEST REPORT

47434A

Client and Project Information

Client: Sedzani Elia Muravha
Address: 20814 Bufterzone
 Mamelodi East
 0122

Attention: Sedzani Elia Muravha
Tel: (081) 443-1539
Email: sedzani.muravha@gmail.com

Project number: N/A
Project name: Temba Cemetery

Sample Information

Matrix: Water
Units: mg/l [ppm] (unless stated elsewhere)
Container: Plastic

Date Received: 2023/11/06
Date Analysed: 2023/11/08
Date Issued: 2023/11/16

SAMPLE ID	E.coli (colonies/100ml)*	Faecal Coliforms (colonies/100ml)*	Total Coliforms (colonies/100ml)*
MW1	0	0	221000
MW2	0	0	570
MW3	0	0	18600
MW4	0	0	131000
MW5	0	0	207000
MW7	0	0	500
MW8	0	0	4000
MW9	0	0	1700

Disclaimers

- 1) The results only relate to the test items provided, in the condition as received.
- 2) This report may not be reproduced, except in full, without the prior written approval of the laboratory.
- 3) Parameters marked " * " are not included in the SANAS Schedule of Accreditation for this laboratory.
- 4) A = Concentration outside calibration range, ** = Outsourced analysis, UTD = Unable to Determine, ND = Not Detected.
- 5) Methods: EPL-WL-001 (Conductivity), EPL-WL-002 (Alkalinity), EPL-WL-003 (pH), EPL-WL-004 (TDS), EPL-WL-005 (Anions by IC), EPL-WL-006 (Cations by IC), EPL-WL-007 (Metals), EPL-WL-008 (Cr(VI)), EPL-WL-009 (TOC), EPL-WL-010 (Hg by DMA), EPL-WL-011 (Anions by Discrete Analyser).
- 6) Uncertainty of measurement for all methods included in the SANAS Schedule of Accreditation is available on request.

Miche Kannemeyer
 Authorised Signatory

Page 1 of 1

TEST REPORT

45817A

Client and Project Information

Client: Sedzani Elia Muravha
Address: 20814 Bufterzone
 Mamelodi East
 0122

Attention: Sedzani Elia Muravha
Tel: (081) 443-1539
Email: sedzani.muravha@gmail.com

Project number: N/A
Project name: Temba Cemetery

Sample Information

Matrix: Water
Units: mg/l [ppm] (unless stated elsewhere)
Container: Plastic

Date Received: 2023/08/28
Date Analysed: 2023/08/31
Date Issued: 2023/09/06

SAMPLE ID	E.coli (colonies/100ml)*	Faecal Coliforms (colonies/100ml)*	Total Coliforms (colonies/100ml)*
MW1	0	0	99400
MW2	0	0	377000
MW3	0	0	10900
MW4	0	0	478000
MW5	0	0	40400
MW7	5000	5000	270000
MW8	0	0	6160
MW9	0	0	13200

Disclaimers

- 1) The results only relate to the test items provided, in the condition as received.
- 2) This report may not be reproduced, except in full, without the prior written approval of the laboratory.
- 3) Parameters marked " * " are not included in the SANAS Schedule of Accreditation for this laboratory.
- 4) A = Concentration outside calibration range, ** = Outsourced analysis, UTD = Unable to Determine, ND = Not Detected.
- 5) Methods: EPL-WL-001 (Conductivity), EPL-WL-002 (Alkalinity), EPL-WL-003 (pH), EPL-WL-004 (TDS), EPL-WL-005 (Anions by IC), EPL-WL-006 (Cations by IC), EPL-WL-007 (Metals), EPL-WL-008 (Cr(VI)), EPL-WL-009 (TOC), EPL-WL-010 (Hg by DMA), EPL-WL-011 (Anions by Discrete Analyser).
- 6) Uncertainty of measurement for all methods included in the SANAS Schedule of Accreditation is available on request.

