INVESTIGATING THE POSSIBILITY OF USING GROUNDWATER ASSOCIATED WITH DOLERITE STRUCTURES TO AUGMENT THE MUNICIPAL WATER SUPPLY TO THE CITY OF BLOEMFONTEIN – INVESTIGATIONS IN THE CENTRAL BUSINESS DISTRICT

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DECLARATION

I, Manthofeela Christinah MAKOAE, hereby declare that the dissertation hereby submitted by me to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State, in fulfilment of the degree of Magister Scientiae, is my own independent work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

I furthermore cede copyright of the dissertation and its contents in favour of the University of the Free State.

Manthofeela Christinah MAKOAE

26 January 2018

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1:
INTRODUCTION

1.1 GENERAL

Bloemfontein lies in the semi-arid region in the Mangaung Metro Municipality (MMM) in the Free State Province of South Africa. The city currently relies on surface water resources that are unreliable and vulnerable to impacts of drought. The water supply to this municipality is currently through three schemes, namely: 1) the Caledon-Bloemfontein Transfer Scheme, 2) the Maselspoort Scheme, and 3) the Caledon-Modder Transfer Scheme (DWA, 2012). Most of the municipality water supply reaches Bloemfontein through the first of these three schemes.

The MMM also purchases water from the Lesotho Highlands Water Project at the Katse Dam. This water is pumped over a large distance to the reservoirs of the city. As a result, only 40% of this water reaches the destination, and 60% gets lost along the way due to leakage of pipelines transporting water to Bloemfontein and illegal connections (DWAF, 2012). The supply of potable water has declined significantly in recent years due to different developmental, demographic and geological factors such as urbanisation, population growth, and high sedimentation rates of dams and rivers. In most cities, including Bloemfontein, surface water from the rivers and dams is utilised for general consumption; however, the current supply seems to be depleting. The supply is negatively impacted by rapid population growth that is triggered by economic growth as a result of agricultural activities, industrial development as well as public service delivery.

In 2014, a project was jointly launched by Bloemwater and the MMM to investigate the possibility of augmenting the municipal water supply from groundwater resources. This project was launched due to the interest in uncovering a viable alternative to address the water scarcity in Bloemfontein. Groundwater is the most accessible and reliable resource for fresh water on Earth. Approximately two thirds of the population in South Africa relies on groundwater for domestic purposes (Adams, 2011). Currently in Bloemfontein, groundwater is mostly used by the private individuals, institutions and companies for small-scale agriculture, gardening and commercial activities (car washes) (refer to Section 5.2). Therefore, there is a potential to utilise this resource in augmenting surface water resources in order to meet the existing water demand. The groundwater resources offer a number of advantages over surface water sources, including (DWA, 2010):

- It is a proximal resource that does not require pumping over great distances,
- It is more resistant to the effects of drought,

- The natural quality of groundwater is usually good, and,
- The groundwater resource can be developed incrementally as the need for water increases.

The city of Bloemfontein is located within the Beaufort Group of the central Karoo Basin of South Africa. The city is underlain by the Karoo Supergroup sedimentary rocks which are characterised by low groundwater potential which is also the case throughout the Karoo Supergroup. However, dolerite intrusions underlie much of the city and its surroundings. These intrusions are due to the extensive magmatism that occurred in the Karoo Basin during the Jurassic Period (approximately 180 Ma) (McCarthy and Rubidge, 2005). Doleritic magmas intruded the sedimentary rocks along zones of crustal weakness and solidified to form linear dykes and near-horizontal sills. During the intrusion, the temperature and pressure was high enough to cause alteration of country sedimentary rocks, resulting in an enhanced groundwater potential of the Karoo rocks within the proximity of the intrusive bodies.

Due to the expected higher yields of aquifers associated with dolerite intrusions, groundwater exploration programmes in the city should focus on the detection and delineation of dolerite structures in order to identify drilling positions with a high likelihood of success. The current study focusses on detection and delineation of a prominent dolerite dyke-structure underlying the CBD of Bloemfontein.

1.2 HISTORICAL BACKGROUND

The city of Bloemfontein is located within the Mangaung Metro Municipality (MMM) in the Free State Province of South Africa. Bloemfontein was named after a strong spring that was discovered by Johannes Brits in 1928. Due to the presence of the beautiful flowers and the presence of the fore-mentioned spring, the city gained its name Bloemfontein from the Great Trek Boers.

According to Roberts (1950), a certain Mr. Norman investigated the geological setting of the spring though he was not a geologist and proposed the theory that the spring was associated with an intrusive ring-dyke which he referred to as a barrier reef. In 1880, the spring was supplying approximately 100 000 gallons of water per day to a population of almost 2 000 Europeans who were living in that area. The construction of a concrete dam was later done along the barrier reef for water supply (van der Merwe, 2014). This spring is no longer visible due to urbanization but one can trace its existence by the flowing stream along the concreted channel that was erected at the location of the spring after which the city was named (Figure 1).

In 1984, Major Warden had a desire to transport water from this spring for half a mile along the south bank to be used by the Garrison. This was accomplished by means of an open furrow which functioned as a tunnel across the Presidency garden. Roberts (1950) stated that a concrete tower that had been built around the spring was constructed to prevent the spring from submerging. This spring is located in a storm water canal within the boundaries of the study area, on the south-eastern side of the Loch Logan Mall.

Figure 1: Concrete structure erected by the Mangaung Metro Municipality at the location of the spring after which the city of Bloemfontein was named adapted from Bloemwater, 2012)

1.3 PROBLEM STATEMENT

The current study investigates the possibility of using groundwater associated with a prominent dolerite ring-dyke to augment the municipal water supply to the city of Bloemfontein. Since the ring-dyke underlies urban and industrial areas of the city, the first obstacle is to locate and delineate the structure. Geophysical methods typically used for mapping dolerite structures, such as the magnetic, electromagnetic (EM) and resistivity methods, are all affected by noise associated with urban and industrial developments. This noise may be in the form of metal infrastructure at surface or in the subsurface, EM radiation from the power grid and other current-carrying sources, and electrical currents in the subsurface due to leakages from buried electrical wires. Detecting and delineating the ring-dyke in the presence of such noise pose a major challenge to the current investigation.

Assuming that the position and orientation of the ring-dyke can be determined, a further challenge relates to the groundwater potential of the possible aquifers associated with the dyke. To assess the possibility of utilising groundwater from such aquifers in a sustainable manner, information on the hydraulic properties of the rock formations hosting the aquifers is required. Obtaining such information in an urban and industrial setting is another significant impediment to the assessment of the aquifer potential and the determination of a sustainable groundwater abstraction rate.

In addition, the quality of groundwater from the potential aquifers needs to be assessed to determine its suitability to augment the municipal water supply. Since the ring-dyke underlies urban and industrial areas of the Bloemfontein CBD, numerous sources of contaminants could have had impacts on the groundwater quality. Such sources include: petroleum products from underground storage tanks at a number of petrol stations, contaminants from caskets and decomposing human remains at a cemetery, contaminated runoff in the storm water canals seeping into the subsurface, contaminated surface water bodies recharging the aquifers, and sewerage from damaged sewer pipes. These potential contaminant sources are all localised and site-specific, making an assessment of the groundwater quality of aquifers associated with the ring-dyke a difficult task.

Furthermore, based on the results of groundwater quality assessment, recommendations for possible water treatment options will be required before the groundwater can be used to augment the municipal water supply. These water treatment options should be robust and should take into account impacts from the diverse potential contaminant sources with very different contaminant signatures.

Moreover, if the groundwater is to be used to augment the municipal water supply, a groundwater monitoring programme will be required to monitor changes in the hydraulic heads of the aquifers, as well as changes in the groundwater quality. Based on the results of the monitoring programme, adaptive management strategies will have to be developed and implemented to ensure that the aquifer is not overexploited and that the quality of the water supplied to the municipality remains suitable for its intended purpose.

The current investigations aim to address the challenges described above.

1.4 AIM AND OBJECTIVES

The aim of the research is to investigate the possibility of using groundwater associated with a known dolerite ring-dyke that underlies the city of Bloemfontein to augment the water supply to the MMM. To address the aim of this research project, the objectives of the study are:

- To detect and delineate the dolerite ring-dyke known to underlie the city of Bloemfontein.
- To investigate the association of the ring dyke with groundwater resources.
- To investigate the current use of groundwater from aquifers associated with the ring-dyke.
- To investigate the hydraulic properties of the aquifers to determine the quantities of water that can be sustainably abstracted from the aquifers.

- To investigate the quality of the groundwater associated with the ring-dyke to assess its suitability for human consumption and other municipal applications.
- To suggest water treatment options to render the groundwater suitable for its intended municipal use,
- To estimate and recommend the abstraction rate from the aquifers for sustainable use of the groundwater associated with the ring-dyke.
- To develop a monitoring programme for early detection of changes in the hydraulic heads and groundwater quality.
- To make recommendations for adaptive management practices to ensure the sustainable use of the groundwater resource associated with the ring-dyke.

1.5 RESEARCH METHODOLOGY

To achieve the aim and objectives of this study, the following research methodology was followed:

- Literature on the geology and geohydrology of the Karoo Supergroup was reviewed in order to gain insight into the occurrence and properties of aquifers within the Karoo rock. Specific focus was placed on the aquifers associated with intrusive dolerite structures, such as ring-dykes. The literature reviews further focussed on the water demand in South Africa, and in particular in the Mangaung Metro Municipality, as well as on groundwater use in the country. Lastly, literature relevant to the use of geophysical methods for groundwater exploration in Karoo rocks was reviewed.
- A desktop study was conducted to characterise the study area in terms of the geological, geohydrological, climatic and topographical conditions, as well as the surface infrastructure. During the desktop study, satellite images covering the study area were inspected to identify visible surface features that may indicate the presence of the ring-dyke. An airborne magnetic map obtained from the Council of Geosciences was also studied to identify prominent magnetic structures within the study area that may indicate the presence of the ring-dyke.
- A ground geophysical survey was conducted to detect and delineate the ring-dyke within the study area using the magnetic and electrical resistivity tomography (ERT) methods. The ground geophysical survey was severely restricted by the presence of surface infrastructure.
- Based on the results of the geophysical investigations, recommendations for the installation of boreholes at suitable positions were made. These boreholes could potentially serve as

investigative boreholes (to assess the geohydrological conditions and aquifer parameters), production boreholes (if high-yielding), and monitoring boreholes.

- A hydrocensus was conducted to investigate the presence of existing groundwater users in the vicinity of the ring-dyke. Groundwater samples were collected from the identified boreholes.
- The groundwater samples were submitted to an accredited laboratory for chemical analyses. The results of the chemical analyses were studied to evaluate the groundwater quality in terms of its suitability for domestic and other municipal uses.
- Based on the results of the chemical analyses recommendations for water treatment options were made.

It should be noted that the initial scope of the research project extended beyond the actions listed above. As part of the initial scope of the project, boreholes were to be installed at the positions proposed from this study. These boreholes would have allowed hydraulic tests to be performed on the aquifers, as well as sampling of the groundwater from the aquifers. From this information, the sustainable yield of the aquifer was to be estimated and the suitability of the groundwater for municipal use was to be assessed. However, due to delays resulting from disagreements between the MMM and Bloemwater, the boreholes have not yet been drilled. This restricted the current investigations and forced the indirect assessment of the potential of using the groundwater associated with the dyke for municipal use by considering data collected at privately owned boreholes. This should be seen as a limitation of the current study, but was beyond the control of the researcher.

1.6 STRUCTURE OF THE DISSERTATION

The dissertation is structured as follows:

Chapter 1 is the introduction of the study, in which the background of the study area, the problem statement, the aims and objectives of the study are highlighted.

Chapter 2 is a literature review in which the work that has been initiated in Bloemfontein by the other researchers relative to the supply of water to Bloemfontein, the geology of the Karoo Basin, geohydrology of the Karoo Basin, water supply and demand in Bloemfontein, the groundwater use in South Africa, sustainable groundwater management and the geophysical investigations are discussed.

Chapter 3 gives a detailed description of the study area. The regional setting, geological setting, regional magnetic setting, the surface hydrology, geohydrology, climatology and the socio economic description are discussed.

Chapter 4 details the results of a hydrocensus conducted in the vicinity of the ring-dyke.

Chapter 5 describes the ground geophysical investigations that were conducted within the study area as well as the results of these investigations.

Chapter 6 describes the hydraulic test that was performed as part of the investigations to assess the hydraulic parameters of the aquifer system associated with the ring-dyke.

Chapter 7 discusses the results of hydrochemical analyses performed on groundwater samples from the boreholes identified during the hydrocensus.

In **Chapter 8** a groundwater monitoring and management programme is proposed to prevent over-exploitation of the aquifer system while ensuring the safe use of the groundwater for its intended purposes.

Finally, in **Chapter 9**, conclusions are drawn based on the results of the research and recommendations for future actions are made.

CHAPTER 2:
LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, literature relevant to the current research is reviewed. Since the research deals with groundwater exploration in an urban environment (the Mangaung Metro Municipality, MMM), in an area underlain by rocks of the Karoo Supergroup intruded by a dolerite ring-dyke, the literature review focusses on:

a) the geology and geohydrology of the Karoo Supergroup, with specific emphasis on the dolerite intrusions and their influence on the aquifer systems found in Karoo rocks (Sections 2.2 to 2.4),
b) the water supply and demand in South Africa and the MMM (Section 2.5),
c) the current use of groundwater in South Africa and the sustainable management of the groundwater resource (Sections 2.6 and 2.7), and,
d) the geophysical techniques used during the current investigations to detect and delineate the dolerite structure (Section 2.8).

2.2 GEOLOGY OF THE KAROO SUPERGOUP

2.2.1 Introduction

The rocks of the Karoo Basin were deposited between the ages of Late Carboniferous to Middle Jurassic (McCarthy and Rubidge, 2005) (Figure 2) and have a cumulative thickness of almost 12 km in the south-eastern portion of the main Karoo Basin towards the eastern end of the Karoo Trough (Johnson *et al.*, 2009). The basin covers an area of approximately 700 000 km² and is filled with clastic and subordinate igneous rocks belonging to the Karoo Supergroup.

According to Botha *et al. (*1996) the Main Karoo Basin is underlain by the Kaapvaal Craton in the northern parts and the Namaqua-Natal Metamorphic Belt in the southern parts (McCarthy and Rubidge, 2005) together with a fold-thrust binding it along its southern margin (see Figure 3). The history behind this fold-thrust is derived from the continental drifting of the Gondwanaland. This resulted in the uplifting of the southern part of Africa, forming the escarpment. This escarpment has a bulgy crust in comparison to the interior of the basin (Johnson *et al*., 2009).

The rocks of the Karoo Basin have been divided in five groups which were deposited at different ages (from Late Carboniferous to Early Jurassic periods) (McCarthy and Rubidge, 2005) with different depositional history. The deposition of these groups will be sequentially elaborated on in this section.

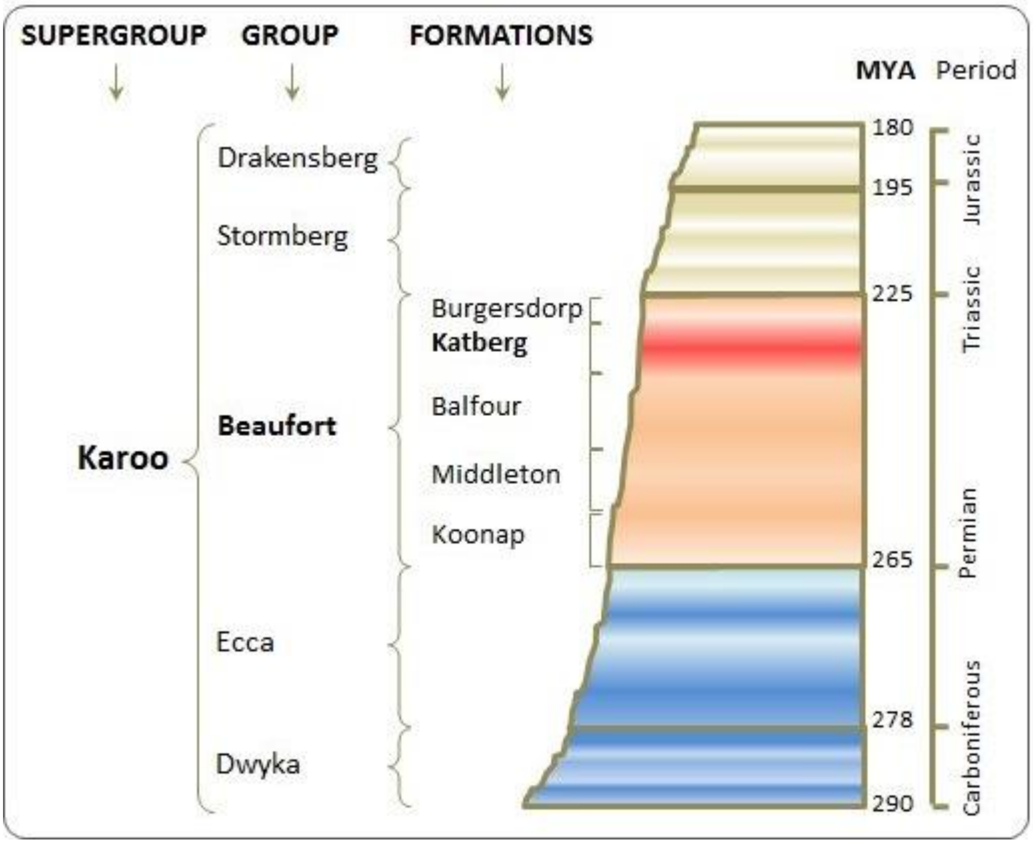

Figure 2: Geological succession of the Karoo Supergroup (adapted after McCarthy and Rubidge, 2005)

2.2.2 Dwyka Group

The Dwyka Group forms the basal part of the Karoo Basin (Johnson *et al.*, 2009). It is underlain unconformably by the rocks of Cape Supergroup in the south and the Natal Group in the east (Figure 4). This group was deposited under a glacial environment forming the first deposits of the Karoo Supergroup in the Late Carboniferous to Early Permian Period (Johnson *et al*., 2009; McCarthy and Rubidge, 2005). This group mainly consists of massive diamictite with some substantial jointing and stratified in some areas (Botha *et al.*, 1998). According to McCarthy and Rubidge (2005), Johnson *et al.* (2009) and Botha *et al.* (1998), other subordinate associate rocks to the diamictite, such as sandstone, rhythmites, conglomerate and mudstone, can be recognised in this group.

