CONCEPTUAL HYDROGEOLOGICAL CHARACTERISATION OF THE CEDARVILLE AQUIFER SYSTEM, EASTERN CAPE PROVINCE, SOUTH AFRICA

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A research report submitted to the Faculty of Science, University of the Witwatersrand, in partial fulfilment of the requirement for the degree of Master of Science in Hydrogeology

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02 November 2021 in Johannesburg

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Master of Science in Hydrogeology at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.


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02nd day of November 2021 at Wits University

Abstract

The research study focuses on the characterisation of the aquifer, which entails a comprehensive hydrogeological investigation that involves field geological mapping, pumping test data analysis, hydrogeochemical analysis, environmental stable isotope analysis and interpretations of the Cedarville Aquifer. The primary objective of the study is to develop a conceptual hydrogeological model of the Cedarville Aquifer System. Cedarville is situated in the Eastern Cape Province of South Africa and forms a basin-shaped topographical profile filled with Quaternary alluvial deposits referred to as the Cedarville Flats. Management of groundwater resources is of paramount importance in ensuring a sustainable water supply to groundwater-dependent communities such as the Cedarville Community. The sustainable management of groundwater resources requires an in-depth understanding of the aquifer system; hence, the conceptual characterisation of the Cedarville Aquifer System is indispensable. The Cedarville Area is underlain by the rocks of the Tarkastad Subgroup, which belong to the Beaufort Group of the Karoo Supergroup. The underlying rocks consist of fractured alternating sandstone and mudstones intruded by dolerite. The aquifer system constitutes alluvium, which forms an unconfined to semi-confined water-bearing strata and is underlain by the fractured semi-confined to confined aquifer of the Karoo Sedimentary Sequence. Assessment of the dominant water-bearing units and reliable hydrogeological features is essential in the characterisation of the Cedarville Aquifer System. Analyses of joints in the area show that the NE-SW trending joint sets are open and were formed due to tensional stresses. These joints were later intruded by magma, which resulted in the NE-SW striking linear dolerite dykes. Pumping test data were analysed using various analytical models to determine the hydraulic parameters, which exhibit that the transmissivity ranges from 23.9 to 105.3 m^2/day with an average storage co-efficient of 0.01. Groundwater recharge was evaluated based on the Chloride Mass Balance (CMB) to the value of 98mm/yr. The hydrochemical analysis demonstrated that ion exchange (Na^+ and Ca^{2+} replacement) is the most dominant hydrogeochemical process in the Cedarville Aquifer System. The groundwater in the Cedarville Aquifer System is characterised to be recently recharged groundwater from rainfall based on hydrogeochemical analysis. This is further collaborated by stable environmental isotopes, which characterise groundwater in the Cedarville Aquifer System to be of meteoric origin. The Cedarville Aquifer System is conceptually modelled as a two-layered system consisting of an unconfined to semi-confined alluvium top layer and semi-confined to confined, fractured hard-rock bottom layer. Rainfall recharges the system, which percolates and reaches the contact zone between the two layers of the model resulting in obvious water strikes when intercepted by drilling. The fractured bottom layer is recharged from the top alluvium layer with horizontal fractures transmitting groundwater laterally, resulting in significant water strikes especially in places where fracturing is enhanced by dolerite intrusion. High yielding productive boreholes are attained by drilling deeper and high yields are attributable to more cumulative water strikes being intercepted at depths.

Keywords: Groundwater, Characterisation, Aquifer, Model, Recharge, Conceptual Model

Dedication

In memory of my brother:

Bonga Bonginkosi Gqiba

1959 - 1983

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Acronyms and Symbols

AGES	:	Africa Geo-Environmental and Engineering Science
amsl	:	Above Mean Sea Level
ANDM	:	Alfred Nzo District Municipality
BCM	:	Buffalo City Metropolitan Municipality
bgl	:	below ground level
CAS	:	Cedarville Aquifer System
CSIR	:	Council for Scientific and Industrial Research
CMB	:	Chloride Mass Balance
DWA	:	Department of Water Affairs
DWAF	:	Department of Water Affairs & Forestry
EC	:	Electrical Conductivity
GMWL	:	Global Meteoric Water Line
GRIP	:	Groundwater Resource Information Programme
K	:	Hydraulic Conductivity
KZN	:	KwaZulu Natal
MAP	:	Mean Annual Precipitation
NWRS	:	National Water Resource Strategy
PPT	:	Precipitation
RSA	:	Republic of South Africa
S	:	Storativity or Storage Co-efficient
SAWS	:	South African Weather Services
S_y	:	Specific Yield
SRK	:	Steffen, Robertson and Kirsten
T	:	Transmissivity
WMA	:	Water Management Area
WRC	:	Water Research Commission
yr	:	Year

CHAPTER ONE – INTRODUCTION

1.1 Background of the study

Groundwater resources remain the sole economical and viable water supply source to address water supply requirements for the small towns and villages in South Africa. This can be attributed to a low capital outlay to develop a groundwater supply system in comparison to a surface water scheme. The operating costs are low since there is generally no treatment required in water sourced from the groundwater system. However, groundwater suffers a bad reputation due to poor management and is often assumed unsustainable for long-term water supply (Braune and Makarigakis, 2010). Most water users and service institutions do not understand the South African aquifer systems and tend to over-exploit groundwater resources with no monitoring plan in place (DWA, 2013). This has subsequently posed doubts about the sustainability of groundwater resources to supply urban and rural communities in South Africa.

Groundwater supply schemes are frequently developed for short-term needs and large surface water schemes are planned for long-term requirements in South Africa. The growing water demand due to population growth and industrial developments in small towns is the key factor that influences the planning of large surface water schemes. Most water services planners in South Africa view groundwater as an important resource even though they doubt the sustainability of groundwater for long-term supply. According to Braune and Makarigakis (2010), groundwater accounts for 98% of the available landmasses fresh water resources excluding freshwater locked in icebergs and glaciers and the remaining 2% covers rivers, lakes and biosphere combined. Thus, groundwater forms the largest proportion of fresh water resources found on the earth's landmasses. It is estimated that 22% of the world's population relies on groundwater as the sole water supply source (Anaman, 2013).

Groundwater plays an important role in the African continent in terms of community water supply with an estimated 75% of the African population using groundwater as its main source of drinking water (Braune and Makarigakis, 2010). It is further estimated that 80% of the 75% groundwater-dependent African communities live in rural areas. In South Africa, approximately 18% of the nation's total water supply originates from groundwater and 90% of those water supply schemes serve rural and small town communities (DWA, 2013). Thus, groundwater resources in the African continent predominantly serve small municipality towns and rural communities. It is imperative, therefore, that groundwater systems be characterised in order to manage the resource sustainably. Subsequently, this study is undertaken to conceptually characterise one of the important aquifer systems in South Africa, the Cedarville Aquifer System.

1.2 The motivation of the study

Groundwater is the sole water supply source for commercial and domestic use in the Cedarville area. The management of the groundwater resources is of paramount importance to ensure a sustainable water supply to the community of the Cedarville area. The public authorities often raise a question of whether the current groundwater supply will sustain the Cedarville community for the forthcoming decades or if the water services authority should plan for other water supply sources such as dams to augment the groundwater supply. The sustainable management of groundwater resources requires an in-depth understanding of the aquifer system in question, hence it needs studies such as this to conceptually characterise the aquifer systems.

According to Holland (2011), the principal tool for investigating the sustainability of groundwater is a groundwater model, the reliability of which depends on a conceptual model with accurate geometric and hydraulic properties of the aquifer system. However, the assessment of the sustainability of groundwater in the Cedarville area requires a thorough hydrogeological characterisation of the Cedarville Aquifer System. Subsequently, the conceptual hydrogeological model forms a corner-stone for addressing the sustainability of any aquifer system. This study will, therefore, provide a framework for further research towards the determination of the sustainability of the Cedarville Aquifer System.

1.3 Aims and objectives

The primary objective of the study is to characterise the Cedarville Aquifer System, which entails the development of a conceptual hydrogeological model of the aquifer system. The aims of the study encompass the following:

- Analysing the tectonic stress regime in the Cedarville system
- Defining the hydrostratigraphical units of the Cedarville Aquifer System
- Assessing the influence of geological structures in the hydrogeology of the Cedarville aquifer System
- Determining the hydraulic parameters that influence the hydrogeology of the Cedarville Aquifer System
- Evaluating the groundwater recharge in the Cedarville Aquifer System
- Analysing the hydrogeochemical regime of the Cedarville Aquifer System including the isotopic analyses

1.4 Research question

The primary question for investigating the Cedarville aquifer system is implicit and addresses the development of a conceptual groundwater flow model that could further be used to determine the sustainability of groundwater resources in the Cedarville area. The secondary question is the determination of the most reliable water-bearing hydrogeological features in the Cedarville Aquifer System. These questions lead to an investigation of whether the thick alluvial deposit that overlies the Karoo Supergroup sediments has the potential to yield boreholes that are more productive than the underlying sedimentary strata. The role played by linear dolerite dykes and joints in controlling groundwater flow regime in the Cedarville Aquifer System is investigated.

1.5 The description of the study area

1.5.1 The locality of the Cedarville Area

The Cedarville Aquifer System is flat, mountain-locked farming land, referred to as the Cedarville Flats, situated in the Eastern Cape Province of South Africa. The land is located in the north-eastern region of the province, which shares borders with the KwaZulu-Natal (KZN) Province of the Republic of South Africa (RSA) and Lesotho. The area is marked by a small farming town, the Cedarville Town along the R56 road between Kokstad and Matatiele, a mere 40 km west of Kokstad Town. The latter town is in the southern region of the KZN Province along the N2 road and borders the Eastern Cape and KZN provinces. Figure 1 is the locality sketch of the Cedarville area.

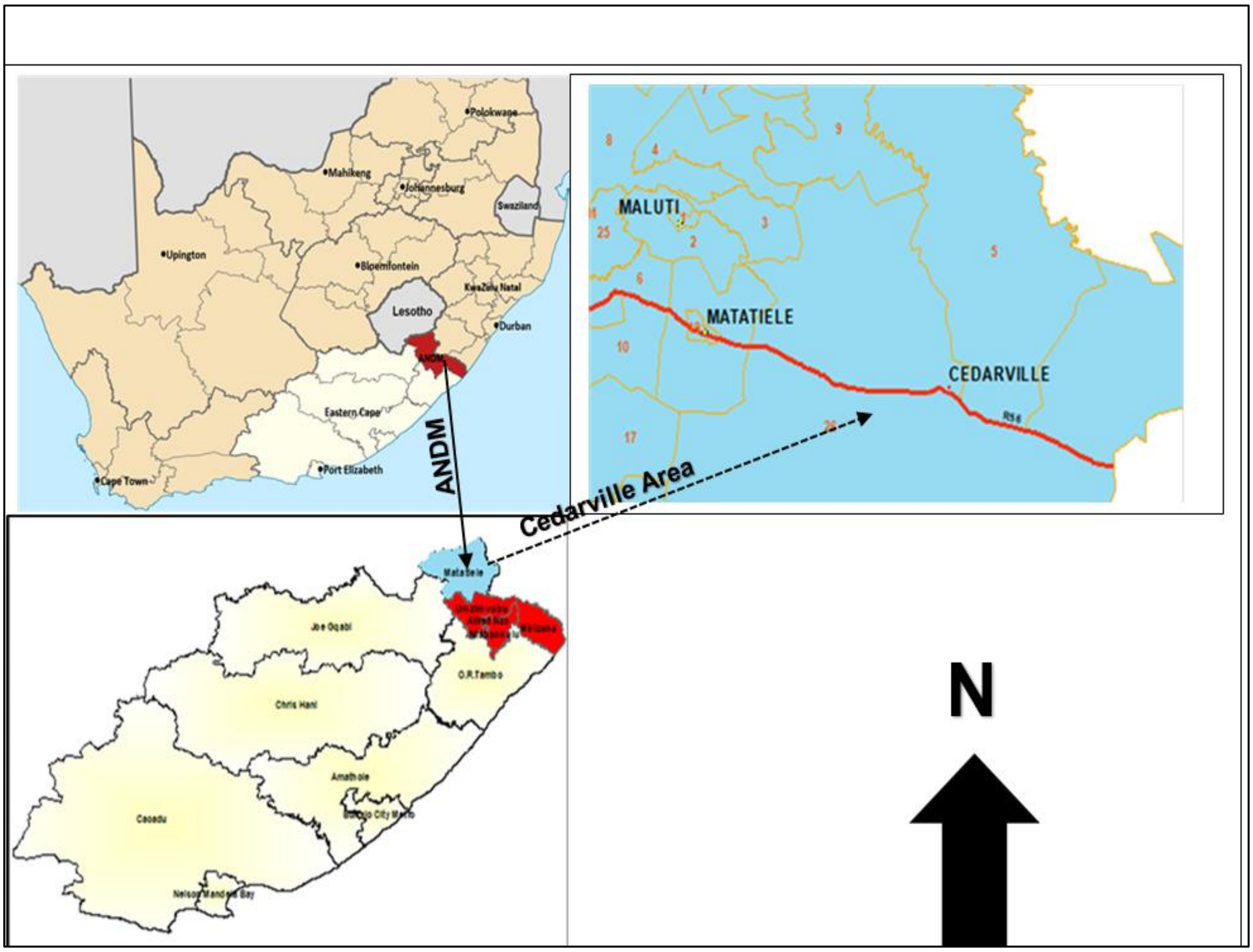


Figure 1: Locality sketch of the Cedarville Area

According to the NWRS (DWA, 2013), Cedarville is located in Water Management Area (WMA) 7, thus the Umzimvubu-Tsitsikama WMA. The Umzimvubu-Tsitsikama WMA is one of the nine WMAs of South Africa and the Umzimvubu-Tsitsikama covers most of the Eastern Cape Province. The Cedarville town's central point co-ordinates present the spatial description of Cedarville Area and are:

Latitude = -30.387831°S; Longitude = 29.041022°E

1.5.2 Topography and drainage of the Cedarville Area

The Cedarville area is positioned on the foot of the Drakensberg escarpment. It is situated on a high relief zone at an average altitude of 1472 m above mean sea level. The area is relatively flat with shallow slopes descending towards the Umzimvubu River (Figure 2). The Cedarville area is surrounded by undulating hills and is bounded on the northern horizon by the high relief Drakensberg Mountains that mark the Lesotho-RSA international border. This forms a "basin-shaped" topography with an extensive flat base referred to as the Cedarville Flats.

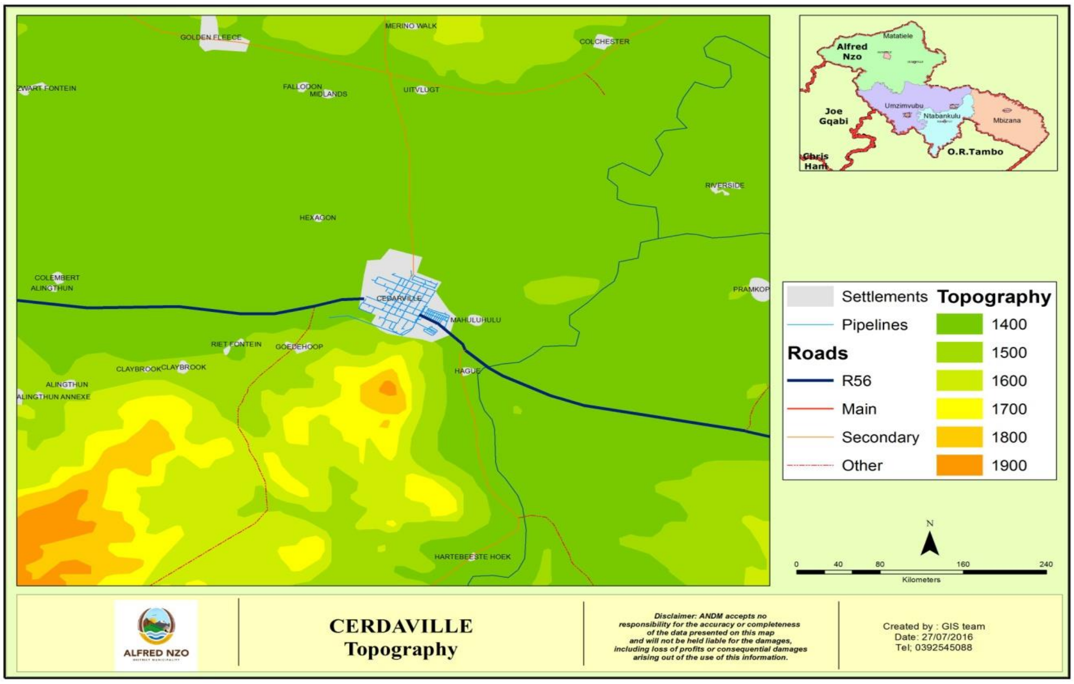


Figure 2: The digital terrain model of the Cedarville Flats

The Umzimvubu River, being the largest river in the region, runs through the Cedarville Flats, and forms the major regional drainage basin with an extensive catchment area of approximately 19800 km^2 (DWAF, 2009). The Umzimvubu Catchment consists of six tertiary catchments, which are T31, T32, T33, T34, T35 and T36 (Figure 3). The primary drainage region incorporates the four major tributaries namely: Tsitsa, Tina, Kinirha and Mzintlava Rivers. The Cedarville area is predominantly covered by T31F and T31G quaternary catchments. There are no major tributaries that feed the Umzimvubu River in these two quaternary catchments except secondary drainage that runs through farming land to feed wetlands and ultimately the Umzimvubu River.

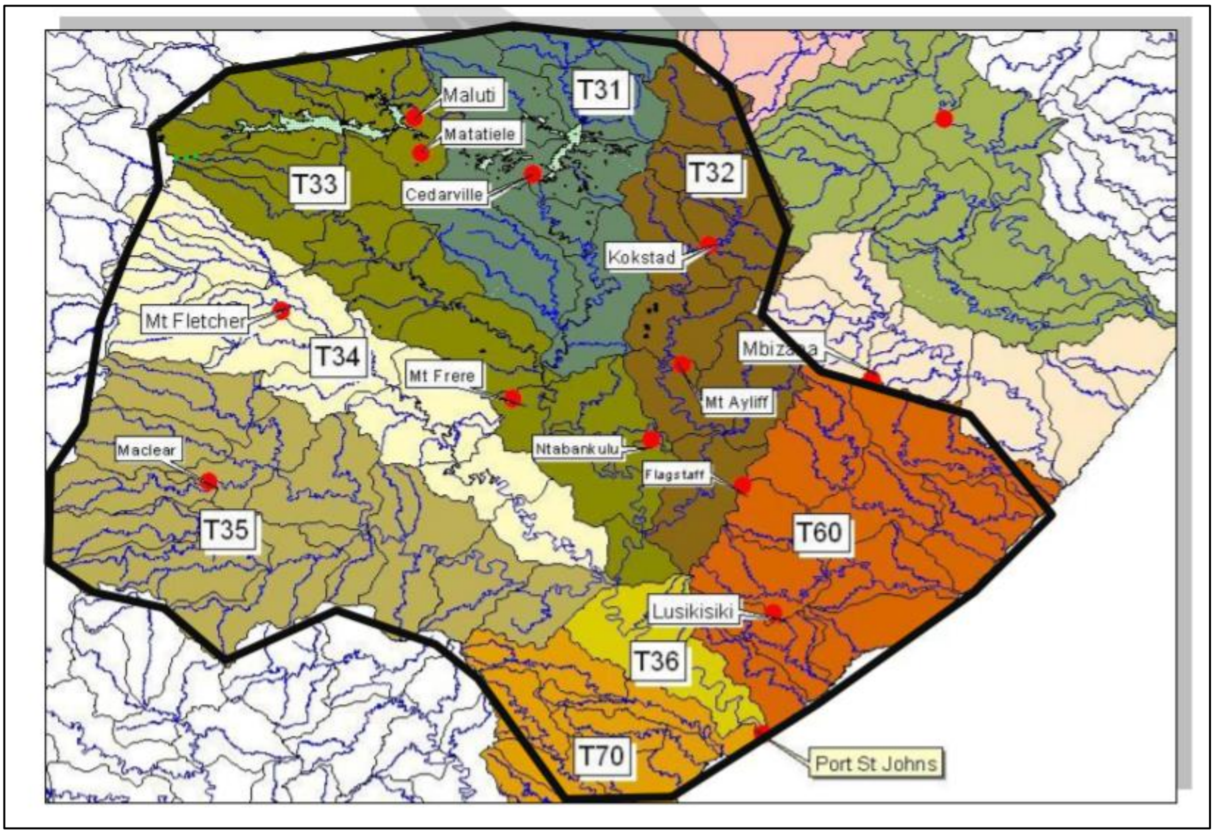


Figure 3: The Umzimvubu Catchment showing the Tertiary sub-catchments (adapted from ERS, 2011)

1.5.3 Climate

The climate of Cedarville is greatly influenced by the Drakensberg escarpment and thus characterised by cold dry winter and hot rainy summer seasons. The average summer daily temperature ranges between 20 and 22.5°C and the average winter daily temperature between 7.5 and 10°C (Smithers and Schulze, 1995). The snowfall frequently occurs during dry winter seasons in the Drakensberg Range. South Africa predominantly fall in the summer rainfall region with an overall mean annual precipitation (MAP) of 464mm, while the southern coastal section receives winter rainfall that exceeds 1000mm (DWAF, 2009). The summer MAP value is far below the overall world MAP of 860mm and as such, South Africa is classified as a low rainfall region with uneven distribution of rainfall, thus rainfall being greatest in the east decreasing gradually westwards. Cedarville is situated in the eastern region of South Africa and the MAP of Cedarville ranges between 801 and 1000mm (Smithers and Schulze, 1995). According to DWAF (2009), the MAP of the Umzimvubu River basin along the Drakensberg escarpment, which includes the Cedarville Town is 820mm. Figure 4 is a graphical representation of the mean annual precipitation recorded over 100 years, obtained from the South African Weather Services (SAWS). The MAP value for Cedarville was calculated to be 760mm based on the 100-year rainfall records (Figure 4).

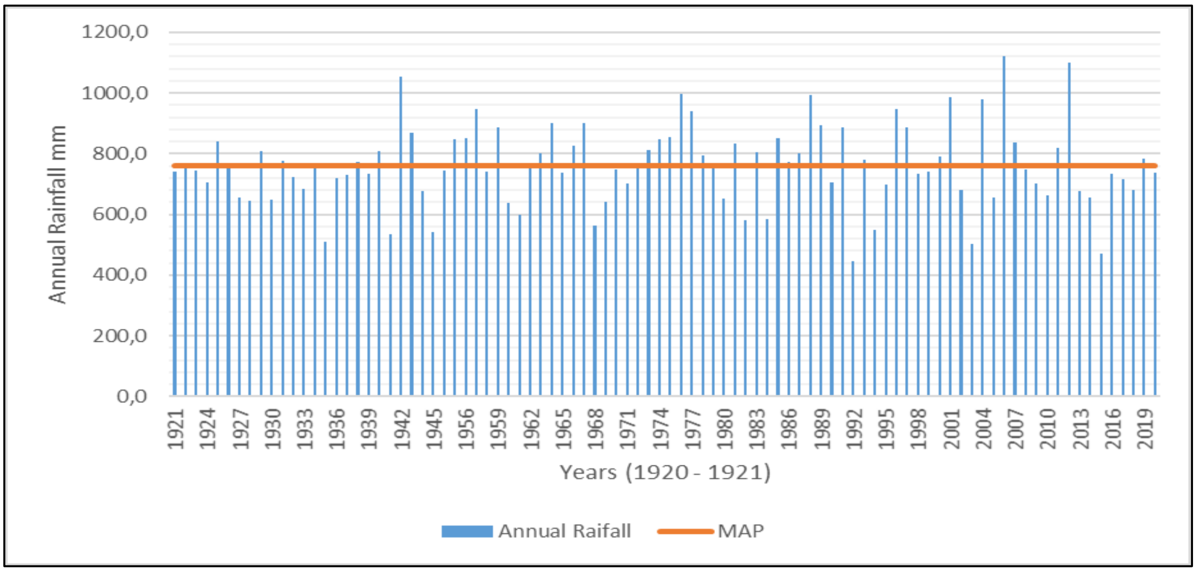


Figure 4: Graphical representation of the mean annual precipitation of Cedarville in 100 years (Source: SAWS)

1.5.4 Vegetation and Soil

The Cedarville Town area consists of loamy sandy soil with high humus content. This can be attributed to flat topography; hence, the area is referred to as Cedarville Flats. There are numerous wetlands in the area, which could be associated with clay lenses in the vadose zone of the soil profile. Such clay lenses impede the infiltration of surface water below the vadose zone and subsequently form the wetlands. Such wetlands enrich the soils with a high humus content due to the ecological life that takes place in the wetlands. The Cedarville flat section is generally a grassland region, thus covered with a grassland biome. It is predominantly savannah grassland with minor shrubs on hilltops.

1.5.5 Land-use, Population and Socio-economy

The town of Cedarville is a small, rural town with minimum income-generating developments. The surrounding land is mainly used for commercial farming. Thus, commercial agricultural activities constitute the main land-use in the Cedarville Flats. Extensively irrigated pasture for dairy farming is observed on the side road (along the R56) from Kokstad to Matatiele town. The major irrigation systems, which comprise of centre pivots are dependent on groundwater sources. The primary farming activities in the Cedarville area are cattle farming (dairy cows in particular) and to a lesser extent crop production. The town of Cedarville is known as a hub for milk production.

Cedarville town is a residential town surrounded by commercial farms. According to the 2011 census (StatsSA, 2011), the population of Cedarville is 4413 and a high proportion of the population resides in Cedarville town. The 2001 census recorded a population of 2070, which suggests a population increase of 2343 over 10 years. The significant population growth rate of approximately 5% annually in Cedarville can be attributed to the urbanisation in the Eastern Cape Province and the influx of immigrants from the Republic of Lesotho. This, therefore, has a bearing in terms of water provisioning for the community of Cedarville, hence it is important to characterise groundwater resources for a groundwater-dependent area such as Cedarville.

The majority of the community of Cedarville is dependent on social grants subsidised by the government. However, there are schools, health centres, police services and other public institutions in which some of the Cedarville community members render services. Some of the community members commute to the nearby towns of Matatiele and Kokstad to render services and others work further afield in places such as Durban, Johannesburg, etc. However, the unemployment rate is high and the socio-economic status of the community of Cedarville lives below the poverty datum line. The latter can be described as households with total earnings of less or equal to R1500 per month (StatsSA, 2011). However, commercial farming and the geographical location of Cedarville town bear positive economic spinoffs to the community of Cedarville.

1.5.6 Regional geology of the Cedarville Area

Rocks of the Karoo Supergroup underlie the Cedarville region. According to the Council for Geoscience (1988), the area consists of rocks of the Tarkastad Subgroup, which belong to the Beaufort Group of the Karoo Supergroup (Figure 5). The main lithological outcrops are the medium to fine-grained, yellow to greyish sandstones alternating with red, purple and bluish green mudstones. This is indicative of the two cycles of sedimentary facies that are associated with the:

- Rising water level (Transgression), resulting in deposition of argillaceous sediments which gave rise to mudstones.
- Withdrawing water level (regression), resulting in deposition of arenaceous sediments which gave rise to sandstones.