Miche Kannemeyer
 Authorised Signatory

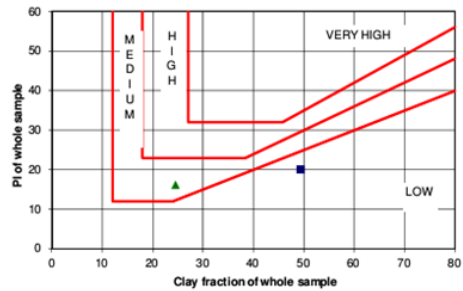
Page 1 of 1

PARTICLE SIZE ANALYSIS

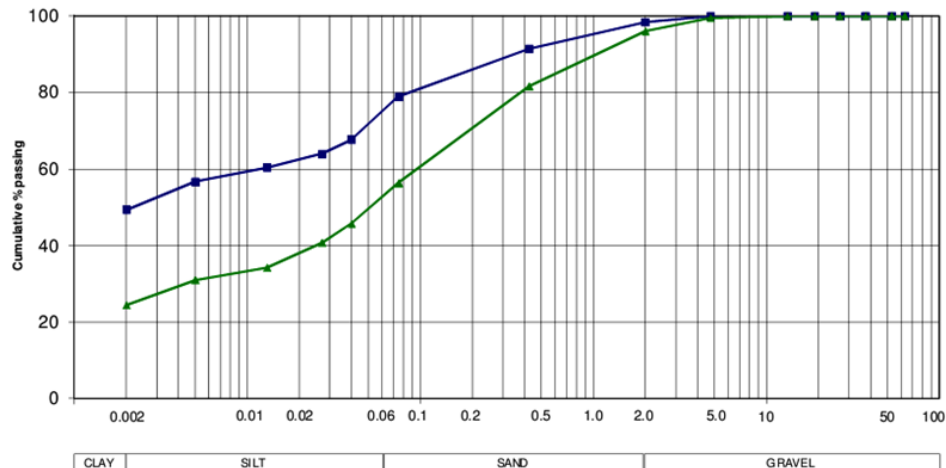
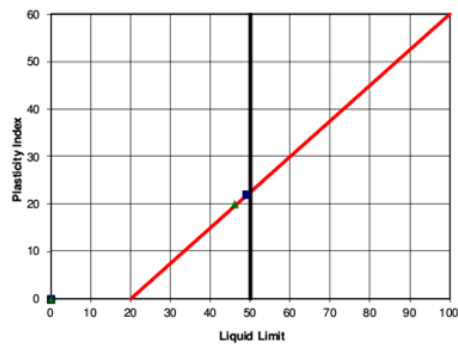
Sample No.		
Soillab sample no.	S12-1201-1	S12-1201-2
Depth (m)	0.64-0.95	0.95-0.96
Position	VT01	VT02
Material	DARK BROWN	LIGHT OLIVE
Description	QUARTZ	QUARTZ
	SILTY CLAY	SILTY SAND
Moisture (%)		
Dispersion (%)		
SCREEN ANALYSIS (% PASSING) (TMH 1 A1(a) & A5)		
63.0 mm	100	100
53.0 mm	100	100
37.5 mm	100	100
26.5 mm	100	100
19.0 mm	100	100
13.2 mm	100	100
4.75 mm	100	100
2.00 mm	98	96
0.425 mm	91	82
0.075 mm	79	56
HYDROMETER ANALYSIS (% PASSING) (TMH 1 A6)		
0.040 mm	68	46
0.027 mm	64	41
0.013 mm	60	34
0.005 mm	57	31
0.002 mm	49	24
% Clay	49	24
% Silt	25	27
% Sand	24	44
% Gravel	2	4
ATTERBERG LIMITS (TMH 1 A2 - A4)		
Liquid Limit	49	46
Plasticity Index	22	20
Linear Shrinkage (%)	12.0	11.0
Grading Modulus	0.31	0.66
Uniformity coefficient	-	-
Coefficient of curvature	-	-
Classification	A-7-6 (18)	A-7-6 (9)
Unified Classification	CL	CL
Chart Reference		