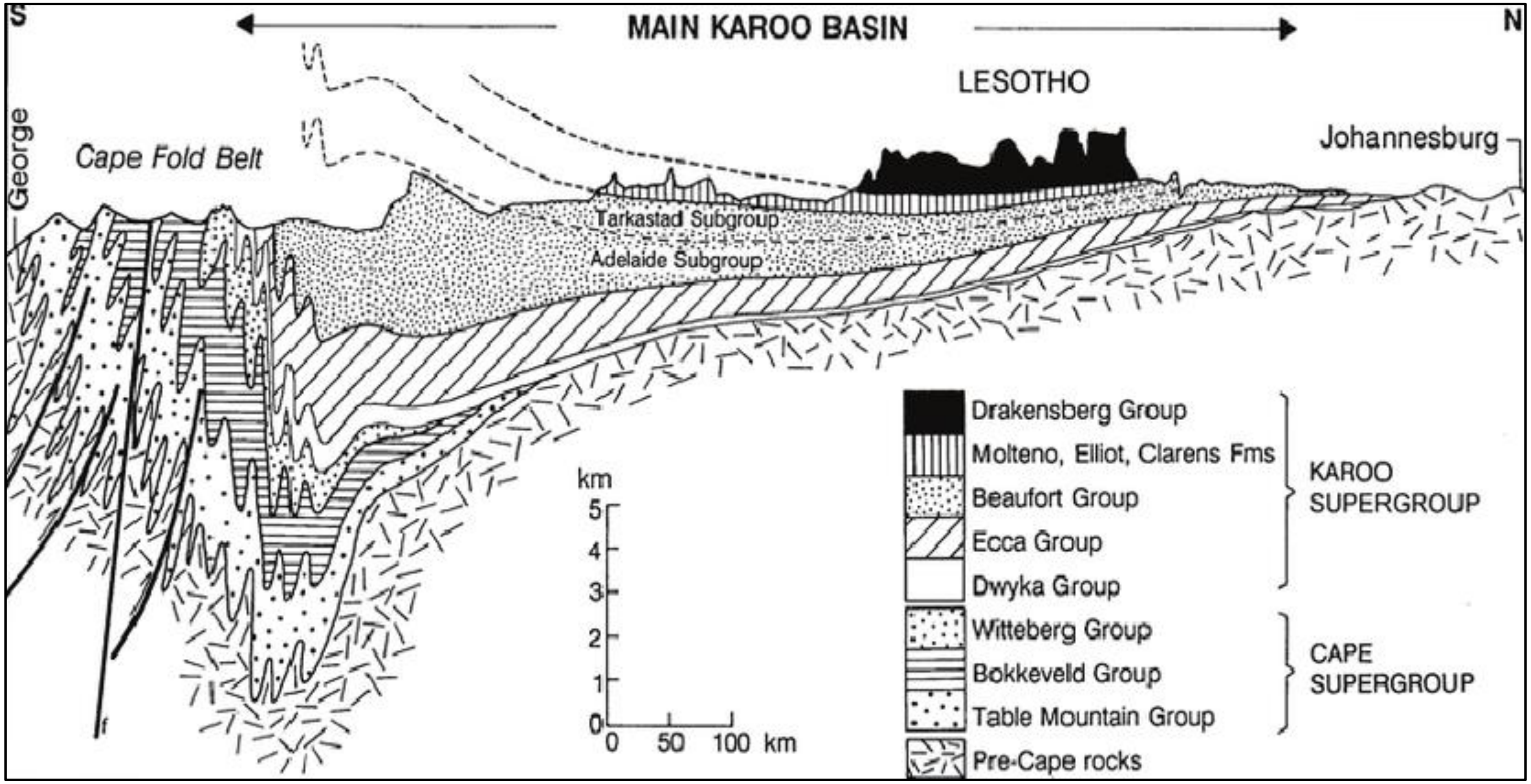

Figure 3: Cross-section through the Main Karoo Basin (adapted from Woodford and Chevallier, 2002)

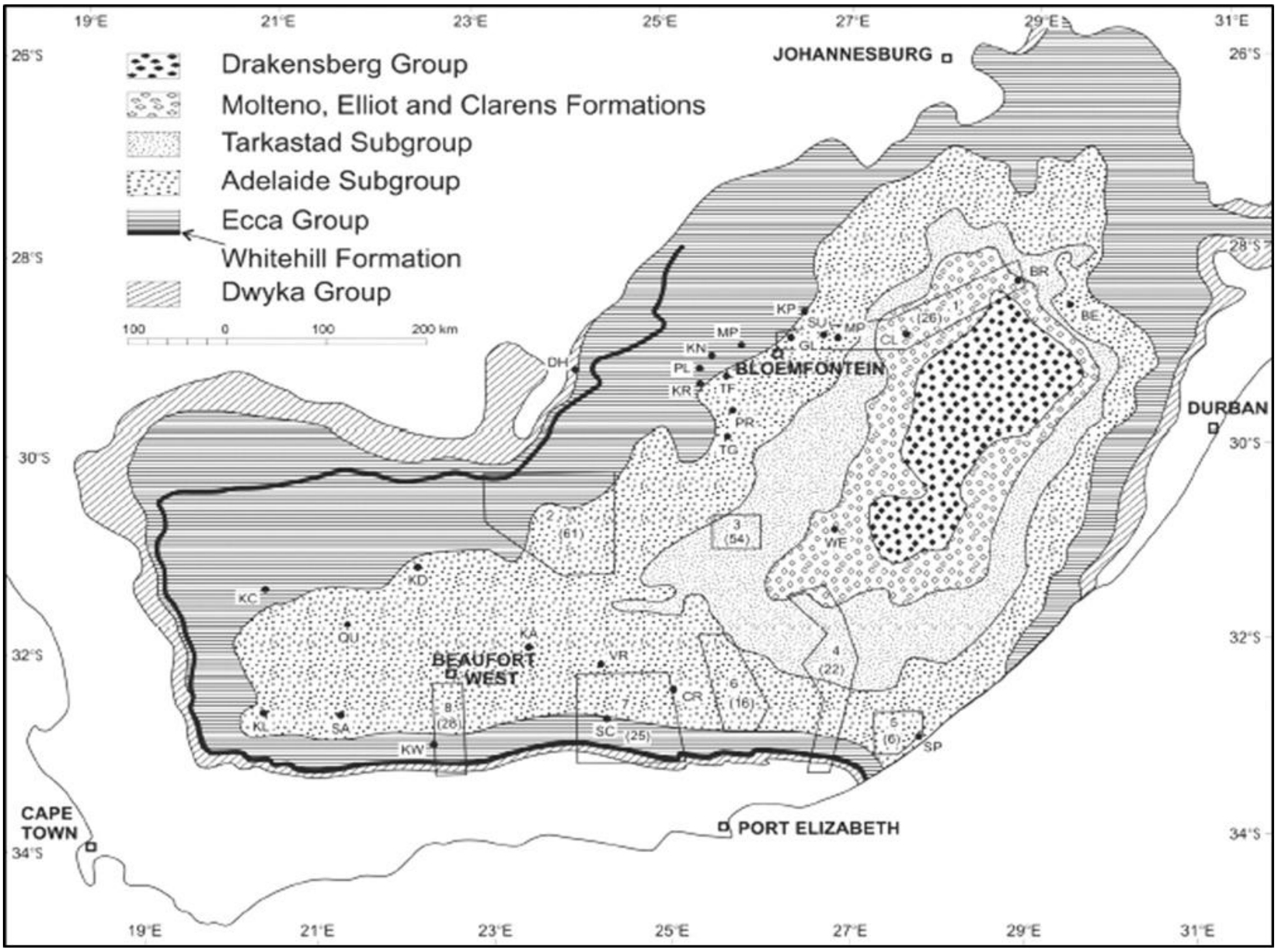

Figure 4: Surface distribution of the geology units of the Karoo Supergroup (adapted from Johnson *et al.*, 2009)

2.2.3 Ecca Group

The Ecca Group was deposited during the Early Permian Period (Von Brunn, 1994; Johnson *et al*., 2009), and comprises a total number of 16 formations (Johnson *et al*., 2009). These formations reflect lateral changes in facies that are indicative of succession during deposition, except for the Prince Albert and Whitehill Formations which show different characteristics (Johnson *et al*., 2009).

The White Hill and Prince Albert Formations which form the basal sediments in the southern, western and north-western regions of the basin (Figure 4) will be briefly discussed. The discussion of the other formations that form the southern part of the basin (namely the Collingham, Vischkuil, Laingsburg, Ripon, Fort Brown and Waterford Formations) will be followed by the western and northern deposits of the Tierberg, Skoorsteenberg, Kookfontein and the north-eastern Pietermaritzburg, Vryheid and Volkrust Formations.

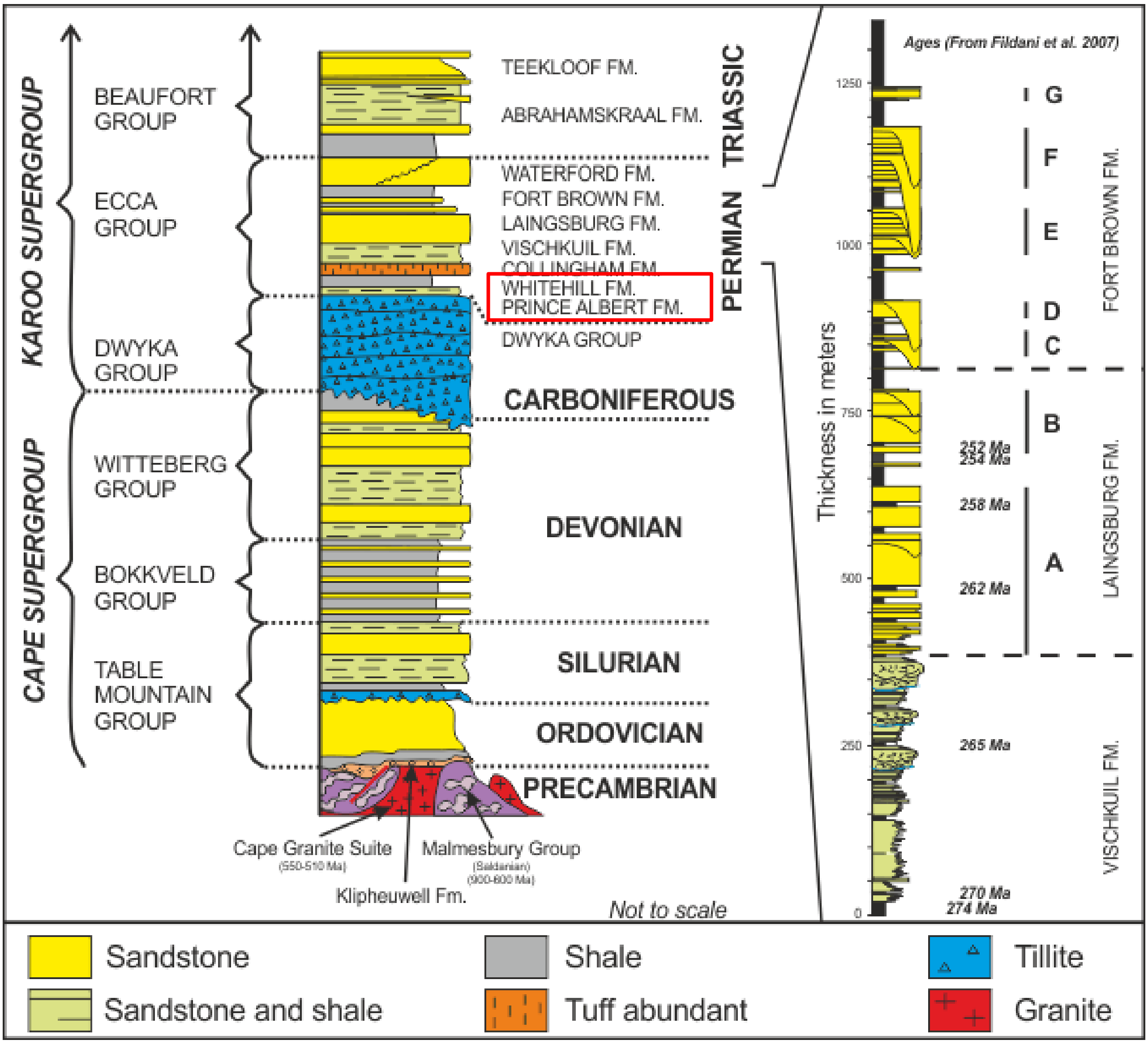

Figure 5: Geology of Karoo Basin and the underlying Cape Supergroup (adapted from Flint *et al.*, 2011)

2.2.3.1 Whitehill Formation

The Whitehill Formation is named based on its appearance at outcrop resulting from the precipitation of gypsum during weathering. A fresh surface reveals millimetre-scale layering of dark grey to black silt and mud, suggesting a high organic content and a probable anoxic conditions during deposition (Johnson *et al*., 2009).

In fresh outcrops and in the subsurface, the predominant facies is black, carbonaceous, pyrite-bearing shale. The shale deposits are very thinly laminated and contain up to 17% organic carbon (Johnson *et al*., 2009). The thickness of the Whitehill Formation varies from 10 m to 80 m towards the north-east. Its lower parts comprise siltstone and very fine-grained sandstone.

2.2.3.2 Prince Albert Formation

The formation is confined to the south-western half of the Main Karoo Basin. Towards the north-east, it thins and locally pinches out against the basement or merges into the Vryheid and Pietermaritzburg Formations (Johnson *et al.,* 2009). The Prince Albert Formation comprises northern and southern facies; the northern facies are characterised by significant greyish to olive-green micaceous shale and grey silty shale, as well as pronounced transitions to the underlying glacial deposit (Smith, 1990). The southern facies is characterised by the preponderance of dark-grey, pyrite-bearing, splintery shale and the presence of dark-coloured chert and phosphatic nodules and lenses.

2.2.3.3 Collingham Formation

The thickness of the Collingham Formation ranges between 30 and 70 m This formation is composed of alternations of thin rhythmic, continuous beds of about 5 cm of hard, dark-grey siliceous mudrock and very thin beds at an average of 2 cm soft yellowish tuff (Figure 6).

Subsidiary sandstone and siltstone units are observed to occur within the upper half of the formation with the Matjiesfontein Chert Bed occupying the lower half at a thickness of about 0.2 to 0.6 m (Tankard *et al*., 2009) .Deposition in this formation was due to traction-current, suspension, low-density distal turbidity currents and air fall-out resulting into the deposition of trace fossils, fine-grained lateral beds, thin sandstone and siltstone layers and tuff layers, successfully (Johnson *et al.,* 2009).

2.2.3.4 Vischkuil Formation

The Vischkuil formation overlies the Collingham Formation in the south-western part of the basin, with the thickness that varies from between 200 and 400 m (Johnson *et al*., 2009). The type of lithology that formed this formation is dark shales, alternating with subordinate sandstones, siltstones and some subsidiary yellowish tuff layers (Johnson *et al*., 2009). Laminations, bedding structures and contact zones (Botha et al.,) are mostly observed in the sandstones with some sedimentary marks such as load casts and sole marks indicative of gravity-flow deposition in a basin plain to outer basin-floor fan environment (Johnson *et al*., 2009).

The evidence of volcanic and seismic activities during the deposition of this formation is indicated by the ash layers and large-scale slumped beds. However, there might have been normal suspension deposition due to the presence of the minor mudrock in this formation (Botha *et al*., 1998).

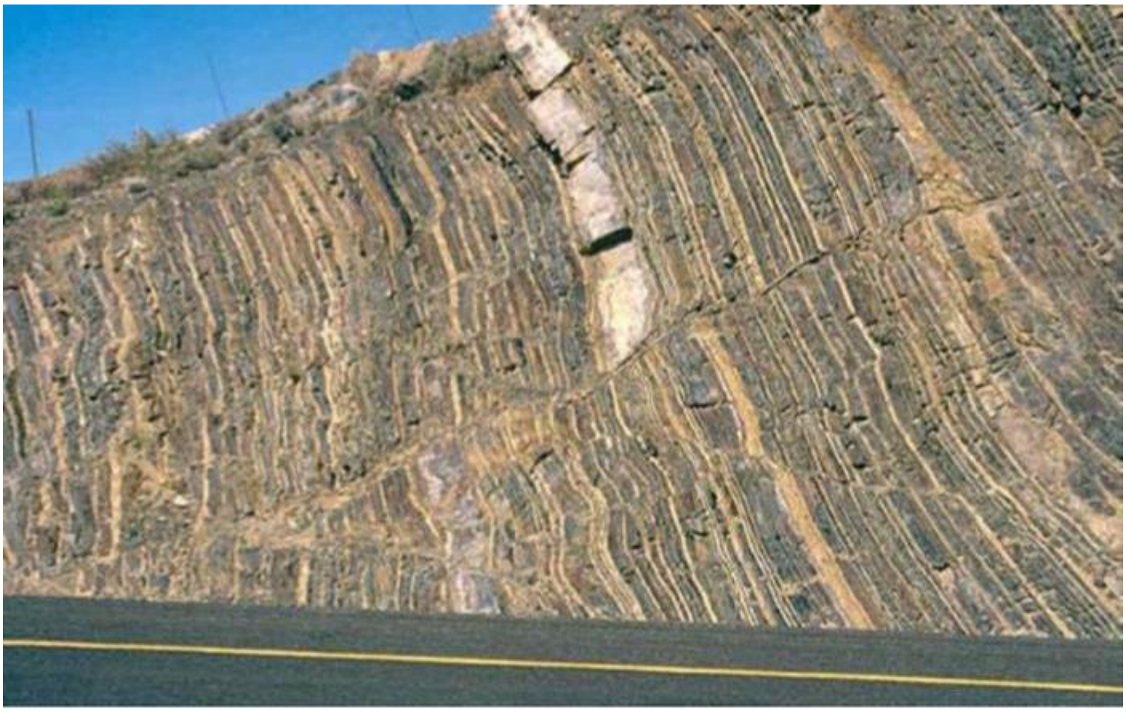

Figure 6: Collingham Formation exposed along the road cutting at Western Laingsburg, South of the Karoo Basin. The yellow beds are altered volcanic tuff interlayed with mudrock and chert is displayed by a whitish thick bed (adapted from Catuneanu, 2005)

2.2.3.6 Laingsburg Formation

The Laingsburg Formation overlies the Vischkuil Formation and wedges towards the west and north. The fine- to medium-grained massive sandstones, dark planar-planar laminated shales that are mostly consisting of lenticular calcareous concretions and some siltstone are rocks that are found within this formation. The formation comprises of abundant plant material mostly in the upper parts. The abundance of sedimentary structures such as contact zones, bedding structures, flame structures, fluid scour marks and load, flute and groove casts along the sandstones grading upwards into planar-laminated siltstones and shale can be observed. The sandstones contain dewatering structures and calcareous concretions and some fish and arthropod trackways are commonly found on the bedding surfaces. The high-turbidity currents along the delta-front indicative of the traction structures and visible grading in the thick-bedded sandstones are responsible for the deposition of this formation (Johnson *et al*., 2009).

2.2.3.6 Ripon Formation

The Ripon formation is subdivided in to Pluto's Vale Member, middle Wonderfontein Member and upper Trumpeters Member in the eastern area (Johnson *et al.*, 2009). This formation comprises of poorly sorted fine- to very fine- grained lithofeldspathic sandstones alternating with dark-grey clastic rhythmites (from sandstone/siltstones) and mudrock. Sharp and gradational contacts are observed from the sandstones into the mudrock (Tankard *et al.*, 2009) and graded bedding is outstandingly observed in the lowermost part of the formation, however, there is poor development of graded bedding with massive individual sedimentation units. There are evident various kinds of trace fossil tracks, trails and burrows occurring in this formation indicating deep-water conditions

2.2.3.7 Fort Brown Formation

This Formation comprises of mudstone that are intercalated with sandstones that are interpreted to have resulted from sea level lowstands where delivery of clastic sediment increased (Johnson *et al*., 2009). The thickness of this formation varies from 500 m to 1 500 m with the outcrops that are confined to the southern margin of the basin.

The silt/clay and sand/silt layers that comprise of rhythmites can be observed in some areas in this formation, where the sand/silt layers display a general upward increase in thickness within the formation (Tankard *et al.,* 2009). Sedimentary structures such as straight-crested oscillation ripples associated with wavy bedding are recognisable along the upper surfaces of more prominent sandstone/siltstone layers. There are massive sandstones with different sedimentary structures such as horizontal lamination, ripple lamination and ripple-drift cross-lamination. Deformation structures such as ball and pillow structures and slump structures can also be observed (Johnson *et al*., 2009).

2.2.3.8 Waterford Formation

The Waterford Formation overlies the Kookfontein and Tierberg Formation with a gradational contact and has a thickness of 130 m. According to Tankard *et al.* (2009), Waterford Formation was deposited entirely above subsiding Namaqua basement and terminates along the edge of the Kaapvaal Craton. The depositional environment seems to be from the delta plain to a mud-rich, sub-aerially exposed upper delta plain, this is indicated by the break in lithology (Johnson *et al*., 2009; Rubidge *et al.,* 2000).

This formation is underlain by the fine- to medium-grained sandstone, siltstone, shale, mudstones, and rhythmites together with clay-pellets occurring sporadically throughout the formation (Grab *et al.,* 2015; Johnson *et al.,* 2009). The calcareous concretions are also common in all rocks of this formation attaining a diameter of approximately 2m. Bioturbation and load clasts are also common in a large part of this formation. The sedimentary flow structures such as slumps can be observed along the upward coarsening cycles that form part of the lower part of the formation. The upper part of the formation is characterised by horizontally laminated and low-angle trough cross-stratified sandstones of up to 8 m thick siltstones, ball and pillow layers with channel-fill deposits. Trace fossils as well as wood fossils are abundant in the sandstones of this formation (Johnson *et al.,* 2009; Tankard *et al.,* 2009).

2.2.3.9 Tierberg Formation

The Tierberg Formation is dominated by the argillaceous succession alternating thicknesses of approximately 700 m along the western margin of the Karoo Basin and 300 m towards the northeast. It connects with the Collingham and Whitehill Formation as well as the Waterford Formation.