The sedimentary rocks in the Cedarville region are almost horizontally bedded, generally dipping at 4° NW (Council for Geoscience, 1988). The thick alluvial deposits cover the region in the immediate north of the town of Cedarville resulting in extremely flat topography; hence, the area is referred to as the Cedarville Flats.

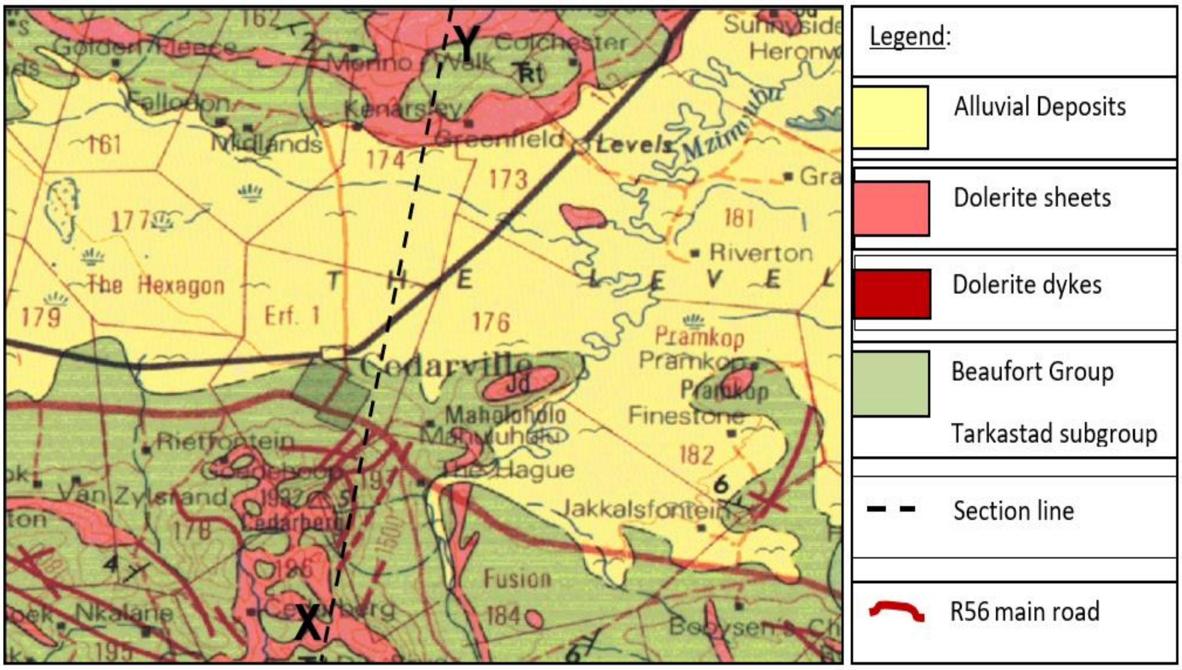


Figure 5: The geological map of Cedarville (adopted from Council for Geoscience - 1:250 000 Geological Map of Kokstad)

1.5.7 The hydrogeological setting

The groundwater occurrence of any area is primarily controlled by the geology of the area. This is particularly the case in the Karoo Supergroup in which the dolerite intrusion plays an important role in the groundwater occurrence and aquifer types. The presence of abundant dolerite dykes and sills indicates significant regional disturbances that must have taken place during intrusions in the host rocks. It is expected that the dolerite intrusions induce fractures in the Karoo sedimentary rocks, which then form conduits for groundwater flow when these fractures are hydraulically connected. Such a network of fractures enhances the transmissivity of the host sedimentary succession to groundwater flow.

According to Botha et al. (1998), the classical explanation for the existence of fractures near dolerite intrusions can be attributed to the energy with which magma is emplaced in the host sedimentary rocks. The associated uplifting and warping of sediments due to magma emplacement propagated bedding parallel fractures in the Karoo Sequence. The existence of fractures adjacent to dolerite intrusions is further attributed to thermal effects associated with magmatic activity (Botha et al., 1998). The changes in temperature associated with magmatic intrusions result in baking and cooling which subsequently cause the expansion and contraction of the host rocks, such thermal stresses, therefore, cause a high density of fractures on the adjacent sediments and within the intrusion itself. Subsequently, the induced network of fractures adjacent to the dolerite intrusions is the hydrogeological target to drill high yielding boreholes in the Karoo sequence (Botha et al., 1998).

The Cedarville area is reputed to have high drilling success rates attributed to the Quaternary alluvial deposits that occur north and northwest of the town of Cedarville (DWAF, 2009). Alluvial deposits generally transmit groundwater except in places where there are widespread clay lenses, which retard or even impede groundwater flow in the alluvium. The sand content in the alluvium enhances the transmissivity of the intergranular aquifer system. The argillaceous content, which also constitutes the alluvium, retards groundwater flow in the deposits. The preferred target to drill a successful borehole in Cedarville alluvial deposit is in places where the deposit is fairly thick and underlain unconformable by less transmissive formation below. Thus, the unconformable contact below the alluvium forms a bedding parallel, transmissive zone for groundwater exploration. According to DWAF (1998), the expected yield of boreholes drilled in the Quaternary Alluvium of Cedarville ranges between 2 l/s and 3 l/s. Thus, the alluvium aquifer system is classified as semi-confined to unconfined depending on the existence of argillaceous confining layers in the deposit.

The sandstones are comparatively more transmissive than the mudstones and are, therefore, aquifers especially in places where they are weathered and fractured (Woodford and Chevalliar, 2002). Sandstones are generally dual porosity aquifers comprising:

- Primary porosity is associated with sand grain packaging in the sandstone formation.
- Secondary porosity is attributed to micro-fissures of high transmissivity when connected to each other.

Sandstones behave in a brittle manner when subjected to tectonic stresses. This behaviour tends to form micro-fractures as opposed to mudstones that have clay content and behave in a ductile manner when subjected to tectonic stresses (Woodford and Chevalliar, 2002). The sandstones in the Cedarville area are often sandwiched between mudstones or dolerite sheets, which results in confined or semi-confined aquifer conditions.

The NE trending dolerite dykes in the Cedarville region are more prominent (DWAF, 1998). It is thought that the NE trending dykes have higher potential for groundwater exploration since the NE trend is expectedly tensional and results in open fractures. Thus, the general perception is that the NE trending dolerite dykes in the Cedarville region have a hydraulically connected fracture network around the dyke margins (AGES, 2017). The dolerite sills occur in high relief zones or rather cap the hills in the Cedarville region. However, the bedding parallel fractures in the Karoo Sequence can be related to the emplacement of dolerite sills (Botha et al., 1998). In the Cedarville region, sills inappropriately occur in areas that are not easily targeted for groundwater exploration. According to DWAF (1998), the expected borehole yields drilled at fractured dolerite contact zones are greater than 5l/s.

The groundwater recharge in the Cedarville region can be estimated at 3% of the Mean Annual Precipitation (Smithers and Schulze, 1995). It is thought that groundwater recharge occurs in the hills and mountains north of Cedarville. It is further thought that snowmelt during the winter season recharges groundwater in the mountains north of the Cedarville area (AGES, 2017). The static water table is observed in some borehole records to range between 2 and 60m below ground level (bgl) in some places (DWAF, 1998). According to DWAF (2009), the hydrogeochemical regime of Cedarville constitutes Calcium-Magnesium-Bicarbonate water with enriched Sodium in some places. It is thought that such a hydrogeochemical regime is indicative of active groundwater circulation with NaCl enrichment occurring through the ionic exchange in the groundwater flow paths (DWAF, 1998). Groundwater conductivities range between 70 and 300mS/m however, higher conductivities (greater than 1000mS/m) were observed in the alluvium.

CHAPTER 2 - METHODOLOGY

2.1 Introduction

The study on hydrogeological characterisation of the Cedarville Aquifer System is divided into two main sections as enshrined in the methodology framework illustrated in Appendix B:

- Literature review and description of the study area
- Hydrogeological characterisation of the Cedarville Aquifer System

The literature view section and description of the study area constituted inferred information from the available literature, maps, reports and recorded information by various agencies such as the rainfall data from the South African Weather Services (SAWS).

The literature view section focused on the origin of the large-scale Karoo Basin in which the Cedarville Aquifer System occurs. Such review encompassed the geodynamic analyses, which include the tectonic history of the Karoo Supergroup. The origin of the Karoo Basin could then be associated with the occurrence and movement of groundwater in the Karoo Supergroup. The hydrogeological analyses of the Karoo rocks, fractured hard rocks in particular are inferred from the literature review in relation to the Cedarville formations. Then, the groundwater hydraulics, thus the aquifer response including flow behaviours is essential when the characterisation of the Cedarville Aquifer System is undertaken.

The descriptive information of the study area such as demography, topography, rainfall, drainage system, hydrogeology and geology were obtained from physical observations or reconnaissance survey of the area. The reconnaissance survey was carried out from 13th to the 16th December 2019, which entailed assessing and noting all the physical features of the study area. However, the population statistics of the study area were inferred from the Stats SA (2011). The other information such as the settlement and land-use information were acquired from the local municipal offices that are situated at Matatiele.

2.2 Acquisition of the geological information of the study area

The methodology for the characterisation of the Cedarville Aquifer System constituted the acquisition and processing of the hydrogeological data in order to develop a conceptual hydrogeological model of the aquifer system. The hydrogeological data were acquired through field geological mapping, borehole pumping test analyses and sampling of water bodies.

2.2.1 Geological mapping information

After the reconnaissance survey, a detailed desktop assessment of the study area was carried, which entailed the interpretation of geological maps, aerial photographs and satellite images of the study area. This then culminated in a field geological mapping exercise, which was conducted from 20th to the 30th January 2020. The 1:250 000 geological map of Kokstad (3029) published by the Council for Geoscience was used as a base map in conjunction with 1:50 000 topographic cadastral map of Cedarville from the Survey General of South Africa.

The primary objective of the geological mapping exercise was to analyse the tectonic stress regime in the Cedarville area. Hence, the focus of the geological mapping was to analyse the joints and other tectonic features of the area. The basic tools of the mapping exercise included the Brunton compass and the hand-held GPS. The Brunton compass was used to measure the trends and plunges of linear tectonic structures, strikes and dips of planar surfaces of rocks. The hand-held GPS measured spatial or geographical co-ordinates in order to plot their positions on maps. The recorded trends and plunges of joints in conjunction with strikes and dips of bedding structures were then plotted on stereo-nets and analysed using stereographic projection. This subsequently led to the interpretation of stress-strain tectonic regime of the Cedarville System, which was later related to the hydrogeological characterisation of the Cedarville Aquifer System.

2.3 Acquisition of the hydrogeological information of the study area

2.3.1 The hydrocensus survey

The hydrocensus survey or borehole survey of the research area was undertaken from the 9th to the 14th March 2020. The objective of the hydrocensus survey was to acquire groundwater information, which would be gathered and analysed in conjunction with the geological information to define the hydrostratigraphical units and geological structures that influence the groundwater flow regime in the Cedarville Aquifer System. Some related borehole information were acquired from the DWS Database archives, GRIP records, Consultants and Drilling Companies reports.

The key borehole data that was acquired during the hydrocensus survey included the spatial co-ordinates, borehole depths, water strikes, depths to water levels and lithological logs. Some of the boreholes are privately owned by farmers and access to the boreholes was granted as requested. The few boreholes that are owned by the municipality were accessed after permission was granted by the municipal authorities. Some of the municipal boreholes were recently drilled by AGES to augment the Cedarville Town Water Supply and the information collected from these boreholes was most recent compared to the farmer's boreholes.

Geographical co-ordinates were recorded in each borehole using the hand-held GPS. Then, the height of the protruding platform above the ground surface was measured using a tape measure and recorded. The depth to water level was measured and recorded using a Geotech 1500 Water Level Meter. The other borehole information such as the borehole depths, the water strikes and lithological logs were recorded from the borehole certificates obtained from the borehole owners. The information for the municipal boreholes were obtained from reports produced by consultants and some municipal borehole information exist in the GRIP database. The hydrocensus information were then consolidated with geological information gathered from the mapping survey in order to develop a conceptual hydrogeological model with components such as the hydrostratigraphical units and associated structures that influence groundwater flow regime. Some borehole information were analysed to draw essential groundwater attributes for the conceptual model such as the highest yielding lithological units.

2.3.2 Borehole pumping test information

The drilling and pumping test of boreholes was not undertaken in this study. However, pumping test data and respective lithological logs were obtained from the AGES reports submitted to the municipality after AGES was contracted to augment groundwater supply in the town of Cedarville by the ANDM. The analysis of pumping test data in conjunction with lithological description and other related borehole drilling data were the prerequisite information in the determination of hydraulic parameters that influence the hydrogeology of the Cedarville Aquifer System.

The boreholes drilled by AGES were undertaken by a Rotary Air Percussion Machine, the drilling was then followed by pumping test operation. The primary focus of AGES borehole pumping test was to determine the sustainable yields of boreholes, hence single borehole tests were performed. However, two of the boreholes (EC-T31-241 and EC-T31-321) were the exception, in which one was used as an observation borehole, thus a multi-well test was conducted in these two boreholes by a SP Series Submersible Pump. Subsequently, such data would allow the determination of all key aquifer hydraulic parameters. The multi-well pumping test data inferred from the AGES reports were analysed using an excel spread-sheet that is based on AQTESOLV, aquifer analysis software. The detailed analyses of pumping test data were carried out to determine aquifer parameters, which included transmissivity, storage co-efficient (storativity) and specific yield. The full description of the aquifer system whether the system is unconfined, semi-confined or leaky aquifer system is entailed in the analyses of the pumping test data.

2.3.3 Groundwater recharge information

Recharge estimation is one of the key components for the hydrogeological characterisation of the aquifer system. There are various methods that are generally employed in the estimation of groundwater recharge including the direct and indirect methods (Connelly et al., 1989). Due to limitations on the availability of data, mainly the empirical method based on rainfall records and Chloride Mass Balance methods were used to evaluate groundwater recharge in the Cedarville Area. Rainfall data that extend for a century were attained from the SAWS. Such data records were utilised for the computation of the mean annual precipitation (MAP), which is the key variable in the estimation of groundwater recharge based on the empirical method. The Chloride Mass Balance (CMB) method is based on the Cl^- concentration in both groundwater and rainwater. Samples of groundwater and rainwater were taken for the hydrogeochemical characterisation of the aquifer system. The Cl^- concentration values were then used for the estimation of recharge based on the CMB method.

2.3.4 Acquisition of the hydrogeochemical information

Water samples were taken for chemical and environmental stable isotopic analyses, which constituted groundwater, rainwater, stream and dam water samples. Groundwater samples were collected in selected boreholes for both chemical and environmental stable isotopic analyses. The sampled boreholes include municipal and privately owned boreholes. Groundwater was sampled from boreholes using a low-flow pump after purging for about 10 minutes. The samples were collected using 250ml HDPVC bottles and taken in duplicate per borehole site. The sample bottles were then properly labelled and stored in portable cool boxes at 4°C until submission to the laboratory. On-site physicochemical parameters were measured and recorded prior to storage in cool boxes, such parameters include temperature, pH and Electrical Conductivity. These parameters were measured in the field using the Hach Multiparameter Probes, which were calibrated frequently before use.

Rainwater samples were grabbed during rainy days using sterilised open bowls and water was transferred immediately to 250mm bottles. Similarly, physco-chemical parameters were measured on site. River and lake water samples were similarly grabbed from the flowing stream and dams that occur in the study area. The proper sampling procedures were followed to avoid cross-contamination of the samples.

The groundwater and rainwater samples were taken to the Buffalo City Scientific laboratory in East London for the major ion analyses. The Ion Chromatographic instrument, the Agilent 700 series ICP, was used in the analysis of major ions. The duplicate samples of groundwater, rainwater, stream and dam water were taken to iThemba Laboratory for the environmental stable isotopes (^{2}H and ^{18}O) analysis of which the ^{2}H and ^{18}O were analysed, using the Liquid Water Isotope Analyser (LosGateos) instrument.

The available chemical analyses of some boreholes were inferred from reports submitted by AGES on the recent groundwater development programme for the Cedarville water supply augmentation. The chemical concentrations of major ions were processed including the calculation of ion balance to ascertain the reliability of such analyses. The major ions were plotted on Schoeller, Piper and Durov diagrams including the sampled water in this study in order to infer the hydrogeochemical groundwater regime of the Cedarville Aquifer system.

CHAPTER 3 – LITERATURE REVIEW

3.1 The geology of the Karoo Supergroup

According to Lurie (1984), the rocks of the Karoo basin covered about one-half of the total area of the Republic of South Africa. The sedimentary sequence, which filled the Karoo basin, is known as the Karoo Supergroup. The sequence is approximately 8000 m thick in the centre of the sedimentary basin and thinned towards the edges (Catuneanu et al., 2005). It consists of four main stratigraphic groups namely; the Dwyka, Ecca, Beaufort and Stormberg Groups which were deposited over 120 Ma (Wheeler, 2015). The stratigraphic units of the Karoo Sequence, which spans from the Late Carboniferous (± 350 Mya) to the Middle Jurassic (± 150 Mya) era, are illustrated in Table 1.

Table 1: Summary of the stratigraphical units of the Karoo Supergroup (Source: Lurie, 1984)

Group	**Subgroup**	**Formation**	**Chronostratigraphic Units**
Lembombo		Drakensberg	Jurassic
Stormberg		Clarens	Triassic
		Elliot	
		Molteno	
Beaufort	Tarkastad	Burgersdorp	Permian
		Katberg	
	Adelaide	Balfour	
		Middleton	
Ecca		Volksrust	
		Vryheid	
		Pietermaritzburg	
		Dwyka	Carboniferous

3.1.1 The stratigraphy of the main Karoo Basin

The Dwyka Group formed the base of the Karoo Supergroup and rested unconformably on the pre-Karoo rocks, which include the Cape Supergroup or Natal

Sandstones and basement granites. The Dwyka Group consists of an almost 600 m thick, glacially influenced argillaceous deposit that accumulated approximately 300 to 290 Ma referred to as the tillite (Catuneanu et al., 2005). The tillite is greenish to bluish in colour and is composed of angular fragments of varying rock types and sizes supported by an argillaceous matrix. It marked the beginning of the Karoo sedimentation and could be traced in all provenances of the continent where the base of the Karoo basin outcrops (Catuneanu et al., 2005).

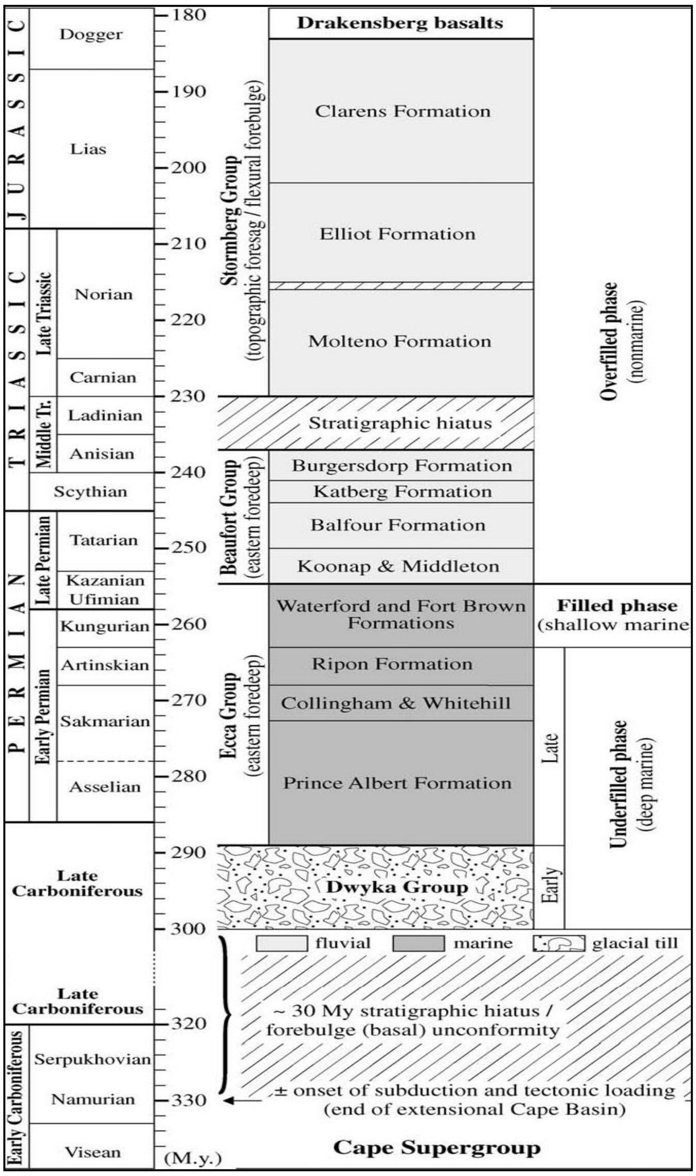


Figure 6: Stratigraphic chart of the Karoo Supergroup in the main Karoo Basin of South Africa (adopted from Catuneanu et al., 2005)

The Ecca Group rested conformably on the Dwyka Group (Figure 6). It consists of shallow marine sedimentary facies that were deposited over a submerged platform of the Dwyka Tillite (Viljoen, 1994). The Ecca Group reached a maximum thickness of 3000 m in the southern part of the main Karoo Basin (Johnson et al., 1996). The rocks of the Ecca Group are essentially a clastic sequence of mudstones, siltstones, sandstones, minor conglomerates and coal in some places. According to Catuneanu et al. (2005), ash beds observed in the southern Karoo Basin were dated at ± 270 Ma. Ecca Group was deposited between the Late Carboniferous and Middle Permian times, occupying most of the Permian time of the Karoo Supergroup lithologies.

The Beaufort Group overlies the Ecca and is subdivided lithostratigraphically into the lower Adelaide and the upper Tarkastad Subgroups. The rocks of the Beaufort Group covered a surface area of approximately 200 000 km^2 which made up 20% of the surface area of South Africa (Johnson et al., 1996). It attained a maximum thickness of 3000 m in the fore-deep or southern part of the main Karoo Basin and thinned rapidly northwards (Catuneanu et al., 2005). According to Lurie (1984), the Beaufort Group Sedimentary sequence consists predominantly of mudstones and siltstones with subordinate lenticular and tabular sandstones deposited by a variety of fluvial systems. The Adelaide Subgroup consists of dark grey shale with subordinate mudstone and sandstone. The Katberg Formation of the Tarkastad Subgroup consists predominantly of sandstone with subordinate brownish-red and grey mudstone, whilst the Burgersdorp Formation consists of mainly brownish-red and grey mudstone with interbedded sandstones. Palaeontological studies conducted by Rubidge et al. (2000) suggested that the Beaufort Group sediments were deposited in the Late Permian and Early Triassic times. According to Rubidge et al. (2000), the geological contact between the Beaufort Group and Ecca Group is transitional and diachronous, recording a gradual change from deltaic to fluvial depositional systems. Thus, the occurrence of laterally persistent delta front sandstones is a useful lithostratigraphical marker of the beginning of the Beaufort Group sedimentation.

The Beaufort Group was conformably overlain by the Stormberg Group consisting of the Molteno, the Elliot and the Clarens Formations, from the base to the top of the sedimentary succession, respectively. The Stormberg Group is the uppermost unit of the Karoo Supergroup and was deposited during the Late Triassic to Mid-Jurassic time. According to Johnson et al. (1996), the three sedimentary formations indicate a climatic condition that was becoming more arid. The fluvial sandstones of the Molteno Formation were overlain by fine-grained sandstones and mudstones of a fluvial and floodplain dominated Elliot Formation. This sedimentary succession was topped by the arid aeolian sandstones of the Clarens Formation. According to Catuneanu et al. (2005), the Stormberg Group attained a maximum thickness of 1200 m in the southern part of the Main Karoo basin of South Africa.

The Drakensberg Group capped the Stormberg Group and outcropped prominently in the mountainous areas of Lesotho and neighbouring areas. The Jurassic age Drakensberg Group consists of flood basalts with a total maximum thickness of 1370 m (Lurie, 1984), which had been associated with the tectonic breakup of Gondwana.

The Karoo Sedimentary Succession was extensively intruded by Jurassic age dolerite bodies. These occurred in various forms, which include:

- Dykes - Vertical dolerite intrusive forms that are discordant with bedding planes of the sedimentary succession
- Sills - Horizontal intrusive forms that are concordant with bedding planes of the sedimentary succession
- Sheets - Widespread dolerite intrusive forms of varying inclination and curvature
- Rings - Vertical dolerite intrusive forms that occur as 3-dimensional ring structures

The dolerite intrusions were regarded as feeders of the Drakensberg Basaltic lava (Lurie, 1984). Dolerite Dykes that are less than 1 metre in thickness occur in some places of the Karoo Basin. According to Lurie (1984), dykes are characteristically encountered in massive arenaceous rocks while sills are common in laminated argillaceous rocks.

3.2 Tectonic origin of the Karoo Basin

According to Catuneanu et al. (2005), the Karoo Basin evolved during the first cycle of supercontinent assembly and breakup of Pangea under the influence of two distinct tectonic regimes sourced from the southern and northern margins of Gondwana

(Figure 7). These tectonic activities resulted in the formation of a foreland system known as the Main Karoo Basin. The tectonic view was substantiated by Woodford and Chevallier (2002) that the southern convergent margin of Gondwana was characterised by shallow angle subduction of the Palaeo-Pacific Plate beneath the Super-continent. This compressional regime associated with collision and terrane accretion led to the formation of a 600 km long Pan Gondwana fold belt, the Cape Fold belt (Figure 8). The Cape orogeny represented by the super crustal (tectonic) load led to the formation of the Karoo retro-arc foreland system, which included the Main Karoo Basin.

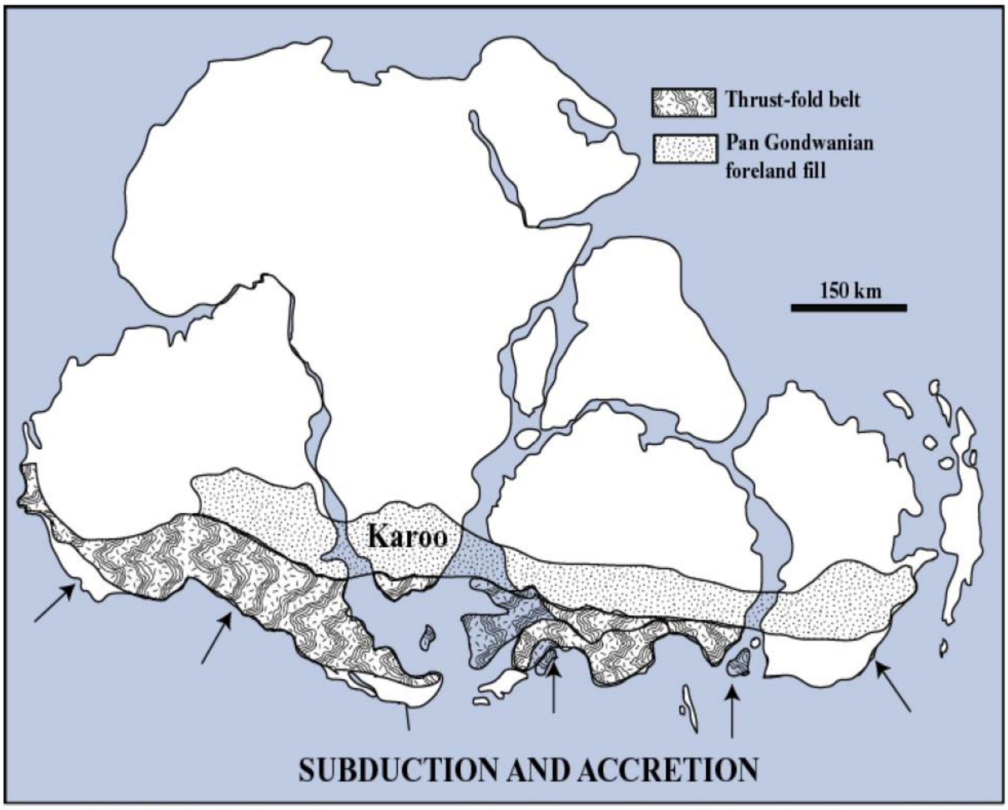


Figure 7: The breakup of the Gondwana (adopted from Catuneanu et al., 2005)

The tectonic regime during Karoo time was defined by compression and accretion along the southern margin of Gondwana with extension propagating into the supercontinent from its Tethyan margin (Woodford and Chevallier, 2002). This unique combination of tectonic stresses sourced from convergent and divergent margins of Gondwana resulted in the formation of different sedimentary basin types across the African continent. However, all the Karoo Basins across southern Africa were extensionally attributable to the intra-cratonic rifts related to the N-S trending basement shear zone.