PROJECT : VADOSE ZONE - TEMBA
JOB No. : S12-1201
DATE : 2012-09-06

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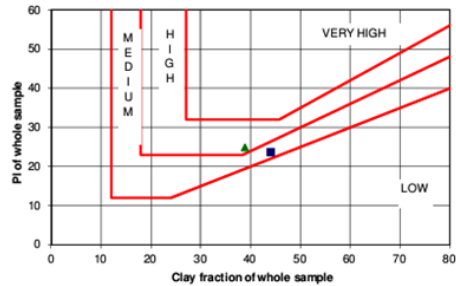
P O Box 72928
Lynnwood Ridge 0040
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PARTICLE SIZE ANALYSIS

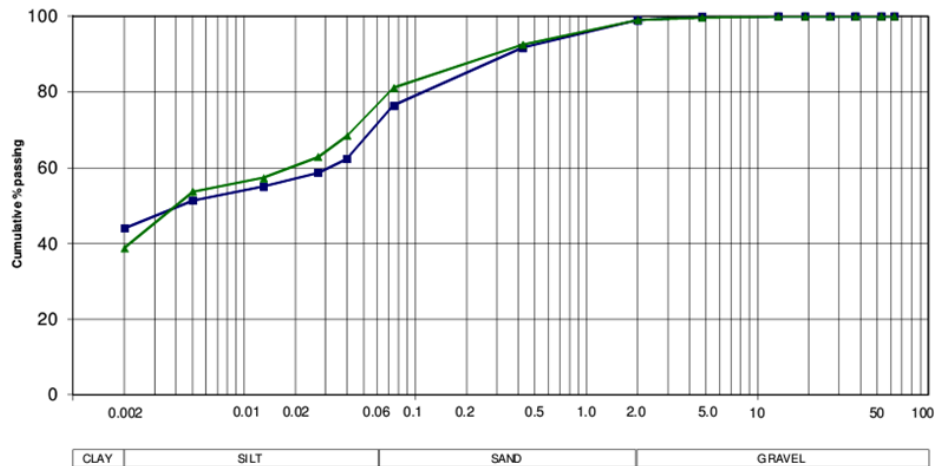
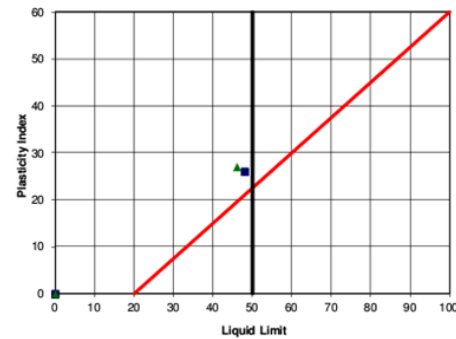
Sample No.		
Soillab sample no.	S12-1201-3	S12-1201-4
Depth (m)	0.15-0.95	0-0.82
Position	VT02	VT03
Material	DUSKY BLUE	DUSKY BLUE
Description	ERRICRETE+QUARTZ	ERRICRETE+QUARTZ
	SANDY CLAY	SILTY CLAY
Moisture (%)		
Dispersion (%)		
SCREEN ANALYSIS (% PASSING) (TMH 1 A1(a) & A5)		
63.0 mm	100	100
53.0 mm	100	100
37.5 mm	100	100
26.5 mm	100	100
19.0 mm	100	100
13.2 mm	100	100
4.75 mm	100	100
2.00 mm	99	99
0.425 mm	92	92
0.075 mm	76	81
HYDROMETER ANALYSIS (% PASSING) (TMH 1 A6)		
0.040 mm	62	68
0.027 mm	59	63
0.013 mm	55	57
0.005 mm	51	54
0.002 mm	44	39
% Clay	44	39
% Silt	26	37
% Sand	29	23
% Gravel	1	1
ATTERBERG LIMITS (TMH 1 A2 - A4)		
Liquid Limit	48	46
Plasticity Index	26	27
Linear Shrinkage (%)	13.0	12.0
Grading Modulus	0.33	0.27
Uniformity coefficient	-	-
Coefficient of curvature	-	-
Classification	A-7-6 (20)	A-7-6 (22)
Unified Classification	CL	CL
Chart Reference		