Tierberg Formation comprises of well-laminated, dark shale, some yellowish tuffaceous beds with a thickness of up to 10 cm occurring along the north and western margins of the basin. Different sedimentary structures such as calcareous concretions, clastic rhythmites, planar lamination, ripple lamination, slump structures and ball and pillow structures are common in this formation. The trace fossils are rarely found in this formation (Johnson *et al*., 2009).

There are numerous upward sequences along the transition zone on the top part of this formation that consist of mudstones, siltstones and very fine-grained sandstone. The presence of abundant wave ripples as well as grain-size trends and distribution of different types of trace fossils are indicative of regression in a shallow environment along a proximal delta to distal delta front depositional environments. According to Tankard *et al*. (2009), the Tierberg Formation is a marine deposit and records an episode of SW-deepening expressed in carbonaceous shales, tuffs and some subsidiary sandstones.

2.2.3.10 Skoorsteenberg Formation

The Skoorsteenberg Formation is a thin lens-shaped arenaceous unit that overlies the Tierberg Formation, with a maximum thickness of approximately 250 m, comprising five sandstone-rich units with shale units forming contact zones between those sandstone units that have an approximate thickness of 60 m (Johnson *et al.,* 2009). Bouma and Wickens (1991), Hodgson *et al.* (2006) and Tankard *et al*. (2009) suggested that this formation has a thickness of 450m with four sand-rich basin-floor fans that intermingle with basinal overlying Tierberg shales. The sandstones in this formation are generally massive, however, there are sedimentary structures like convolute bedding, rip-up clasts, dewatering structures, graded bedding, and different marks (Johnson *et al.,* 2009).

The structures observed in this formation are indicative of deposition along the unstable delta-front slope of either fluvially dominated delta system or at the mouth of the river during flood events, and accumulated as coalescing fans and aprons to form a basin-floor fan complex. The sediment transport seems to be from the southwest, west and northwest. Trace fossils and plant fragments such as Glossopteris are abundant in this formation (Johnson *et al.,* 2009).

2.2.3.11 Kookfontein Formation

The Kookfontein Formation is approximately 350 m thick and overlies the Skoorsteenberg Formation with a sharp contact and an upward grading towards the Waterford Formation. The formation comprises of horizontally laminated dark-grey shales intercalated with clastic rhythmites forming upward thickening cycles. The siltstones alternating with thin beds of sandstones are also observed along the top of the formation. Common sedimentary structures in this formation are slump and load structures, planar lamination and ripple cross-lamination.

Sedimentation in this formation is indicative of continuous prodelta and unstable depositional environment. The presence of abundant ripple marks and bioturbation are the indication of deposition during prodelta progradation (Johnson *et al.,* 2009).

2.2.3.12 Vryheid Formation

The Vryheid Formation overlies the Pietermaritzburg Formation thinning towards the north, west and south from a maximum thickness of approximately 500 m. According to Tankard *et al.* (2009), the Vryheid Formation is an eastward-thickening wedge of overlapping deltaic sequences of about 500 m thickness (Cadle and Caincross, 1993). The facies gradation along the lower and upper parts of this formation into the shales of the Pietermaritzburg and Volkrust Formations had resulted into the thinning and pinching-out towards south-western and east of the formation.

There is difference in litho-facies in this formation, suggesting the deltaic origin and they are arranged in upward-coarsening cycles. This formation is underlain by the dark grey muddy siltstones, immature sandstones of different grain sizes, dark siltstones and mudstones. There are also sedimentary structures such as hummocky cross-beddings, slump structures (Figure 7) (Grab *et al*., 2015) and high turbidites indicating deposition along the delta front on an unstable slope (Turner, 1983; Lucas and Hancox, 2001).

The Vryheid Formation can be subdivided into three intervals, namely lower fluvial-dominated deltaic, middle fluvial and the upper fluvial-dominated deltaic interval bearing lower sandstones, coal zone and upper sandstones, representatively.

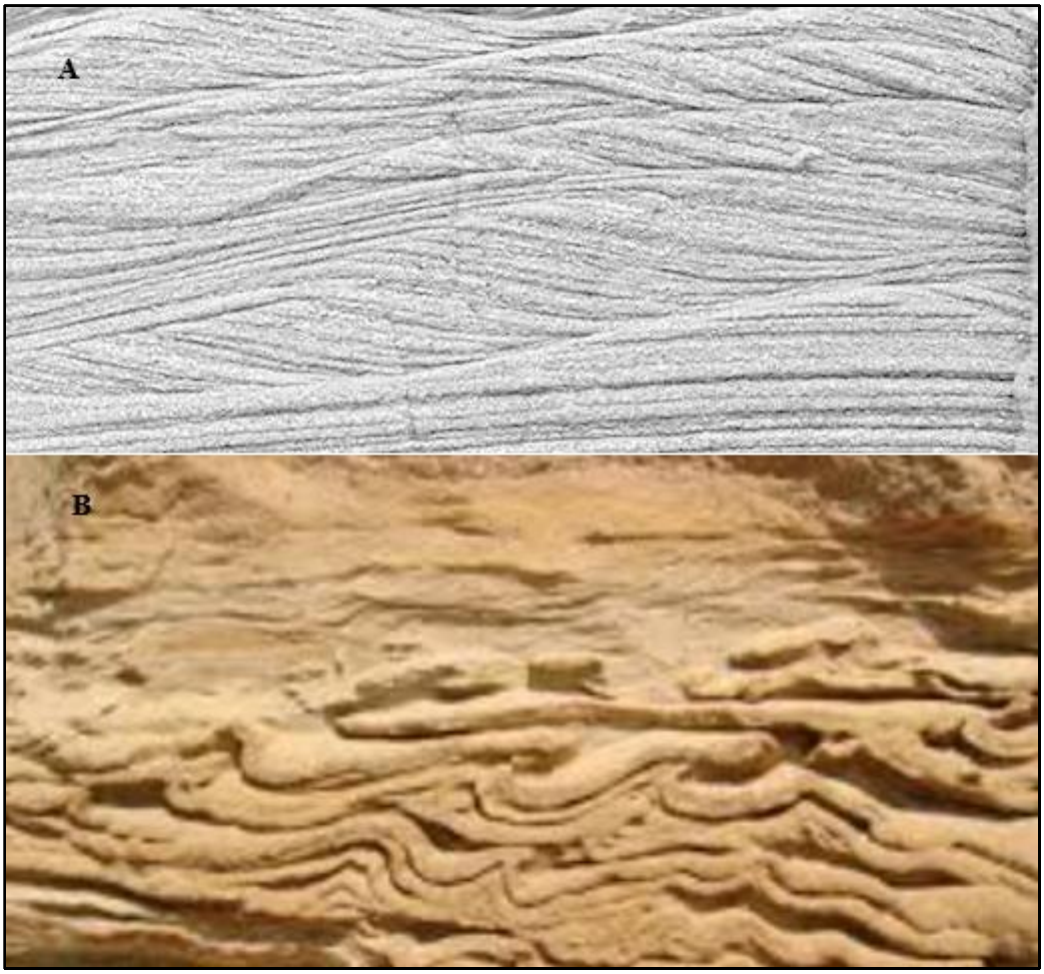

Figure 7: Examples of hummocky cross bedding structures (A) and slump structures (B) that can be observed along the Vryheid Formation in the Ecca Group (adapted from Grab *et al*., 1982)

2.2.3.13 Pietermaritzburg Formation

The Pietermaritzburg Formation lies in the north-eastern part of the Karoo Basin and forms the lower most unit of the basin, generally overlying the Dwyka Group. The rocks that underlie this formation are silty mudrock with coarser sandstones and some glacial drop-stones that drape the uppermost Dwyka deglaciation sequence forming an upward coarsening (Johnson *et al.,* 2009; Visser, 1994, 1997; Tankard *et al.,* 2009). The mudrock have bioturbation structures, whereas the invertebrate fossils presence can be observed along the bedding planes of the carbonated-cemented mudrock (Johnson *et al.,* 2009).

The presence of abundant carbonate concretions suggests the changes in Eh-pH levels that was probably along an unstable shelf, on shallow water (Johnson *et al.*, 2009). The nature of the sediments along the top part of this formation is indicative of progradation along the shoreline.

2.2.3.14 Volkrust Formation

The argillaceous dominated Volkrust Formation overlies the Vryheid formation. The thickness of this Formation is ranging between 100 to 380 m (Johnson *et al*., 2009, McCarthy and Rubidge, 2005).

The Volkrust Formation comprises of grey to black silty shale with thin, bioturbated, siltstones or rather sandstone lenses and beds, mostly observed towards the lower and upper boundaries. There are thin phosphate and carbonate beds as well as concretions.

The depositional environment indicative of the substantial thickness, fine-grained lithology and the lateral extent of this formation seems to have been along an open transgressive shelf sequence consisting of mud deposited from suspension. The depositional environment that is indicative of the lacustrine to lagoonal and shallow coastal embayment can be observed in the lower and upper parts of this formation (Johnson *et al*., 2009).

2.2.4 Beaufort Group

The Beaufort Group is the third of the main subdivisions of the Karoo Supergroup strata, following conformably the Ecca Group (Johnson *et al.,* 2009; Rubidge *et al*., 2000). It consists largely of the sandstones and shales that have been deposited between the ages 265 and 225 Ma. The Beaufort Group is composed of the lower Adelaide and the upper Tarkastad Subgroups. The lower Adelaide subgroup was deposited in the Late Permian Period and it comprises of the Koonap, Middleton and Balfour Formations in the south-eastern part of the basin and the Abrahams-kraal and Teekloof Formations in the west of the basin. The deposition of the Beaufort Group is one of the events that brought up its exceptionality from the other Groups of the Karoo Supergroup, as it consists of different types of rock (Smith, 1990; Johnson *et al*., 2009). The processes that were responsible for the deposition of the Beaufort Group were the two fluvial processes namely; braided and meandering rivers (Smith, 1990, 1995).

The channels of the streams tend to migrate laterally though they are not stationary, whereas in the braided streams the migration has a broader extension. The lateral migration of the channels tends to produce cycles in which the coarser-grained channel deposits are overlain by the fine-grained deposits. The sheet-like and wedge-shaped sandstone layers that are intercalated with the shale lenses that are often characteristic of the Beaufort are ascribed to the braided river, whereas the alternating horizontal layers of sandstone, siltstone and mudstone result from the meandering rivers.

2.2.4.1 Adelaide Subgroup

The Adelaide Subgroup is an upward- fining basin-filling unit that has a thickness of approximately 5000 m in the south-east with a rapid decrease of 800 m in the centre then about 100-200 m to the north of the basin (Tankard *et al*., 2009; Rubidge *et al.*, 2000). This subgroup consists of alternating bluish-grey, greenish-grey or greyish-red mudrocks and grey, very fine- to medium-grained lithofeldspathic sandstones in the southern and central parts of the basin. The northern part of the basin hosts coarse to very coarse sandstones. The Adelaide Subgroup is a host to massive and blocky weathering mudrocks in some other formations except for the Normandien Formation where horizontal lamination and rhythmites can be observed. The Abrahamskraal Formation is a host to brown-weathered limestone layers that extend up to 2 km together with cherty layers that are greenish-grey in colour.

The presence of high mud or sand ratios as well as fine-grained sandstones is indicative of meandering rivers rather than the braided streams deposition (Tankard *et al*., 2009; Johnson, 2009; Rubidge *et al.*, 2000). Johnson *et al*. (2009) suggested that the sandstones were formed as channel deposits and the mudstones represent over-bank deposits that have settled from suspension on the adjacent floodplains. The levee deposits are tabular siltstones and thin sandstones that are intercalated with mudstone units. The crevasse splay deposits are indicated by horizontally laminated sandstones.

2.2.4.2 Tarkastad Subgroup

The Tarkastad Subgroup was deposited during the Early Triassic Period. This subgroup comprises of the abundant reddish mudstones and sandstones as compared to the counterpart Adelaide Subgroup. It has a maximum thickness of about 2000 m in the south, 800 m in the middle and at 150 m or less in the far north of the basin. In the lower part of the Tarkastad Subgroup lies the Katberg Formation whereas the upper part hosts the Burgersdorp Formation, enriched with sandstone and mudstone, respectively (Johnson *et al.*, 2009).

The sandstones in the Katberg Formation are fine- to medium-grained, light brownish-grey or greenish-grey coloured, with scattered pebbles up to 15 cm in diameter. Sedimentary structures such ripple lamination is rare in the Katberg Formation, indicating that the streams had shallow channels that were characterised by swift flow and mostly upper flow regime flatbed sedimentation. Katberg sedimentation took place during arid climatic conditions. However, some of the features that can be observed in this formation (coarse grain sized, virtual absence of interbedded mudstones) are evident to deposition resulting from braided rivers.

The absence of fossil in this formation is a reflection of a hostile, arid climate with almost no evident fresh flowing water. (Grab *et al*., 2015) suggested that the sediments were deposited by the ephemeral streams that emerged into the shallow lakes in the distal parts of the Beaufort basin and frequently dried out. According to Johnson *et al.* (2009), Burgersdorp Formation is a mudstone dominant formation; however, there are subsidiary fine grained, greenish grey or light brownish grey sandstone with horizontal lamination, cross-bedding and ripple lamination. The depositional environments were predominantly flood-basin or rather meandering streams (Turner, 1978).

2.2.5 Molteno Formation

The Molteno Formation was deposited during the Late Triassic (Grab *et al.,* 2015) with a thickness of almost 10 to 60 m (Johnson *et al.,* 2009). This formation comprises of alternating medium- to coarse-grained sandstones and grey with secondary overgrowths of quartz showing glitters on the sandstones. In this formation, there is fossil content of insects and plants, with the occurrence of sporadic coal seams. The deposition was mostly of ephemeral streams and braided streams that were broad and shallow, during a wet and cool climate (Rubidge *et al*., 2000; Woodford and Chevallier, 2002).

2.2.6 Elliot and Clarens Formations

The vertebrate dominant Elliot Formation is composed of the red and greenish mudrock units that range between 5 and 100 m that intercalate with subordinate yellowish-grey to pale red fine- to medium-grained sandstones (Bordy *et al.,* 2004). The vertebrate footprint and desiccation cracks together with flat bedding and trough cross-bedding are common in this formation which is indicative of red bed fluvial environment (Jonson *et al.,* 2009).

According to Johnson *et al*. (2009) and McCarthy and Rubidge (2005), during the deposition of this formation, progressive warming and aridity conditions prevailed. The deposition was from the north to the northwest, however, aeolian conditions also prevailed during the deposition of the Elliot Formation, and this is represented by the sediments that are observed along the upper-part of this formation (Bordy *et al*., 2004; McCarthy and Rubidge, 2005; Johnson *et al.,* 2009).

The Clarens Formation sedimentation was during the Late Triassic to Early Jurassic and represents the last phase of the Karoo Supergroup sedimentation (Kitching and Raath, 1984). The deposition was mainly by aeolian together with playa lake, sheet flood and ephemeral streams depositional mechanisms which are indicated by the beds of fine-grained sandstone (Johnson *et al*., 2009). Beukes (1969) stated that; sand was transported by westerly winds. However, there are some homogeneous siltstone and silty fine-grained sandstone that can be found forming part of the southern outcrop area of this formation (Smith, 1990) together with some lava flows that reflect the commencement of the magmatic eruption that marked the termination of the Karoo sedimentation (Johnson *et al.*, 2009). The deposition of this formation was during more arid conditions (McCarthy and Rubidge, 2005).

2.2.7 The Karoo Volcanic Sequence

The volcanic sequence marks the final deposition of the Karoo Basin with its two subdivisions mainly due to their difference in rock type (Johnson *et al*., 2009). These subdivisions are the volcanic rocks of the Central Area named the Drakensberg Group and volcanic rocks that are in the Lebombo area that are grouped as Lebombo Group. These rocks represent the different formations that form each of these groups that are relatively different in geochemical compositions.

The Drakensberg Group forms the second subdivision of the volcanic sequence and forms the rocks of the Central Area, whereas the rocks in the Lebombo Area form the other subdivision named the Lebombo Group. These groups form the uppermost units of the Karoo Supergroup where they are observed. The Drakensberg Group is mostly dominated by the basaltic rock forming its two formations namely; the Lesotho and Barkly Formations. The Lebombo Group is dominated by different volcanic rock such as basalt, rhyolite, and rhyodacite, picritic basalt and nephelinite.

2.2.7.1 Lebombo Group

The Lebombo Group is composed of rocks of different types such as basalt, rhyolite, rhyodacite, picritic basalt and nephelinite. According to Johnson *et al.* (2009), these rocks appear to be found within different formations making it possible for the Lebombo Group to be subdivided (Table 1) (Johnson *et al*., 2009).

The Lebombo Group is subdivided into six formations. The Mashikiri Formation comprises of the nephelinite rock with the thickness of approximately 170 m. The Mashikiri Formation forms the basement of the volcanic sequence the northern Lebombo extending further to the southeast of Zimbabwe. The Letaba Formation is overlying the Mashikiri Formation and comprises a sequence of picritic lavas that are rich in olivine. This formation forms a mafic unit in the northern Lebombo area and spreads towards the southern central of the group (Johnson *et al.,* 2009).

The Sabie River Formation comprises of the basaltic rocks and extents to southern end of the Lebombo Group. The Jozini Formation overlies the Sabie Formation and comprises of bulky silicic volcanic rock, rhyodacite and rhyolites. The outcrops of this unit are the major component of the Lebombo Mountains as result of is resistance to erosion. The overlying Mbuluzi Formation extents towards Swaziland and consist of massive, quartz-phyric rhyolite. The Movene Formation is in the latest sequence of the Lebombo Group. This formation comprises of the basaltic rocks and is confined to Mozambique; however, there are some of its occurrences in the Kwazulu-Natal and south of Mozambique.

2.2.7.2 Drakensberg Group

The Drakensburg Group which intruded during the Late Jurassic Period (180 Ma), is probably the last episode of the volcanic sequence that marked the last deposition of the Karoo Supergroup. The Drakensberg Group is largely composed of the basaltic rocks and subdivided into two formations; the Barkly East and Lesotho Formations that are somehow not easier to distinguish from each other due to similarity in mineralogy and texture of their rocks (Johnson *et al.*, 2009).

The Barkly East Formation is subdivided into eight units relatively to their variations in geochemical compositions, but all of the units are comprising of the tholeiitic basalt. Johnson *et al.* (2009) suggested that the basalts in this formation are sourced from different volcanic eruptions that could have possibly erupted at the same time from widely separated eruptive centres probably separated by topographic barriers. The Lesotho Formation that constitutes of Mafika-lisiu, Maloti, Senqu and Mothae units that are present with uniform thickness throughout the Lesotho-Eastern Cape lava piles, suggest that they were built along a planar surface from the widely spread network of fissures (Johnson *et al.*, 2009).

Table 1: Karoo Volcanic Sequence (redrafted from, Reynolds, 1997)

KAROO VOLCANIC SEQUENCE			
Drakensburg Group		**Lebombo Group**	
Formation	***Rock Type***	***Formation***	***Rock Type***
		Movene	Basalt
		Mbuluzi	Rhyolite
		Jozini	Rhyodacite
Lesotho	Basalt	Sable River	Basalt
Barckly	Basalt	Letaba	Picritic Basalt
		Mashikiri	Nephelinite

2.3 KAROO DOLERITE

2.3.1 Introduction

The Karoo dolerite is significant to the commencement of the volcanic sequence that intruded the Karoo Basin sediments that are presumed to be of the same age (McCarthy and Rubidge, 2005; Woodford and Chevallier, 2002). The particular tectonic events of the Karoo Basin dolerite intrusion are difficult to be singled out as these intrusions are composed of interconnected networks of dykes and sills. From the morphology of the sills and dykes, it can be deduced that various fractures were intruded by the magmas of the same period (Woodford and Chevallier, 2002).

2.3.2 Dykes

According to Woodford and Chevallier (2002), three different dolerite dyke swarms form the major structural domains in the Karoo Basin namely; the Western Karoo Domain, the Eastern Karoo Domain and the Transkei-Lesotho- Northern Karoo Domain exist (see Figure 8).