According to Woodford and Chevallier (2002), there are numerous regional tectonic features that were determined from geophysical and remote sensing studies of the Main Karoo Basin. Of utmost importance for this study is the Matatiele fault, which formed an extension of a curvilinear, morphological feature that cuts across Lesotho. The Matatiele fault was observed to have a down-thrown of some 240 m to the north. It is thought that the faulting in the Quaternary deposits was responsible for the alluvium filled in the Cedarville Flats (Woodford and Chevallier, 2002).

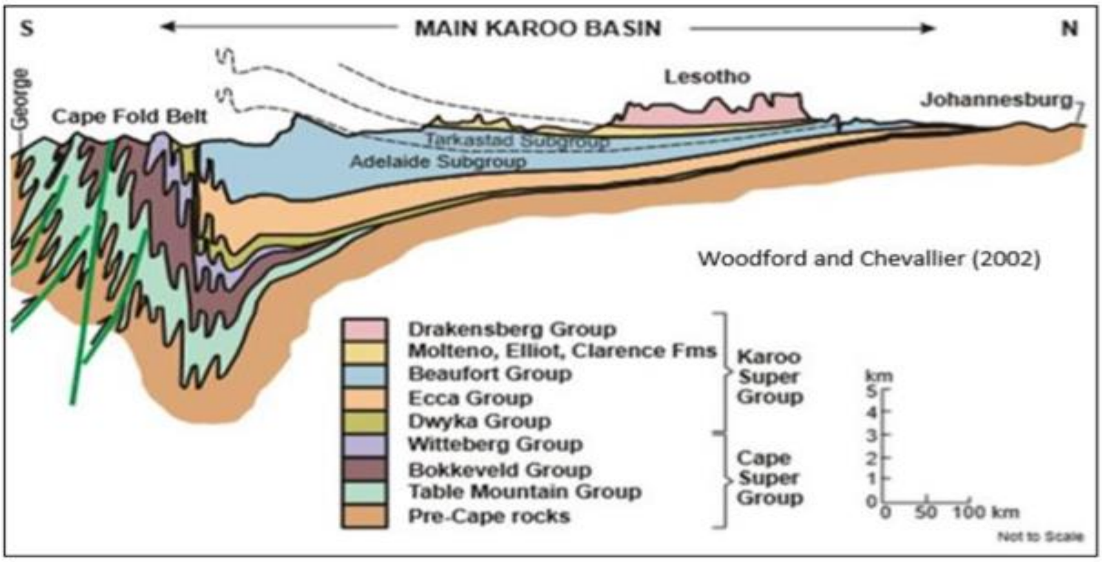


Figure 8: The longitudinal cross-section of the Karoo Basin (adopted from Woodford and Chevallier, 2002)

3.3 The Karoo Dolerite Intrusions

According to Botha et al. (1998), the magmatic intrusions in the Karoo Supergroup were related to the tectonic movement of Gondwanaland during the Late Triassic to Early Cretaceous ages, some 204 to 120 Ma. The magmatic activity in the Karoo Supergroup could be divided into two phases, an extrusive phase and an intrusive phase. The Drakensberg lavas covered a wide areal extent especially in the Kingdom of Lesotho and some regions of the North Eastern Cape, over the Drakensberg Escarpment. Botha et al. (1998) suggested that the Drakensberg volcanic event was accompanied by huge extensional forces, which opened fractures in the Karoo Sedimentary Sequence. Such fractures formed weak zones that resulted in the extensive dolerite intrusive phase. Thus, a large number of fractures in the host sedimentary sequence were intruded by magma, which resulted in the widespread dolerite intrusive network.

Dolerite dykes are vertical to sub-vertical intrusive forms that are discordant with sedimentary bedding in the Karoo Supergroup. They present linear discontinuous structures on a vertical (planar) view, which are observed as swarms of dykes. Woodford and Chevallier (2002) categorised dolerite dyke swarms in the Main Karoo Basin into three major domains:

a) The Western Karoo Domain consisting of E-W and NNW trending dyke intrusions
b) The Eastern Karoo Domain consists of E-W striking dyke swarm along the coast, curving NNW to NS inland and NNE trending dyke swarm
c) The Transkei-Lesotho-Northern Karoo Domain with 2 major swarms, namely:
    - NW trending dykes curving to E-W in the Free State region of South Africa
    - NE trending dykes mainly occur along side the Lesotho basalt lavas.

The NE trending dolerite dykes are more prominent in the Cedarville area. This, therefore, suggests that the Cedarville area consists of the Transkei-Lesotho-Northern Karoo Domain dyke swarm as categorised by Woodford and Chevallier (2002).

According to Woodford and Chevallier (2002), dolerite sills are the most dominant form in which dolerite intrusives were emplaced in the Karoo Supergroup. They tend to follow the bedding planes concordantly. Consequently, the lithology of the country-rock controls the emplacement of the sills since preferential dolerite sill emplacement occurs along the geological contacts and other lithological boundaries. Subsequently, lateral fracturing or horizontal bedding plane fractures were propagated by dolerite intrusion, which stressed along the horizontal lithological discontinuities. Thus, the theory of dolerite intrusions (Botha et al., 1998) showed that it was more common for magma to fracture the overburden along bedding planes and flow along the horizontal fracture to form sills.

3.4 Groundwater occurrence in the Main Karoo Basin

The Main Karoo Basin consists predominantly of secondary aquifers in which groundwater transmissivity is controlled by the interconnected networks of joints and fractures (Woodford and Chevallier, 2002). These fractures were generated by dolerite dykes, faulting and other tectonic influences such as isostatic uplift and subsidence effects (Botha et al., 1998). The primary aquifers are observed in alluvial deposits along flood plains of major rivers (Woodford and Chevallier, 2002). The permeability in the alluvial deposits is reduced by clay lenses that commonly occur as interbeds in the alluvium. Boreholes drilled in the Main Karoo Basin are generally low yielding; however, high yields are attained in fractured aquifer systems associated with dolerite dyke intrusions. According to Parsons (1995), the aquifers in the Main Karoo Basin can be classified as a Minor Aquifer System. The Minor Aquifer Systems are described as fractured or potentially fractured rocks, which do not have primary permeability or other formations of variable permeability. Such aquifer systems have a limited extent and variable water quality. Although these aquifers seldom produce large quantities of water, they are important for local supplies and base flow provision for rivers (Parsons, 1995). Thus, the Minor Aquifer Systems typically describe the most common aquifers of the Main Karoo Basin.

The Main Karoo Basin consists of sandstones, mudstones, shales and siltstones that generally have low permeability. According to Woodford and Chevallier (2002), the majority of boreholes drilled in the Main Karoo Basin have low yields (i.e. yields less than 1 l/s). However, the general view was that Karoo aquifers play a significant role in the provision of water for domestic and commercial purposes, especially for the rural communities of South Africa even though they do not necessarily produce high yielding boreholes (Parsons, 1995).

The Dwyka Group consists mainly of tillites and shales that have very low hydraulic conductivities in the range of 10^{-11} to 10^{-12} m/s (Botha et al., 1998). These rocks have virtually no primary voids and as such non-transmissive to groundwater flow (Botha et al., 1998). The Dwyka Tillite tends to form aquitards, however, exploitable groundwater occurs at few localities of the Main Karoo Basin where deep weathered zones and fracturing is encountered. The folded Dwyka rocks in the southern Karoo

Basin are well fractured at great depths and yielded sufficient groundwater for domestic use (Woodford and Chevallier, 2002). According to Botha et al. (1998), the Dwyka Group rocks are not ideal formations for the development of aquifers.

The Ecca Group consists predominantly of dense shales, which are generally accepted to be non-transmissive to groundwater flow. Subsequently, the Ecca Group was generally overlooked as probable aquifers that could yield significant sources of groundwater (Woodford and Chevallier, 2002). Botha et al. (1998) reported that in the Free State Province of South Africa (at Petrusberg), vast farming land is irrigated from boreholes drilled in the Ecca Shales. It may therefore be inferred that Ecca Group sediments possible bear economically viable aquifers especially in the northern regions of the Main Karoo Basin. The Ecca Group, therefore, cannot be neglected as significant source of groundwater. The sandstone interbeds possibly transmit groundwater, especially in areas where secondary permeability is enhanced by dolerite dyke intrusions, faulting and major jointing. Woodford and Chevallier (2002) reported boreholes with median yields of 0.33 l/s that were drilled through sandstones of the Vryheid Formation (Ecca Group, Table 4) in KwaZulu Natal Province and 62% of them yielded more than 1 l/s. Further studies need to be undertaken in order to fully understand the groundwater resource potential of the Ecca Group in the Main Karoo Basin.

The Beaufort Group consists of mudstones, shales and fine-grained sandstones, which have very low hydraulic conductivities (Botha et al., 1998). The Beaufort Group sediments are fluvial deposits in nature and therefore, thought to be anisotropic (Woodford and Chevallier, 2002). Thus, aquifers in the Beaufort Group are expected to be multi-layered and multi-porous with variable thicknesses. The geological contact between two different lithological layers causes discontinuity in the hydraulic properties of an aquifer. Subsequently, groundwater tends to flow laterally along the contact planes. The sandstone interbeds in the Beaufort Group strata are generally more permeable and were thought to be the aquifers since they are more transmissive than the underlying and overlying sediments. However, these tend to form confined and semi-confined aquifer systems due to the confining beds. According to Woodford and Chevallier (2002), the existence of high yielding boreholes in the Beaufort Group is influenced by aquifers being regularly recharged. This, therefore, suggested an immediate response to climatic changes by the Beaufort Group aquifers.

The Stormberg Group constitutes coarser-grained sedimentary strata in the Main Karoo Basin and as such were thought to bear ideal aquifers (Botha et al., 1998). However, the lithological formations of the Stormberg Group do not occur over a large area and tend to occur on high relief areas even capping mountain peaks of the Main Karoo Basin. Subsequently, it is very difficult to explore high yielding boreholes in the Stormberg Group and determine their hydrogeological behaviour (Woodford and Chevallier, 2002). The Molteno Formation at the base is more arenaceous being overlain by the Elliot Formation, which consists of red mudstones and sandstones. The latter formation could represent aquitards rather than aquifers due to the abundance of argillaceous units. The Clarens Formation which overlies the Elliot Formation consists of well-sorted, medium to fine-grained sandstones and was thought to form ideal aquifers. According to Woodford and Chevallier (2002), even though Clarens Formation has a relatively high uniform porosity, it is poorly fractured and has low transmissivity. Thus, secondary permeability was thought to be the main controlling parameter in the exploration of high yielding boreholes in the Main Karoo Basin.

The Quaternary deposits occur along most major rivers, in topographical flat flood plains of the Main Karoo Basin. A typical example includes the terraces of the Umzimvubu River (the Cedarville Flats) which forms the study area of this research work. These are generally covered by dark clayey–humic sand and sometimes by lateritic soil (Woodford and Chevallier, 2002). The deposits might reach 50 m in thickness, constituting alluvium, which is composed of alternating sand of variable grain size and clay. The clay may in some localities occur as lenses that form a perched water table in the saturated deposits. The alluvium forms a primary aquifer system when saturated with groundwater that tends to behave in an unconfined to semi-confined manner depending on the proportion of clay lenses. These aquifers supply large volumes of groundwater to many towns and commercial farms in the Main Karoo Basin. The composite alluvial aquifers containing significant volumes of groundwater were observed along the Salt River in Beaufort West of South Africa (Woodford and Chevallier, 2002).

3.5 The role of dolerite intrusions in the groundwater occurrence of the Main Karoo Basin

The hydrogeology of the Main Karoo Basin was greatly influenced by the presence of abundant dolerite dykes and sheets that indicate significant regional disturbances, which might have taken place during intrusions in the host rocks (Woodford and Chevalliar, 2002). It is expected that the dolerite intrusions induced fractures in the Karoo sediments, which then formed conduits for groundwater flow when hydraulically connected. Such a network of fractures enhanced the transmissivity of the host sedimentary succession to groundwater flow. The dolerite intrusions are the hydrogeological targets to drill high yielding boreholes in the Main Karoo Basin (Botha et al., 1998).

According to DWAF (1998), the expected borehole yields drilled at the fractured dolerite contact zones range between 5 and 10l/s. The occurrence of fractures, which formed the 2-Dimensional aquifers with double porosity aquifer system (i.e. the rock matrix porosity and the fracture porosity), could be attributed mostly to linear dykes which induced fractures in the host sediments, especially during emplacement. These fractures are frequently denser adjacent to dolerite dykes than in the disturbed sedimentary rocks. However, the areal extent, continuity, interconnection and width of these fractures is the key determinant of developing high productive and sustainable boreholes drilled through the aquifer system (Botha et al., 1998). These fracture properties (extent, interconnection) ensure proper groundwater transmission that is recharged at a regional scale. However, the linear dolerite dykes induced or enhanced the formation of these fractures by various mechanisms. However, the fracture configuration which best fit the fracture properties described above is the bedding parallel fractures which are generally interconnected and extend regionally rather than vertical fractures. The bedding parallel fractures in the Main Karoo Basin were observed to be the dominant conduits that channel groundwater. The linear dolerite dykes acted as an impermeable barrier and that allowed water to dam adjacent to the barrier boundary (Woodford and Chevalliar, 2002).

According to Botha et al. (1998), there were several mechanisms for fracture formation related to dolerite intrusions. Such mechanisms include the thermal effects, which encompassed baking and chilling of the host sediments. Such a mechanism is observed in sediments that are intruded by dolerite dykes in the Karoo Basin. The two most important mechanisms of fracture formation that were associated with linear dyke intrusions are dilation and bending (Botha et al., 1998). Dilation occurs when an inclined intruding-dyke shifts the overburden on top of it. The magma tends to cool off more rapidly at its contact with the host rock, thereby, forming a chilled edge. The brecciation and shearing of the dyke-sediment contact commonly occurs in this mechanism. It was observed that dolerite dykes that causes dilation are often accompanied by slickensides, usually slicken-sided quartz in the host Karoo Sediments (Botha et al., 1998). The diagrammatic representation of the dilation mechanism is illustrated in Figure 9; the offset indicates the shift in the host sedimentary strata. The rocks that behave in a brittle manner are more susceptible to this form of fracture-forming mechanism and most fractures tend to have a vertical configuration.

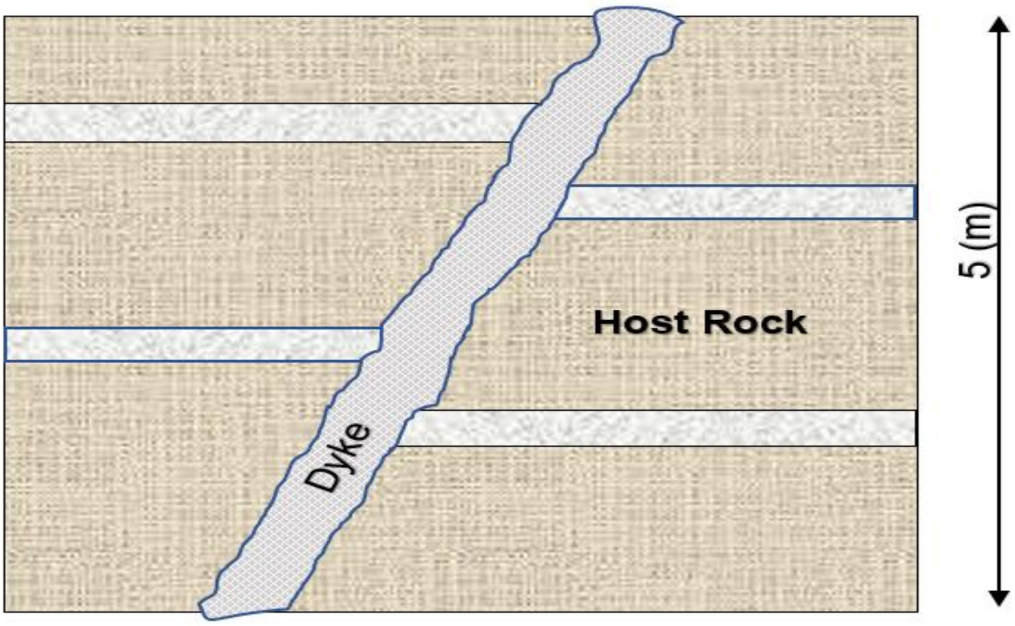


Figure 9: Schematic illustration of the phenomenon of dilation (adapted from Botha et al., 1998)

According to Botha et al. (1998), the bending mechanism occurs when the surrounding rocks are bent concavely by the intruding linear dykes. The frictional forces that exist between the dyke and host rock cause ductile deformation. This type of bending enhances the formation of bedding parallel fractures and can fracture the host rock considerably near the dyke (Botha et al., 1998). The rocks that behave in a ductile manner are more susceptible to this form of fracture-forming mechanism and most fractures tend to have a horizontal configuration, hence the bedding parallel fractures are formed under this mechanism (Woodford and Chevalliar, 2002). The diagrammatic representation of the bending mechanism is illustrated in Figure 10; the pulled-up contact sediments are discernible as concave structure adjacent to the dyke (Figure 10). This indicated that the geological contact is the zone of weakness, obviously more vulnerable to fracturing associated with linear dyke intrusions. The associated fractures in this zone are the bedding plane fractures that can be attributed to the bending deformation mechanism associated with the linear dyke emplacement (Botha et al., 1998).

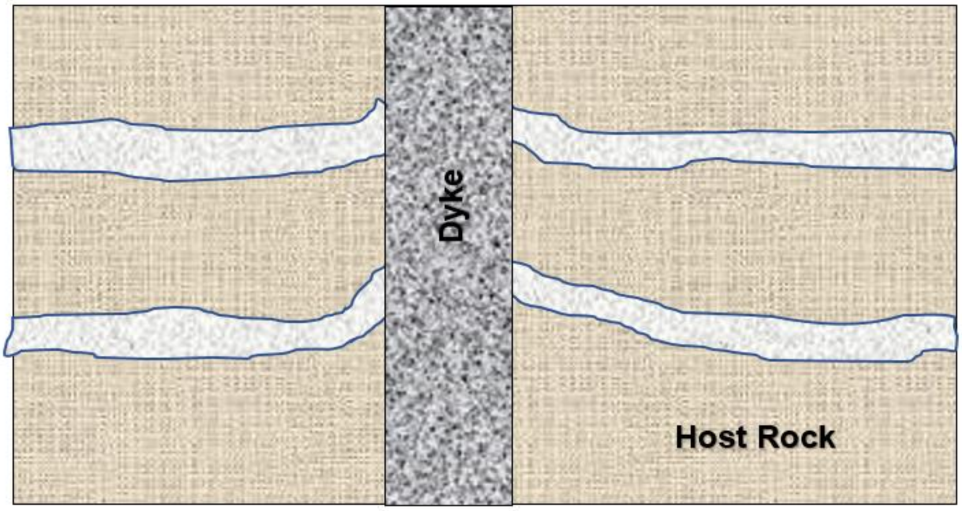


Figure 10: Schematic illustration of the bending of Karoo rocks by a linear dolerite dyke (adapted from Botha et al., 1998)

3.6 Hydrogeological characterisation of the aquifer system

The main outcome of the characterisation of an aquifer system is the development of a conceptual hydrogeological model of the aquifer system. The later assists in the understanding of the aquifer and may be advanced to a numerical model of the aquifer system. The characterisation of the aquifer system primarily covers the geological, hydrogeological and hydrogeochemical frameworks of the aquifer system.

3.6.1 The geological framework

The geological framework entails the definition of geological boundaries and analysis of the tectonic stress regime. These key aspects of the geological framework form the basis of a conceptual characterisation of the aquifer system. Both aspects influence groundwater flow in the aquifer system. The associated information of the geological framework can be acquired through geological cross-sections, geological mapping and analysis of joints and dykes. The geological cross-section can be depicted from the drilling logs and geological maps. The geological mapping encompasses the analysis and description of the geometric configuration of geological structures in relation to the aquifer system. Such structures include linear dolerite dykes, joints, bedding planes and unconformities.

3.6.1.1 The analysis of joints

Joints are defined as fracture surfaces along which there has been imperceptible movement (Davis, 1984). According to Singhal and Gupta (1999), joints are structures that originate from deformational stresses, which result in dilation and distortion of rock masses. Joints generally control the storage and influence the transmission of groundwater in an aquifer system. Joints and fractures enhance secondary porosity in crystalline and sedimentary rocks.

It is imperative, therefore, that the origin and the geometric configuration of joint structures must be understood in order to characterise groundwater flow in an aquifer system. The analysis of the tectonic stress regime is paramount in the characterisation of groundwater flow in an aquifer system. Joints are thought to be the manifestation of various stress conditions sustained by geological formations, consequently, the investigation of joints and fractures will enable an understanding of the formation of the aquifer system (Singhal and Gupta, 1999).

According to Singhal and Gupta (1999), joints are still not well studied even though they are extremely common and widespread in rock formations. Complex stress and strain processes are believed to be involved in the origin of joints, which are related to the geological history of an area. Joints are primarily created by stresses, which have diverse geological origins (Singhal and Gupta, 1999) such as:

- Tectonic stresses related to the deformation of rocks
- Residual stresses due to events that happened before the formation of joints
- Contraction due to shrinkage because of cooling of magma and desiccation sediments
- Surficial movements such as landslides or movement of glaciers
- Erosional unloading of deep-seated rocks
- Weathering in which dilation may lead to an irregular extension of cracks and dissolution which may cause widening of cavities or cracks

According to Singhal and Gupta (1999), joints are defined into two broad types, namely, the systematic and non-systematic joints. The non-systematic joints are irregular and curved. This type of joint does not cross other joints and tends to terminate at the bedding surface. They form a curvilinear pattern in plan and are dilational in nature (Singhal and Gupta, 1999). The systematic joints are planar and more regular in distribution. These are parallel systematic fractures that are treated as a set of joints. Systematic joints are extensive and detailed tectonic stress regime may be inferred from the systematic joints (Singhal and Gupta, 1999).

Systematic joints were classified into three main categories (Singhal and Gupta, 1999), namely, the geometric classification, the extent of development and genetic classification. The geometric classification of systematic joints considered the geometric relationship with bedding or foliation and was further subdivided into the following types:

- Strike joints are those that strike parallel to the strike of bedding planes
- Dip joints are those whose strike direction runs parallel to the dip direction of rocks
- Oblique or diagonal joints are those that strike at an angle to the strike of the rock formation
- Bedding joints are those that are essentially parallel to the bedding plane of the associated sedimentary rocks

Systematic joints may be sub-divided into two types depending on the extent of fracture development. These types are the first-order and second-order joints. The first-order joints cut through several layers of rock formation and the second-order are limited to a single layer.

According to Singhal and Gupta (1999) systematic joints are further sub-divided into three types based on genetic classification as follows:

- Shear joints which may exhibit shear displacement and are co-genetically developed in conjugate sets with dihedral angle (2i) greater than 45°
- Dilational joints which are of tensile origin, are commonly developed perpendicular to the bedding plane and are open fractures with no evidence of shear movement
- Hybrid joints exhibit features of both shear and dilational origin. They may occur as conjugate sets with dihedral angle (2i) less than 45°. These joints are open (i.e. extensional) and may be partly filled with veins.

According to Singhal and Gupta (1999), it is often difficult to distinguish between shear and extension joints since rheological principles indicate no sharp categorisation between the two types of joints. However, from a hydrogeological point of view, it is important to distinguish between the two types of joints since dilational joints are more open and possess more hydraulic conductivity than shear joints. The general features that were used to discriminate shear from dilational joints (Singhal and Gupta, 1999) include the following:

- Shear joints exhibit displacement parallel to the plane of the fracture which is absent in the case of extension joints
- Shear joints commonly occur in conjugate sets which may be indicated by statistical analysis
- Dilational joints are generally open and shear joints are tight

Further, the cumulative trend diagram of joints may provide information on the relative stress field and, therefore, the likely trend of shear and extension fractures may be defined.

3.6.2 Hydraulic characteristics of the aquifer system

The hydrogeological characterisation of aquifer systems entails the determination of the hydraulic properties of an aquifer. Such hydraulic properties include transmissivity (T), hydraulic conductivity (K), storativity (S), specific yield (S_y) and hydrogeological boundaries depending on the type of aquifer. The pumping tests became the standard procedure to determine aquifer parameters (Amah and Anam, 2016). According to Amah and Anam (2016), pumping tests simultaneously provide information on the hydraulic behaviour of the well, the reservoir and the reservoir boundaries that are essential for efficient characterisation of the aquifer system. The main objectives of the pumping test (van Tonder et al., 2002) are:

- To develop a better understanding of the aquifer system
- To quantify the hydraulic properties of an aquifer
- To assess both the sustainable yield and efficiency of the borehole

The first two objectives of pumping tests are more relevant for this study since the primary aim is to characterise the Cedarville Aquifer System.

The standard technique of pumping tests constitutes stressing the aquifer through highly controlled pumping. The normal practice involves pumping a well at a specified discharge rate and time, recording the drawdown in the pumping well or observation well located at a known distance from the pumping well. The time-drawdown data obtained is then used to estimate the aquifer parameters such as T and S by employing methods such as Theis, Cooper and Jacob, Chow Methods (Theis, 1935; Krusemann and De Ridder, 1976).

According to Krusemann and De Ridder (1976), methods for the analysis of pumping test data encompass the underlying assumptions, which should be adhered in order to produce accurate results. Further, there is pre-requisite information that must be considered for accurate analysis of the pumping test data such as the correct geological conceptual model and the boundary conditions especially no flow and fixed head boundaries (Krusemann and De Ridder, 1976).