PROJECT : VADOSE ZONE - TEMBA
JOB No. : S12-1201
DATE : 2012-09-06

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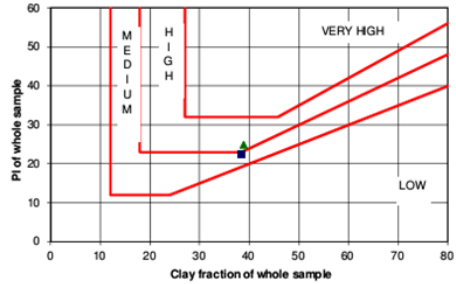
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PARTICLE SIZE ANALYSIS

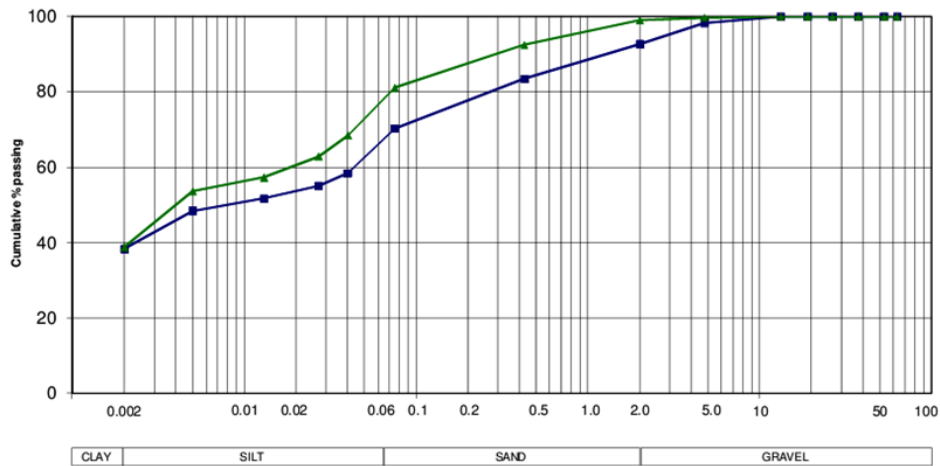
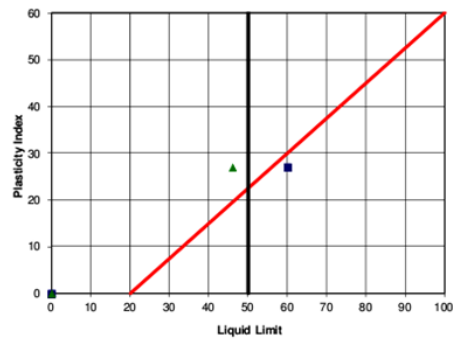
Sample No.		
Soillab sample no.	S12-1201-5	S12-1201-6
Depth (m)	0.82-1.4	1.4-2.05
Position	VT03	VT03
Material	LIGHT OLIVE	LIGHT OLIVE
Description	FERRICRETE+CALCRETE	FERRICRETE+CALCRETE
	QUARTZ	QUARTZ
	SANDY	SILTY
	CLAY	CLAY
Moisture (%)		
Dispersion (%)		
SCREEN ANALYSIS (% PASSING) (TMH 1 A1(a) & A5)		
63.0 mm	100	100
53.0 mm	100	100
37.5 mm	100	100
26.5 mm	100	100
19.0 mm	100	100
13.2 mm	100	100
4.75 mm	98	100
2.00 mm	93	99
0.425 mm	83	92
0.075 mm	70	81
HYDROMETER ANALYSIS (% PASSING) (TMH 1 A6)		
0.040 mm	58	68
0.027 mm	55	63
0.013 mm	52	57
0.005 mm	48	54
0.002 mm	38	39
% Clay	38	39
% Silt	27	37
% Sand	27	23
% Gravel	7	1
ATTERBERG LIMITS (TMH 1 A2 - A4)		
Liquid Limit	60	46
Plasticity Index	27	27
Linear Shrinkage (%)	14.0	12.0
Grading Modulus	0.54	0.27
Uniformity coefficient	-	-
Coefficient of curvature	-	-
Classification	A-7-5 (20)	A-7-6 (22)
Unified Classification	MH	CL
Chart Reference		