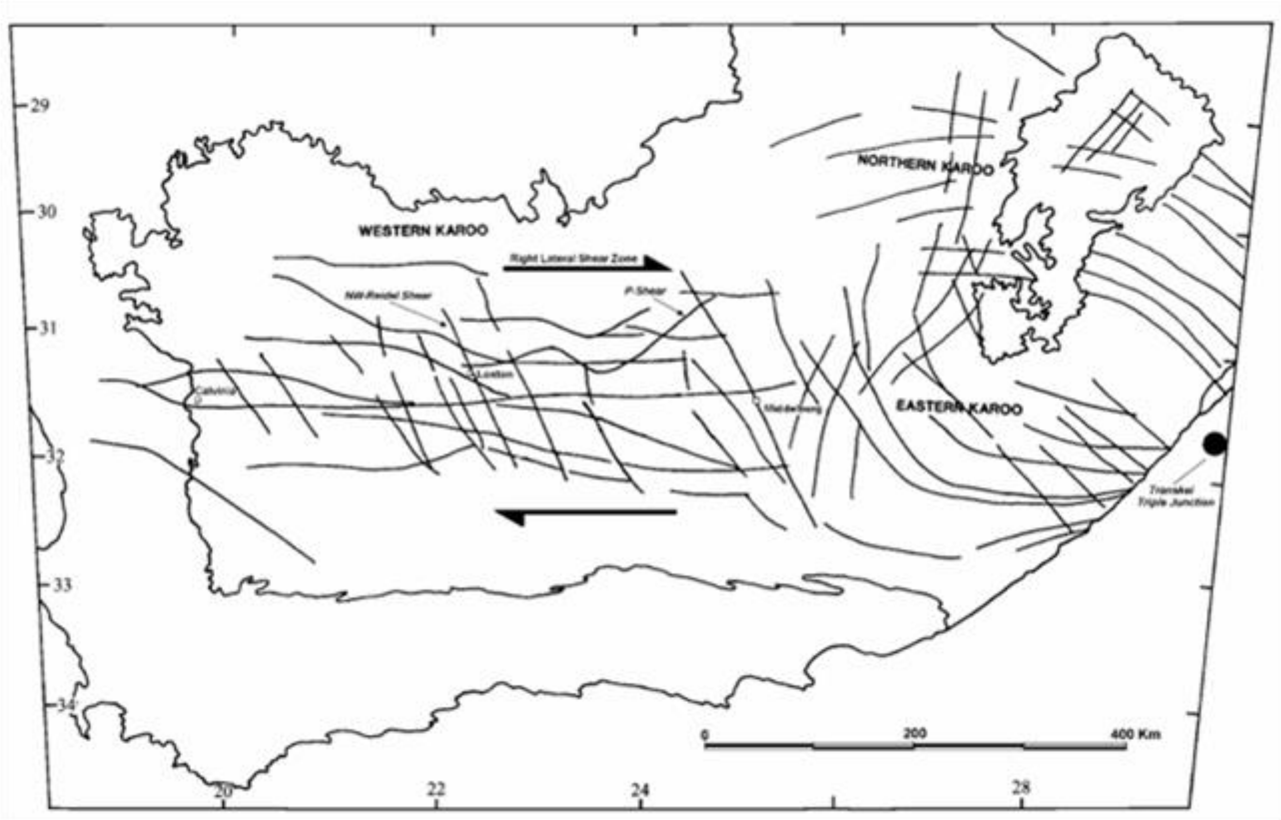

Figure 8: Main Karoo Basin dolerite dykes (adapted from Woodford and Chevallier, 2002)

2.3.2.1 The Western Karoo Domain

The Western Karoo Domain extents from Calvinia to Middleburg and it is characterised by the two distinctive structural features namely; the EW Dyke Intrusion and the NNW Dyke Intrusion. The EW Dyke Intrusion dykes were intruded along the major right lateral E-W dislocation or shear zones that are accompanied by NW Riedel shears and NE-P Fractures (Woodford and Chevallier, 2002).

The dykes of the NNW Dyke Intrusion are regularly spaced from east across the Western Karoo Domain. The trend of these dykes varies along the trajectory curving from WNW in the south to the NS in the north. The Middleburg Dyke demarcating the Western Karoo Domain in the east and the Loxton Fracture Zone in the centre of the domain form the two dyke systems that are specifically well developed (Woodford and Chevallier, 2002).

2.3.2.2 The Eastern Karoo Domain

These domain extents from East London to Middleburg and it comprises of two major dyke swarms; an arcuate swarm of extensive dykes diverging from a point offshore of East London which displays a strong curvi-linear pattern. These dykes trend approximately E-W along the coast and curving NNW to NS inland (Woodford and Chevallier, 2002). These dykes are characterised by very thick-widths of up to 300 m. the minor NNE trending dykes that represent the extension and probably the termination of the Lesotho NE trend.

2.3.2.3 Transkei-Lesotho-Northern Karoo Domain

The Transkei-Lesotho-Northern Karoo Domain consists of the two major swarms namely; the NW trending dykes in the Transkei region, curving to EW in the Free State and the NE trending dykes that mainly occur within alongside the Lesotho basalts. This appear to converge towards the Limpopo-Lebombo Triple Junction (Woodford and Chevallier, 2002).

2.3.3 Sills and Ring Complexes

Karoo landscape is more famous of most prominent numerous dolerite sills and ring-complexes. They all have similar geographical distribution as the dolerite dykes (Woodford and Chevallier, 2002). Woodford and Chevallier (2002) further state that the dolerite sills and dykes form a complex intrusive network that control the geomorphology of the Karoo landscape. These intrusive structures can be easily identified by the use of the satellite images where their orientation is like a sub-circular saucer-like shape, the rims of which are commonly exposed as topographic highs and form ring-like outcrops (Woodford and Chevallier, 2002). There are five major regional ring complex units that can be recognised extending from western to eastern Karoo Basin, namely; the Sutherland, Victoria West, Middelburg, Queenstown and the Umtata mega-basins.

Woodford and Chevallier (2002) state that, many dolerite ring systems are composed of many linear to curvi-linear segments that are likely following the regional trend of dykes and fractures. However, there is a relationship that exists between the size of the dolerite basins and Karoo Supergroup stratigraphy. The more extensive sills forming these megastructures have been intruded near the base of the Karoo sediments, while the smaller structures (diameter of 10 km and less) have been intruded into the upper parts of the Karoo Supergroup (Woodford and Chevallier, 2002).

2.3.4 Dolerite Intrusion in the Beaufort Group

The presence of dolerite intrusions interactively with groundwater exploration within the Mangaung Metro Municipality and the Karoo Basin at large should be taken into consideration, because they are associated with good aquifers (Botha et al., 2004). Steyl *et al*. (2011) in their results obtained from the research they did on this area, highlighted the contribution of dolerite intrusive structures on groundwater potential of the MMM and stated that dolerite intrusions (dykes, sills, rings) are the target when it comes to groundwater exploration, because they are often associated with good aquifers. They further itemized that along the contact zones of the dolerite intrusions and the country rocks (sedimentary rocks) as well as some lineaments and faults, are potentially rich targets for groundwater development.

In the low-lying areas in the Mangaung Metro- Municipality, soils are well drained and as a result, the dolerite sills and dykes reflect high degrees of weathering as compared to the higher lying areas of the same area. According to Steyl *et al*., (2011) this extensive weathering is caused by the fact that such areas are below the aquifer water table level. These dolerite sills form the shallow confined intergranular aquifers that can be exploited for groundwater as they have a capability to store quite larger quantities of water. However, abstraction in these aquifers can only be possible where extensive weathering has occurred (Steyl *et al*., 2011).

2.4 GEOHYDROLOGY OF THE KAROO BASIN

2.4.1 General

The geohydrology of the Karoo Supergroup is described by Woodford and Chevallier (2002) as being complicated due to the unpredictable behaviour of Karoo aquifers. This results from the dominant type of lithology that the Supergroup consists of, such as mudstones, sandstones, shale and siltstone. The dominance of these geological formations have rendered these aquifers to be characterised by low permeability that range from approximately 0.0 to 87 md (Woodford and Chevallier, 2002) therefore, some of the boreholes in the Karoo are rather dry or have relatively lower yields of approximately less than 0.1 L/s proving correct the meaning of Karoo, which is a Hottentot word for dry (Woodford and Chevallier, 2002).

However, there is uncertainty in the statement already made about the dryness of the boreholes drilled in the Karoo as there are some wellfields that are pumped to supply some towns and large quantities of groundwater that are pumped from the mines and some buildings’ basements where Karoo formations are underlying such areas. There are some areas in which the Karoo aquifers had been used for water supply for quite a bit longer period in this country; we can refer to towns like Louriefontein, De Aar and Limpopo Province. Perhaps the strong high or long yielding aquifers are those that are associated with some intrusions.

This section gives a general overview of the geohydrology of the Karoo Basin in terms of its aquifers, the hydraulic properties of its rocks, the occurrence of groundwater and the Karoo aquifers associated with dolerite dykes.

2.4.2 Aquifers of the Karoo Basin

The aquifers of the Karoo Basin in South Africa are formed in sedimentary rocks such as shales, sandstones, siltstones and mudstones of the Karoo Basin (Botha and Cloot, 2004). These sedimentary rocks have been extensively intruded by the magmas and as a result they have been fractured and metamorphosed at different degrees. The type of these aquifers is referred to as *fractured metasedimentary aquifers* (secondary aquifers) as proposed by Colvin *et al.* (2003). Botha *et al.* (1998) refer to the aquifers of the Karoo Basin as the multi-porous fractured aquifers. The argument is based on the Karoo formations that characteristically display a porous medium geometry with large variations in porosities that are sporadically intersected by the bedding-parallel fractures from the main conduits of water (Woodford and Chevallier, 2002).

The conclusion that was reached by Woodford and Chevallier was such that; the determinant to the behaviour of the Karoo Basin is its inexplicable geometry which is resultant to the presence of horizontal bedding-parallel fractures. These horizontal bedding-parallel fractures are mostly concentrated on the sandstones in the Karoo Aquifers. Sandstones are therefore classified as the most water bearing formation in Karoo aquifers as the fractures present on such formation act as the pathways for groundwater extraction from the Karoo aquifers. It should be noted that fractures along any formation cannot act as storage for groundwater due to the fact that their piezometric pressure drops rapidly when boreholes that intersect them are pumped. However, these fracture can always act as pathways and interactions between the aquifers or surface water.

The two flow types in Karoo aquifers are identified by Botha *et al*. (1998) as *matrix flow and fracture flow (mesofracture flow).* Fracture flow is mainly determined by the three components namely, *dimensions, orientation and connectivity* of the fracture. The orientation of the bedding-parallel fractures that are hosted in the Karoo aquifer is horizontal and uniformly distributed; however, there are vertically orientated fractures that can slightly be observed in some of the formations such as in weathered doleritic intrusions and rarely in sandstones. These render the connection between the numerous bedding-parallel fractures to the transitional rock matrix to be weak. Therefore, the significant apertures of the bedding-parallel fractures (at a range of approximately 1 and 10 mm) will be the main determinant regarding the ability of the Karoo aquifer to transmit water.

Matrix flow in the aquifer is the flow of water from the matrix to the fracture. This type of flow can be significantly low as compared to the fracture flow; however, the flow of water over a large area can be quite significant and the water supply to the bedding-parallel fracture from the matrix can be large over a large area. Botha *et al.* (1998) suggested that this is possible due to little micro-fractures and pores that are present in such rock matrix, which are common in interbedded sandstones, mudstones, siltstones and shale, the major formations in the Karoo aquifers.

2.4.3 The Hydraulic Properties of the Karoo Rocks

Woodford and Chevallier (2002) have identified changes in terms of the primary hydraulic properties (*permeability and porosity*) of the Karoo rocks from the south to the north of the Karoo Basin. The porosity changes from the south to the north of the Karoo Basin are indicative of the decrease in diagenesis during compaction and lithification. These variations can be observed along the sandstones that are found in the southern part of the Karoo Basin; according to Woodford and Chevallier (2002) sandstones that are found in the southern part of the latitude 29^{o}S have an extremely low primary porosity as well as their permeability. The permeability and porosity of the Middle Ecca sandstones to the north of latitude 29^{o}S indicate improvement from south to north over the Main Karoo Basin.

The porosity of the Karoo sediments tends to be higher near the Earth's surface, probably due to weathering and leaching of rocks that are within the upper reaches of 30 m (Woodford and Chevallier, 2002). The case is similar with the porosity of the sediments that is expected to decrease with depth as a result of an increase in lithostatic pressure and temperatures. Botha *et al.* (1998) states that, the porosities of the sedimentary rocks decrease at the range of 0.1 to 0.2 from north of the latitude 28^{o}S and to the southern-part of the Karoo Basin, with an increase in bulk density that are estimated from 2 000 to more than 2 650 kg.m^{-3}.

In terms of the other hydraulic properties, such as storativity and transmissivity of the Karoo aquifers, the general overview is that; the Karoo aquifers are composed of the sedimentary formations. These formations have some micro-fractures in quartz grains and bedding planes, which increase the storativity of the Karoo aquifers resulting to the significant decrease in hydraulic conductivity of these aquifers. However, due to the complexity of the Karoo aquifer geometry, there is variation in terms of storativity values as in a case of where the aquifer is mostly dominated by fracturing, the hydraulic conductivity values will increase significantly dropping the storativity values. Due to the fact that most of these aquifers are characterised by massive fracturing, the Karoo aquifers are generally identified to have low storativities, though they may vary with distance (Botha et al.,2004).

As an example of the hydraulic parameter values that can be expected for Karoo rocks, the aquifer at the test site of the University of the Free State may be considered. Using tracer techniques, Riemann *et al.* (2002) estimated the horizontal and vertical hydraulic conductivities of the matrix (K_{mh} and K_{mv}), as well as the horizontal hydraulic conductivity of a bedding-plane fracture in the rock matrix

(K_{fh}). The specific storativity of the matrix (S_{sm}) was also estimated. The estimated values for these hydraulic parameters are listed in Table 2. From these estimates, it can be seen that the horizontal hydraulic conductivity of the matrix (K_{hm}) is significantly higher than the vertical hydraulic conductivity (K_{vm}). This is probably due to the effects of compaction in the vertical direction. The horizontal hydraulic conductivity of the fracture (K_{hf}) is seen to be several orders of magnitude larger than the hydraulic conductivities of the matrix. A value of 3 600 m/day was found for K_{hf} which, if multiplied by the thickness of the fractured zone of about 0.2 m, yields a *T*-value of 720 m^2/day (Riemann *et al*., 2002).

Table 2: Estimated transmissivity and storativity values for aquifer in the UFS Campus (adapted from Riemann *et al.*, 2002)

Parameters	Estimated Values
K_{hm} (m/d)	0.158
K_{vm} (m/d)	5.52×10^{-3}
S_{sm} (L^{-1})	5.65×10^{-5}
K_{hf} (m/d)	3.6×10^{-3}

2.4.4 Groundwater Occurrence in the Karoo Basin

Groundwater exploration in the Karoo Supergroup is mostly associated with presence of doleritic structures that are mostly regarded as the resourceful pathways for groundwater to the surface. This is due to the fact that along the contact zones with the country rock (sedimentary rocks); dolerite intrusions have caused fracturing as a result of baked and extensively metamorphosed sandstone during the intrusions (Loock, 2011; Woodford and Chevallier, 2002). These fractures have also contributed in the possible weathering of both sandstones and the dolerite intrusions (sills and dykes) as a result of water percolating through them from the surface. The structure and orientation of dolerite dykes differ accordingly. There are linear and ring dykes and the orientation maybe either vertical (in most cases restricted to linear dykes) or sub-vertical.

As already stated earlier, dolerite intrusions are best associated with thin, linear zones of relatively higher permeability due to the presence of fractures along the contact zones, which act as pathways for groundwater in directions parallel to the strikes of the dykes. However, it should be noted that the dolerite dykes can sometimes respond negatively to being pathways for groundwater, as a result of being semi- to permeable to groundwater movement in cases where the directions are perpendicular to the strikes of the dykes (Woodford and Chevallier, 2002). Dolerite dykes are often associated with the presence of the ever surviving vegetation even in dry seasons, without the use of geophysical methods a line of these vegetation can be a link to the presence of dykes.

Though it seems to be a norm that groundwater exploration in the Karoo Basin should be based on investigating the geological structures as targets for groundwater exploitation, the alluvial deposits from the unconsolidated sediments are also exploitable for groundwater. These groundwater bearing bodies often have a limited areal extent to a thin strip along the river courses. According to Kirchner *et al*. (1991), Vegter (1995) and Woodford (1990), the quantity of water supplied by these aquifers is remarkable; this is evident in some towns like Ficksburg which gets almost 50% of its supply from alluvial beds in the Caledon River. De Aar also is one of the towns that benefit from groundwater extracted from the alluvial aquifers in the Karoo Basin; it extracts its water from the alluvial beds of the Brak River and its tributaries (approximately $3.0 \times 10^6 m^3$ per annum).

2.4.5 Groundwater Occurrence Associated with the Dolerite Dykes

Groundwater in the Karoo Basin is associated with the presence of dolerite intrusions mostly dolerite dykes. It was earlier stated that the presence of the dykes is indicative of possible fracturing and weathering along the contact of those intrusions with the sedimentary rocks (Woodford and Chevallier, 2002).

The fracturing of the sedimentary rocks (country rocks) often occurs during and after the dyke emplacement, in which the fracture forms a set of master joints that are parallel to the strike of a dyke (Woodford and Chevallier, 2002). In some cases, the dyke metamorphoses the country rock and as it cools down it exhibits the effects of contact metamorphism, which is where the other minerals along the contact will be altered from their origin.

The alteration of the minerals along the contact zone of the dyke and the country rock makes them less resistant to weathering and as a result the dyke exhibit a prominent chill margin that consists of a fine rounded, melanocratic dolerite that weathers to form well rounded, small white-speckled boulders at about 0.5 to 1.5 m wide from the dyke (Woodford and Chevallier, 2002). Along these weathered zones, sporadic fractures and meta-sedimentary veins can be encountered; however, they do not extent into the country rock. These characteristics are common in dykes that have a thickness greater than 8 m. Dykes that are less than 3 m are often resistant to weathering, but in case of where they weather; they produce small rounded, white-speckled boulder that are hosted in a fine angular groundmass (Woodford and Chevallier, 2002).

According to Reynolds (1998), the most prevalent geophysical methods that are utilised to delineate doleritic structures in the Karoo Basin are magnetic and resistivity methods (Woodford and Chevallier, 2002). Dolerite intrusions (structures) have a simple geometry that can allow easy conceptualization and borehole siting at the field. Dolerite dykes have always been and are still cost-efficient groundwater targets due to numerous properties of the dolerite dykes (Woodford and Chevallier, 2002):

- They can be highly magnetic and can be easily detected with existing geophysical methods
- They are often associated with the formation of fractures in the contact zones (Botha *et al* 1998)
- There is an apparent higher probability of drilling wet borehole in or nearer to a dyke than in the host rock away from the dyke.

The importance of dolerite intrusions is quite substantial for groundwater exploration, hence why the hydrogeologists and groundwater-dowsers have managed to site many successful boreholes along and on these structures.

2.4.6 Aquifers of the Beaufort Group

The intricacy of the aquifers in the Beaufort Group is subsequent to the different depositional environments that were responsible for the deposition of this group. The sedimentary units in the Beaufort Group usually have very low permeabilities contributing to the complicated aquifer geometry as a lateral migration of meandering streams over a floodplain (Woodford and Chevallier, 2002). The other characteristics of the Beaufort Group aquifers are; they are multi-layered and multi-porous with variable thicknesses (Steyl *et al.,* 2011).

When the hydraulic tests are performed in these kinds of aquifers, there is drastic piezometric pressure drop on more permeable layers as opposed to the less permeable layers. According to Woodford and Chevallier (2002), the more permeable layers of multi-layered aquifers of the Beaufort Group can be extracted without affecting the piezometric pressure in the lower (less) permeable layers. This can occur as a result of discontinuities along the contact plane between different sedimentary layers.

In other regions, there are many lens-shaped coarser and more permeable sedimentary bodies which further contribute to the complex behaviour of aquifers in this group. Woodford and Chevalier (2002) suggest that there is limitation in life-time for a high yielding borehole in this group, unless there is frequent recharge to the aquifer. It is therefore evident that siting a borehole in the Beaufort Group may be difficult, or rather unproductive as the types of the aquifers in this group are unreliable with reference to all the characteristics stipulated. This is further proved by the results that Kirchner *et al.* (1991) obtained after drilling 40 boreholes at Dewetsdorp as part of study; among those boreholes, only three boreholes had yields in access of 3.6 m^3h^{-1}, with the rest not productive.