3.6.2.1 The unsteady state semi-confined aquifer

Based on the general knowledge of the Karoo Aquifers, the most appropriate method for the analysis of pumping test data is the unsteady state for semi-confined aquifers solution and is more relevant for the Cedarville Aquifer System. According to Krusemann and De Ridder (1976), the time-drawdown data analyses determine some hydraulic parameters including T, S and S_y based on certain underlying assumptions such as:

- The aquifer is semi-confined
- The flow to the well is in an unsteady state
- The well diameter is very small

3.6.2.2 The fractured aquifer system

The greater proportion of aquifers in the Karoo Basin are the hard rock aquifers or fractured aquifer systems. According to van Tonder et al. (2002), conventional groundwater flow equations do not adequately describe flow in fractured rocks. Fracture geometry and permeability of the system are thought to have a large influence on the drawdown (van Tonder et al., 2002). Hence, guidelines for analysis of pumping tests in fractured rocks were developed in South Africa. The estimation of hydraulic parameters remains the key objective of this study even in fractured rock aquifers. In fractured rock aquifer systems, the constant discharge rate test is the primary method for determining the hydraulic parameters. However, the discharge rate must be chosen such that the main water strike (i.e. the main fracture) will not be dewatered during the test.

Various analytical models were used to analyse pumping tests in fractured rock aquifers such as double porosity, single fracture of infinite or finite conductivity. If the fractured aquifer reacts as a homogeneous porous aquifer, then Theis or Cooper-Jacob methods can be used to estimate hydraulic parameters. The T and S values estimated from these methods represent the entire aquifer without differentiating between fracture and matrix. All these models are fused in the Flow Characteristic Model (FC-Model) to solve the flow equations through the fractured rock aquifer system, which will enable the determination of the hydraulic parameters (van Tonder et al., 2002).

3.6.2.3 Groundwater recharge

Groundwater recharge is the amount of rainfall or surface water that reaches the water table either by direct contact in the riparian zones or by downward percolation through the unsaturated zone (Connelly et al., 1989). Groundwater recharge is the quantity of water that is available for abstraction and supporting the base-flow component of rivers. It is essential that groundwater recharge has to be accurately estimated for proper characterisation of the aquifer system (Adomako et al., 2010). The groundwater recharge process is categorised into direct and indirect recharge mechanisms. The direct recharge mechanism encompasses direct infiltration of precipitation and subsequent percolation through the unsaturated zone to a groundwater body. The indirect groundwater recharge mechanism involves the accumulation of precipitation in surface water bodies (e.g. lakes and rivers) and subsequent concentrated infiltration and percolation through the unsaturated zone to a groundwater body. There are a number of methods that are used to estimate groundwater recharge. However, selected direct recharge methods would be used for this study. The empirical relationship between rainfall and groundwater recharge will be the easiest and most practical method to be considered for this study. Recharge is considered to be directly related to rainfall although this relationship is thought to be nonlinear (Beekman and Xu, 2003). Figure 11 illustrates such a nonlinear relationship as adopted from Beekman and Xu (2003).

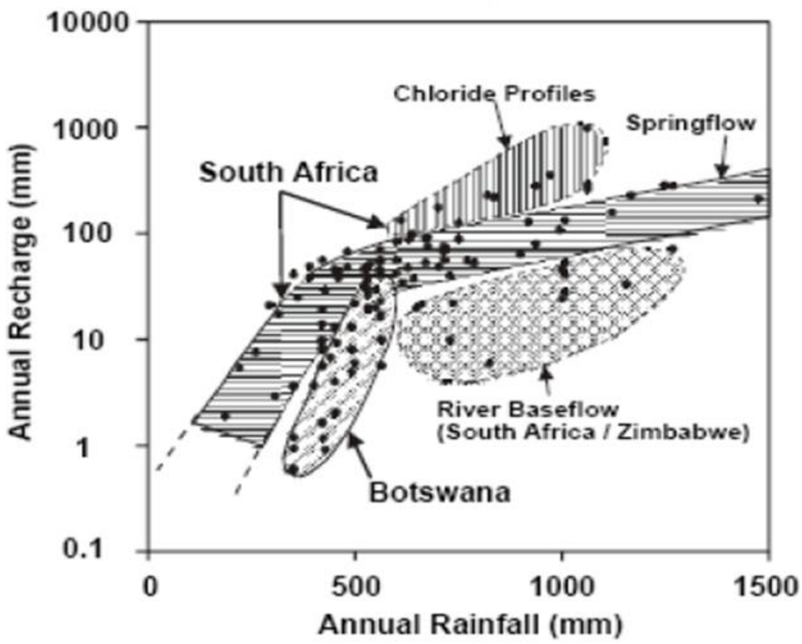


Figure 11: Non-linear relationship between annual recharge and annual rainfall (Source: Beekman and Xu, 2003)

According to Nel (2007), historical estimates of recharge rates for most aquifer systems in South Africa range between 5% and 10% of the annual precipitation. However, Abiye (2016) observed that the Chloride Mass Balance (CMB) method resulted in groundwater recharge of 4% of the annual precipitation around Johannesburg while it reaches 20% when rainfall exceeds 600 mm/yr. In the study area, the annual precipitation exceeds 600 mm/yr, subsequently; a factor of 10% of the annual precipitation would be optimal in estimating groundwater recharge in the Cedarville Aquifer System.

The Chloride Mass Balance method is one of the most appropriate methods for estimating groundwater recharge in this study. The CMB method is thought to be the most reliable technique for estimating groundwater in fractured rock aquifer systems (Scanlon, 2002). The recharge is estimated based on the proportional concentration of Cl^- in rainwater and groundwater. It is calculated as:

$$\textbf{Recharge} \quad = \frac{[Cl_{ppt}]}{[Cl_{g\omega}]} \times \boldsymbol{PPt}$$

Where $[Cl_{ppt}]$ = concentration of Cl^- in precipitation,

$[Cl_{gw}]$ = concentration of Cl^- in groundwater

PPt = annual precipitation

The CMB method is thought to give a minimum estimated recharge rate since there will be additions of Cl^- due to groundwater interactions with the host weathered and fractured rocks (Abiye, 2016; Nel, 2007).

The environmental stable isotopes of Oxygen (^{18}O) and Hydrogen (^{2}H) are the commonly used stable isotopes in most groundwater tracer studies and groundwater recharge estimation (Adomako et al., 2010). ^{18}O and ^{2}H are used extensively in catchment hydrological studies to determine groundwater recharge, transient times and groundwater flow paths (Adomako et al., 2010).

3.6.3 Hydrogeochemical characteristics of the aquifer system

The hydrogeochemical characterisation of an aquifer system is one of the important areas in the conceptualisation of aquifer systems. The origin and residence time determination of groundwater could be described through the analysis of the hydrogeochemical regime of an aquifer. Such an analysis entails the understanding of controlling chemical processes that influence the quality of groundwater in that specific aquifer system. The analysis of the hydrogeochemical process must be integrated with the geology of an area in order to define all the processes that affect the quality of groundwater. The hydrogeochemical evolution of groundwater requires an understanding of the relationship between mineralogy and flow regime since these determine the occurrence, sequence, rates and progress of reactions (Hiscock, 2005). Some of the processes such as the ion-exchange, sorption, oxidation-reduction processes influence the quality and evolution of groundwater.

CHAPTER 4 – GEOLOGICAL MAPPING OF THE CEDARVILLE BASIN

4.1 Geological information

The basic geological mapping information of the Cedarville Basin was inferred from geological maps, a review of available reports from Consultants, Google Earth Images and a brief field mapping exercise. A geological cross-section of the Cedarville was produced from the 1:250 000 geological map of Kokstad along the line X-Y of Figure 5 and is shown in Figure 12.

4.1.1 Description of the geological section

The geological section displays the alluvium that covers the entire basin with the maximum thickness occurring in the centre of the basin.

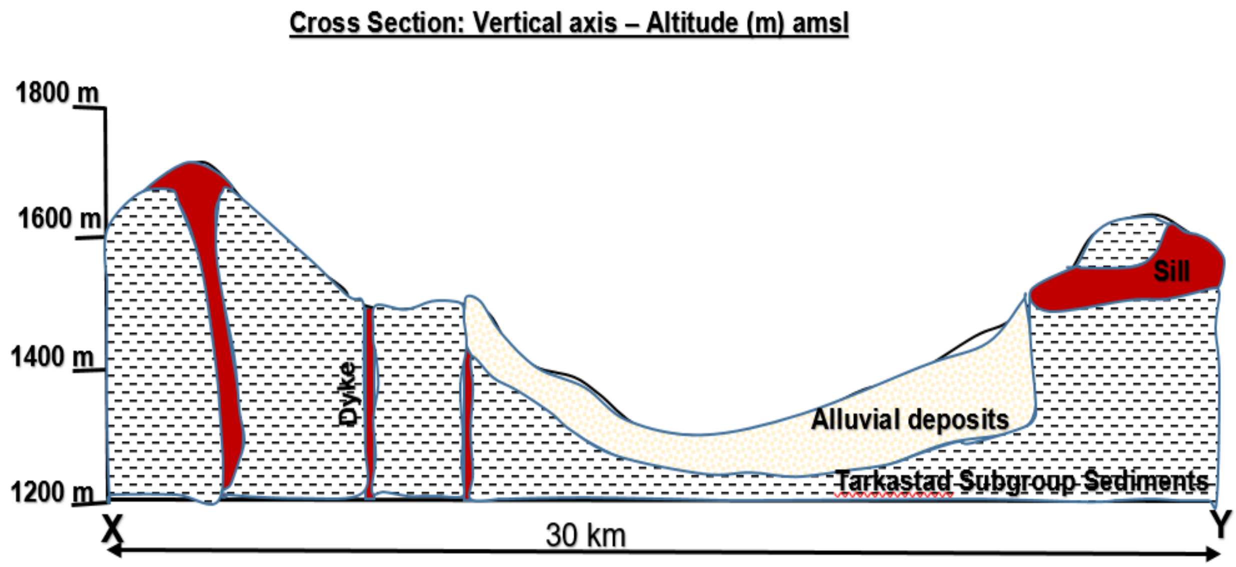


Figure 12: Illustration of the geological cross-section of the Cedarville Basin (Line X-Y in Figure 5)

4.2 The origin of the Cedarville Basin

The orogenic processes that are thought to have formed the basin date back to the Karoo magmatisation era in the early Jurassic period some 180ca years ago (Woodford and Chevallier, 2002). The basin is surrounded by elevated hills, formed by dolerite intrusions. It can be observed that during Karoo magmatisation, intrusive bodies lifted the sedimentary sequence of the Beaufort Group, the Burgersdorp Formation in the locality of Cedarville.

The uplift formed a periphery or high lifted margins of the basin that were induced by intrusive magma. It is thought that the elevated sediments were later eroded and filled into the basin. Subsequently, the eroded sediments filled the basin-like geomorphological feature, resulting in a widespread thick alluvium deposit that comprises of clay-sand material. It is apparent that the abundant clay content in the deposition was derived from the weathering of shales and mudstones of the Beaufort Group sediments. The sandy content of the deposition is thought to be the weathering product of the sandstone interbeds in the sedimentary strata of the Beaufort Group. Consequently, the magmatic intrusion controlled the formation of the Cedarville Basin. The sedimentary filled basin was observed to have formed the Cedarville Aquifer System. There is no evidence that suggests the tectonic theory of the Cedarville flats being the downthrown side of the Matatiele normal fault along the Drakensberg escarpment (Woodford and Chevalliar, 2002). The Cedarville flats do not extend to the close proximity of the Matatiele or Drakensberg and there is no indication of secondary faulting that can depict the tectonic origin of the Cedarville basin.

4.3 Field geological mapping

Rock outcrops are insufficient in the study area to undertake a detailed field-based geological mapping of the Cedarville aquifer system. The Quaternary alluvium deposits that gave rise to grassland, patched with wetlands, cover the basin and the vast proportion of land is used for commercial farming. However, elevated hills show some exposures, though the outcrop is predominantly dolerite boulders that are generally loose.

Fair rock exposures are observed in open quarries and road cuttings. The localities of the observed rock outcrops are illustrated in Figure 13. The strata were described as observed from the exposed rock faces and the geometry of the strata (i.e. strike and dip of the bedding planes) were measured. The joint or fracture analysis was the primary objective of this exercise, subsequently, joint description and measurement were undertaken in each of the observed outcrops.

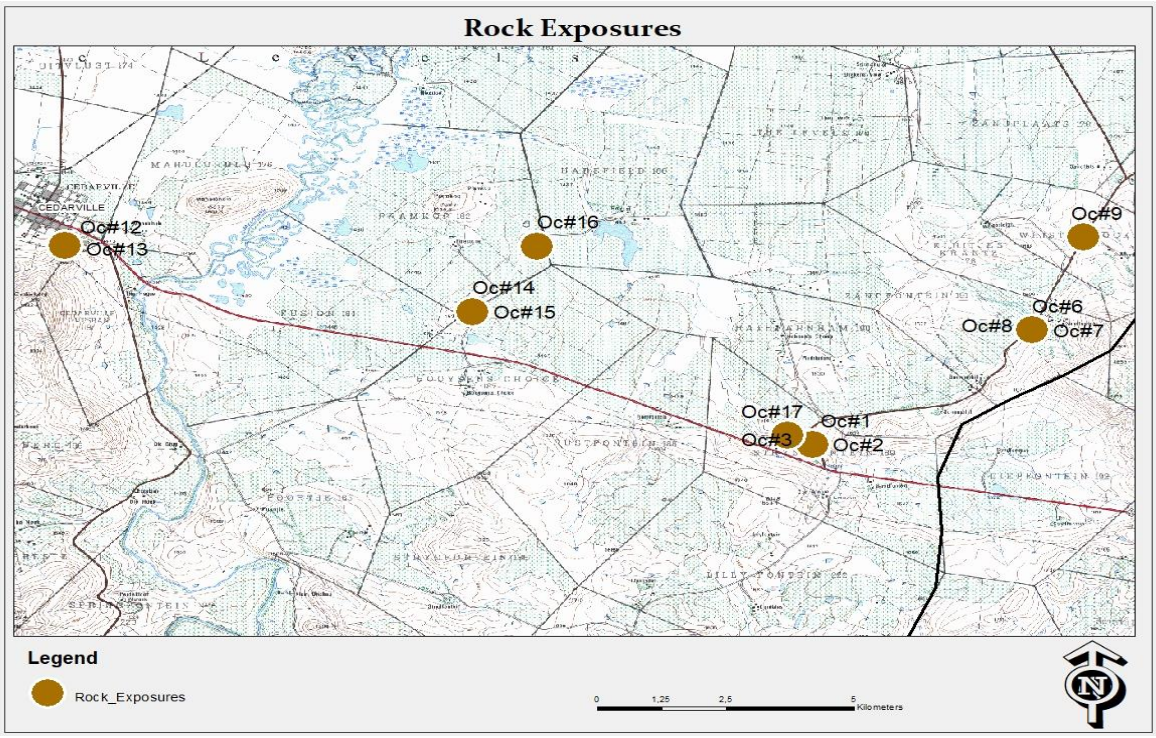


Figure 13: Localities of the mapped rock outcrops in the Cedarville Area

4.3.1 Description of the geological outcrops

Numerous outcrops were observed (Figure 13) and the geology is generally similar in all outcrops. The outcrops were observed in localities where rocks were quarried primarily for aggregate to be used in roads and building construction. The target material is the dolerite aggregate; hence, almost all the quarried exposures were transversed by dolerite intrusions. The lithostratigraphy of the Tarkastad Subgroup was observed in most of the rock exposures. The reddish-brown mudstones were underlain by the dark-grey shales that were thermally metamorphosed into slates adjacent to dolerite intrusions (i.e. contact metamorphism). The mudstones were overlain by the fine-grained, light-grey sandstone that varies in thickness from one locality to another (Figure 14). This appears to be a sequence of shales, mudstones and sandstones, typically an upward coarsening sequence, thus indicative of regressive water levels in the depositional environment.

Figure 14: Picture showing dipping strata of the Tarkastad Subgroup

The observed strata are shallow dipping at angles that vary from 2° to 5°SE. The strike varies substantially but the 210°seem to be the most common strike direction in most rock outcrops. The overlying sandstones are almost horizontally dipping than the underlying rock strata. There is no indication of tectonic disturbances except the effect of dolerite intrusions, which seemed to have changed the strike orientation of the sedimentary beds.

Dolerite dykes were observed in most quarry exposures of the Cedarville Area. The dolerite dykes vary in width in the research area from 3 to 20 m wide. However, the dolerite dykes are extensively weathered into reddish-brown, highly jointed rock mass with speckling, greenish micaceous minerals (Figure 15). The dolerite is dark grey, medium to coarse-grained and crystalline on fresh surfaces. Spheroidal weathering and columnar joints were observed in deep-quarried dolerite outcrops. It was observed that the dykes originated from high temperature, pressurised magma. The nature of joints and extensive thermal metamorphism of the host sediments suggested the nature of stresses that were exerted on the sediments. The observed joints in the outcrops were induced by the dolerite dykes and apparently formed by dilational mechanism as suggested by Botha et al. (1998). The brecciation and shearing of the dyke-sediment contact is indicative of dilational fracturing (Figure 15). The joints were later filled by calcite and quartz veins with calcite veins being the most dominant. However, the bending joint formation mechanism occurs at depth in the study area, since the sediments are more ductile at depths greater than 100m. Thus, at the surface vertical joints are more prominent and bedding parallel fractures more pronounced at depth.

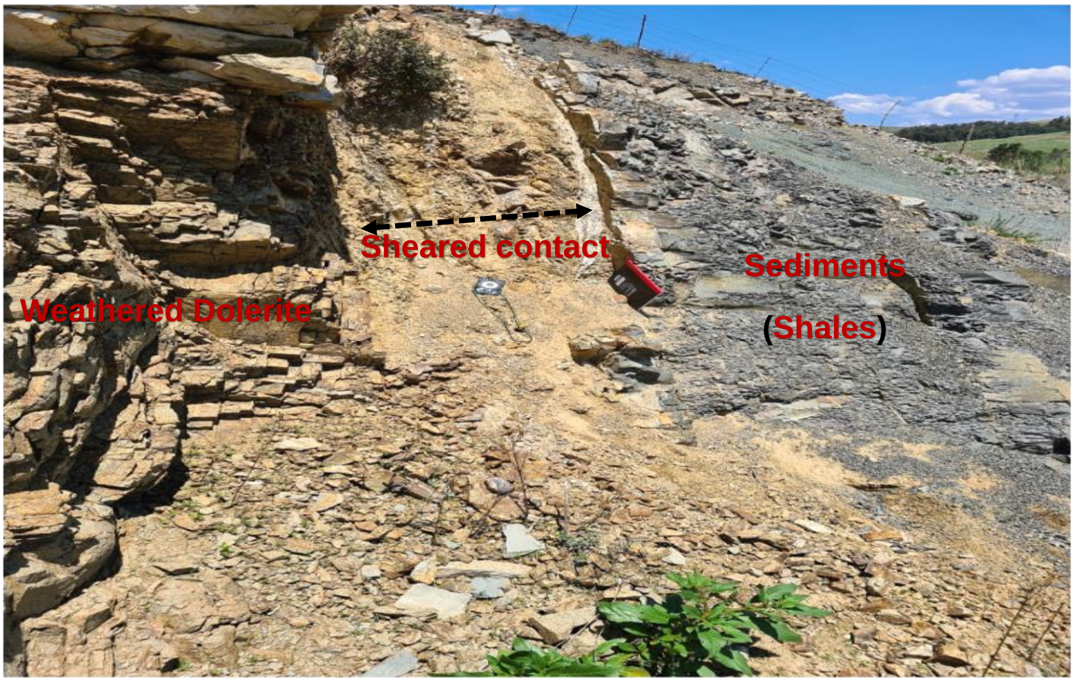


Figure 15: The dolerite dyke outcrop showing extensive fracturing

The NE-SW (071°) trend orientation of the dolerite dykes is very common in the study area. The dolerite dykes strike in the NE-SW direction similarly to the joint direction. It may be inferred that such joints were generally extensional and exhibit zones of weaknesses, hence, they were exploited by high pressure and high temperature intrusive magma. The observed NE-SW trending dykes confirms that dykes in the Cedarville area belong to the Transkei-Lesotho-Northern Karoo Domain dyke swam (Woodford and Chevalliar, 2002).

4.3.2 Mapping of joints

Joints were observed in all the outcrops that were examined in the study area and the trend directions were measured. Most joint sets were more discernible on sandstones and thermal metamorphosed slates and shales that behave in a brittle manner when subjected to stresses (Figure 16) than in mudstones. However, there were joints that were observed on reddish-brown mudstones, though they were not so pronounced (Figure 17).

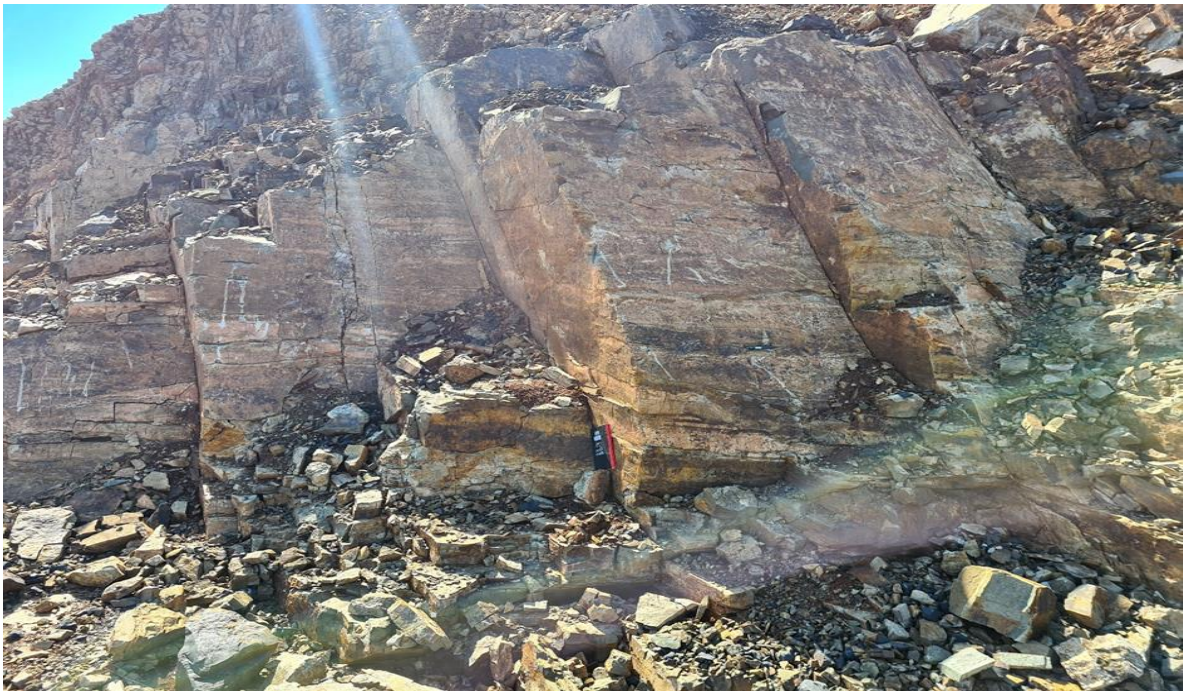


Figure 16: Extensively jointed and thermal metamorphosed sandstones and shales

All joint sets that were mapped are the systematic joints since they were planar, extensive and more regular in distribution (Singhal and Gupta, 1999). There were few joint sets that were observed to form the conjugate sets, however, the predominant sets of joints were dilational joint sets. This implies that the stress regime that formed these joints was extensional since dilational joints are open joints (Singhal and Gupta, 1999). Most joint sets were diagonal or oblique to the strike of the rock formation and were first-order joints since they cut through several layers of rock formation (Figure 17).

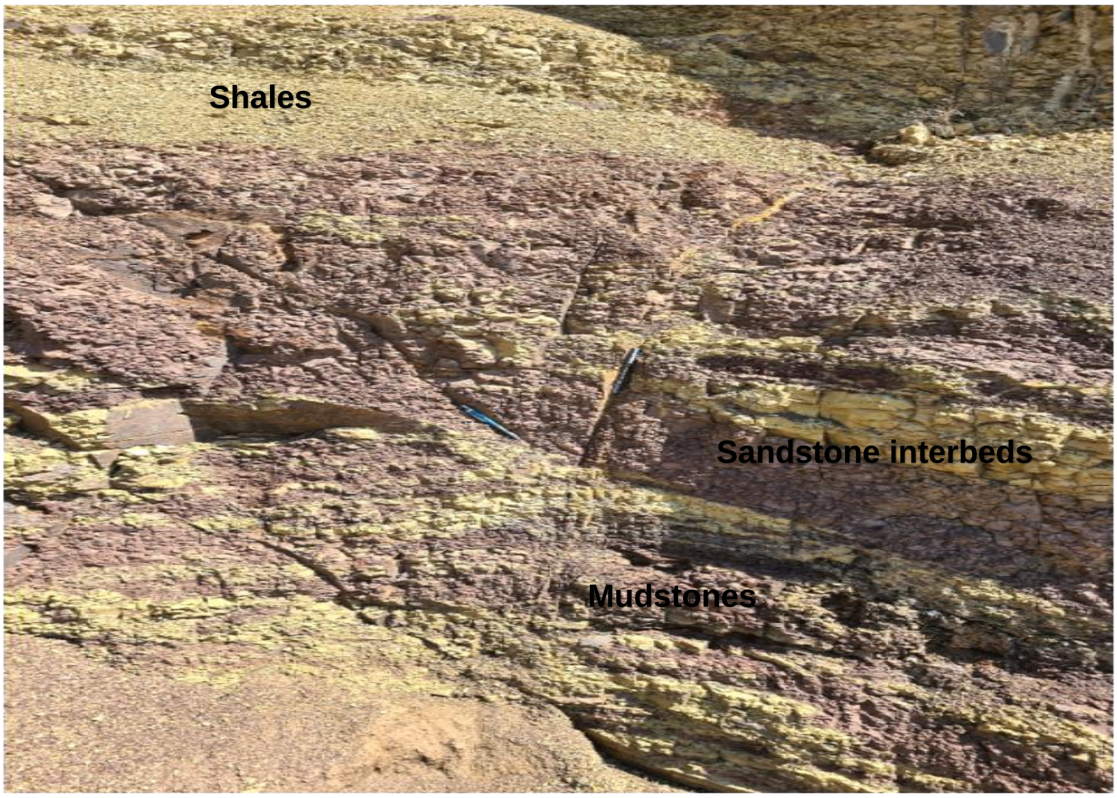


Figure 17: Joint sets that cut through layers of rocks

There was no observable shear displacement in most joint sets. Most joints were hybrid joints with a dihedral angle of less than 45°. Thus, the predominant joint sets in the study area are of tensile origin with no evidence of shear movement. Such joint sets are dilational joints and present favourable conditions for groundwater flow when connected at depth.