PROJECT : VADOSE ZONE - TEMBA
 JOB No. : S12-1201
 DATE : 2012-09-06

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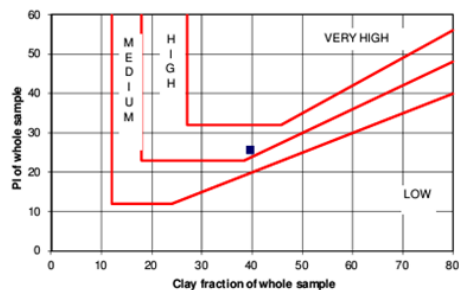
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PARTICLE SIZE ANALYSIS

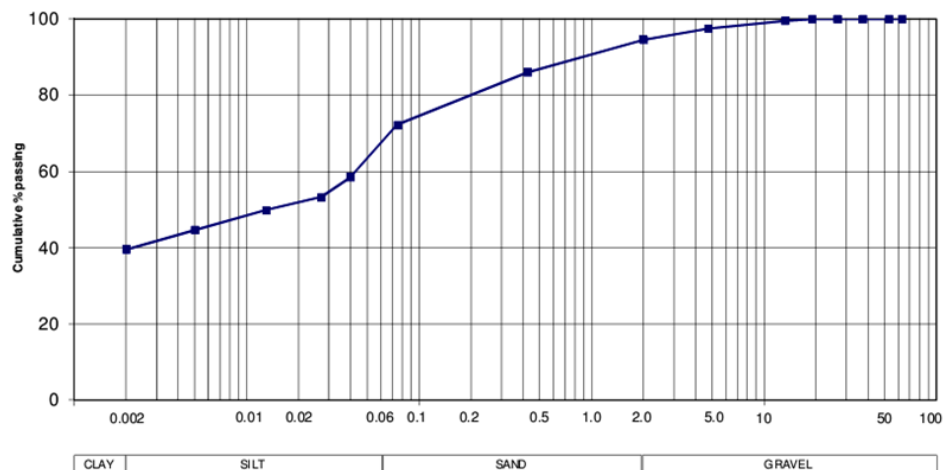
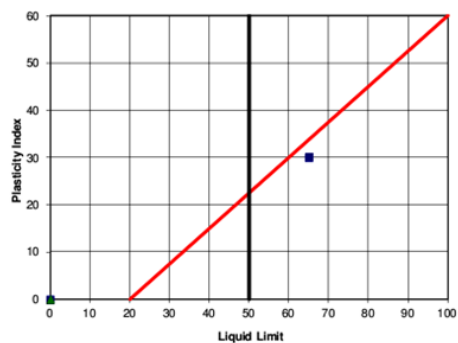
Sample No.		
Soillab sample no.	S12-1201-7	
Depth (m)	2.05-2.4	
Position	VT03	
Material	LIGHT OLIVE	
Description	CALCRETE+QUARTZ	
	SANDY CLAY	
Moisture (%)		
Dispersion (%)		
SCREEN ANALYSIS (% PASSING) (TMH 1 A1(a) & A5)		
63.0 mm	100	
53.0 mm	100	
37.5 mm	100	
26.5 mm	100	
19.0 mm	100	
13.2 mm	100	
4.75 mm	97	
2.00 mm	95	
0.425 mm	86	
0.075 mm	72	
HYDROMETER ANALYSIS (% PASSING) (TMH 1 A6)		
0.040 mm	58	
0.027 mm	53	
0.013 mm	50	
0.005 mm	45	
0.002 mm	40	
% Clay	40	
% Silt	27	
% Sand	28	
% Gravel	6	
ATTERBERG LIMITS (TMH 1 A2 - A4)		
Liquid Limit	65	
Plasticity Index	30	
Linear Shrinkage (%)	14.0	
Grading Modulus	0.47	
Uniformity coefficient	-	
Coefficient of curvature	-	
Classification	A-7-5 (23)	
Unified Classification	MH	
Chart Reference		

PROJECT : VADOSA ZONE - TEMBA
JOB No. : S12-1201
DATE : 2012-09-06

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Appendix V: Test Pits Photos