2.5 WATER SUPPLY AND DEMAND IN SOUTH AFRICA

2.5.1 Introduction

Water is an essential resource for economic development, job creation and poverty alleviation through the commercial and industrial sectors. The essentiality of water can be observed on food production and food security, most particularly in the rural areas where unemployment levels are high. Water is a basic human need for drinking, cooking and washing and it has a social and an economic value. In order to meet the demands for social and economic purposes, the environmental integrity of water resources must be protected and maintained. When the integrity of water resources is compromised, the chances of sustainable development are slim (WRC, 2006).

Water supplies in South Africa (SA) seem to be more challenged lately due to different factors, such as, drought, and floods resulting to siltation of surface water sources that were previously and currently partially relied on. The other contributing factors in hampering the proper distribution of water supplies to the communities within SA are the illegal connections from the water pipes mostly by the famers as well as vandalization on the pipelines. South Africa is currently buying water from Lesotho at great costs; however, this water does not reach its users at the anticipated volumes due to already stated factors as well as a high evaporation rate that is lately experienced. The increasing population rate is also a challenge to the supplies in this country as the more population increases, water supply and sanitation becomes a challenge. In order to further review more details on water demand in South Africa; this section will further focus on elaborating more about the current supply as well as future water demand in the Mangaung Metro Municipality.

2.5.2 Current Water Supply in Mangaung Metro Municipality

2.5.2.1 Introduction

The Mangaung Metro Municipality (MMM) is situated within the Modder River Catchment (Modder/Riet Sub-catchment) within the semi-arid upper Orange Water Management Area. The current water supply in MMM is mainly from the surface water resources such as rivers and dams, which is then transferred from the Caledon River through the transfer schemes. However, the current sources are highly challenged by the impacts of Global Warming as most of the sources have dried up or rather silted as a result of high temperatures and flooding in different seasons, respectively.

MMM has the three water transfer schemes located within the Greater Bloemfontein Supply Systems (GBSS) that are responsible for the current water supply in the municipality. These transfer schemes are; Caledon-Modder transfer, Maselspoort Transfer and Caledon- Bloemfontein Transfer (refer to Figure 9).

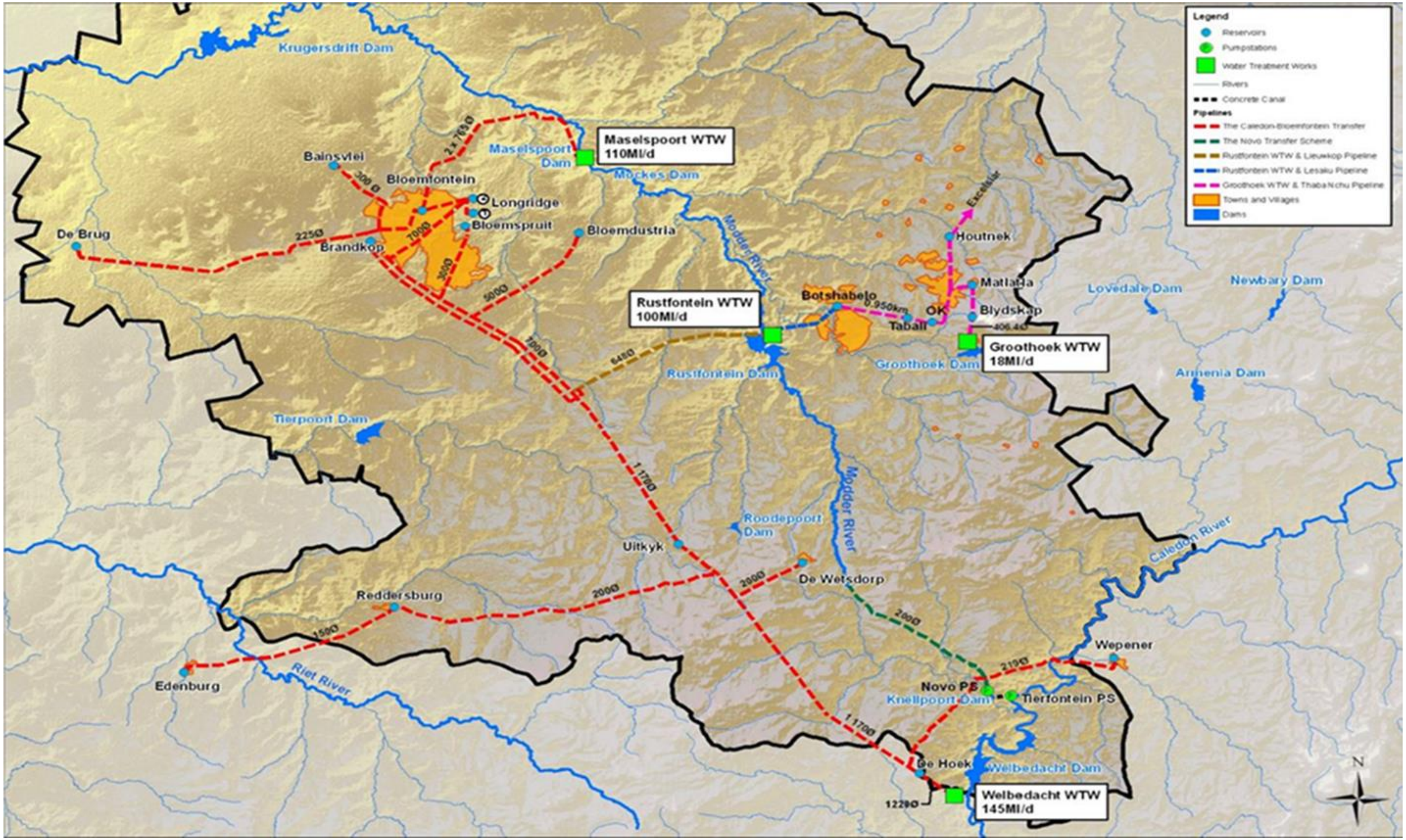

Figure 9: Current Infrastructure Supplying water to Bloemfontein (adapted from Bloemwater, 2012)

The Modder River serves as a main channel in which three water treatment works that serve Bloemfontein are situated. Within these transfer schemes, there are three primary surface water resources that are used in supplying the municipality namely; Welbedacht Dam, Rustfontein Dam and Mockes Dam. The historical firm yields of these sources as well as their registered water use (Mm^3) can be viewed in **Error! Reference source not found.**.

2.5.2.2 Caledon Modder Transfer Scheme

According to the Bloemwater (2012), the Caledon-Modder Transfer Scheme (Novo Transfer scheme) was first commissioned in 1999. The report states that this scheme transfers unprocessed water directly from the Caledon River to the Knellport Dam then to the upper part of the Modder River Basin upstream of the Rustfontein Dam nearer to Thaba Nchu. This is done through the Novo Pump Stations at Knellport Dam with a pipeline of approximately 29.7 km and a river channel of 12 km. this scheme is not active but can be operational as a result of Bloemfontein demands that is currently increasing; it will therefore be developed in stages. The scheme is expected to reach the maximum 150 million m^3/a by 2030 (ORASECOM, 2013).

The following towns in the Mangaung Metro-Municipality (MMM) are supplied with the water from Welbedacht Dam via the Caledon-Bloemfontein Canal; Bloemfontein, Wepener, Excelsior, Botshabelo, Thaba Nchu, Reddersburg and Edenburg (DEA, 2013). According to ORASECOM, 2013, the Novo Transfer Scheme conveys water to supplement Bloemfontein demands, together with Botshabelo and Thaba Nchu.

2.5.2.3 The Caledon-Bloemfontein Transfer Scheme

The Caledon-Bloemfontein Transfer Scheme which is owned and operated by Bloem-water; is an indirect transfer scheme that was commissioned in 1974. The purpose of this transfer scheme was to supply potable water from the Welbedacht Dam on the Caledon River to Bloemfontein, Botshabelo, Thaba Nchu, Dewetsdorp, Reddersburg, and Edenburg. As sediment deposition has significantly reduced the yield from Welbedacht Dam, Knellport Dam was commissioned to supplement the supply. It transfers purified water via a 107 km Caledon-Bloemfontein pipeline from Welbedacht Dam to municipal reservoirs around Bloemfontein (Bloemwater, 2012). The Welbedacht Water Treatment Works (WTW) is in the Caledon-Bloemfontein Transfer Scheme and has a capacity of 145 ML/day. This treatment works is situated along downstream of Welbedacht Dam, with its water pumped after purification along a 6.5 km pressure pipeline and a 106 km gravity pipeline to Bloemfontein.

2.5.2.4 The Maselspoort Scheme

The Maselspoort Scheme is located downstream of Mockes Dam, along the Modder River and within this scheme there is Maselspoort Water Treatment Works with a capacity of 110 Ml/day as well as Maselspoort Weir. This WTW is owned by the Mangaung Metro Municipality (MMM) and is meant to supply approximately 25% of the water requirement in Bloemfontein.

2.5.3 Water Demand in the Mangaung Metro Municipality

2.5.3.1 Previous water consumption

According to bulk water consumption data (Table 3) that was collected by Bloem water (BW) and MMM from their supply systems for 2008-2011, the bulk water consumption data indicate that water supplied to smaller towns accounted for almost 4 % of the total water supply to the MMM.

Table 3: Bulk water consumption for towns supplied with water from Greater Bloemfontein Water Systems (adapted from Bloemwater, 2012)

	2008			2009			2010			2011		
	BW	MMM	Total	BW	MMM	Total	BW	MMM	Total	BW	MMM	Total
Year Supplier Town	million m³			million m³			million m³			million m³		
Bloemfontein	40.66	20.31	60.97	35.83	30.13	65.97	37.1	27.71	64.82	37.91	22.72	60.63
Botshabelo	8.18		8.18	9.21		9.21	7.87		7.87	10.06		10.06
Thaba Nchu	5.14		5.14	4.64		4.64	6.04		6.04	6.3		6.3
Excelsior	0.17		0.17	0.16		0.16	0.19		0.19	0.17		0.17
Wepener	0.8		0.8	0.82		0.82	0.75		0.75	0.74		0.74
Dewetsdorp	0.84		0.84	0.92		0.92	0.96		0.96	0.76		0.76
Reddersburg	0.85		0.85	0.86		0.86	0.69		0.69	0.43		0.43
Edenburg	0.53		0.53	0.53		0.53	0.53		0.53	0.43		0.43
Total	**57.19**	**20.31**	**77.48**	**52.97**	**30.13**	**83.11**	**54.13**	**27.71**	**81.84**	**56.8**	**22.72**	**79.52**

Figure 10 shows the water supply rates per annum from 1993 to 2011. The demand for water supply is seen to have increased from 50 Mm^3/annum to approximately 84 Mm^3/annum, with particularly prominent increases observed in the period 2003 to 2009. However, a steady decline is observed in the years 2010 to 2011 in which a decrease in demand from 82 Mm^3/annum to approximately 80 Mm^3/annum can be observed.

Rademeyer *et al.* (2012) suggested that the improvement in service delivery through different government programmes could have triggered the increase in water consumption that is observed for the period 1993 to 1999. They further stated that local economic growth jointly with some other developmental projects within the communities, such as the eradication of the bucket system, some low income housing and the onsite water projects, would have contributed to an increase in water consumption from 2003 to 2009. In the period between 2010 and 2011, the decline in water consumption was attributed to the higher than average rainfall that was experienced during this period (Rademeyer *et al.*, 2012).

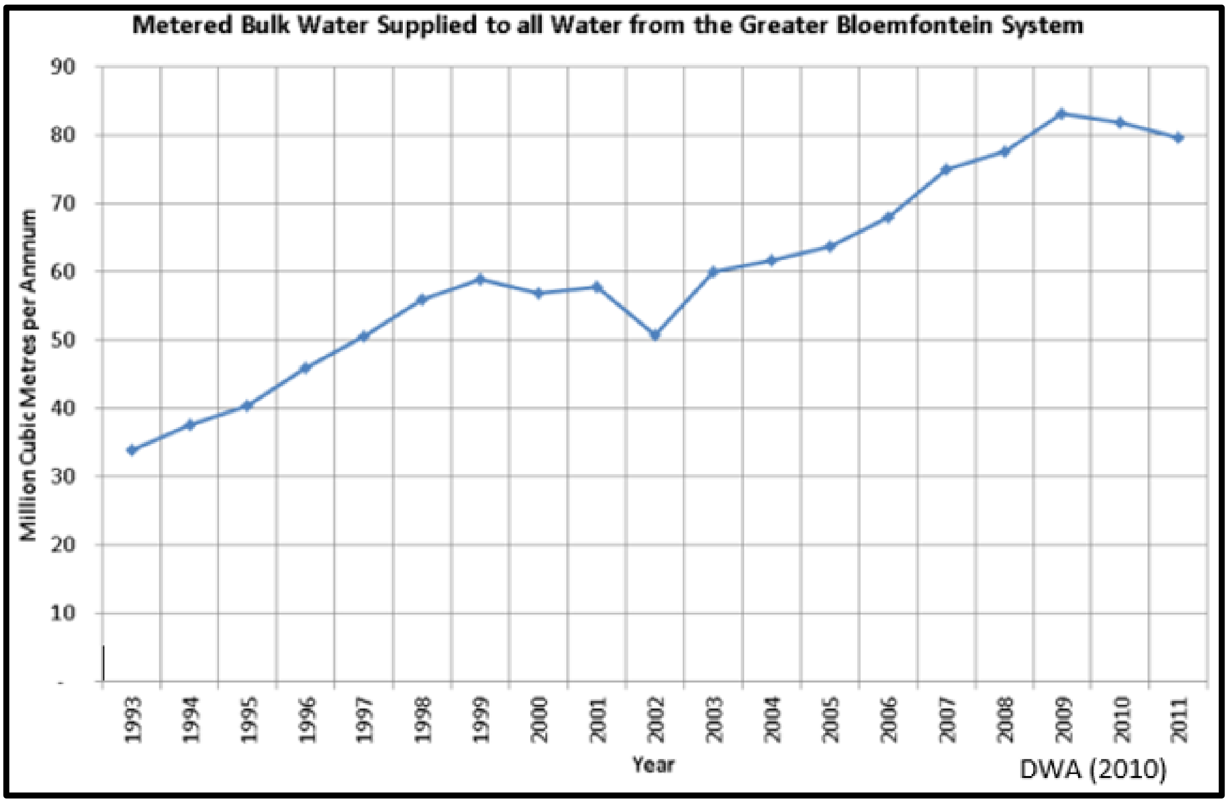

Figure 10: Metered bulk water supply from the Greater Bloemfontein Supply System to the MMM (adapted from Bloemwater, 2012)

The possible negative impact on water supply in MMM that can contribute to an increase in water demand could be an increase in population rate that would have possibly being influenced by urbanisation and immigration (refer to Figure 12). According to the population census that was recorded for the period of 1996 to 2011, the steady incline is reflected mostly from 2001 to 2011 with a population increasing quiet substantial with reference from 645 440 to 750 629 reflected in Figure 12.

A	BLOEMFONTEIN MONTHLY RAINFALL (mm)									
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	AVE
JAN	63.3	141.6	33.8	46.1	159.7	101.9	123.2	88.3	220.6	74.3	88.9
FEB	82.5	98.5	12.5	43.8	168.5	27.8	125.0	23.9	172.8	33.9	100.1
MAR	92.3	145.3	23.3	72.8	95.6	77.2	33.5	102.6	114.5	25.6	75.8
APR	63.0	2.5	18.2	30.2	8.2	24.2	60.3	35.0	11.5	25.8	50.5
MAY	4.3	0.0	0.0	7.2	0.0	37.5	0.4	30.9	2.3	57.9	17.0
JUN	20.4	21.8	0.0	1.4	0.8	0.5	0.0	18.3	0.0	0.5	11.0
JUL	8.3	4.1	0.2	0.0	1.1	0.1	33.0	16.6	5.2	2.6	8.7
AUG	16.3	0.0	19.2	27.7	0.0	3.1	2.9	5.3	0.0	0.5	13.0
SEP	1.1	42.7	0.1	0.0	0.2	7.6	19.7	14.1	21.8	0.4	20.7
OCT	3.5	216.0	23.3	179.6	0.4	77.3	26.8	20.0	80.4	87.1	50.2
NOV	2.9	54.3	116.5	39.0	34.4	83.1	156.0	18.1	67.2	35.0	61.2
DEC	66.2	52.0	13.3	28.1	18.9	145.5	163.0	34.4	43.9	138.1	63.1
TOTAL	424.1	778.8	260.4	475.9	487.8	585.8	743.8	407.5	740.2	481.7	563.9
MAX	92.3	216.0	116.5	179.6	168.5	145.5	163.0	102.6	220.6	138.1	
MIN	1.1	0.0	0.0	0.0	0.0	0.1	0.0	5.3	0.0	0.4	
% AVE	75	138	46	84	86	103	131	72	131	85	

B	BLOEMFONTEIN MONTHLY RAINFALL (mm)										
	2000	2001	2002	2003	2002	2004	2005	2006	2007	2008	AVE
JAN	143.4	16.2	112.9	####	####	####	####	####	####	####	88.9
FEB	60.4	126.9	62.5	####	####	####	####	####	####	####	100.1
MAR	127.0	93.3	33.3	####	####	####	####	####	####	####	75.8
APR	50.5	87.8	41.1	####	####	####	####	####	####	####	50.5
MAY	10.4	12.9	71.8	####	####	####	####	####	####	####	17.0
JUN	2.3	30.7	4.8	####	####	####	####	####	####	####	11.0
JUL	4.1	0	0	####	####	####	####	####	####	####	8.7
AUG	1.0	15.9	94.3	####	####	####	####	####	####	####	13.0
SEP	46.3	37.4	9.4	####	####	####	####	####	####	####	20.7
OCT	34.2	45.7	18.6	####	####	####	####	####	####	####	50.2
NOV	77.2	103.3	20.5	####	####	####	####	####	####	####	61.2
DEC	90.0	89.9	77.1	####	####	####	####	####	####	####	63.1
TOTAL	646.8	660.0	546.3	####	####	####	####	####	####	####	563.9
MAX	143.4	126.9	112.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
MIN	1.0	0.0	0.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
% AVE	114	117	96	0	0	0	0	0	0	0	

Figure 11: Rainfall data indicating high rainfall rates with reference from 1993 (A) up to 2002 (B). The red colour indicates high rainfall experienced, the blue colour indicates less rainfall while values of 0.0 indicate unrecorded data. Long-term average rainfall is 563.9 mm (Bloemfontein annual rainfall average) (SAWS, 2017)

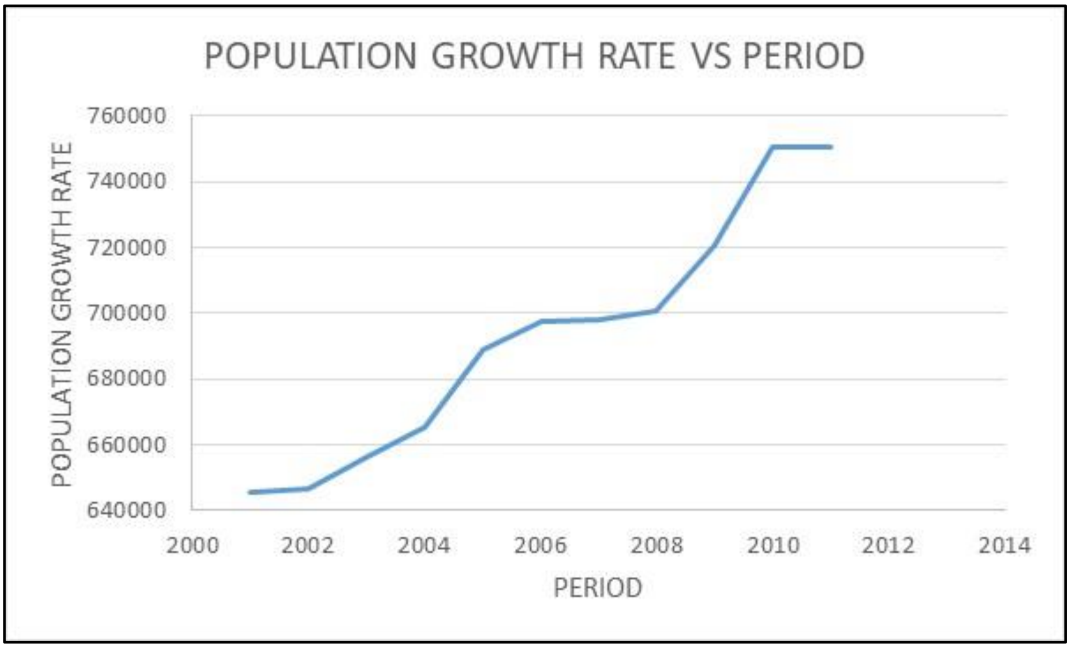

Figure 12: Population growth in the MMM from the period of 2001 to 2011 (modified from Census 2011)

2.5.3.2 Current water demand

In Bloemfontein, the rate at which water is used increases due to an increasing population rate. Table 4 lists the results of a population census conducted in 2011 for the different municipalities in the Free State Province. It is seen that the MMM has the highest population of the municipalities included in the census. The increasing water demand in the MMM is likely to be related to population increases in the municipality. MMM (2014) found that the water requirements of the different sectors vary significantly (refer to Table 5). It is seen that almost two thirds of the water supplied is used by agricultural.