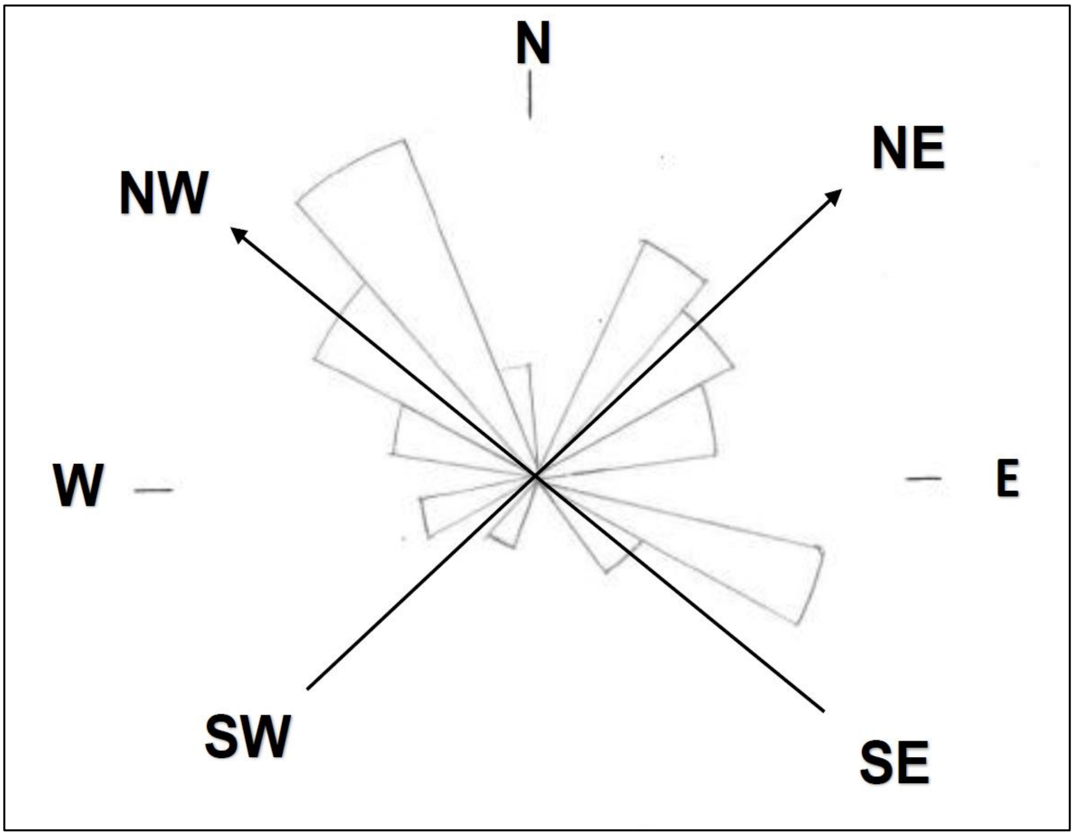


Figure 18: Rose diagram of joint sets mapped in the Cedarville Study Area

Figure 18 is the rose diagram of the measured joint sets. The most prominent joint set trend is observed to be NW-SE and NE-SW trend is also common. The later trend, NE-SW, is consistent with the dolerite dyke trend in the study area. Thus, the NE-SW orientation can be associated with open joints and subsequently the Cedarville area was subjected to NW-SE tensile tectonic stress regime. According to Visser (1987), the NW-SE orientated tension can be traced during the tectonic break-up of Gondwana and resulted in NE-SW regional joint pattern. The NW-SE can be assumed compressional in nature and, therefore, closed in terms of groundwater flow.

CHAPTER 5 – HYDROGEOLOGICAL CHARACTERISATION OF THE CEDARVILLE AQUIFER SYSTEM

Most of the hydrogeological information used for the evaluation of the Cedarville Aquifer System was obtained from, but not limited, to the following sources:

- Brief hydrocensus survey that was carried out in the study area, focusing mainly on the commercial farmers' boreholes
- GRIP information which is available in the National Groundwater Database (NGDB) of the DWS and AGES archives
- Boreholes drilled by AGES, a groundwater consulting company that was contracted by the Alfred Nzo District Municipality to:
  - Drill and pump test boreholes at Cedarville for domestic water supply
  - Submit hydrogeological reports with recommendations on safe pumping episodes and results of borehole water quality laboratory analyses
- Available reports and records from SRK Consulting, a hydrogeological consulting company
- Hydrogeological maps and records from libraries

5.1 Hydrocensus survey of the Cedarville Boreholes

The research area is dominated by vast open land, the majority of which is occupied by commercial farmers with the exception of Cedarville town, which is mainly residential, with minor businesses. The Cedarville area is predominantly dependent on groundwater as a source of water supply. Thus, the Cedarville Aquifer System is the strategic water resource for domestic, farming and commercial purposes. The town of Cedarville is served by five boreholes that pump water to storage tanks. This water is then gravitated to households. According to StatsSA (2011), the total population of Cedarville Town is 4413 and is expanding at an estimated rate of 5% per annum. The latter population rate suggests an exponential increase in water demand for domestic usage in the Cedarville area. This indicates that the Cedarville Aquifer System will soon be over-exploited and therefore, suggests that proper groundwater management procedures are needed to sustain the current and future water requirements.

According to the GRIP database (Appendix C), more than 30 boreholes were drilled in the Cedarville Aquifer System. About 90% of boreholes drilled in the area were productive with yields greater than 0.1l/s. Table 2 illustrates the borehole statistics as inferred from the GRIP records.

Table 2: The borehole statistics as inferred from the GRIP data

Parameter	**No. of Records**	**Min**	**Max**	**Mean**	**Median**
Borehole Depth (m)	30	47	145	92.3	87
Water Strike depth (m)	30	17.8	111	55.6	44.5
Water level (bgl) (m)	30	2.0	66.6	14.7	14.5

Spatial correlation was undertaken between the production boreholes especially the high-yielding boreholes and the linear dolerite dykes (Figure 19). It was observed that there is a positive correlation between the high-yielding boreholes and linear dolerite dykes in the Cedarville basin. Most high-yielding boreholes were drilled adjacent to dolerite dykes in the area. Thus, the dolerite dyke fracturing enhances the transmissivity of the aquifer system.

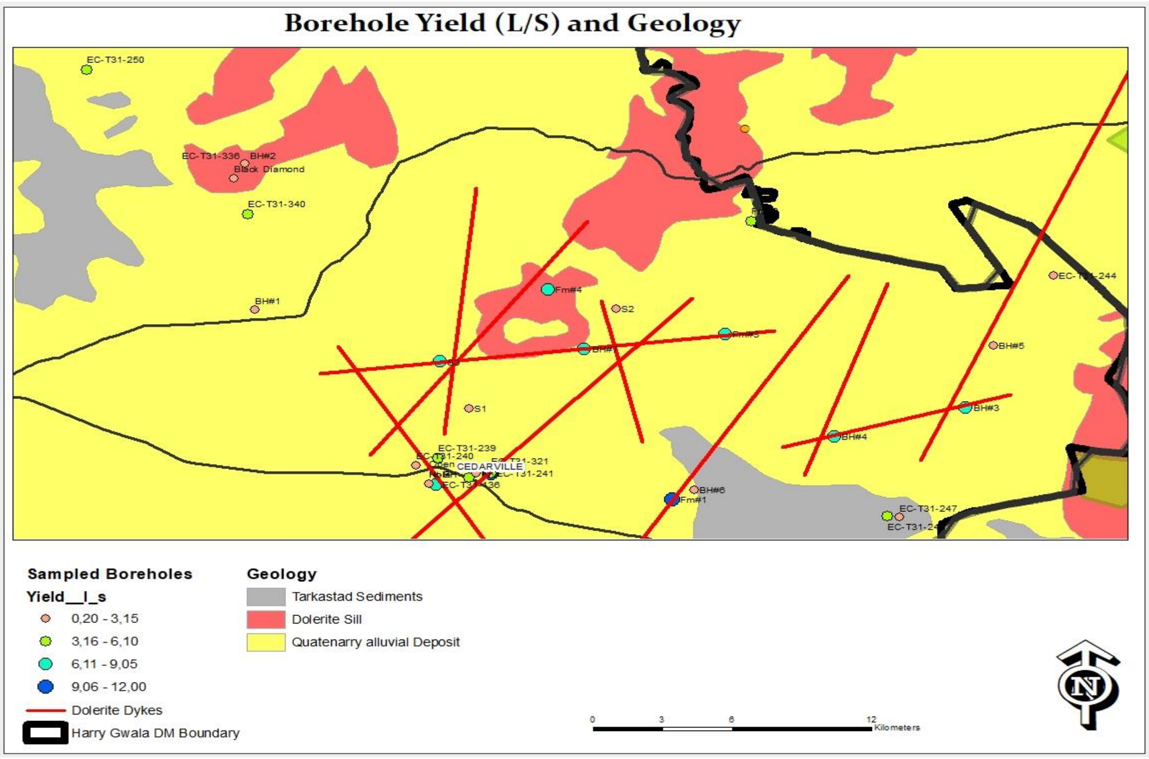


Figure 19: Illustration of the spatial correlation between high yielding boreholes and linear dykes

Linear regression analysis was performed to establish the correlation between borehole depths and borehole yields (Figure 20). A linear correlation co-efficient (R^2) of 0.7 was attained which suggests a positive correlation between borehole depth and yield. Based on statistical interpretation, a positive linear correlation between two variables (e.g. Borehole yield and Borehole depth) suggests that an increase in one variable (Borehole depth) results in a proportional increase in the other variable (Borehole yield). However, it may not be concluded that by drilling a deep borehole high yield will be attained. Boreholes that are drilled deeper attain water strikes in the overlying alluvium and additional water strikes are intersected in the underlying rocks of the Beaufort Group. Such cumulative water strikes gave rise to high-yielding boreholes in conjunction with dolerite induced fracturing at depth in the study area.

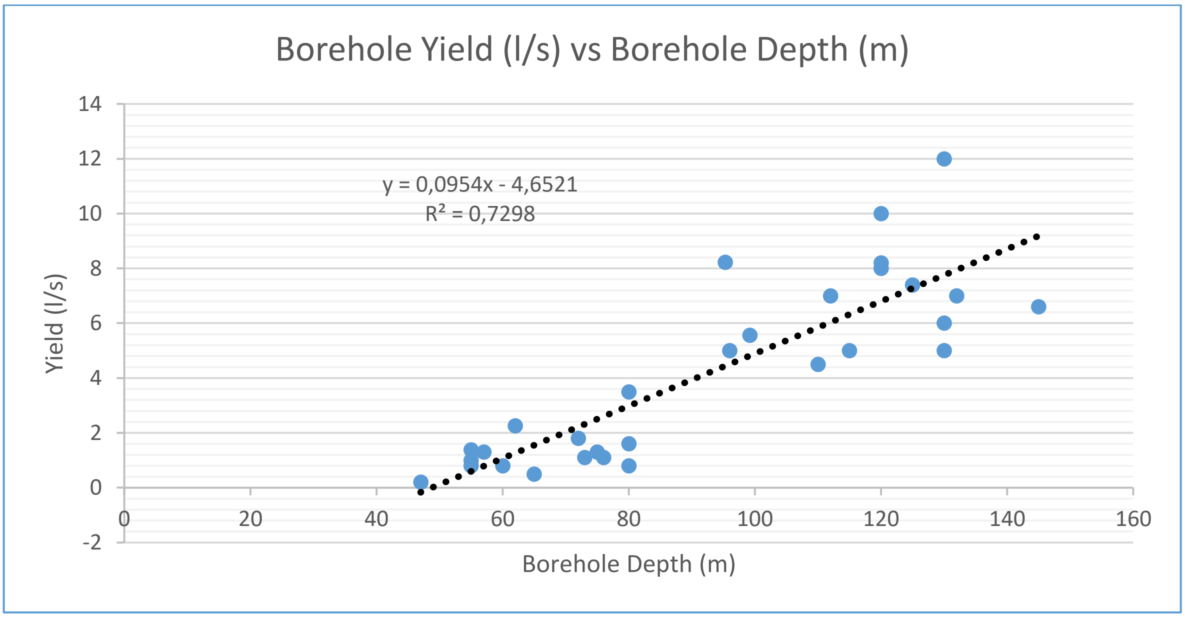


Figure 20: Linear correlation between borehole depth and yield

The cumulative distribution of borehole water level depths below the ground surface is illustrated in Figure 21. The depth to water level is extremely variable ranging between 2 and 66.5 m below ground surface. The median water level in the study area is 14.5 m below ground surface (Table 2), but it can be inferred that 80% of boreholes drilled in the Cedarville area attain a water level of less than 15 m bgl (Figure 21).

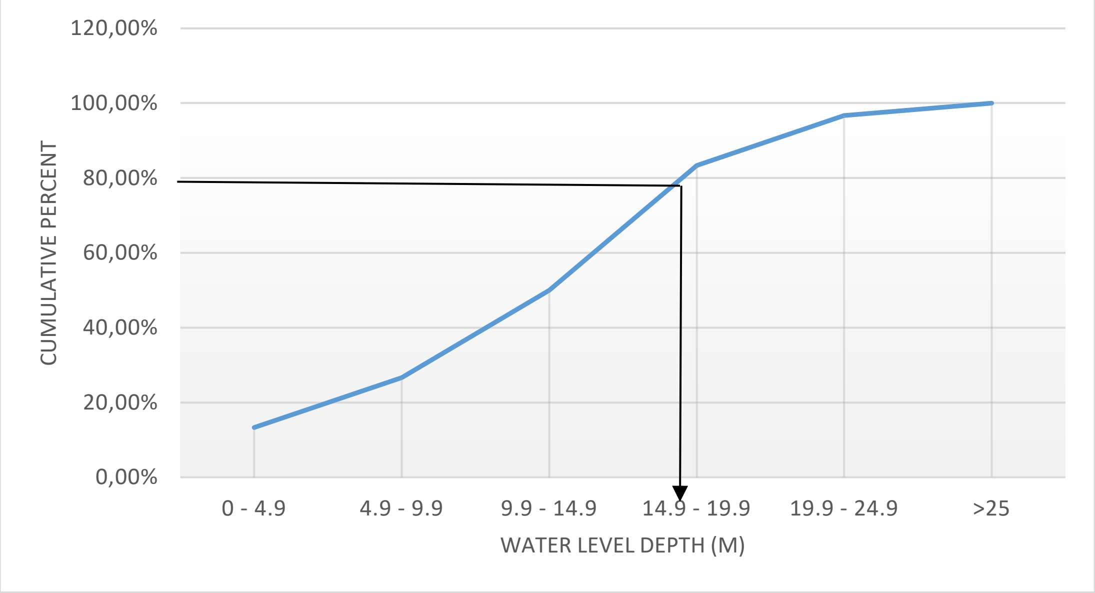


Figure 21: The cumulative distribution of water level depth (bgl)

It was observed that the relatively higher yielding boreholes occur at approximately the same depth (120 to 140 m depth interval) as illustrated in the scatter plot of boreholes depth and water strikes depth (Figure 22). It can presumably be inferred that such water strikes occur on the same lithology, taking into consideration the shallow dipping sedimentary beds of the Beaufort Group in the study area. It may then be inferred that secondary features such as fracture zone, lineaments and dykes are the major controlling factors in groundwater occurrence in the Cedarville area.

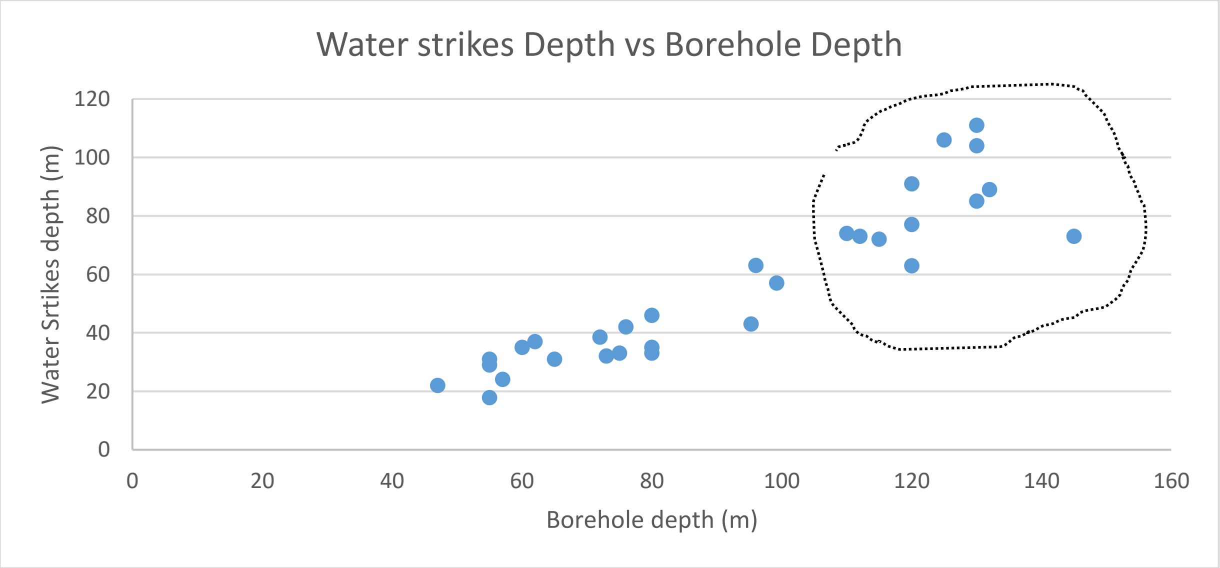


Figure 22: Scatter plot of high borehole yield and borehole depth

5.2 Evaluation of the hydrogeological characteristics

The evaluation of the hydrogeological characteristics entails the determination of aquifer parameters, which is based on the borehole drilling and pumping test data analyses. The later data were obtained from AGES reports; AGES was contracted by the ANDM to develop groundwater sources to improve the domestic supply of water at Cedarville Town. They drilled and pump tested three boreholes of which one was used as an observation borehole during the pumping tests.

5.2.1 Borehole drilling records

Three boreholes were drilled by AGES to augment the water supply for domestic usage at Cedarville Town. The data gathered from the three boreholes (EC-T31-239, EC-T31-240 and EC-T31-321) reports were used in the hydraulic analysis of the Cedarville Aquifer System, the drilling logs are illustrated in Appendix D.

5.2.1.1 Drilling records of borehole EC-T31-239

The borehole was drilled to a final depth of 130 m. Drilling penetrated through alluvium to a depth of 48 m, then into coarse-grained sandstone to a depth of 69 m. The first water strike was intercepted at 48 m depth that is the contact between the overlying alluvium and sandstone beds of the Tarkastad Subgroup. Further drilling continued through a crystalline, slightly weathered dolerite to a depth of 83 m and again penetrated through coarse-grained sandstone to 92 m depth and again through crystalline dolerite to 110 m depth. The second water strike was intercepted at 90 m depth in the fracture zone of sandstone and dolerite contact. Then drilling continued through a brownish-grey mudstone to a depth of 120 m and then through coarse-grained sandstone to a final depth of 130 m (Appendix D: EC-T31-239). The third water strike was attained at a depth of 111 m (i.e. the dolerite and mudstone contact). The final blow yield for this borehole was measured to be 6 l/s.

5.2.1.2 Drilling records of borehole EC-T31-241

The borehole was drilled to a final depth of 96 m below ground level. Drilling penetrated through 5 m of sandy clay soil. Then, drilling continued through a greyish brown alluvium to a depth of 34 m. The borehole was drilled further through a highly fractured mudstone to a depth of 52 m. Then drilling continued through coarse-grained, fractured sandstone until the intersection of dolerite at 72 m depth and again through coarse-grained, highly weathered sandstone to a final depth of 96 m (Appendix D: EC-T31-241). The main water strikes were intercepted at 34 m and 60 m depths, which then gave rise to a final blow yield of 5 l/s.

5.2.1.3 Drilling records of borehole EC-T31-321

The borehole was drilled to a final depth of 120 m. Drilling penetrated through 5 m of sandy clay soil, then through greyish brown alluvium to a depth of 31 m. Then, further drilling continued through highly fractured greyish brown mudstones to a depth of 50 m. A water strike was intercepted at 30 m i.e. overlying alluvium and mudstone contact. Drilling continued through alternating coarse-grained, weathered sandstones and mudstones to a depth of 90 m. Finally, drilling penetrated through dolerite to a depth of 120 m. the main water strike was attained at 90 m depth (Appendix D: EC-T31-321) i.e. fractured sandstone and dolerite contact with the final blow yield of 10 l/s.

5.2.2 Conceptual hydrogeological framework

Based on the drilling data of the three boreholes, it may be inferred that the aquifer system constitutes the overlying alluvial deposits that vary in thickness from 30 to 50 m and the underlying fractured hard rock sediments of the Tarkastad Subgroup. The high-yielding strikes are attained in the fractured contact zones, especially the contact zones between:

- Alluvium and underlying sandstone strata
- Sandstone and dolerite
- Mudstone and dolerite

The drilling logs depicted the Cedarville Aquifer System as the Tarkastad Subgroup geological formation, consisting of alternating sandstones and mudstones that are intruded by dolerite and overlain by almost 50 m thick clay-sand alluvium. Thus, the dolerite played a significant role in developing the fractured aquifer underlying the alluvial deposits. However, the alluvium and hard rock sandstone contact is the anticipated interception of groundwater in this geological scenario. It is thought that the thickness, recharge and transmissivity of the alluvium are the key determinants of the anticipated yields in this contact zone (Figure 23).

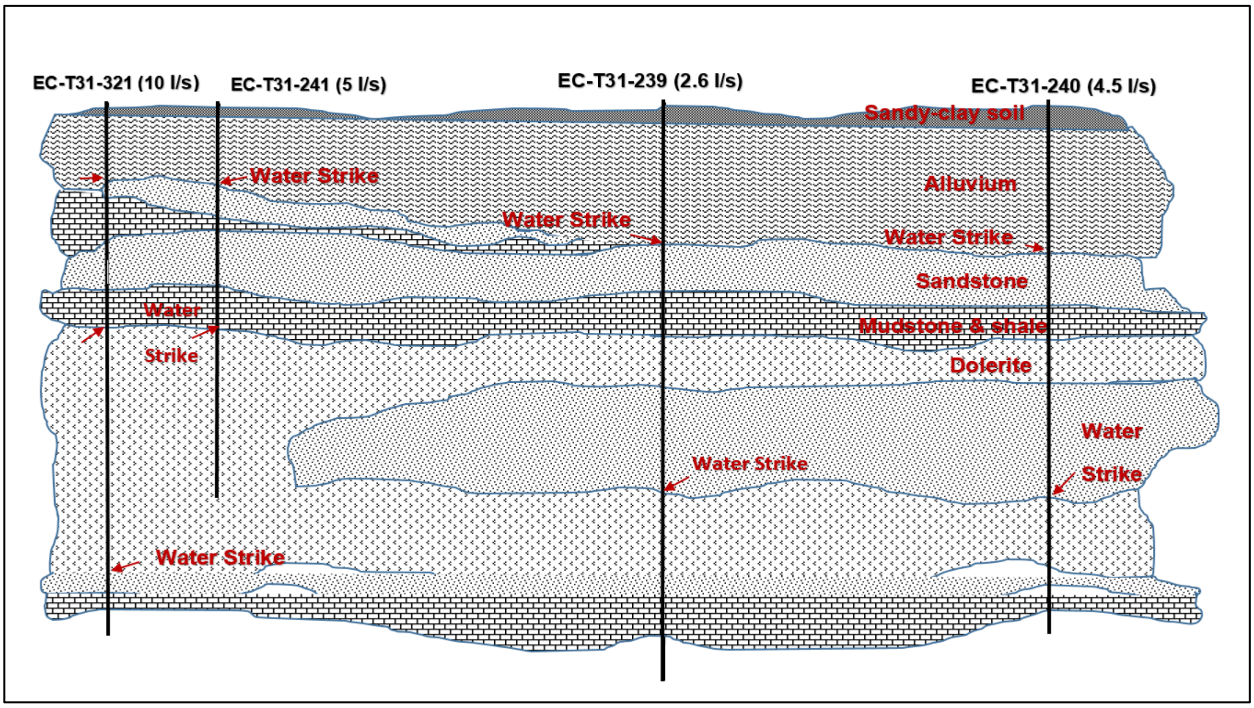


Figure 23: Illustration of the conceptual geological cross-section of the Cedarville Aquifer System

Rainfall is thought to directly recharge the alluvium by infiltrating through sandy clay top soil and percolating through alluvium until it reaches the hard rock formation of the Tarkastad Subgroup, commonly sandstone. The vertical flow is then retarded and begins to flow laterally depending on the geometry of the rock surface i.e. angle of dip and the degree of vertical fracturing in the underlying hard rock formation. The fractured rock surface will enhance groundwater to flow vertically to the deeper horizons, else the contact zone will bear groundwater or allow water to flow horizontally. Subsequently, the latter will give rise to the observed water strikes at the alluvium and the underlying Tarkastad Subgroup Sedimentary contact. The recharged water through the alluvium may be diverted by the widely occurring clay lenses in the Cedarville formation, which then lead to a perched water table. This then gives rise to the occurrence of wetlands in the Cedarville area, especially in areas where the clay lenses are shallow. The fractured underlying hard-rock aquifer may be indirectly recharged from un-localised sources and directly from the rainfall through the alluvium.

5.2.3 Borehole pumping tests of the Cedarville Aquifer

The main objectives of the pumping test data analysis are to (van Tonder et al., 2002):

- Estimate the hydraulic parameters of an aquifer
- Estimate the long-term sustainable yield for a borehole

Africa Geo-Environmental and Engineering (AGES) Consultants performed pumping tests in drilled boreholes of Cedarville with one primary objective being to determine the sustainable yield of boreholes. The sustainable yield is essential for water supply purposes to ensure that the resource is pumped at an optimal yield that will not over-abstract the borehole or under-utilise the resource. However, in this study, the pumping test data was used to determine the aquifer parameters. Hence, the data set that constituted a pumping well and observation well time-drawdown measurements were used to estimate the hydraulic parameters of the Cedarville Aquifer System.

The pumping test data were inferred from the two boreholes tested by AGES (i.e. EC-T31-241 and EC-T31-321). The two boreholes are 10.7 m apart, EC-T31-321 was pumped whilst in EC-T31-241 time-drawdown data were measured and recorded. The rest water levels were measured to be 19.09 m and 11.5 m below ground level in EC-T31-321 and EC-T31-241, respectively. The SP Series Submersible pump was set to a depth of 91.10 m below ground level in the pumping well (EC-T31-321). The step drawdown, constant discharge rate and recovery tests were performed and time-drawdown measurement was recorded in the observation borehole (EC-T31-241). However, constant discharge rate and recovery tests were the main tests for the estimation of aquifer parameters in this study, though step drawdown test data could be analysed to estimate the aquifer parameters. The constant discharge rate test was carried out at an average rate of 10 l/s for a duration of 1440 minutes (24 hours). The end-drawdown after 1440 minutes of pumping was recorded as 34.98 m and 0.81 m in the pumping and observation wells, respectively. Figure 24 is the schematic conceptualisation of the two boreholes pumping test set-up.