Table 4: The results of the 2011 population census for different municipalities in the Free State (Census2011, 2017)

Name	Type	Population	Area
Fezile Dabi	District Municipality	488036	20667.97
Lejweleputwa	District Municipality	627626	31930.28
Mangaung	Metropolitan Metropolitan Municipality	747431	6283.99
Thabo Mofutsanyane	District Municipality	736238	33269.19
Xhariep	District Municipality	146259	37673.74

Bloemwater is the main water board that supplies potable water to MMM. The current operational water systems that serve the municipality are overloaded with the increasing demand due to aspects such as climatic trends, increasing population, urbanisation and industrialisation. According to the press release by the MMM (2016) the amount of water that was supposed to be consumed per day within the municipality was 170 mega-litres, but this limit was not adhered to as the consumption was 200 mega-litres per day. Table 6 displays the water service delivery levels within Bloemfontein indicating the highest percentage of population relying on surface water resources as opposed to other sources (approximately 2.1%). These 'other' sources could include groundwater, although this is not directly stated in the report (MMM, 2014).

Table 5: Percentage requirement of water per sector (MMM, 2014)

Sector	Percentage per Requirement
Agricultural	66.0%
Urban	23.0%
Rural	2.6%
Mining and Bulk Industry	0.6%
Other services	7.8%

Table 6: Water delivery services in Mangaung Metro Municipality (MMM, 2014)

	Households	Percentages
Water: (above min level)		
Piped (tap) water inside dwelling/institution	106819	45.0%
Piped (tap) water inside yard	94156	40.0%
Piped (tap) water on community stand: distance less than 200m from dwelling/institution	23743	10.0%
Minimum Service Level And Above sub-total	224718	95.0%
Water: (below min level)		
Piped (tap) water on community stand: distance between 200m and 500m from dwelling/institution	4403	2.0%
Piped (tap) water on community stand: distance between 500m and 1000m (1km) from dwelling/institution	1330	0.6%
Piped (tap) water on community stand: distance greater than 1000m (1km) from dwelling/institution	591	0.3%
No access to piped (tap) water	811	2.1%
Below Minimum Service Level And Above sub-total	11246	5.0%
Total	235964	100.0%

2.5.3.3 Future water demand

The major factors that trigger the demand for water supply in any area are population growth as well as local economic growth. The Mangaung Metro Municipality is one of the developing municipalities in South Africa, so it is affected negatively by such factors in as far as water supply is concerned. The factors can function collaboratively since development in a region is typically associated with an influx of people.

There are other factors that also contribute towards water demands in a region, such as the level of service delivery (as suggested by the 2011 census), improvements in educational facilities and level, improvements in water services, sanitation, health awareness (DWA, 2012) and better housing facilities.

Two scenarios were identified for the future water demand for this municipality (DWA, 2012):

High Growth Water Requirement Scenarios will highly be influenced by the high level of population growth and high level of better service delivery. When taking consideration on the past figures relative to population growth recorded and water demand, the rate at which water demand has grown is approximately 3% rate per annum (DWA, 2012,). According to DWA, 2012 it was decided that it will be best to use long term historical growth rate of 3% per annum as the basis for the high growth scenario.

Low Growth Water Requirement Scenarios was decided to be based on growth on water requirement of 1% per annum considering the fact that this will be impacted by the low population growth and low economic growth.

Figure demonstrates both low and high growth water requirement scenarios with the actual water requirement. According to DWA, 2012 these projections were projected based on the data that was recorded in 2009 basically on some reasons such as:

- There were significant summer rains in the 2011 and this may have resulted in a depressed demand.
- It is still too early to ascertain whether or not the drop in 2010 can be ascribed to structural reasons (e.g. improved metering, WC/WDM) or is as a result of climatic influences.
- It is conservative to plan from a higher base. As future years' actual water requirements become known, the base from which the projections are made can always be changed

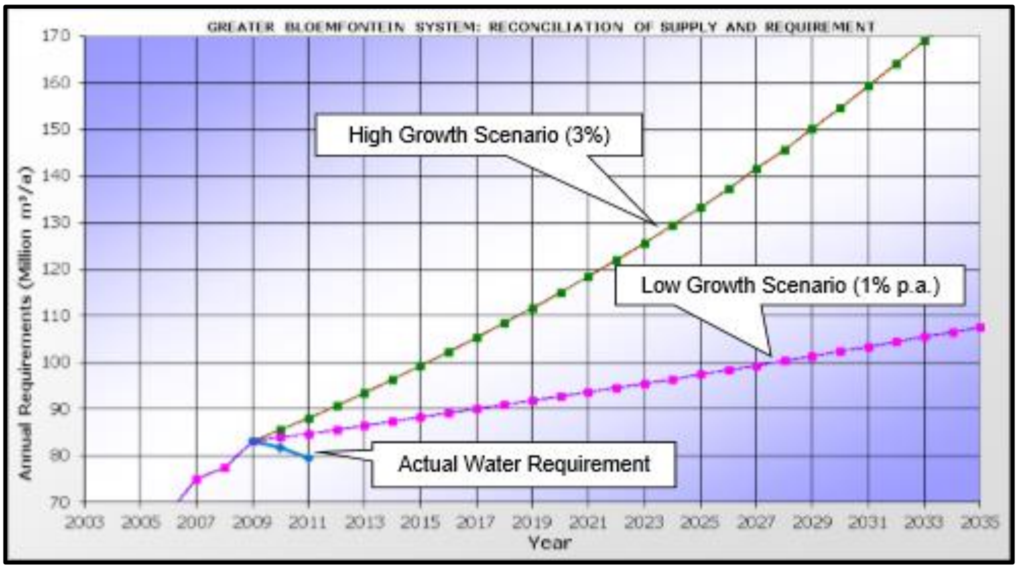

Figure 13: Low and high water requirement scenarios (adapted from DWA, 2012)

2.6 GROUNDWATER USE IN SOUTH AFRICA

2.6.1 Introduction

South Africa (SA) is a water-stressed country. Being semi-arid with limited annual rainfall supply and a lack of perennial streams, the future implications of population growth combined with the uncertainty of climate change are likely to have significant financial, human and ecological impacts on already scarce water resources (Adams, 2011). Much of South Africa's water supply originates from groundwater sources. These occur widely and geographically and almost two thirds of South Africa's population depend on it for their domestic water needs. This is true to mostly easterly based regions of the Karoo Supergroup such as in the Eastern Cape where there is much of rural settlements in which the accessibility is highly challenged by the type of terrain, compelling the dwellers to be reliant on only springs or rather boreholes (WRC, 2006).

On a global scale, groundwater is an essential freshwater resource for both socio-economic and environmental systems, and forms a critical buffer during periods of drought. This makes the protection of groundwater supplies (management, pollution control and remediation) essential, particularly in developing countries where groundwater management is neither strongly emphasized in national water legislation, nor implemented where it is needed. The role of groundwater in South Africa (SA) is often underestimated as it is approximately two thirds of its population that depend on groundwater for their domestic needs. Although many water users rely on surface water, most small water supplies depend on groundwater (Adams, 2011). These supplies are critical to the livelihoods, health and dignity of many South Africans. When referring to most of the water sources that are relied upon in most of the rural areas SA, groundwater is the major source of both domestic and agriculture even industrial in regions that are highly challenged in terms of surfaces water resources.

2.6.2 Groundwater utilization

In SA, the estimated total volume of renewable groundwater is at 10.34 billion m^3 per year according to Engineering News, 2011. Only between 2 and 4 billion m^3 of groundwater is currently used in the country, showing that there is potential to considerably increase the groundwater supplies in South Africa (Adams, 2011). These volumes should be compared with the assured yield of surface water resources which amounts to 12 billion m^3 per year, but of which more than 80% has already been allocated (Adams, 2011).

According to Pavelic *et al.* (2012), secondary aquifers are the major sources of groundwater in South Africa. The quantity of water that is stored in this type of aquifer is not sufficient and the permeability of such aquifers is typically very low (Woodford and Chevallier, 2002). These aquifers are the host to almost 90% of groundwater in SA and due to their low permeability, the yield of the boreholes drilled is also usually low. The water from this kind of aquifers is therefore usually applied to provide for small communities and towns, for domestic use, livestock watering and for irrigation on a small scale.

The results of census surveys indicated a definite pattern of groundwater use in SA, with different sectors using different portions of the abstracted groundwater, as seen in Table 7. From the data displayed in this table it is seen that agriculture is the primary user of groundwater at approximately 78% of the total use. Urban use of groundwater amounts to only 3.9%. However, Pavelic *et al.* (2012) stated that the stimulant to groundwater use is electrification of rural areas which has led to an increase in the percentage of groundwater used for rural domestic supply.

Table 7: Breakdown of groundwater use per sector (adapted from Pavelic *et al.,* 2012)

Water Use Sector	Use (Mm^3yr^{-1})	Percentage of Total(%)
Urban Use	70	3.9
Rural Domestic Use	120	6.7
Stock Watering	100	5.6
Irrigation	1,400	78.2
Mining	100	5.6
Total	**1,790**	**100**

In Bloemfontein, groundwater is currently not used as a source of potable municipal water (Bloemwater, 2012). However, individuals do abstract groundwater for irrigation of gardens in residential areas. Farmers within the municipality also use groundwater for stock watering, irrigation and some other agricultural activities. Currently, water for rural villages, approximately 36 in total, in the vicinity of this scheme is supplied through boreholes. The boreholes are maintained and operated by Bloemwater (DWA, 2010). There are also a number of privately owned boreholes which are mostly used irrigation of gardens. Car washes also make use of groundwater, as will be seen in the results from the hydrocensus (refer to Section 5.2).

The use of groundwater resources is much more reliable as opposed to the surface water resources because of the following reasons (Bloemwater, 2012):

- Groundwater is a proximal source that does not need to be pumped at great distances,
- It is not a costly resource, meaning it does not require extensive installations,
- It does not need to be purified like surface water, and,
- Groundwater does not get much affected by climatic changes.

WRC (2006) stated that groundwater resources are more reliable for the following reasons:

- Groundwater is often not subject to contamination from surface pollution.
- In times of disease outbreaks such as cholera it is regarded as a safe supply if the borehole is protected.
- It is ideal for small scale operations where large construction and engineering works are impractical and unaffordable.

- With appropriate technology, the maintenance and operation of groundwater pumps and supply systems can be done by community members in many cases.
- It is not subject to the extremes of surface water resources such as flooding.
- In times of drought, groundwater can continue to provide a reliable source of water if properly managed.

2.7 SUSTAINABLE GROUNDWATER MANAGEMENT AND ABSTRACTION

2.7.1 Introduction

Sustainability of water resources can be defined as the use of water sources while ensuring that there is no impact on those sources for the future generations to use (Kennel, 2009). According to DWA (2010), sustainability along with equitable access to water, is one of the main principles of the National Water Act. 'Sustainability' in groundwater implies groundwater use that does not cause long-term deterioration of the overall resource, in terms of quality and quantity.

The *quantity* and *quality* of water are significantly impacted by urbanization, population growth and effects of climate change. When there are developments on the region, population increases as a matter of job opportunities and better housing, as a result, people migrate from their rural homes to gain themselves supposedly better life. Migration of people causes the overstressed system per area, the water sources become stresses as the result of high demand of supply, and water quality also gets poor as the demand gets higher. In addition, regional developments also can cause pollution to the water sources as well as climate change. It is therefore advisable to consider the essentiality of balancing the economic growth and developments with water resources (DWA, 2012, 2006).

Groundwater sources are on the other hand different from the surface water sources as their vulnerability to these impacts is minimal as it is stored far beneath the earth's surface. However, in case of the unconfined aquifer, the situation may be different since it is more vulnerable to pollution compared to the confined aquifer.

2.7.2 Groundwater Monitoring

Good monitoring and management of groundwater resources is the key to reliable, efficient groundwater supplies. This applies equally to schemes as small as a single borehole and to large wellfields supplying urban areas. Monitoring (borehole water levels, water quality, pumping rates, etc.) is probably the single most important component of good groundwater management. The management of groundwater sources should involve:

- Monitoring of the sources in order to identify the rate at which the aquifer performs at different seasons,
- To do hydrochemical tests and analysis in order to investigate the quality of water for further recommendation,
- To identify the suitability of water for either consumption or for other purposes, and,
- To investigate the possible recharge and the discharge zones of groundwater.

Monitoring should be conducted on a regular basis, such as on a weekly to monthly basis. Communities residing in rural areas entirely depend on the supply from groundwater sources, therefore such sources of groundwater should be monitored in order to identify changes in yields and water levels so that recommendations can be made on how much can be abstracted in order to avoid over-exploitation of the source.

The aquifers that are in the proximity of overpopulated and developing areas are much likely to be impacted by the pollutants as a result of anthropogenic activities.

2.7.3 Groundwater Abstraction

The rate at which groundwater should be used does not deviate from surface water use which are both governed by the National Water Act No: 36 of 1998 Section 26 (1) (NWA, 1998). This act requires that the use of water from a water resource be monitored, measured and recorded; while Section 26 subsection 4 (c) and (e) stating that, "when making regulations, the Minister must take into account all relevant considerations, including the need to prevent wasteful water use and to facilitate the management of water use and waterworks".

In order to assign the rate at which each individual should abstract water, the amount of recharge to the aquifer must be known so that water balance equilibrium can be reached. In case where groundwater abstraction is less than recharge that is termed *capture* (DWA, 2010). The Department of Water Affairs assumes responsibility in terms of the National Water Act for the control of abstraction of groundwater in order to prevent (DWAF, 2000):

- Depletion or damage to the reserve;
- Temporary or permanent loss of the use of aquifers through over-abstraction or unnecessary de-watering;
- Loss of surface water base flow or damage to wetlands and riverine environments which depend on groundwater;
- Deterioration of groundwater quality; and

- Intrusion of saline or contaminated groundwater into otherwise uncontaminated aquifers

The total volume of available, renewable groundwater in South Africa (the Utilisable Groundwater Exploitation Potential, or UGEP) is 10 343 million m^3/a (or 7 500 million m^3/a under drought conditions. The map in Figure 14 illustrates different regions with amount utilisable groundwater exploitation potential per $m^3/km^2/a$. The highest values are observed to occur in regions that are situated along the coastal regions and the highly elevated areas like the Drakensburg and Lebombo Ranges at approximately 100,00 $m^3/km^2/a$ and are indicated by a blue colour. The little values can largely be observed on lower lands and arid regions indicated by a dark pink colour.

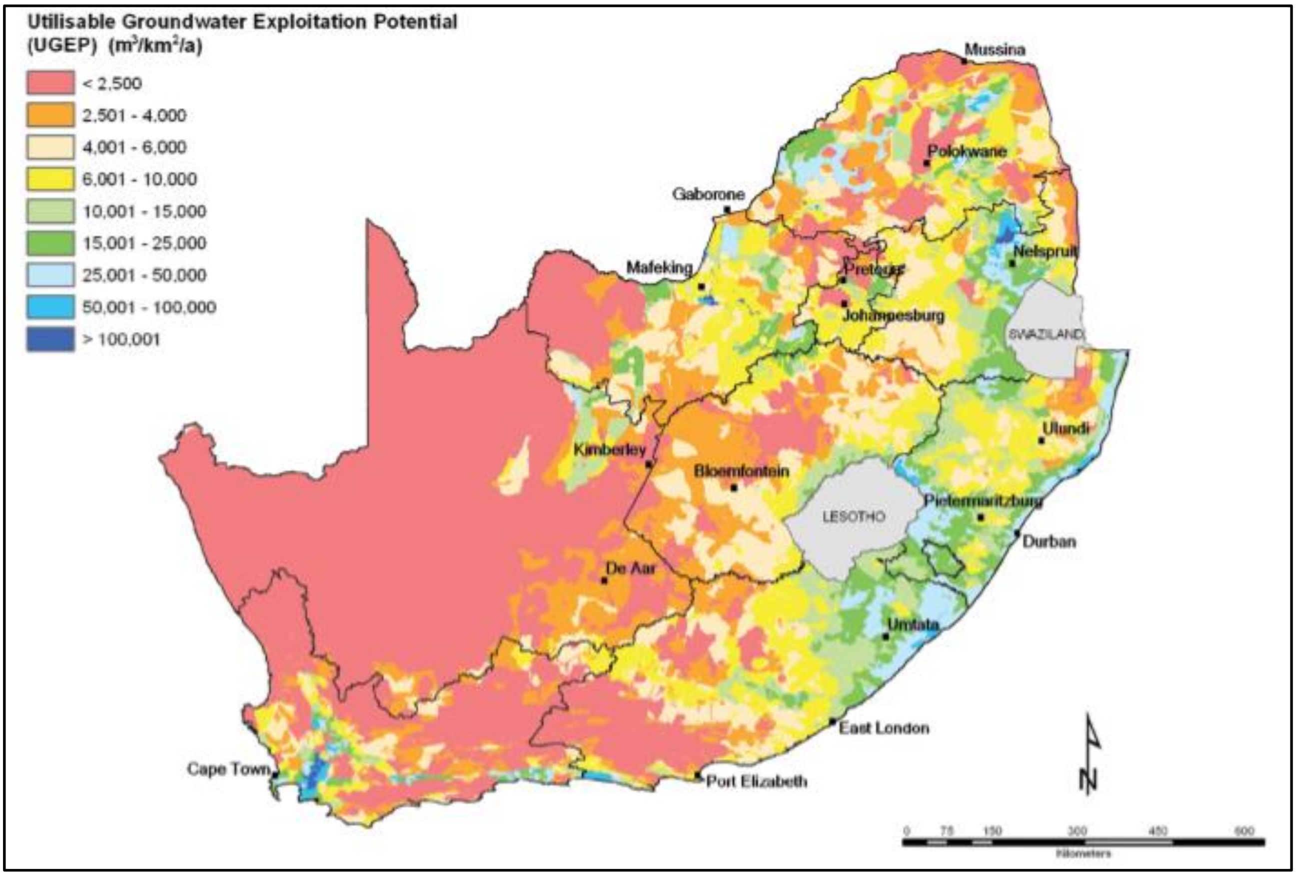

Figure 14: Groundwater exploitation map (adapted from DWA, 2010)

2.8 GEOPHYSICAL METHODS FOR GROUNDWATER EXPLORATION IN KAROO ROCKS

2.8.1 Introduction

Geophysical methods have been used for a number of applications particularly groundwater potential zone identification. Accurate and reliable results have been obtained when these methods are proposed with thoroughly understanding of geological, geomorphological and hydrogeological environments, water table conditions and topography in a specific location. Geophysical methods respond to the physical properties of the sub-surface material such as rocks, sediments, water, voids;

and they can be classified into two distinct types namely, passive and active methods. Passive methods detect variations within the natural fields associated with the Earth for example magnetic and gravitational field whereas, active methods use artificially generated signals that are transmitted into the ground such as seismology and resistivity methods (Reynolds, 1997).

There are different geophysical methods that can be used for groundwater exploration in Karoo rocks, but for this research two methods were instigated namely the magnetic methods and the resistivity methods. In this section these techniques are discussed with reference to the principles on which they operate and their application to groundwater exploration.

2.8.2 The Resistivity Method

2.8.2.1 Introduction

This technique is one of the geophysical investigation tools that are less costly and easy for operation as well as easier results interpretations. The electrical resistivity method has been widely used to image the resistivity structure of near surface targets within a few metres of the ground surface (Rubin and Hubbard, 2005). In groundwater exploration, resistivity surveys are utilised as a tool to delineate and determine the position of the geological structure and to investigate the in-depth of contacts between the different geological units as the results of their difference in apparent resistivity values (Vegter, 2001).

The method involves introducing electrical current into the ground and measuring the electrical potentials to determine the apparent resistivity of the subsurface. Resistivity data are then processed to produce models of the subsurface resistivity distribution.

2.8.2.2 The basic concepts of electrical resistivity

According to Herman (2001), resistivity of a material is a measure of how much an object or a material can resist or detain the electrical current flow. The statement that is brought by Reynolds (1997) states the current *(I)* that is passed through an electrically uniform object of a length*(L)*, the material through it can resist the conduction passing it and course a potential drop *(V)* between the opposite faces (refer to Figure 15). Ohm’s Law states that resistivity of a material can be related with electrical current *(I)* and potential difference *(V)* across a material (Equation 1), in which the resistance (*R)* is proportional to the length *(L)* of the resistive material and inversely proportional the cross sectional area

$$V = IR \tag{1}$$

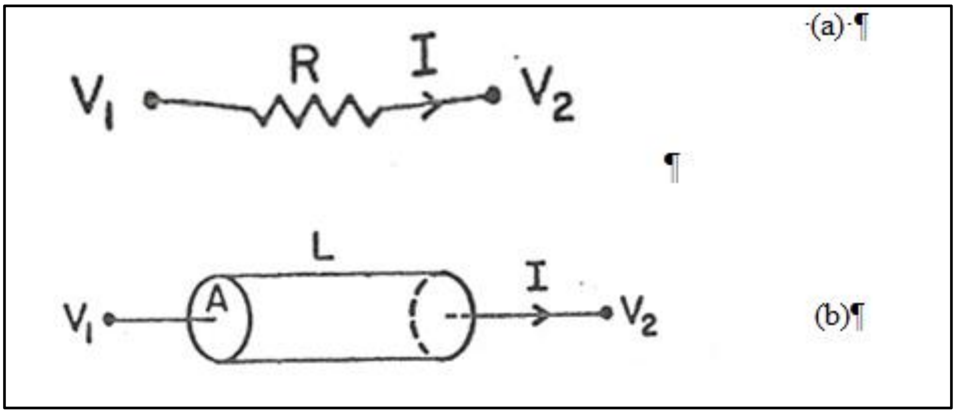

Figure 15: Presentation of Ohm's Law (adapted from Reynolds, 1997)

Equation (2) demonstrates that resistivity (R) depends upon the length of a cylinder (L), the cross-sectional area (A) and a characteristic property of a cylindrical material. Herman (2001) states that; the resistivity (ρ) of the material appears as the material specific constant of proportionality in the expression for the total resistance of the cylinder.

$$R = \rho \left(\frac{L}{A}\right) \quad (2)$$

For a cylinder consisting of homogeneous material, the resistivity ρ (unit: Ohm.meter, Ωm) can thus be expressed by using Equation (3):

$$\rho = \left(\frac{V}{I}\right)\left(\frac{A}{L}\right) \quad (3)$$

The deductions that can be made with reference from equation (2) is such that the resistance of a cylindrical object is dependent on both the material properties (ρ) and the geometry (L/A) of the object.

2.8.2.3 Resistivity surveys

When the resistivity surveys are done the resistivity of the ground is measured by injecting the electrical current into the subsurface material and then the resulting electrical potential difference at the surface of the earth is then measured.

The method is based on the fact that different geological units are more or less resistive to electrical current flow (Reynolds, 1997). On a normal set up two pairs of electrodes are required, that is two electrodes for measuring the resulting potential difference (denoted A and B) and two pairs of electrodes that are used to inject current into the subsurface (current electrodes, denoted M and N) (Figure 16).

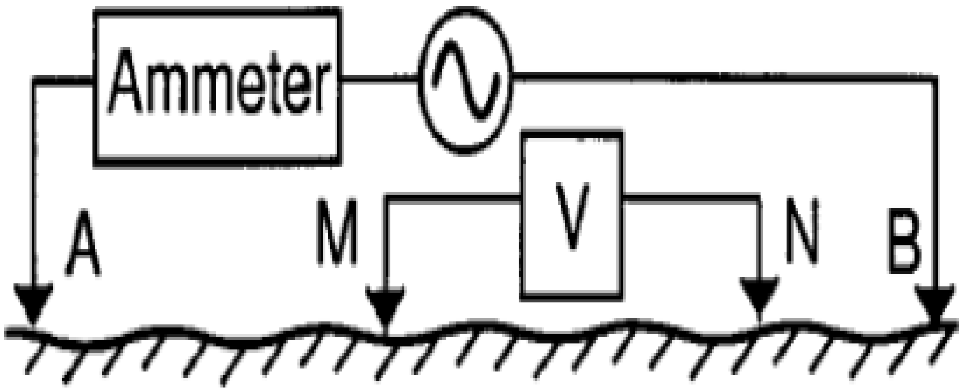

Figure 16: Normal configuration during resistivity surveys (adapted from Reynolds, 1997)

A DC or slowly varying AC current is injected into the earth by means of pairs of grounded current electrodes. The voltage drops between different pairs of grounded potential electrodes are then measured at selected positions at surface. These voltage drops are dependent on the resistivities of the materials through which the electrical currents are flowing. By assuming that the Earth is homogeneous and isotropic, measurements of the injected electrical current and measured voltage drops, as well as the distances between the different electrodes, may be used to calculate an apparent resistivity for the Earth at a specific position and (pseudo-) depth to obtain a pseudo-section of the Earth.

The apparent resistivities recorded during a survey may be inverted to obtain a model of the resistivity distribution within the subsurface. The modelled resistivity distribution may now be interpreted in terms of the local geological conditions by incorporating known information on the geology of the site. Two-dimensional (2D) resistivity techniques (also called electrical resistivity tomography, ERT) allow rapid recording of resistivity data at different positions and depths along the survey line. ERT systems usually employ multi-core cables that connect to numerous electrodes at constant spacing. A switcher unit automatically selects which electrode pairs on the cables act as current electrodes and potential electrodes. For each electrode selection an apparent resistivity value is calculated.

2.8.2.4 Electrode configurations and geometric factors

Reynolds (1997) states that, the value of the apparent resistivity depends on the geometry of the electrode array that is used as defined by the geometric factor *K*. which is defined by the expression:

$$K = 2\pi \left[\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right]^{-1} \tag{4}$$

This expression can be worked out by using correct values for Wenner arrays to substitute electrode pairs that are denoted by A, B, N and M:

$$K = 2\pi \left[\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right]^{-1} = 2\pi a$$

There are three main types of electrode configuration in which two of them are named after inventors namely; Frank Wenner and Conrad Schlumberger and some other range of sub-types, most commonly used arrays are highlighted in bold letters (see Table 8). These arrays have different geometric factors as it can be seen in Table 9.

Table 8 : Electrode configurations (adapted from Reynolds, 1997)

Wenner Arrays	**Standard Wenner** **Offset Wenner** Lee-partitioning array Tripotential (∝,βand γ array)
Schlumberger Arrays	**Standard Schlumberger** Brant array Gradient array
Dipole-dipole Arrays	**Normal** (axial or polar) Azimuthal Radial Parallel Perpendicular Pole-pole **Equatorial** **Square** (special form of equatorial)

Table 9: Apparent resistivity values for given geometric factors for electrode configurations (adapted from Reynolds, 1997)

Wenner array	$\rho a = 2\pi aR$ *(alpha/beta arrays)* $\rho a = 3\pi aR$ *(gamma rays)*
Two-electrode	$\rho a = 2\pi sR$
Lee array	$\rho a = 4\pi aR$
Schlumberger array	$\rho a = \frac{2\pi a^2}{b}(1\text{-}\frac{b^2}{4a^2})R;\ a \geq b5$
Gradient array	$\rho a = 2\pi \frac{L^2}{a}\frac{1}{G}R$ *Where* $G = \frac{1-X}{(Y^2+(1-X)^2)3/2} + \frac{1+X}{(Y+(1+X)^2)3/2)}$
Dipole-dipole array	$\rho a = \pi n(n+1)(n+2)aR$
Pole-pole array	$\rho a = 2\pi n(n+1)aR$
Square array	$\rho a = \pi a(2+\sqrt{2})R$

2.8.2.5 Depth of investigation

According to Reynolds (1997), the choice of array type includes the amount of space that has to be surveyed in order to lay out an array and the labour intensity of each technic. The sensitivity of an array to lateral inhomogeneity (Habberjam and Watkins 1967; Barker 1981) and to dipping interfaces (Broadbent and Habberjam, 1971) is some of the important factor that has to be considered.

The depth of investigation during a resistivity survey using the standard four-electrode configuration is dependent on the distance between the current electrodes (the AB distance). Larger current electrode spacing leads to greater depths of investigation since larger volumes of the subsurface are sampled for increasing current electrode separations (Telford *et al*., 1990). This property of resistivity surveys allows the investigation of resistivity changes at different depths in the subsurface.

2.8.2.6 Modes of deployment

When conducting the resistivity surveys, the investigations are based on delineate the electrical resistivity distributions on both lateral and vertical boundaries in the subsurface with depth. The vertical electrical resistivity measurement is referred to as sounding, whereas lateral or horizontal electrical resistivity measurement is called profiling.

Reynolds (1997) states that there are two main modes of deployment of electrode arrays in which one of them is meant for depth sounding (determination of the vertical variation of resistivity) and is known as vertical electrical sounding (VES). Constant separation traversing (CST) which is also called electrical resistivity traversing is used for to determine the horizontal variation of resistivity. Brookes and Kearey (1991) have identified three categories of field techniques that exist for conventional resistivity analysis of the subsurface. These techniques are vertical electric sounding (VES), constant separation traversing (CST), and combined procedures which utilize characteristics of both VES and CST.

Vertical electrical sounding

Vertical electric sounding (VES) employs collinear arrays designed to output a 1-D vertical apparent resistivity versus depth model of the subsurface at a specific observation point. In this method a series of potential differences are acquired at successively greater electrode spacings while maintaining a fixed central reference point. The induced current passes through progressively deeper layers at greater electrode spacing. The potential difference measurements are directly proportional to the changes in the deeper subsurface. Apparent resistivity values calculated from measured potential differences can be interpreted in terms of overburden thickness, water table depth, and the depths and thicknesses of subsurface strata. The two most common arrays used for VES are the Wenner array and the Schlumberger array. Figure 17 demonstrates the Wenner array configuration in which potential electrodes are nested within the current electrodes with a common lateral distance between adjacent electrodes called the electrode a-spacing.

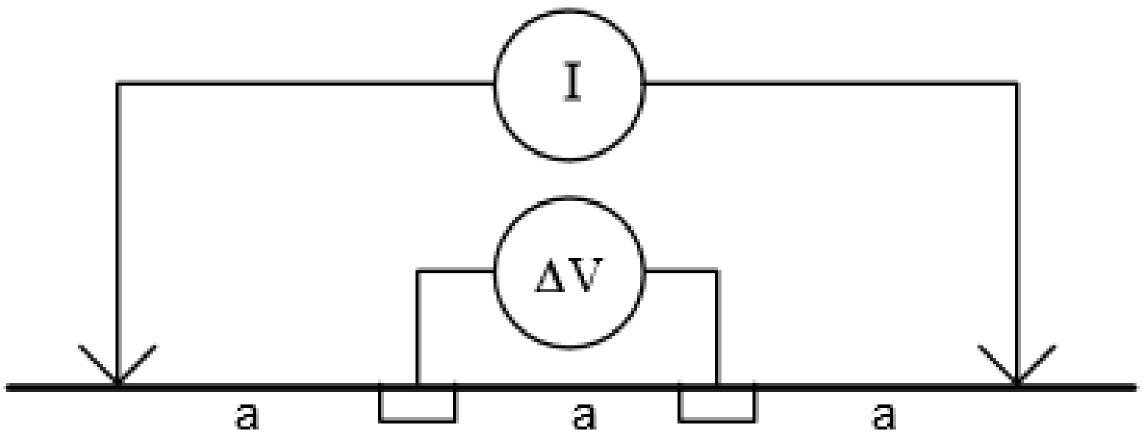

Figure 17: Wenner array configuration, depth of sounding is controlled by distance a (adapted from Ward, 1990)

Constant separation traversing

Constant separation traversing is the electrical profiling technic that uses collinear arrays to determine lateral resistivity variations in the shallow subsurface at a more or less fixed depth of investigation. The current and potential electrodes are moved along a profile with constant spacing between electrodes. The two most common array types used for CST are the dipole-dipole and pole-dipole arrays, where a dipole is a pair of current or potential electrodes.

Combination of VES and CST

The combination of vertical electrical sounding and constant separation traversing is used for clear delineation of subsurface anomalies because that often requires a technique for determining both lateral and vertical features. Three of the resistivity arrays (Wenner, Schlumberger, and pole-dipole) are capable of performing either lateral measurements (CST) or vertical measurements (VES), but it is generally inefficient for the individual arrays to simultaneously accomplish both sounding and profiling. This mode can be used in order to overcome the limitations that are associated with purely profiling and sounding techniques. Dipole-dipole technic is regarded as the best array for this technic as it has both sounding capabilities and profiling applications (Ward, 1990).

Advantages

- Soundings can be used to determine the depth and thickness of subsurface layers, depth to the water table, and bedrock.
- Profiling can be used to detect and locate contaminant plumes.
- Resistivity values can be used to estimate geological formations.

Limitations

- Like all geophysical methods resistivity data are ambiguous, meaning that many different "models" can produce the same data. To narrow down the number of possible models, other geological information is needed (borehole and/or monitoring well data).
- Electrical resistivity is slow because electrodes must be driven into the ground between measurements.
- Arrays cannot be oriented parallel to bury electrical power lines, utilities and fences since the current injected into the ground will flow more easily through the metal feature.
- Data are influenced by near surface conductive layers. The current will always travel most easily along highly conductive layers. If the surface is highly conductive it may not be possible to collect data below the top layer.

2.8.2.7 Resistivity of rocks

The resistivity of rock material is a complicated function of porosity, permeability, clay mineralisation and ionic content of the pore fluids. According to Parkhomenko (1967), the electrical resistivity of rocks is dependent on the porosity and the pore structure of the rock, amount of water (saturation), salinity of the water, temperature, water-rock interaction and alteration, pressure and steam content in the water. However, the most dependable factors are porosity, temperature, salinity and water-rock interaction and alteration.

Figure 18 and Figure 19 demonstrate the difference in resistivity of rocks, in which magmatic rocks display high resistivity values. The deductions that can be made from these are such that, since these rocks have lower porosities (see Table 10) as opposed to the other rocks which mostly consist of altered minerals their resistivity values are therefore higher. Resistivity values also increase with lower content of moisture in rocks and decrease with increase in clay mineral content in rocks.

Table 10: Porosity percentages of different types of rocks and soil (adapted from Palacky, 1987)

Rock or soil type	Maximum porosity (%)
Soil	>50%
Soil snd Gravel	20-47%
Clay	>49%
Cemented sand	5-25 %
Sandstone	10-15%
Limestone (and Marble)	5%
Oolitic limestone	10%
Chalk	up to 50%
Igneous rocks	<1.5%
Metamorphic rocks	very low, generally

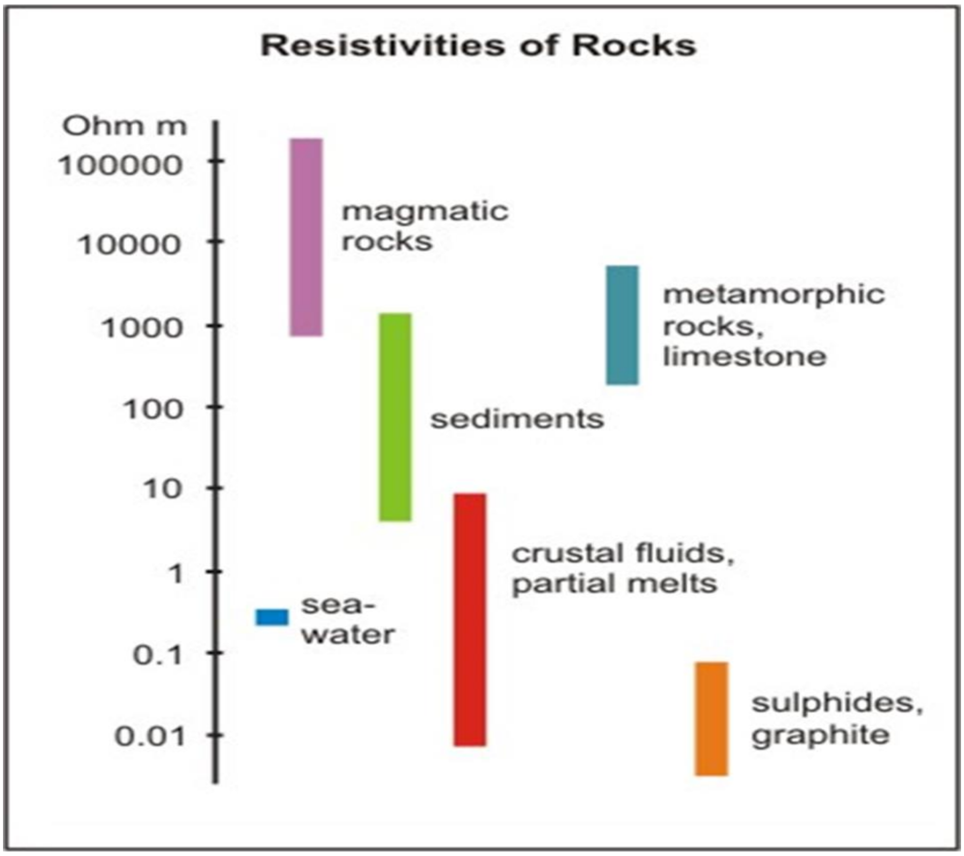

Figure 18: Differences in resistivity of rocks (Geonics, 1980)

Rocks, minerals, ores	Resistivity (ohm-m)
Sediments	
chalk	50–150*
clay	1–100
gravel	100–5000
limestone	50–10^7
marl	1–100
quartzite	10–10^8
shale	10–1000
sand	500–5000
sandstone	1–10^8
Igneous and metamorphic rocks	
basalt	10–10^7
gabbro	1000–10^6
granite	100–10^6
marble	100–10^8
schist	10–10^4
slate	100–10^7

Figure 19: Resistivity values of rocks and soil (adapted from Palacky, 1987)

2.8.2.8 Electrical resistivity tomography (ERT)

The electrical resistivity tomography (ERT) is a geophysical technique in which DC electrical current is injected into the ground using a pair of electrodes, then measuring voltage between a pair of electrodes. According to Vikas *et al.*, (2012), ERT is a geophysical technique that is flexible, fast and cost effective for mapping the shallow subsurface anomaly. It covers a wide spectrum of resistivity ranging from <1 Ohm.m to several thousands of Ohm.m. Two-dimensional (2D) resistivity techniques (also known as electrical resistivity tomography, ERT) allows rapid recording of resistivity data at different positions and depths along the survey line. ERT systems usually employ multi-core cables that connect to numerous electrodes at constant spacing (Figure 20).

Figure 21 is a typical set up of electrodes using ABEM Lund Imaging System; the multi-core cable is attached to an electronic switching unit which is connected to the resistivity meter. A laptop microcomputer together with an electronic switching unit is used to automatically select the relevant four electrodes for each measurement (Loke, 1999). A switcher unit automatically selects which electrode pairs on the cables act as current electrodes and potential electrodes. For each electrode selection an apparent resistivity value is calculated (Ramirez and Binley, 2005).