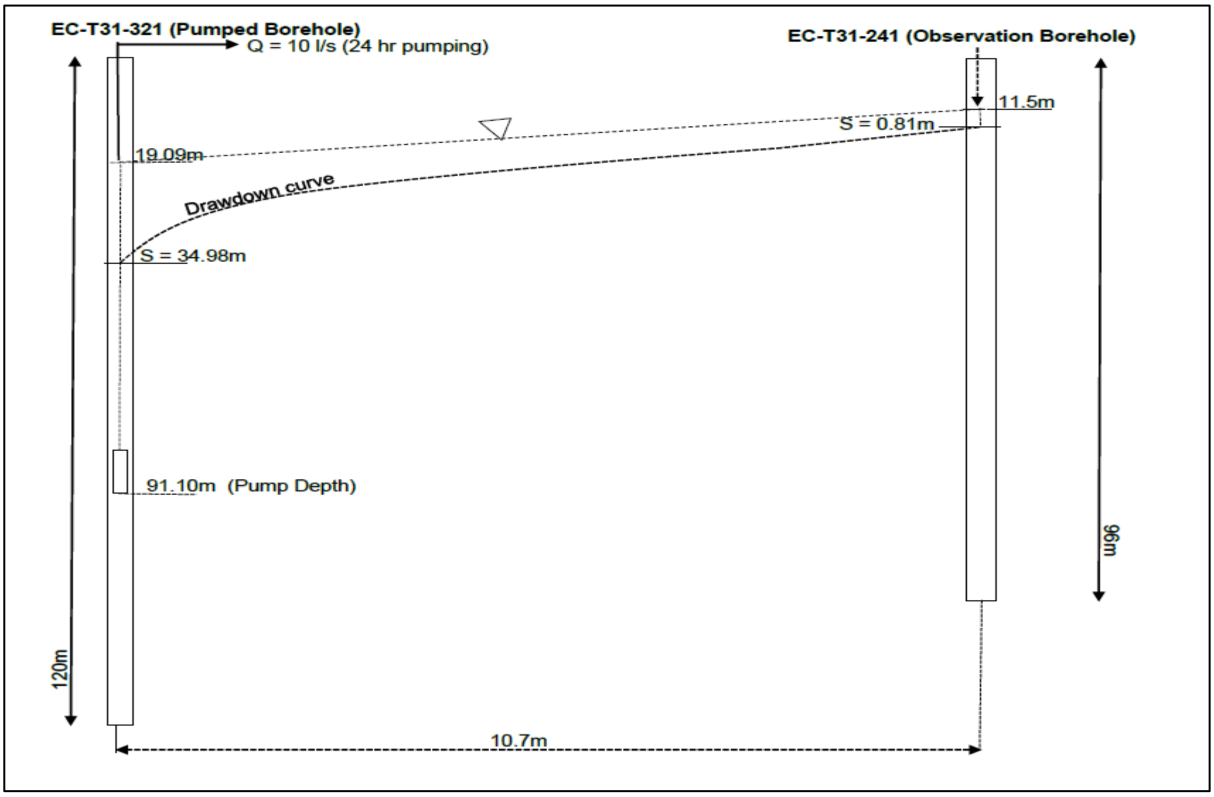


Figure 24: Schematic pumping set-up of the two boreholes (EC-T31-321 and EC-T31-241)

5.2.3.1 Analysis of pumping test data

There are various methods to analyse pumping test data, however, analytical models remain the most widely used techniques for the determination of hydraulic parameters of aquifer systems. Based on the conceptual hydrogeological framework as depicted in Figure 23, the best possible analytical model to fit the observed data would be for semi-confined, unsteady-state solution with possible leakage from the overlying alluvium. The fractured rock formation underlying the alluvium needs to be considered as:

- 80 m of unconfined to semi-confined, sedimentary deposit (i.e. highly weathered sandstone) with a network of interconnected matrix fractured system that behaves as an unconfined primary aquifer system.
- Fractured contact zone at depth of 71 m, between dolerite and sandstone, which behaves as a semi-confined secondary aquifer system.

<u>The Theis model</u>

The Theis model was first considered even though it is applicable to a confined, unsteady state solution and might not be necessarily relevant to the hydrogeological model observed in the study area. The observed pumping test data do not best fit the Theis curve (Figure 25). There is an indication of recharge boundary in the late time-drawdown data. This depicts either leakage or recharge boundary. It may be presumed that the fracture system is drained and water is drawn from the semi-confined system overlying the fracture system. The depicted T and S values are 65.6m^2/day and 0.32558, respectively. The modelled storativity value is very large for a confined aquifer system, hence the Theis model would not be appropriate to determine the aquifer parameters based on the conceptualised scenario.

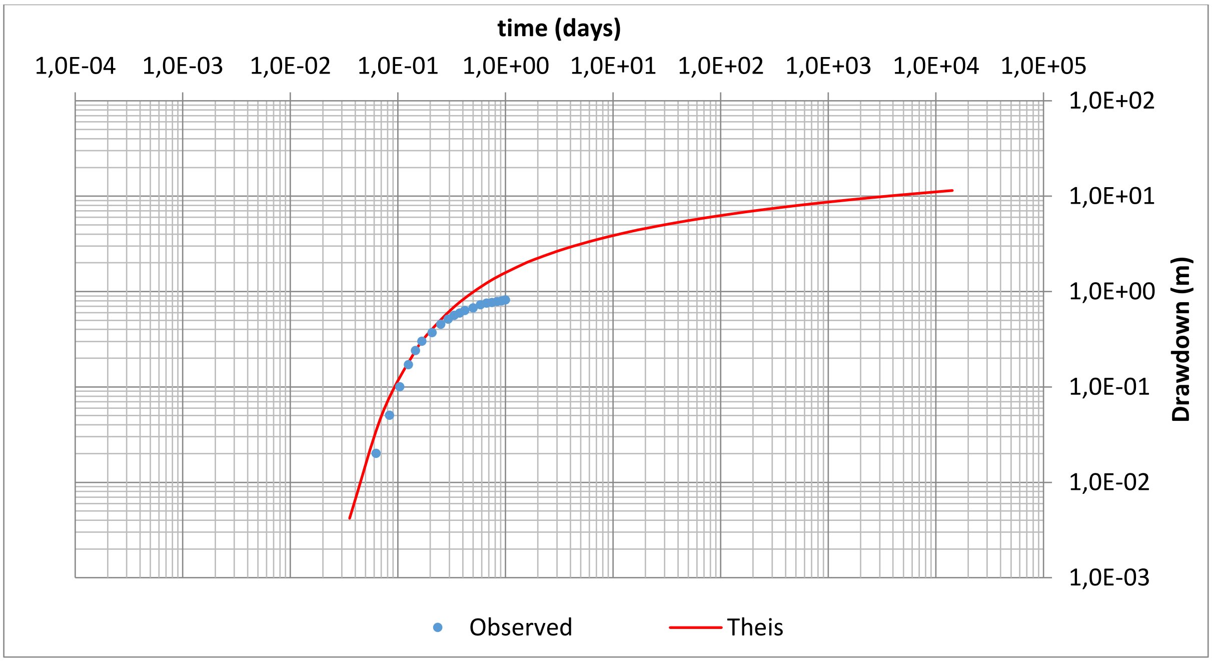


Figure 25: The Theis curve-fitting model

The Neuman model

The Neuman model is applied in double layered, unconfined unsteady state aquifer systems. Thus, the alluvium layer and the Tarkastad sediments could be assumed to be unconfined layers. The observed pumping test data fit well on the Neuman model, especially the late-time curve (Figure 26). This depicts a non-equilibrium radial flow in an unconfined aquifer system. It can then be inferred that the unconfined behaviour of fractured and intergranular systems show a more pronounced effect during pumping. However, the best fit is observed in the early time response of the analytical model. According to Neuman (1974), such a response is controlled by transmissivity (T) and elastic storage co-efficient (S), which is analogous to a confined aquifer system. Thus, the aquifer behaves as a confined aquifer in the analytical solution that is applicable to unconfined aquifer system. The depicted aquifer parameters from the Neuman model are:

$T = 105.3 m^2/day$, $S = 0.01$, $S_y = 0.194$, $b = 35m$, $\beta = 0.06$, $K_v/K_h = 0.64198$

(b =35m is the recharging semi-confining layer (aquitard) thickness).

The empirical relationship between T and b (aquifer thickness) is utilised to evaluate other horizontal and vertical hydraulic conductivities i.e. K_h and K_v, respectively:

$T = K_h b$, therefore $K_h = T/b = 105.3/35 = 3.0085 m/day$

$K_v/K_h = 0.64198$ therefore $K_v = 3 \times 0.64198 = 1.931 m/day$

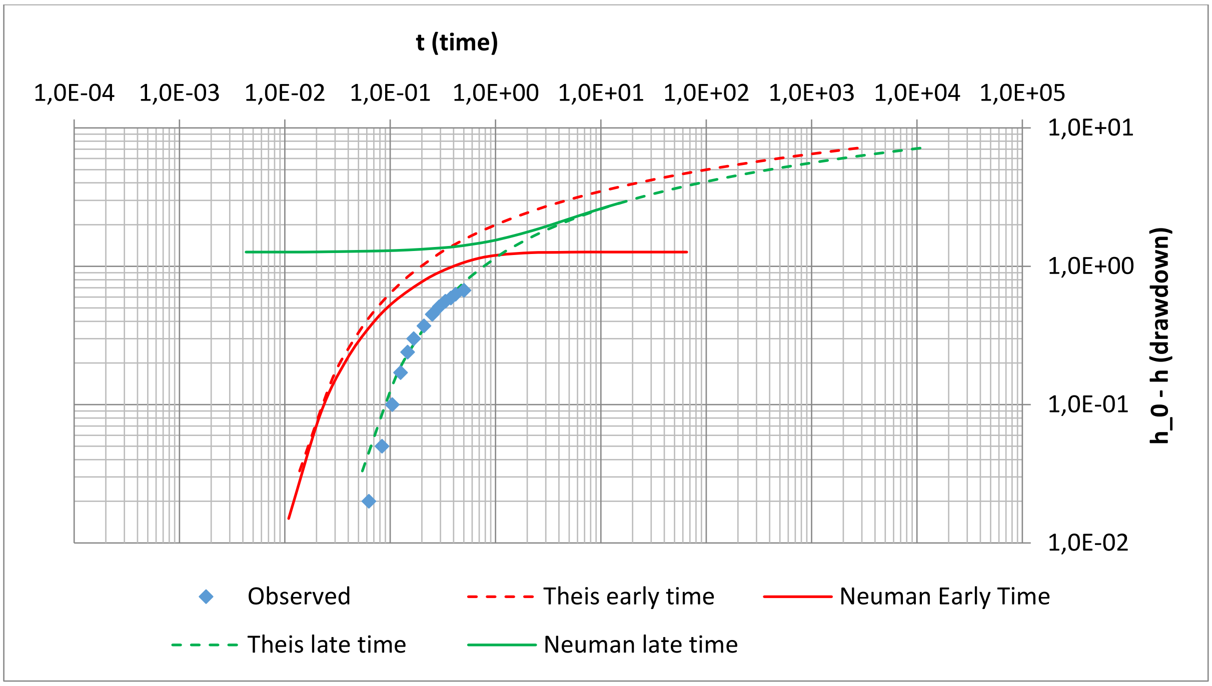


Figure 26: The Neuman curve-fitting model

The Hantush model

The Hantush model is applied in semi-confined aquifers with unsteady state solution. The conceptual hydrogeological model depicts a semi-confined condition in both layers (i.e. the alluvium and fractured underlying hard rock). It can be observed that the pumping test data fit the Hantush theoretical curve (Figure 27) well and as such depict a non-equilibrium radial flow in a leaky, semi-confined aquifer system. The model correlates well with the assumption of a semi-confining layer recharging the fractured system. The depicted T and S values from the Hantush model are 23.9m^2/day and 0.01349, respectively.

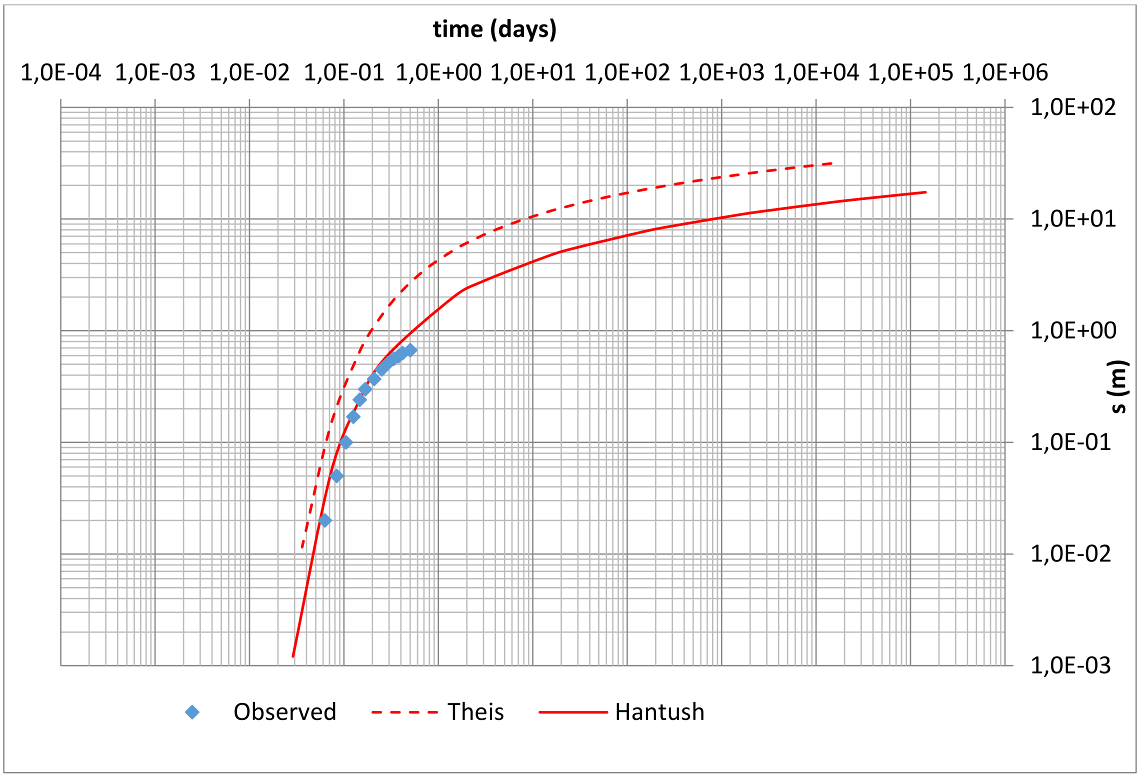


Figure 27: The Hantush curve-fitting model

According to Fetter (1988), the following formula can be used to best estimate the T value from the pumping test data:

$T = 15.3 [Q/(h_0-h)]^{0.67}$ (Formula 7-90a, page 257)

Where T = Transmissivity (m^2/day), Q = Discharge (m^3/day), h_0-h = drawdown (m)

With Q = 875.232 m^3/day, Drawdown (end drawdown) = 34.98m, then:

$T = 15.3 [875.232/34.98]^{0.67}$

T = 110.847 m^2/day

Table 3: Summary of analytically modelled aquifer parameters

Model	T (m^2/day)	S	S_y	K_h (m/day)	K_v (m/day)	b (m)
Theis	65.6	0.32558	-	-	-	-
Neuman	105.3	0.01	0.194	3.0085	1.931	35
Hantush	23.9	0.01349	-	-	-	-
Empirical (Fetter, 1988)	110.847	-	-	-	-	-

5.3 Groundwater recharge evaluation

The direct recharge was estimated in the study area based on two techniques:

- Empirical method as a function of the annual precipitation
- Chloride mass balance method

5.3.1 Empirical method of evaluating groundwater recharge

Nel (2007) stated that historically estimates of recharge rates for most aquifers in South Africa range between 5 and 10% of the annual precipitation. However, Smithers and Schulze (1995) had used a percentage factor of 3% of the annual precipitation to estimate the recharge in the Cedarville area. In an endeavour to present an optimal recharge figure, 10% of the annual precipitation was used in this study. The mean annual precipitation of the Cedarville area was calculated to be 760mm based on a 100-year period of rainfall records. This, therefore, gave rise to an estimated recharge:

Recharge = 10% of 760 mm/yr

= 0.1 x 760

= 76 mm/yr

The results from the chemical analysis of groundwater were inferred from the borehole drilling reports of Cedarville developed by SRK Consulting (2012) and AGES (2017). The records showed the chloride concentration (Appendix E) from the three boreholes that were drilled in the area. Further sampling of three boreholes and rain were undertaken in this study and laboratory analysis results recorded the concentration of Cl^- in rain and groundwater as illustrated in Table 4.

Table 4: Summary of the Cl^- concentrations for the recharge determination

Sample Source	**Sampling Agent**	**Borehole No.**	**Cl^- Conc (mg/l)**
Borehole	SRK	EC-T31-141	2.7
Borehole	SRK	EC-T31-136	4.5
Borehole	AGES	EC-T31-321	21
Borehole	This Research study	S1	19

Borehole	This Research study	S3	9
Borehole	This Research study	Nt-BH	5
Average Cl^- concentration in groundwater			**7.76 mg/l**
Rain 1	This Research study	Sr1	1
Average (geometric mean) rain Concentration (refer Appendix E)			**1 mg/l**

The geometric mean was used to calculate the average concentration of Cl^- ions in groundwater (Appendix E: Calculation):

Average Cl^- concentration in groundwater = 7.76 mg/l

Average Cl^- concentration in rain water = 1 mg/l

Recharge = $\frac{[1mg/l]}{[7.76mg/l]} * 760\ mm/yr$

= 98 mm/yr

Table 5: The estimated recharge values for the Cedarville Aquifer System

Method	Average Annual Precipitation (mm)	Recharge (mm/yr)
Empirical Method	760	76
CMB Method	760	98

The calculated recharge value of 98 mm/yr based on CMB method seems to be comparative to the empirically estimated value of 76 mm/yr (Table 5). Scanlon et. al. (2002) suggested that the CMB method is the most reliable technique of estimating recharge in fractured rock aquifers. However, the conceptual model would ideally be built on reliable values of which the CMB value would be used to characterise the hydrogeological scenario of the Cedarville Aquifer System.

CHAPTER 6 – HYDROCHEMICAL CHARACTERISATION

6.1 Sources of hydrochemical data

The hydrogeochemical characterisation of groundwater in the Cedarville Aquifer System enabled the interpretation of the distribution of hydrochemical constituents, the evolution of groundwater and an understanding of the dominant hydrogeochemical processes in the Cedarville basin. The hydrochemical data used to understand the hydrogeochemical regime of the Cedarville basin were inferred from the:

- AGES borehole drilling reports
- SRK pumping tests reports for the Cedarville Town
- Sampled groundwater in the research area

Groundwater samples were taken for this research study in some boreholes located in the farms, including those that are currently used for water supply in the Cedarville Town (Figure 28). The groundwater sampling procedures were applied such as the on-site pH, EC and temperature that were measured and recorded as soon as the water samples were collected. The samples were stored in cool conditions as they were immediately transported to the laboratory for the chemical analyses. S1, S3 and Nt-BH were the three groundwater samples and Sr1, the rain samples that were analysed for the major ions in this study. The results of the laboratory analyses are shown in Table 6 and calculated ion balance expressed in percentage. It can be observed that the ion balance ratio is below 10% and as such the chemical analysis was reliable.

Table 6: Chemical analyses of the sampled water in the Cedarville area

Major ions	**EC-T31-141**	**EC-T31-136**	**EC-T31-321**	**S1**	**S3**	**Nt-BH**	**Sr1**
Charge Balance	5.4%	3.74%	6.14%	4.33%	1.64%	5.32%	-0.48%
pH	7.76	7.16	7.6	7.12	7.01	6.9	7.3
T°C	19.5	21	18	19.9	22	18.7	17
EC mS/m	29.8	40.2	91.0	78.5	31.2	42.3	4.9
Na^+ mg/l	30.4	12.8	78	39	63	34	ND
K^+ mg/l	0.76	0.76	1.6	0.85	0.06	0.44	0.21
Ca^{2+} mg/l	51.2	83.9	56	89.42	8.73	37.22	8.15
Mg^{2+} mg/l	32.4	32.4	34	21.17	0.65	15.17	ND

Fe^{2+} mg/l	0.21	0.35	0.06	0.065	0.040	0.024	ND
HCO_3^- mg/l	346	402	435	407	167	239	22
Cl^- mg/l	2.7	4.5	21	19	9	5	1
SO_4^{2-} mg/l	7	9	12.5	2.82	6.59	3.53	1.31

The other available chemical analyses results were obtained from the pumping tests reports undertaken by AGES and SRK hydrogeological consulting companies (Appendix E: Chemical analyses results). Such hydrochemical information was inferred from groundwater sampled in boreholes EC-T31-321 (AGES pumping tests), EC-T31-141 and EC-T31-136 (SRK pumping tests).

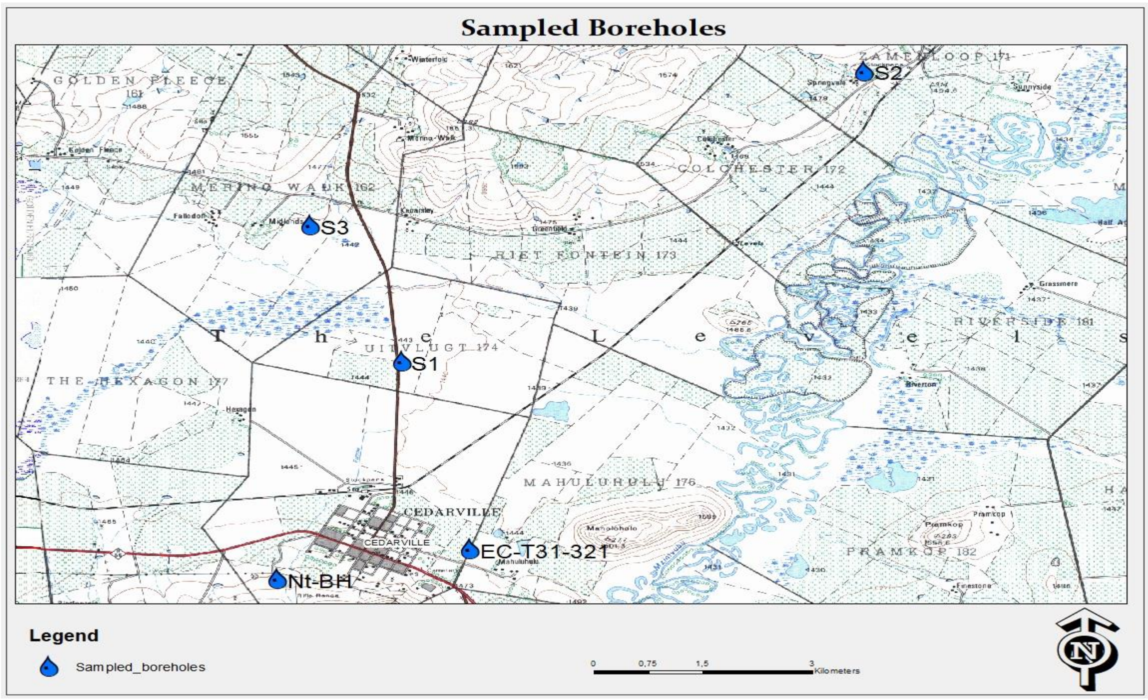


Figure 28: Map showing positions of the sampled boreholes in the study area

6.2 Representation of the hydrochemical data

Figure 29 is the Schoeller diagram that represents anions and cations concentrations of hydrochemical data obtained from the Cedarville boreholes. The chemical analyses that were inferred from reports are plotted as bold lines, whilst those that were sampled and analysed are shown as dashed lines in Figure 29. The concentrations are represented in meq/l on the vertical logarithmic scale. The Schoeller diagram characterises water sampled from the Cedarville boreholes to be predominantly Na-

Ca-Mg bicarbonate type water. Na^+ was observed to be more dominant in boreholes S1, S3 and EC-T31-321 than other cations with HCO_3^- being the dominant anion in all sampled boreholes. The Cl^- and SO_4^{2-} are much lower in concentration than HCO_3^- anions in the sampled groundwater. The divalent cations (Mg^{2+} and Ca^{2+}) are observed to be remarkably low in S3 sampled groundwater. The Fe^{2+} was observed in the analysed groundwater samples to be almost insignificant with concentration ranging between 0.024 and 0.35mg/l (Table 6).

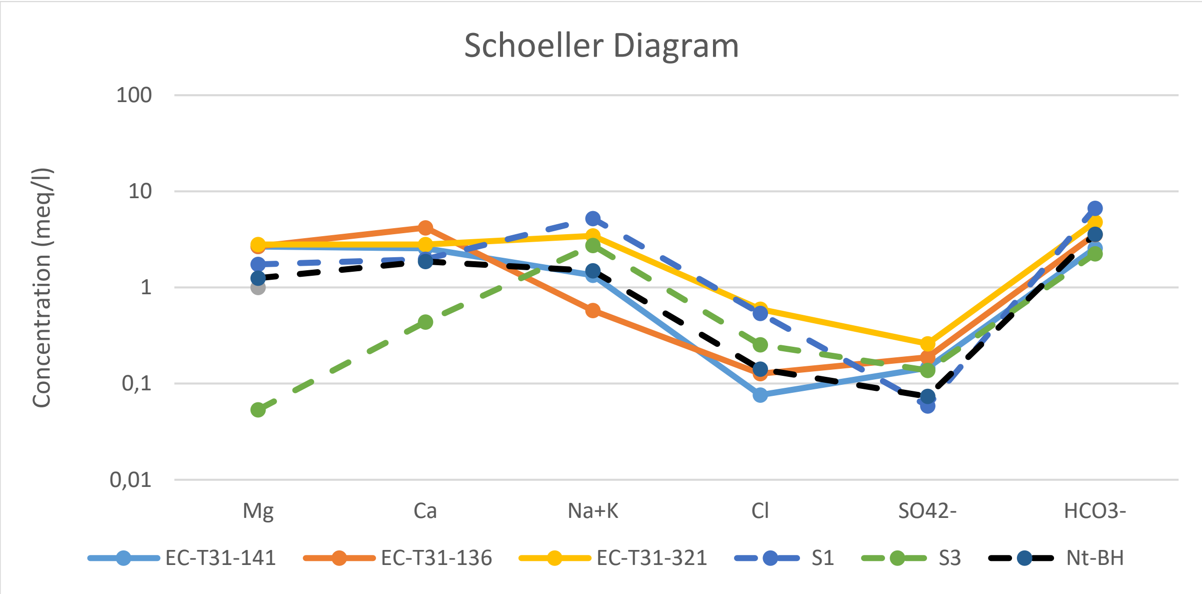


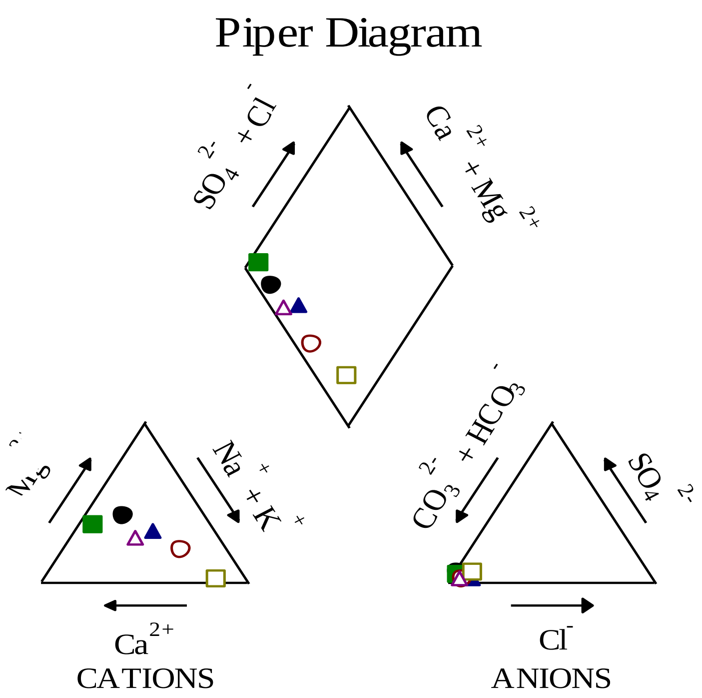
Figure 29: The Schoeller diagram of the sampled borehole analyses of Cedarville Area

The temperature of the samples as recorded on-site ranges between 17°C and 22°C (Table 6). According to Hitchon et al. (1999), groundwater temperature is generally constant hence, the low temperature variability is observed in the samples taken from the Cedarville Aquifer System. The observed groundwater temperature range is low and the aquifer system could be assumed shallow, since deep aquifers have higher temperatures due to Earth's thermal gradient (Hem, 1985).

The recorded pH ranges between 6.9 and 7.76 (Table 6). In the normal groundwater with pH range of between 6 to 8, the predominant carbonate species is the bicarbonate (Hem, 1985). It can be observed that the sampled groundwater has a pH that falls between 6 and 8, consequently, the bicarbonate ion is the dominant carbonate species. The total dissolved solids (TDS) of the sampled groundwater in the Cedarville Aquifer System ranges between 237 and 613 mg/l. According to Hitchon et al. (1999), freshwater has a TDS of less than 1000 mg/l and as such, the sampled groundwater in the Cedarville Aquifer System could be classified as freshwater. The recorded electrical conductivity (EC) values range between 28.8 and 91 mS/m. According to Hem (1985), EC of aqueous systems measures the specific conductance and as such is the indication of salinity of water. Most groundwater has an EC that ranges between 10 and 250 mS/m and any sample that has an EC in excess of 250 mS/m could be regarded as saline water. Subsequently, the sampled groundwater in the Cedarville Aquifer System may be taken as low saline water since the recorded maximum EC is 91 mS/m.

6.2.1 The Piper plot hydrochemical data representation

The analysed groundwater sampled from the Cedarville area plot on the Na-Ca-Mg bicarbonate field of the trilinear Piper diagram (Figure 30). Groundwater sampled from S3 borehole appears to be predominantly Na^{+} type water and EC-T31-136 predominantly Ca^{2+} type water. The sampled groundwater mainly displays HCO_3^{-} as the dominant anion. The Na-Ca-Mg bicarbonate generally illustrates fresh groundwater that had less residence time and did not evolve from far distances. This suggested groundwater that is locally and directly recharged by either rainfall or migrated through interconnected fracture networks from proximal sources.



LEGEND		LEGEND	
Black shaded circle	EC-T31-141	Brown open circle	S1
Green shaded square	EC-T31-136	Orange open square	S3
Blue shaded triangle	EC-T31-321	Purple open triangle	Nt-BH

Figure 30: The Piper diagram of the Cedarville sampled groundwater

6.2.2 The Durov diagrammatic representation of hydrochemical data

The sampled groundwater analyses from the Cedarville boreholes were represented on the Durov diagram as shown in Figure 31.

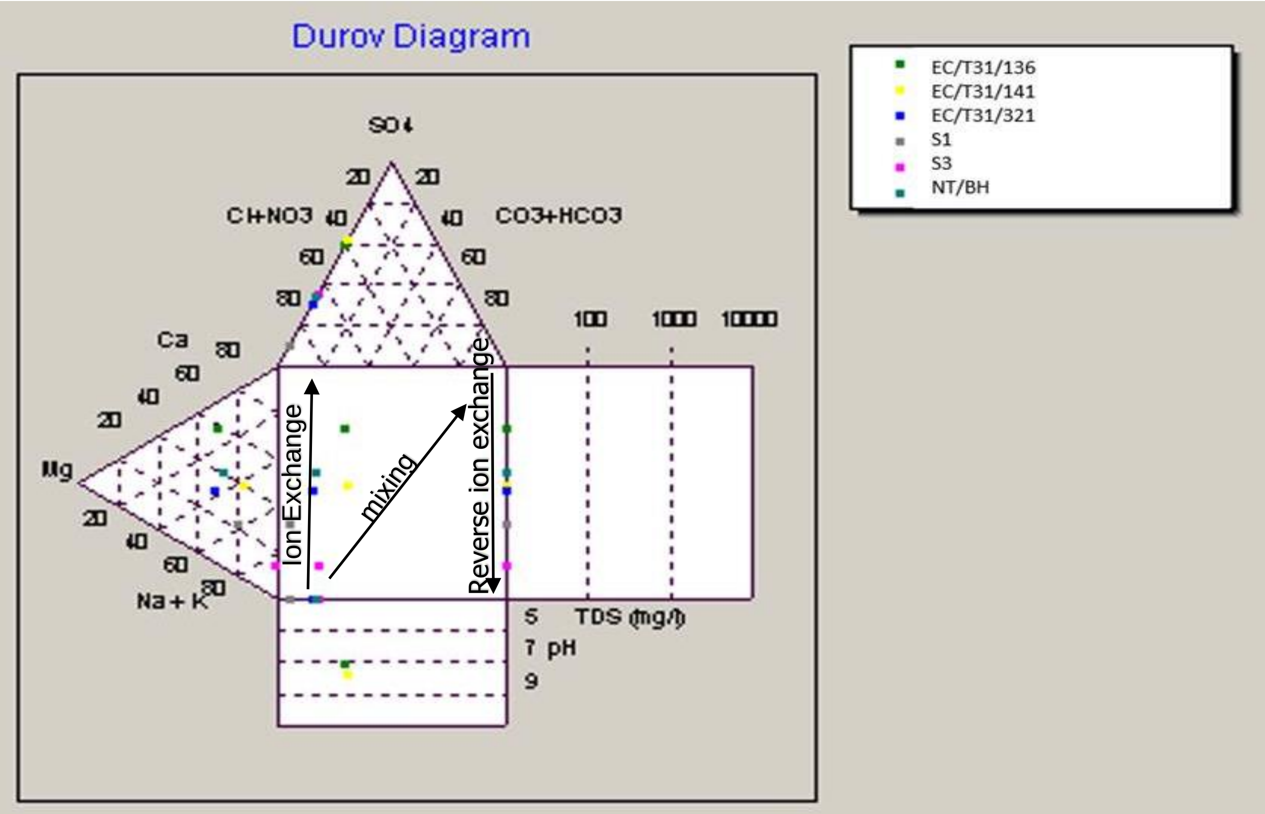


Figure 31: The Durov diagram of the Cedarville sampled groundwater

It can be observed that almost all the groundwater analyses plot on the ion exchange and reverse ion exchange fields of the Durov diagram. According to Lloyd and Heathcote (1995), the observed Durov diagrammatic representation displays that the ion exchange process is the dominant chemical reaction in the Cedarville Aquifer System.

6.3 Hydrochemical reactions

It is evident that the main chemical reaction that dominates in the Cedarville Aquifer System is the ion exchange process. The abundance of clay minerals in the alluvium and Tarkastad sediments provides sufficient surfaces for the cation exchange reactions to prevail. According to Hitchon et al. (1999), in recently recharged groundwater such as the Cedarville Aquifer System cation exchange process tends to extract divalent cations from the solution and replace them with monovalent cations. The variable concentrations of Na^+ and Ca^{2+} ions indicate the replacement of one by another depending on the abundance of clay lenses in the lithological profiles of the borehole localities. An increase in Na^+ concentration in the hydrogeochemical system is an indication of an ion exchange process whilst the reduction in Na^+ concentration is an indication of the reverse ion exchange process (Lloyd and Heathcote, 1995). Such chemical processes are observed in the sampled water from the boreholes EC-T31-141, EC-T31-136 in which Na^+ concentration is reduced in the aqueous system. The higher concentration of Na^+ cation in sampled groundwater from borehole S3 provides evidence of the ion exchange process.

The low salinity water based on low TDS and electrical conductivity of the sampled water (Table 6) is indicative of an open system. The conceptual hydrogeological framework illustrated porous alluvium and fractured hard rock system, which depicted an open thermodynamic system. The low concentration of Fe^{2+} with less than 1mg/l in all the analysed groundwater samples indicates an aerobic (or oxidising) environment. The Fe^{3+} could precipitate as ferric hydroxides and gave rise to the observed ferricrete material found in the sandy clay soil of the alluvium.

6.4 Stable isotope analysis

According to Weaver et al. (1999), environmental isotopes are used in hydrogeological studies to:

- Provide a signature to a particular water type
- Identify the occurrence of mixing of two or more water types
- Provide information on water-rock interaction
- Provide residence time information about groundwater
- Provide information concerning travel times and groundwater velocities

However, in this study the stable environmental isotopes of ^{18}O and ^{2}H were analysed to be used in providing isotopic signatures to water types, identifying the occurrence of mixing between two or more water types and providing information on water-rock interaction. Groundwater samples were taken from EC-T31-321, S1, S2, S3 boreholes and rainwater samples Sr1, Sr2 and Sr3 for stable isotope (^{18}O and ^{2}H) analyses. The positions of the sampled boreholes are shown in Figure 28.

6.4.1 Results of the isotopic analyses

The samples were submitted to iThemba Labs, Gauteng for isotopic analyses and the results thereof are illustrated in Table 6. The isotope analytical results are expressed as delta ratios:

$$\delta^{18}O({}^{0}/_{00}) = \left(\frac{\left(\frac{^{18}O}{^{16}O}\right)_{Sample}}{\left(\frac{^{18}O}{^{16}O}\right)_{Standard}} - 1 \right) \times 1000\,{}^{0}/_{00}$$

$$\delta^{2}H({}^{0}/_{00}) = \left(\frac{\left(\frac{^{2}H}{^{1}H}\right)_{Sample}}{\left(\frac{^{2}H}{^{1}H}\right)_{Standard}} - 1 \right) \times 1000\,{}^{0}/_{00}$$

Table 7: Environmental stable isotope (^{2}H and ^{18}O) analyses

iThemba Labs – Environmental Isotope Laboratory: Wits				
Lab No.	**Sample Field**	**Sample No.**	**$\delta^{2}H$‰ SMOW**	**$\delta^{18}O$‰ SMOW**
WITS 1456	Rain Sample	Sr1	-131.9	-18.13
WITS 1461	Rain Sample	Sr2	5.7	-1.25
WITS 1462	Rain Sample	Sr3	-49.6	-7.67
WITS 1457	Farm Borehole 1	S1	-25.9	-4.97
WITS 1458	Farm Borehole 2	S2	-13.1	-3.06
WITS 1459	Farm borehole 3	S3	-20.9	-4.48
WITS 1460	Municipal Borehole	Nt-BH	-19.6	-4.12
WITS 1463	River Sample	Sw1	15.6	3.6
WITS 1464	Dam Sample	Sw2	-8.2	-0.2
WITS 1465	Dam Sample	Sw3	7.1	3.32

Figure 32 displays the graphical representation of the $\delta^{2}H$ and $\delta^{18}O$ in relation to the Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL)

GMWL: $\delta^{2}H = 8\delta^{18}O+10$ (Craig,1961)

LMWL: $\delta^{2}H = 6.76\delta^{18}O+13.99$

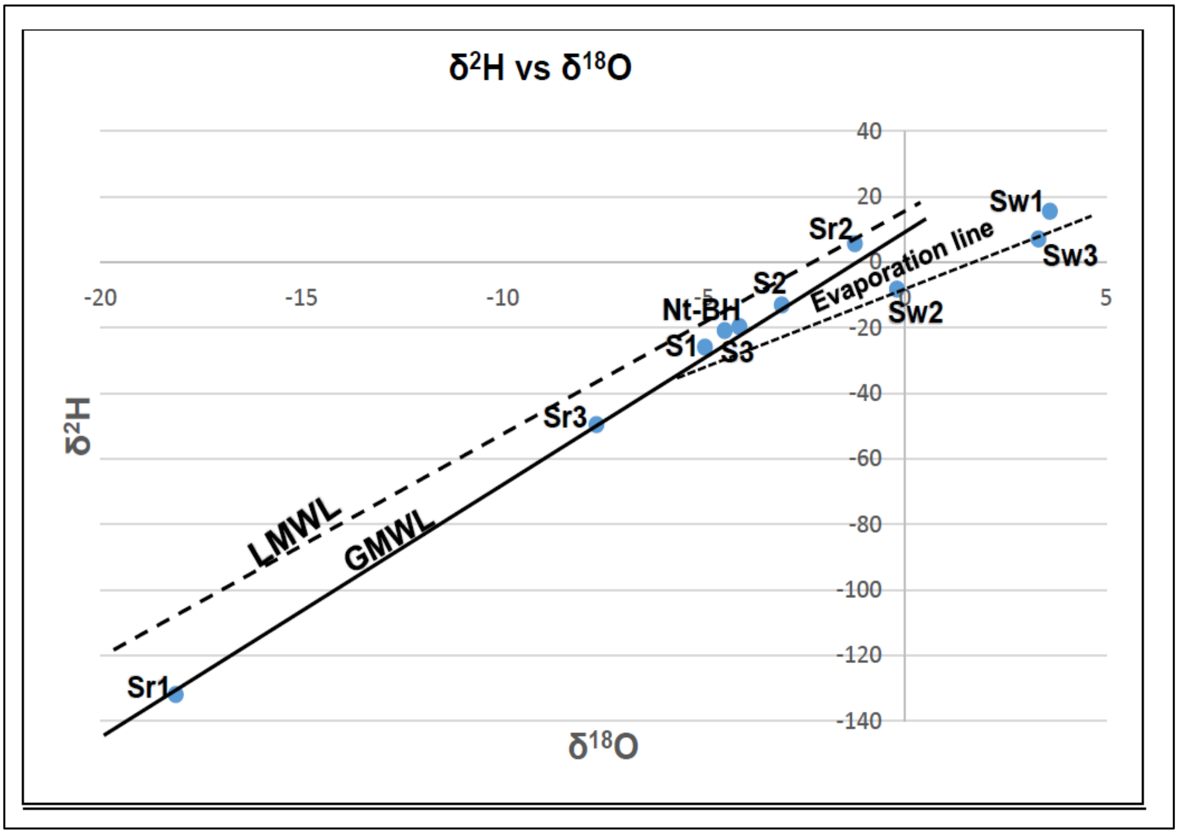


Figure 32: The Cedarville isotopic data relative to the GMWL (Craig, 1961)

It can be observed that the Cedarville isotopic ratio of ^{2}H and ^{18}O for samples (Table 7) taken from various boreholes and rain plotted on the GMWL (Figure 32). It can then be inferred that such water originated from the atmosphere and was not affected by the other isotopic processes (Clark and Fritz, 1997). Evaporation and water-rock interaction are thought to be the most commonly observed processes causing deviations from the GMWL (Weaver et al., 1999). It may, therefore, be inferred that evaporation and water-rock interaction processes did not affect groundwater recharged in the Cedarville Aquifer System. The isotopic composition of groundwater is, as such, meteoric. There are no observed isotopic signatures of surface water due to the evaporation process in the groundwater samples. The evaporation line is observed for samples collected from the surface water bodies i.e. river water sample (Sw1) and dam water samples (Sw2 and Sw3). It may be inferred that surface water bodies such as rivers or lakes did not recharge the Cedarville aquifer. The system was primarily recharged by direct rainfall or indirectly through interconnected fractures that transmit groundwater from proximal sources.

Rainwater (Sr1) appears to be more depleted in heavy isotopes of ^{2}H and ^{18}O (Figure 32). The Cedarville area is situated in a higher altitude zone at 1472 m amsl and a fair distance from the coastal area, hence the altitude and continental effects, respectively, probably played a role in the depletion of the heavy stable isotopes of rainwater. However, samples Sr2 and Sr3 are observed to be more enriched than Sr1, though they all plot on the GMWL.

CHAPTER 7 – DISCUSSION OF RESULTS

7.1 Origin of the Cedarville Basin

The Cedarville Aquifer System constitutes an approximately 50 m thick layer of clay-sand alluvial deposit that overlies fractured alternating sandstones and mudstones of the Tarkastad Subgroup of the Beaufort Group sedimentary sequence. The sedimentary sequence was further intruded by Jurassic age dolerite, which enhanced the secondary transmission of groundwater in the aquifer system. The Quaternary Alluvium was deposited in a “basin” like or depression landform bounded by mountainous edges.

The formation of this secondary basin filled with Quaternary deposits requires detailed investigation. However, Woodford and Chevallier (2002) suggested the tectonic theory associated with the Matatiele normal fault along the Drakensberg in which they perceived the Cedarville Basin to be the downthrown side of the fault. According to this research study, there is no evidence that suggests the occurrence of a normal faulting event. If there were major faulting events, which led to the formation of a major landform depression such as the Cedarville Basin, then secondary tectonic effects of such a displacement of strata would be observed. Subsequently, the normal fault theory for the formation of Cedarville Basin is debatable in this study. The Cedarville Basin is thought to be related to isostatic uplift associated with intrusive magma. The topographical depression was later filled by eroded sediments from the uplifted Tarkastad Subgroup formations. Consequently, the origin of the Cedarville basin is a subject for further investigation

7.2 The hydrostratigraphy of the Cedarville Aquifer System

The Cedarville Aquifer System is conceptually described as a complex 2-layered water-bearing unit consisting of the top alluvium layer and the bottom fractured hard rock layer, the Tarkastad Subgroup formations.

7.2.1 The top alluvium layer

The alluvium layer behaves as an unconfined to semi-confined aquifer. The clay lenses create confining zones within the alluvium profile hence the top layer does not fully behave as an unconfined system. The abundance of clay lenses, therefore, increases the confining effect in the alluvium. Such lenses are visible in the study area as they manifest themselves in widespread wetlands especially when they occur at shallow depths.

The vertical flow component of percolating groundwater is more dominant in the alluvium layer. Such flows are generally impeded by the horizontal clay lenses, which then result in horizontal groundwater flow within the alluvium or even appear on the surface as wetlands. Thus, vertical hydraulic conductivity is the key parameter for the circulation of groundwater in the top alluvium layer. The vertical hydraulic conductivity is generally influenced by the porosity of the alluvial clay-sand deposit. The relatively high porous sand material transmits groundwater to greater depths of the alluvium layer.

The percolating groundwater migrates laterally or even percolates through vertical fractures upon reaching the hard rock surface of the bottom second layer, the underlying Tarkastad Subgroup sediments. The horizontal flow direction will primarily be determined by the angle of dip of the underlying rock surface. However, it was observed on surface geological mapping that the strata were almost horizontally bedded and therefore it could be very difficult to depict groundwater flow direction beneath the top layer.

The contact zone of these two layers forms groundwater storage that recharges the underlying Tarkastad Subgroup sediments through vertical joints. This, therefore, explains the occurrence of water strikes in all boreholes drilled through the alluvium layer at Cedarville. The thickness of the alluvium layer plays a role in increasing the groundwater storage at the contact zone. In places where the alluvium is thick (±50 m), more groundwater should collect at the contact zone of the two layers and significant water strikes are anticipated to be intercepted by drilling. The impact of clay lenses and lower porosity of the intergranular alluvium retards the vertical flow and thus reduces the yield of the intercepted water strikes. The retardation of vertical flow provides water for crop production at the root zone and as such are beneficial for agricultural production.

7.2.2 The bottom Tarkastad Subgroup sedimentary layer

The second layer consists mainly of sandstone, mudstone and shale. The sandstone beds have primary porosity but do not contribute significantly to the transmissivity of this layer. The network of interconnected fractures and major horizontal and vertical fractures play a significant role in the flow of groundwater in the bottom layer. The vertical fracture system enhances the vertical migration of groundwater from the top layer through to the bottom hard rock system. Thus, vertical hydraulic conductivity remains the hydraulic parameter that affects the vertical flow of groundwater in the bottom second layer.

The horizontal fractures allow groundwater to flow laterally in the bottom second layer. The major water-bearing fractures in this layer are thought to be horizontal fractures. The main water strikes are presumably taken as the interception of groundwater flowing through the horizontal fractures. Thus, the horizontal hydraulic conductivity reflects the permeability of horizontal fractures in the bottom layer. The horizontal fractures are recharged through the vertical joints from the overlying alluvium or may be recharged laterally from adjacent aquifer systems of the Karoo Supergroup. However, it was observed in this study that the aquifer is predominantly recharged from rainfall, which suggests the vertical recharge of horizontal fractures.

The joints that transmit groundwater in the bottom layer are generated by dolerite dykes. The dolerite sills played a critical role in the formation of horizontal fractures since they intruded the existing bedded strata concordantly. The dolerite dykes are thought to enhance the occurrence of vertical fractures, though the bending theory suggested that the dolerite dykes also form horizontal joints (Botha et al., 1998). Conceptually, groundwater flow in the bottom hard rock layer could also be modelled as semi-confined to confined system with the influence of connected rock matrix fracture network, primary porosity of the sandstone beds, major vertical and horizontal fractures. Thus, the key variables to characterise flow in the bottom hard rock layer include the primary porosity, vertical and horizontal hydraulic conductivities, matrix and fracture storage co-efficient, fracture and horizontal transmissivities and other properties of the fracture system.

7.3 The aquifer boundaries of the Cedarville Aquifer System

The definition of boundaries is essential in the characterisation of an aquifer system. The Cedarville Aquifer System is conceptualised as a basin, subsequently, it has edges or peripheries that bound the system. In the case of the Cedarville Aquifer System, the edges constitute the elevated hills that presumably form groundwater flow boundaries. The other boundaries include the dolerite dykes that cross-cut the basin. However, dykes are not visible throughout the basin and may be identified by satellite images since they are covered by alluvium. Dykes were intruded prior to the deposition of the Quaternary alluvium in the basin. The dolerite dyke outcrops occur prominently in elevated regions of the Cedarville basin.

The major drainage system, the Umzimvubu River with minor streams that are tributaries form boundaries in the characterisation of the Cedarville Aquifer System, the constant head or fixed head boundaries. Consequently, both conceptualised layers will assume the elevated hills as edges that form no-flow boundaries. The Umzimvubu River assumes a constant head boundary in the top alluvium layer of the Cedarville Aquifer conceptual model.

7.4 The influence of geological structures in the hydrogeology of the Cedarville Aquifer System

The mapped joints in the Cedarville area were of tectonic origin. The analysis of these joints showed that they are oblique or diagonal to the strike of the lithological beds and are first-order joints since they cut across various lithological layers. The joints were observed to be dilational and could therefore be described in a hydrogeological sense as open joints. This implies that such joints are open for the transmission of fluids, unlike shear joints, which are often regarded as closed.

The majority of the mapped joints exhibit the NW-SE trend, however, some display the NE-SW orientation. The NW-SE and NE-SW were the two most prominent trends for the mapped joints (Figure 18). The dolerite dykes in the research area display the NE-SW strike that is consistent with the NE-SW trend of the joints. It is therefore apparent that the NE-SW joints were formed due to tensional stress and should be open; hence, they were exploited by intrusive magma. It may therefore be inferred that the NW-SE joint sets were the manifestation of the compressional stress regime. This suggests that the Cedarville rocks were subjected to compressional stress, which resulted in the formation of NW-SE joint sets, followed by tensional stress regime resulting in the NE-SW joint sets.

The two stress episodes are consistent with tectonic stress regime described in the Karoo Basin (Catuneanu et al., 2005). The compressional stress regime observed in the Karoo Basin was associated with the tectonic subduction or collision, which then led to the formation of the NW-SE joint sets.

The open or dilational joints played a major role in the circulation of groundwater in the Cedarville Aquifer System. However, these joints allowed percolating groundwater to vertically flow through the Tarkastad Subgroup that underlies the alluvium layer. The intersection of the vertical joints with the horizontal fractures results in lateral flow in the fractured rock system. Horizontal joints commonly occur at geological contact zones in the horizontally bedded strata. Such contacts include the dolerite–sediment rock contacts, which are often fractured zones and subsequently act as horizontal groundwater flow conduits. The interconnected rock matrix fracture network that represents the inherent secondary porosity of hard rock formation subsequently enhances groundwater flow.

The dolerite dykes play a significant role in the fracturing of the host sedimentary rocks in various mechanisms including thermal effects on surrounding rocks and mechanisms described by Botha et al. (1998). However, the bending mechanisms (Figure 10) as described by Botha et al. (1998), play a significant role in the formation of bedding parallel fractures, which results in horizontal groundwater flow. The dolerite sills, which intrude the sediments concordantly, enhance the formation of horizontal or bedding parallel fractures. The water strikes that are intercepted by drilling in the fractured rock system are hypothetically the horizontal groundwater flows. Linear dolerite dykes also play a role by impeding the horizontal flow, creating a barrier, which impounds groundwater forming deep flow. However, in the Cedarville Aquifer System, the effects of dolerite intrusions could be applied in the fractured hard rock layer beneath the alluvium. It was observed that horizontal flows in the fractured hard rock gave rise to high borehole yields and such horizontal fractures could be associated with dolerite sill and geological contacts.

7.5 Groundwater potential of the Cedarville Aquifer System

The Cedarville Aquifer System has sufficient storage to yield groundwater that meets the current water demand for the Cedarville community. However, intensive programmes must be undertaken to ensure that the groundwater resource is sustainably managed to meet the current and future demand. The groundwater management programme includes setting groundwater monitoring networks in the entire Cedarville basin. The over-exploitation of the resource poses the highest risk especially by commercial farming; hence pumping procedures for individual farmers must be developed as a strategy to curb over-pumping in the area. The groundwater resource is directly recharged from rainfall as such drought events pose a potential risk for the aquifer system to yield sufficient water for the Cedarville Community.

The main geological features that yield significant water strikes include the following:

- Contact zone between alluvium and Tarkastad Subgroup sediments
- Tarkastad Subgroup sediments and dolerite intrusion contact
- The sandstone interbeds
- Fractured sandstone and shales

The overlying alluvium and Tarkastad Subgroup sedimentary contact guarantees interception of water strikes. However, the yield of such water strikes depends on the thickness of the alluvium and the existence of clay lenses in the alluvium profile. The thickness of the alluvium enhances more groundwater storage at the contact zone. Contrastingly, clay lenses retard the vertical flow through the alluvium and consequently reduce the storage at the contact zone.

It is apparent that the overlying alluvium layer does not significantly produce high-yielding boreholes. On the other hand, the underlying fractured rock system produces higher yielding boreholes as shown by the borehole depth–yield relationship (Figure 20). Most high-yielding boreholes were drilled adjacent to dolerite dykes or drilling intersected dolerite intrusion at depth and such contacts produce high-yielding water strikes. The sandstones occur as interbeds at depth and are generally bounded by mudstones. The coarse-grained sandstones are enveloped between mudstones.

There is generally a high probability of intercepting high-yielding water strikes at depths. The high yields attained from deep boreholes were cumulative from both the fractured and alluvium layers. According to hydrocensus records, 45% of boreholes yield greater than 5l/s. This suggests therefore that the Cedarville Aquifer System has the potential to produce high-yielding boreholes.

7.6 Hydraulic parameters for the characterisation of the Cedarville Aquifer System

The primary parameters that are required in the hydrogeological characterisation of an aquifer system include the hydraulic conductivity, transmissivity and storage co-efficient of the aquifer. Porosity is one of the important parameters required to develop a conceptual model, however, porosity was not experimentally determined in this study. The porosity values were inferred from Woodford and Chevallier (2002) and are given for the two layers as follows:

- Porosity for unconsolidated sand (alluvium) is estimated at 25%
- Porosity for fractured Beaufort Group rocks ranges between 2 and 10%

Thus, the top alluvium layer will then be assigned a porosity value of 0.25 and the underlying fractured hard rock a porosity value of 0.1. Then, the rest of the other hydraulic parameters were determined from the pumping test analysis based on Neuman model and were then assigned as illustrated in Table 8.

Table 8: Hydraulic parameters determined for the Cedarville Aquifer System

	Description	Parameters	Source of information
Layer 1	Clay-sand alluvium, with lenses of clay	Porosity = 0.25	Woodford and Chevallier (2002)
		K_v = 1.931m/day	Pumping Test: Neuman Model
		Sy = 0.194	Pumping Test: Neuman Model
		T = 23.9 m2/day	Pumping Test: Hantush Model
		Thickness = 35m	Pumping Test: Neuman Model
Layer 2	Fractured sandstones, mudstones and shales of the Tarkastad Subgroup, intruded by dolerite in some places	Porosity = 0.1	Woodford and Chevallier (2002)
		K_v = 1.931m/day	Pumping Test: Neuman Model
		K_h = 3.008m/day	Pumping Test: Neuman Model
		T = 105.3m^2/day	Pumping Test: Neuman Model
		S = 0.01	Pumping Test: Neuman Model
		Thickness = 60m	Drilling records

The alluvium layer could be modelled as a semi-confined to unconfined system; hence, S_y is assigned in this layer. The aquifer thickness is required in layer 1 and K_v is a very important parameter. The system is characterised as an anisotropic with $K_v \neq K_h$ and $K_h > K_v$ in layer 1. The transmissivity value of 105.3m^2/day is used for layer 2. However, if a numerical model could be applied the T value would be determined from the model. Thus, the numerical model would detail Transmissivity into fracture transmissivity and matrix transmissivity for layer 2 and computes the transmissivity of layer 1 as a function of hydraulic conductivity and aquifer thickness. The storage co-efficient (S) is assigned to layer 2, which is assumed to be semi-confined to confined aquifer. Based on the evaluated aquifer hydraulic parameters, the Cedarville Aquifer System could be conceptually modelled as shown in Figure 33. The elevated hills bound the system and the Umzimvubu River System assume constant head boundary. The hydraulic parameters are assigned accordingly to both layers of the aquifer system.

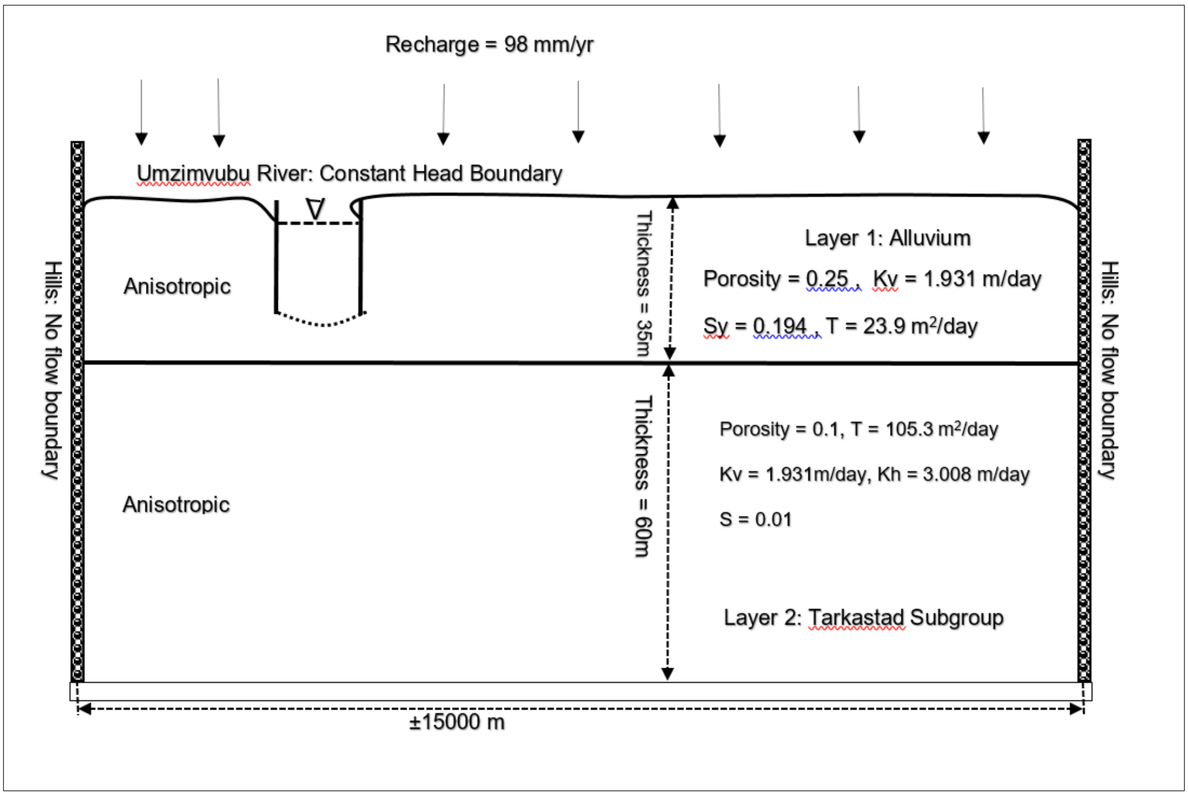


Figure 33: The conceptual model diagram of the Cedarville Aquifer System

7.7 Recharge value for the Cedarville Aquifer System

Recharge was estimated using empirical and CMB methods to values of 76 and 98mm/yr, respectively. The empirical value was based on 10% of the average annual precipitation. The calculated value was more conservative and the estimated recharge value is much lower. The CMB method is more reliable according to Scanlon et al. (2002). The estimated recharge value based on the CMB method would be used in the characterisation of the Cedarville Aquifer System. Such a value would be a recharge value for layer 1 and layer 2, both conceptualised layers of the Cedarville Aquifer System. It is expected that recharge would be reduced as it percolates through the underlying Tarkastad Subgroup sediments (layer 2). However, the conceptual model would be simplified by assuming a value of 98mm/yr as a recharge value for both layers.

7.8 The hydrogeochemical regime of the Cedarville Aquifer System

The hydrogeochemical characterisation of the Cedarville Aquifer System suggested a Na-Ca-Mg bicarbonate type water based on the sampled and available hydrochemical data. Thus, typical of recently recharged or freshwater that had less residence time in subsurface rock formations. Such hydrogeochemical regime could be associated with groundwater that was directly recharged from rain.

The ion exchange was observed to be the dominant hydrogeochemical process that occurred during the migration of water through the alluvium layer. The ion exchange was associated with the abundant clay lenses in the alluvium layer, the interaction of infiltrating and percolating water with clay minerals allowed the exchange process of Na^+ and Ca^{2+} ions. There was no well-defined indication of oxidation-reduction reaction observed in the chemical analyses of the sampled groundwater from the Cedarville Aquifer System. The Fe^{2+} concentrations were low in the analyses of groundwater samples. However, during groundwater sampling borehole S3 emitted H_2S odour, which suggested the reducing conditions in the borehole. It was then reported that the borehole was drilled deep to a depth of 140m. This, therefore, suggested that the hydrogeochemical conditions become more reducing with depth.

The isotopic analyses of stable isotopes (^2H and ^{18}O) of the sampled groundwater in the Cedarville Aquifer System were consistent with chemical analyses of major ions. They reflect water that originated from the atmosphere, which was not affected by isotopic processes attributable to the evaporation and water-rock interaction processes. This, therefore, suggested groundwater that was recharged from direct rainfall. The Cedarville Aquifer System was not recharged from any surface water bodies, as there were no surface water isotopic signatures. Groundwater was mainly recharged from rainfall events based on isotopic analyses.

CHAPTER 8 - CONCLUSIONS

The Cedarville Aquifer System is recharged directly from rainfall based on the isotopic and major chemical ion analyses. There is no indication of surface water bodies recharging the groundwater system in the research area. Rain infiltrates through clay-sand and percolates down to reach the underlying sediments of the Tarkastad Subgroup. It is impeded or retarded as it percolates through the alluvium by clay lenses, which subsequently form wetlands on the surface where the clay lenses occur at shallow depths. The recharging rainwater either percolates through vertical fractures of the underlying hard-rock formation or migrates laterally along the planar surface of the hard rock formation. The horizontal flows result in obvious water strikes when intercepted by drilling at the contact between the alluvium and hard rock formation.

The yield of water strikes at the alluvium-hard rock contact zone depends on the thickness and porosity of the overlying alluvial deposit. However, the alluvium contact zone does not produce the highest-yielding water strikes. The underlying fractured hard rock formations of the Tarkastad Subgroup produce higher-yielding water strikes in the research area, especially in places where dolerite intrusion had enhanced fracturing. It was observed that higher-yielding boreholes were drilled through fractured formations that were intruded by dolerite dykes. It may then be concluded that the underlying consolidated rocks play a significant role in terms of the potential to produce high-yielding water strikes in the study area.

It was observed that the linear dolerite dykes display the NE-SW strike orientation, which is consistent with the trend orientation of some joint sets. Such NE-SW trending joint sets can be concluded to be dilational joints and be assumed open for the flow of groundwater. These joints were thought to have formed by tensional stress regime that prevailed during the origin of the entire Karoo basin. Thus, the joints in the research area were observed to be of tectonic origin.

It can be concluded that the ion exchange process is the predominant hydrogeochemical process in the research area based on the analysis of the hydrochemical data. The hydrogeochemical analyses of groundwater display a fresh water system with no indication of extensive interaction with the host rock. There were no isotopic signatures of evaporation and rock interaction processes in the isotopic analyses of groundwater sampled from the research area. It can be concluded that groundwater that occurs in the Cedarville Aquifer System is mainly of meteoric origin.

The development of a conceptual model depends mostly on the determination of the hydraulic parameters, which characterises the aquifer system. Pumping test data analysis was used to determine the aquifer properties. The Neuman model produced the best analytical results to be used in characterising the Cedarville Aquifer System. It can be concluded that the Cedarville Aquifer System is modelled conceptually as a 2-layered system consisting of the top alluvium layer and bottom fractured sedimentary layer. The alluvium was characterised to be unconfined to a semi-confined system, hence the specific yield (S_y) attained from the Neuman analytical solution was assigned to this layer. The second bottom layer is more complex with a fractured system, constituting the matrix fractures, main fractures (horizontal and vertical fractures) and coarse-grained interbedded sandstones. The entire aquifer system was characterised to be an anisotropic with $K_h > K_v$. The mountains would be modelled as no-flow boundaries at the edges of the Cedarville System and dolerite dykes also act as the no-flow boundaries. The Umzimvubu River system in the research area would assume constant head boundaries. The recharge was estimated based on the CMB method to be 98 mm/yr. An investigation on the origin of the Cedarville Quaternary basin should be investigated and a numerical model must be developed to further characterise groundwater flow in the Cedarville Aquifer System.

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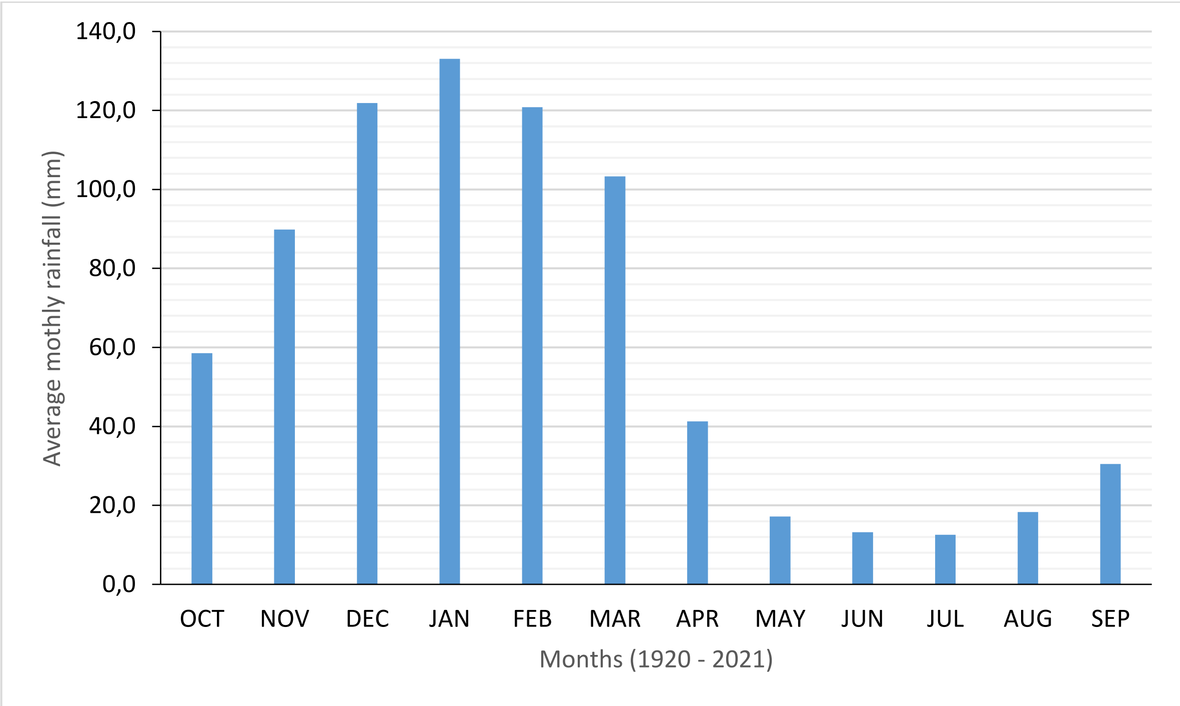
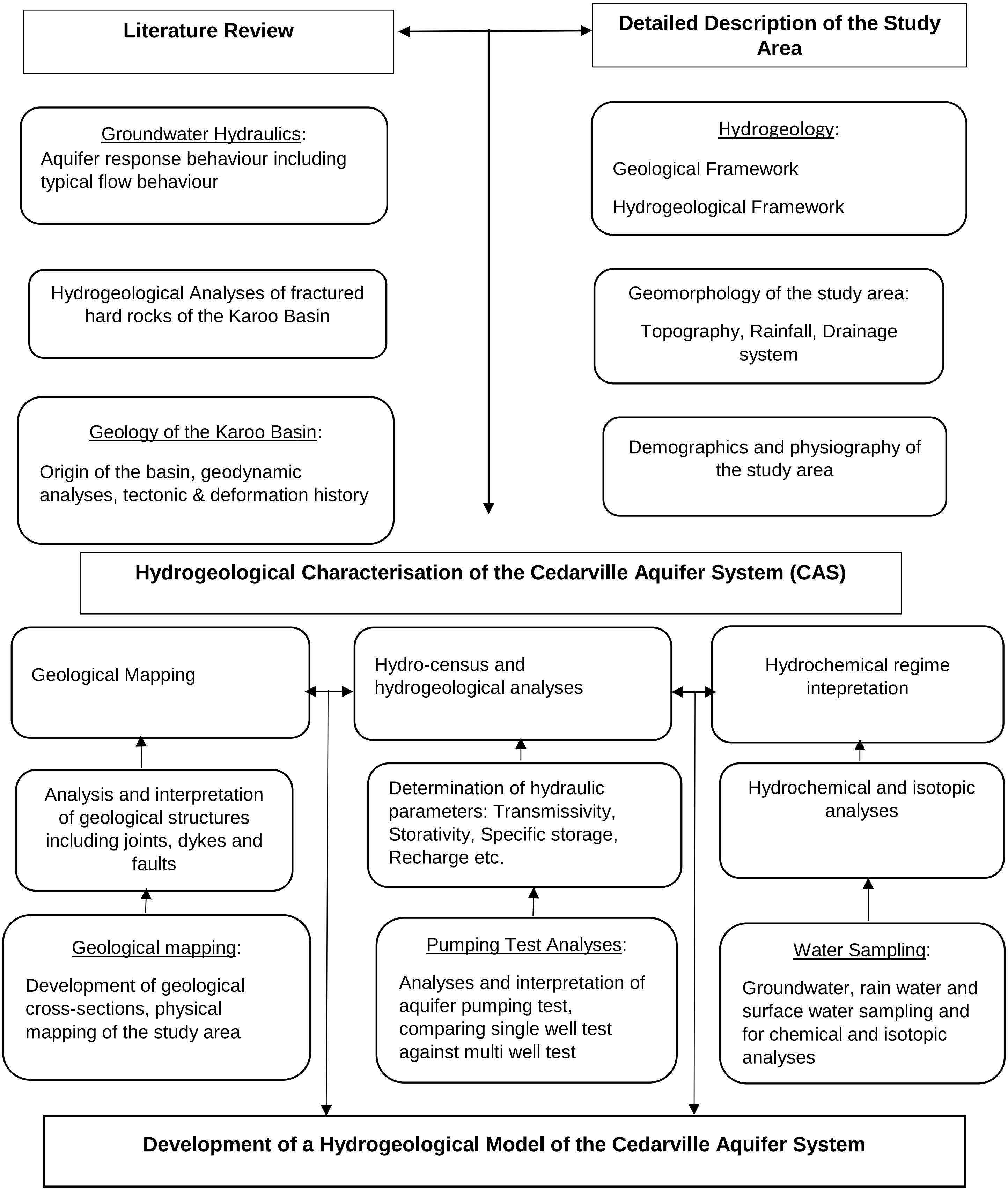
APPENDIX A: Graph of average monthly precipitation for a 100-year period (1920 – 2021) of Cedarville Area



APPENDIX B: Methodology framework for the characterisation of the Cedarville Aquifer System



APPENDIX C: Cedarville hydrocensus data

Borehole Number	Longitude	Latitude	Depth (m)	Water Strike Depth (m)	Yield (l/s)	Water Level (m) bgl
EC-T31-136	29°01´54.16"	30°23´35.34"	95,27	43	8,22	17
EC-T31-141	29°02´40.2"	30°23´24.40"	99,21	57	5,56	21
Black Diamond	28°57´13.0"	30°15´26.32"	65	31	0,5	14
Open Hole	29°01´45.05"	30°23´33.36"	62	37	2,26	13
KK1	29°02´50.03"	30°23´16.91"	75	33	1,3	5,5
EC-T31-321	29°03’11.1”	30°23’16.9”	120	62,92	10	20,1
Fm#1	29°07´24.27"	30°23´58.82"	130	85	12	21
Fm#2	29°09´13.69"	30°16´34.82"	115	72	5	17
Fm#3	29°08´38.31"	30°19´34.82"	120	91	8	15
Fm#4	29°04´30.79"	30°18´23.89"	112	73	7	17
EC-T31-239	29°01´57.65"	30°22´53.62"	130	111	6	12,19
EC-T31-240	29°01´27.01"	30°23´03.88"	57	24	1,3	6,88
EC-T31-241	29°03´11.02"	30°23´16.58"	96	63	5	15,29
EC-T31-247	29°12´40.90"	30°24´27.25"	55	17,8	1	2,3
EC-T31-248	29°12´23.72"	30°24´24.62"	80	46	3,5	3,7
EC-T31-244	29°16´16.07"	30°18´01.62"	72	38,52	1,8	2,62
EC-T31-250	28°53´47.51"	30°12´33.19"	110	74	4,5	2,02
BH#1	28°57´42.80"	30°18´56.64"	80	33	1,6	13
BH#2	28°57´28.22"	30°15´03.28"	47	22	0,2	15
EC-T31-336	28°57´28.22"	30°15´03.28"	60	35	0,8	17
EC-T31-340	28°57´33.01"	30°16´23.92"	130	104	5	66,63
S1	29°02’40.6”	30°21’33.8”	55	31	1,38	12
S2	29°06’05.9”	30°18’54.0”	76	42	1,1	7
S3	29°02’00.1”	30°20’19.0”	145	73	6,6	15
Nt-BH	29°01’45.4”	30°23’33.5”	80	35	0,8	17
BH#3	29°14’13.04”	30°21’31.97”	132	89	7	19
BH#4	29°11’09.80”	30°22’17.68”	120	77	8,2	14
BH#5	29°14’51.55”	30°19’52.66”	55	29	0,8	6,4
BH#6	29°07’54.29”	30°23’42.8”	73	32	1,1	13
BH#7	29°05’21.56”	30°19’58.63”	125	106	7,4	19

APPENDIX D: Lithological Logs

Borehole: EC-T31-239

Depth (m)	Lithological description	Water Strikes
0 - 3	**Sandy-Clay**: Dark greyish-brown sand-clay topsoil	
3 -48	**Alluvium**: Greyish-brown, medium to fine-grained clay-sand	Water strikes @ 30 m of 0.8 l/s
48 - 69	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	
69 - 83	**Dolerite**: Dark grey, fractured medium to coarse-grained dolerite with quartz vein	
83 - 92	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	Water strike @ 90 m of 9.8 l/s
92 - 110	**Dolerite**: Dark grey, fractured medium to coarse-grained dolerite with quartz vein	
110 - 120	**Mudstone**: Greyish-brown, highly fractured mudstone with abundant quartz and calcite veins	
120 - 130	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	

Borehole: EC-T31-241

Depth (m)	Lithological description	Water Strikes
0 - 5	**Sandy-Clay**: Dark greyish-brown sand-clay topsoil	
5 -34	**Alluvium**: Greyish-brown, medium to fine-grained clay-sand	Water strikes @ 34 m of 1.2 l/s
34 - 52	**Mudstone**: Greyish-brown, fractured mudstone with abundant quartz and calcite veins	
52 - 72	**Sandstone**: Greyish-brown, fractured and weathered, coarse grained sandstone with abundant quartz veins	Water strike @ 60 m of 4.8 l/s
72 - 78	**Dolerite**: Dark grey, fractured medium to coarse-grained dolerite with quartz vein	
78 -96	Sandstone: Grey, highly weathered and fractured, medium to coarse-grained sandstone with abundant quartz vein	

Borehole: EC-T31-321

Depth (m)	Lithological description	Water Strikes
0 - 5	**Sandy-Clay**: Dark greyish-brown sand-clay topsoil	
5 -31	**Alluvium**: Greyish-brown, medium to fine-grained clay-sand	Water strikes @ 30 m of 0.8 l/s
31 - 50	**Mudstone**: Greyish-brown, highly fractured mudstone with abundant quartz and calcite veins	
50 - 55	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	
55 - 65	**Mudstone**: Greyish-brown, highly fractured mudstone with abundant quartz and calcite veins	
65 - 72	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	
72 - 83	**Mudstone**: Greyish-brown, highly fractured mudstone with abundant quartz and calcite veins	
83 - 90	**Sandstone**: Grey, fractured and weathered, coarse-grained sandstone with abundant quartz veins	Water strike @ 90 m of 9.8 l/s
90 - 120	**Dolerite**: Dark grey, fractured medium to coarse-grained dolerite with quartz vein	

APPENDIX E: Chemical analyses results and Ion Balance Calculation

Ion Balance = $\frac{(\sum \text{Cation} - \sum \text{Anion})}{(\sum \text{Cation} + \sum anion)}$ x 100%

Borehole EC-T31-141: Major ion analysis			Ion Balance = 5.4%		
Inferred from SRK Reports: Lab – Pollution Technologies Laboratory in East London					
pH = 7.76; Temperature = 19.5°C, EC = 29.8 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	30.4	1,3224	HCO_3^{2-}	346	5,67094
K^{+}	0.76	0,0194332	Cl^{-}	2.7	0,076167
Ca^{2+}	51.2	2,55488	SO_4^{2-}	7	0,14574
Mg^{2+}	32.4	2,665224			
Fe^{2+}	0.21	0,0075201			
Total		6,5694573	Total		5,892847

Borehole EC-T31-136: Major ion analysis			Ion Balance = 3.74%		
Inferred from SRK Reports: Lab – Pollution Technologies Laboratory in East London					
pH = 7.16; Temperature = 21°C, EC = 40.2 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	12.8	0,5568	HCO_3^{2-}	402	6,58878
K^{+}	0.76	0,0194332	Cl^{-}	4.5	0,126945
Ca^{2+}	83.9	4,18661	SO_4^{2-}	9	0,18738
Mg^{2+}	32.4	2,665224			
Fe^{2+}	0.35	0,0125335			
Total		7,4406007	Total		6,903105

Borehole EC-T31-321: Major ion analysis			**Ion Balance = 6.14%**		
Inferred from AGES Reports: Lab – Talbot & Talbot Laboratory in Pietermaritzburg					
pH = 7.6; Temperature = 18°C, EC = 91.0 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	78	3,393	HCO_3^{2-}	435	7,12965
K^{+}	1.6	0,040912	Cl^{-}	21	0,59241
Ca^{2+}	56	2,7944	SO_4^{2-}	12.5	0,26025
Mg^{2+}	34	2,79684			
Fe^{2+}	0.06	0,0021486			
Total		9,0273006	Total		7,98231

Borehole S1: Major ion analysis			**Ion Balance = 4.33%**		
Sampled during the research study: BCM Scientific Services Laboratory in East London					
pH = 7.12; Temperature = 19.9°C, EC = 78.5 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	39	1,6965	HCO_3^{2-}	407	6,67073
K^{+}	0.85	0,0217345	Cl^{-}	19	0,53599
Ca^{2+}	89.42	4,462058	SO_4^{2-}	2.82	0,058712
Mg^{2+}	21.17	1,7414442			
Fe^{2+}	0.065	0,00232765			
Total		7,92406435	Total		7,265432

Borehole S3: Major ion analysis			Ion Balance = 1.64%		
Sampled during the research study: BCM Scientific Services Laboratory in East London					
pH = 7; Temperature = 22°C, EC = 31.2 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	39	2,7405	HCO_3^{2-}	407	2,73713
K^{+}	0.85	0,0015342	Cl^{-}	19	0,25389
Ca^{2+}	89.42	0,435627	SO_4^{2-}	2.82	0,137204
Mg^{2+}	21.17	0,053469			
Fe^{2+}	0.065	0,0014324			
Total		3,2325626	Total		3,128224

Borehole Nt-BH: Major ion analysis			Ion Balance = 5.32%		
Sampled during the research study: BCM Scientific Services Laboratory in East London					
pH = 6.9; Temperature = 18.7°C, EC = 42.3 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	34	1,479	HCO_3^{2-}	239	3,91721
K^{+}	0.44	0,0112508	Cl^{-}	5	0,14105
Ca^{2+}	37.22	1,857278	SO_4^{2-}	3.53	0,073495
Mg^{2+}	15.17	1,2478842			
Fe^{2+}	0.024	0,00085944			
Total		4,59627244	Total		4,131755

Borehole Sr1: Major ion analysis			Ion Balance = -0.48%		
Rain - Sampled during the research study: BCM Scientific Services Laboratory in East London					
pH = 7.3; Temperature = 17°C, EC = 4.9 mS/m					
Cation Analysis			**Anion Analysis**		
Cation	**Conc (mg/l)**	**Conc (meq/l)**	**Anion**	**Conc.(mg/l)**	**Conc.(meq/l)**
Na^{+}	ND	0	HCO_3^{2-}	22	0,36058
K^{+}	0.21	0,0053697	Cl^{-}	**1**	0,02821
Ca^{2+}	8.15	0,406685	SO_4^{2-}	1.31	0,027274
Mg^{2+}	ND	0			
Fe^{2+}	ND	0			
Total		0,4120547	Total		0,416064

Note: ND = Not Detectable

Geometric mean calculation

Calculation of the geometric mean of the Cl^{-} concentration in groundwater sampled from the Cedarville aquifer System:

Geometric Mean = $(2.7mg/l \times 4.5mg/l \times 21mg/l \times 19mg/l \times 9mg/l \times 5mg/l)^{1/6}$

= 7,76 mg/l