Figure 20: Electrode spacing along the traverse during resistivity survey using 2-D ERT

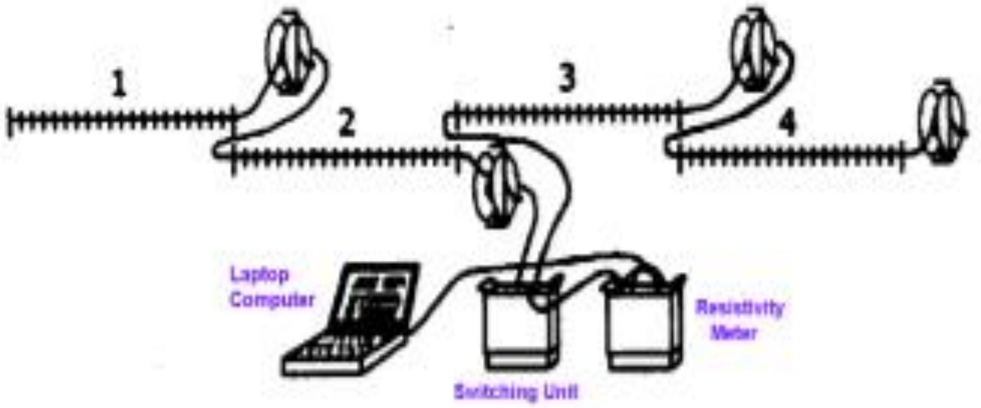

Figure 21: A typical set up of electrodes using ABEM Lund System in 2-D ERT surveys (adapted from Loke, 1999)

2.8.2.9 Applications of ERT

Electrical resistivity tomography (ERT) is commonly used to locate near-surface resistive features, such as weathered dykes and fracture zones, to profile the contact between two layers of different but uniform resistivity and to produce pseudo-resistivity depth profiles using multi-electrode and cable configurations (Vegter, 2001). The method can also be used to detect and delineate buried geological structures, such as dolerite dykes, if there is an adequate contrast between the resistivities of the structures and the host rock.

Advantages of ERT

- It is possible to create a 3-D image using parallel survey lines
- It is possible to do survey beneath a raised building and across water.
- The survey does not necessarily need manpower as the setup can be done by a single person without involving other people, however the mobilization of the equipment can require two or more persons.
- It is easier to learn and to interpret ERT surveying as opposed other methods.

Limitations

- ERT provides measurements of electrical resistivity not interpretations
- Massive bedrock without water will not show any contrast between frozen and unfrozen conditions

2.8.3 The Magnetic Method

2.8.3.1 Introduction

The magnetic method of geophysical exploration involves measurements of the direction, gradient, or intensity of the Earth's magnetic field and interpretation of variations in these quantities over the area of investigation. Magnetic surveys can be made on the land surface, from an aircraft, or from a ship. Most exploration surveys made today measure either the relative or absolute intensity of the total field or the vertical component. Measurements of magnetic intensity can be made with simple mechanical balances or with elaborate electronic instruments.

When magnetic surveys for groundwater exploration are conducted the major focus is to delineate the most magnetic geological features on the subsurface that could enhance the possible pathways for groundwater to the surface. The measurements of the Earth's magnetic field are taken to detect changes in the magnetic properties of the subsurface materials and the changes that are observed during the survey called magnetic anomalies can be interpreted in relation to their possible geological origins.

2.8.3.2 Magnetic field origin

Magnetic field is a force which is generated due to energy change in a volume of space. A magnetic field is produced by an electrical charge in motion e.g. current flowing in a conductor, orbital movement and spin of electrons. The electromagnetic theory states that, the magnetic field is a consequence of a flow of electrically charged particles (electric current). According to Ampère's Law, a current I in a conductor of length Δl creates at a point P a magnetizing field ΔH:

$$\Delta H = (I\Delta l) \times \frac{\boldsymbol{r1}}{4\pi r^2}$$

where **r1** is a unit vector pointing from the conductor to the point of observation, and r is the distance between the conductor and the point of observation.

2.8.3.3 The magnetic field of the Earth

The Earth has a magnetic field which is mainly produced within its interior and forms a protecting shield around the planet, called the magnetosphere. The magnetosphere protects Earth's inhabitants from the highly energetic and dangerous particles from the sun and it prevents the Earth's atmosphere from being blown away by the solar wind (Gunnarsdóttir, 2012). There is also a magnetic field produced by the induced currents in the crust, mantle and oceans which adds to the total geomagnetic field.

The magnetic field of the Earth originates from the beginning of Earth and Life as stated by most of the geoscientists. According to Roberts and King (2013), the Earth is surrounded by a magnetic field which is generated and maintained by convective motions of molten rock in the fluid outer core which is made of molten iron and nickel. Convection currents in the core result in motion of charged particles in a conductor, producing a magnetic field. The field behaves as though there is a north magnetic pole in the southern hemisphere and a south magnetic pole in the northern hemisphere. Figure illustrates the earth being pictured as a large magnet dipole, composed of the positive poles at the South Pole and negative pole at the North Pole. The field lines form outside the Earth connecting from the South Pole (+) to the North Pole (-).in the Northern Hemisphere the field lines are orientated facing downward into the earth and vice-versa in the Southern Hemisphere (Gunnarsdóttir, 2012).

The magnetic field is similar to that of a dipole field generated by a bar magnet with a north and a south pole. The imaginary bar magnet has an axis which is approximately tilted at about 11.5 degrees when compared to the geographic Earth's rotational axis, therefore, the Earth's magnetic pole do not coincide with its geographic north (refer to Figure 22).

In Figure 23 the components and angles of geomagnetic field are displayed, in which F is the *total intensity* of the magnetic field, which intersects the Earth at an angle I, which is referred to as the *magnetic inclination* with respect to the horizontal. There are two components in which F can be split into, H which is parallel to the earth's surface and Z which normal to the earth's surface. D is the *declination angle* that is in between H and the geographic or rotational north (refer to Figure).

The geometric relations of these components are as follows (Gunnarsdóttir, 2012):

$$X = F \cos D \cos I \qquad Y = F \sin D \sin I \qquad Z = Fsin\, I$$

$$\tan I = z/H \quad \tan D = y/x$$

$$H = F \cos I = \sqrt{}(x^2 + y^2) \quad F = \sqrt{(x^2 + y^2 + z^2)} = \sqrt{(H^2 + z^2)}$$

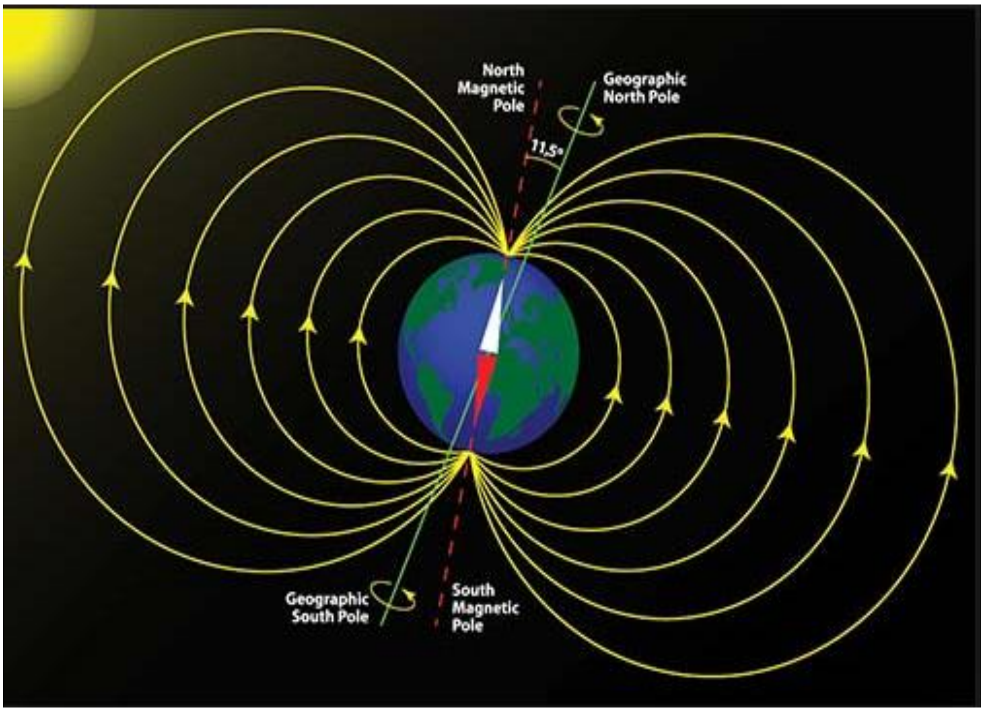

Figure 22: Earth's magnetic field (adapted from Gunnarsdóttir, 2012)

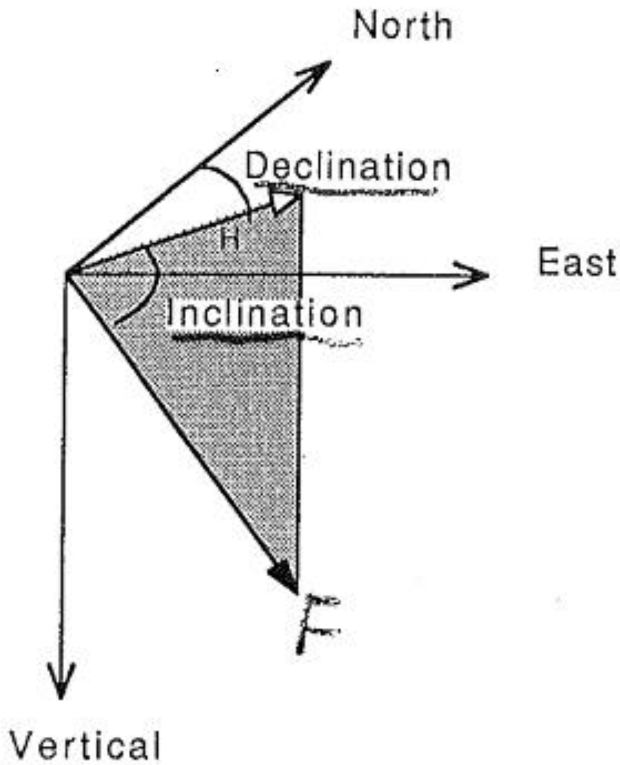

Figure 23: components and angles of the geomagnetic field (adapted from Gunnarsdóttir, 2012)

2.8.3.4 Variations in the Earth's magnetic field

The Earth's magnetic field varies significantly with time ranging from seconds to millions of years due to its instability. There are two main groups in which these time variations are divided namely; long time and short time variations. These variations can be differentiated in terms of their origin i.e.

long term variations originate from the interior of the earth whereas the short term variations originate from the external of the earth.

The scalar factor of long term variations is ≥5 years and they are named secular variations, while the short term variations can be on a scale ranging from seconds up to less than a year. The secular variations are said to appear as the main field variations caused by electrical currents in the ionosphere, induced by solar radiation (Gunnarsdóttir, 2012). The short term variations are normally produced by the induced currents in the Earth's crust and oceans. Periodic variation of the magnetic field as a result of the rotation and /or orbital motion of the Earth, Sun, and the Moon can be encompassed within a short term variation group. These changes are particularly severe during large solar activity, which are often referred to as magnetic storms.

2.8.3.5 Induced and remanent magnetism

The state of charged particles in association with the crystal structure-motions of the electrons and the interaction among the electrons determine the magnetic properties of rocks and create their magnetic moment. There are two basic kinds of magnetization: induced magnetization and remanent magnetization. In the presence of an externally applied magnetic field the magnetization of a substance maybe written as the sum of an induced and a remanent (or spontaneous) component (Stacey, 1963; Reynolds, 1997).

$$\mathbf{M} = \mathbf{M_i} + \mathbf{M_r}$$

The remanent component, $\mathbf{M_r}$ is generated by the material itself, and without this contribution there would be no possibility of a rock recording the paleomagnetic field. The constitutive relation, which is commonly written as

$$\mathbf{M} = y\mathbf{H}$$

describes the induced magnetization acquired when a material is exposed to a magnetic field **H**; χ is the magnetic susceptibility and describes the response of electronic motions within the material to the applied field.

Natural remanent magnetism (NRM) is magnetism that is present in the rock as a result of its formation either due to volcanic, sedimentology or metamorphic origin. The component of NRM which is acquired during the formation of a rock is referred to as *primary NRM* whereas the *secondary NRM* component results from the alteration of the rock primary NRM. Both of these components can sum up to produce NRM;

$$NRM = primary\, NRM + secondary\, NRM$$

There are three basic forms of natural remanent magnetism; thermoremanent magnetism that is acquired during cooling of rocks, chemical remanent magnetization which is acquired by the growth of ferromagnetic grains below the curie temperature and detrital remanent magnetization which is formed as a result of accumulation of sedimentary rocks containing detrital ferromagnetic minerals Stacey, 1963).

2.8.3.6 Magnetic susceptibility of rocks

Ferromagnetic minerals like magnetite, pyrrhotite and ilmenite are the best determinants in terms of magnetic susceptibilities of rocks. The content of these minerals within the geological units magnetise them by the Earth's magnetic field and they possibly have their own magnetic fields associated with them.

These local magnetic fields that are due to the magnetised geological units will be superimposed on the Earth's regional magnetic field. Measurements taken in the vicinity of magnetised geological units will therefore show local variations or departures from the undisturbed magnetic field of the Earth (called the regional field). These departures are referred to as anomalies. The shapes of the anomalies are dependent on a number of factors regarding the physical properties and dimensions of the magnetised geological units.

Figure 24 and Figure 25 is the demonstration of different types of rocks with their different magnetic susceptibilities, in which basic igneous rocks elucidate the high values as compared to the other rocks. Basic igneous rocks have a higher quantity of mafic minerals which are formed by the likes of the magnetic minerals. These rocks have formed as a result of cooling of the magma; in that case they preserve primary NRM which could highly support the higher maximum values of magnetic susceptibilities that would have been locked within during their formation.

Sedimentary rocks show the least values of magnetic susceptibilities which could be resultant from the alteration of some ferromagnetic minerals causing the rock to have secondary NRM. The presence of acidic minerals like quartz in a rock reduces its ability to be magnetic as they are incompatible with such ferromagnetic minerals (some of the mafic / basic minerals).

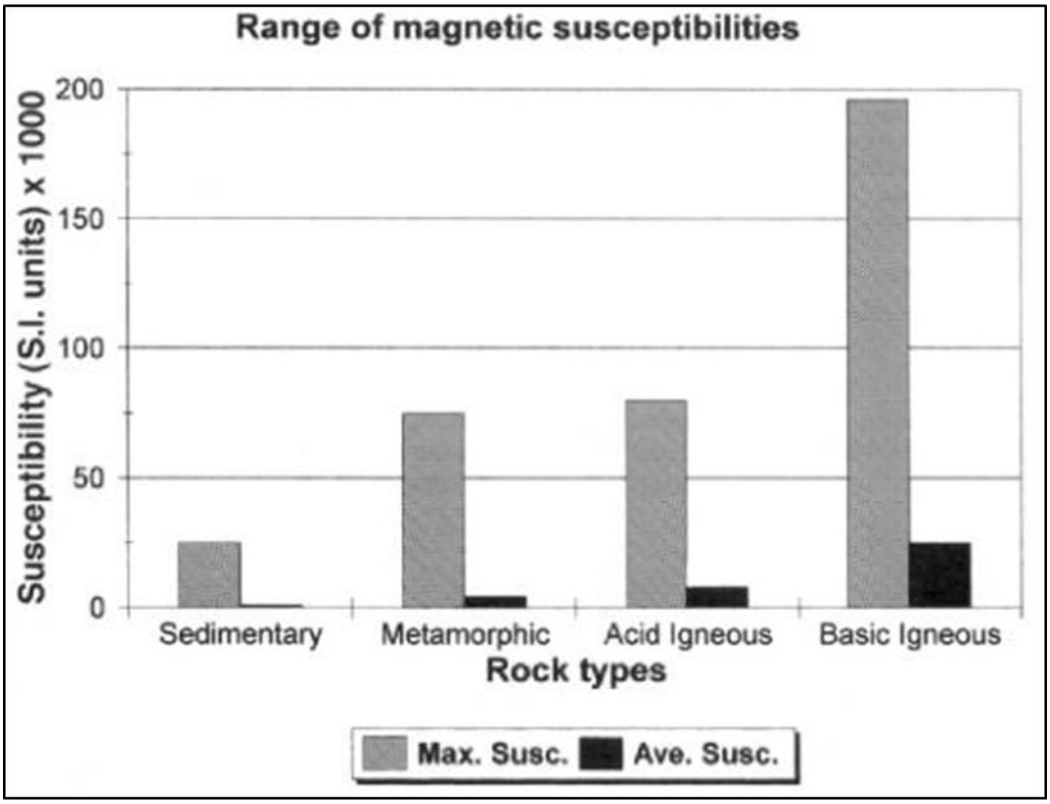

Figure 24: Magnetic susceptibility of different rock types (UKM, 2017)

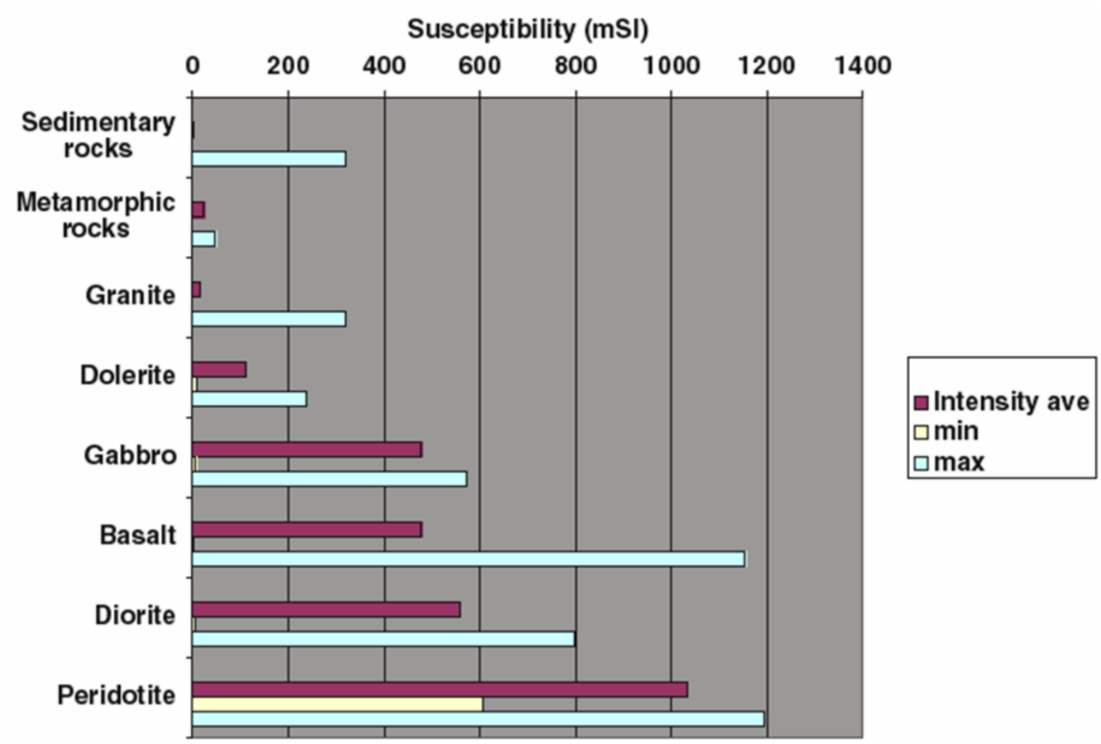

Figure 25: Differences in magnetic intensities of rocks (USGS, 2015)

2.8.3.7 Magnetic surveys

When the magnetic surveys are conducted, the main focus is to investigate the magnetic susceptibility distribution of the subsurface materials and to delineate the possible geological features such as fractures as lineaments in the subsurface. The most magnetic geological units are the basic rocks that mostly host the ferromagnetic minerals such as the doleritic intrusions (dykes and sills), which along their contact zones with the country rocks the fractures and lineaments can be encountered.

During the reconnaissance survey intrusive geological features such as dolerite outcrop were observed along the study area (Figure 47). These intrusions as well as the dense vegetation along the study area were linked to the existing knowledge about the geological units; the magnetic surveys were conducted along the study area. By incorporating existing knowledge on the geological conditions at the site being surveyed, the magnetic anomalies recorded during a survey may be interpreted in terms of the local geological conditions. Dolerite is typically very magnetic as compared to Karoo sedimentary rocks. This contrast in the magnetic properties of the rocks makes the magnetic method well-suited for the detection of dolerite intrusions.

The magnetic survey is mostly or preferably done on open areas where there is no fencing, wiring or buildings at the closest range to the study area. The purpose of this is to avoid the unreliable or incorrect magnetic data as the already mentioned items are highly magnetic. The purpose of conducting the magnetic surveys is to detect the magnetic intensity of the rocks within the study area. According to Telford *et al*. (1990), the principles in which magnetic techniques operate state that:

- Magnetic surveys play an integral part in recording and mapping magnetic variations in the Earth’s magnetic field particularly as a result of changes in magnetic properties of the basement rock. Ferromagnetic minerals such as pyrrhotite and ilmenite presence within the rocks contribute in determining the magnetic susceptibility of a rock, which will influence the development of high amplitude of the magnetic anomalies.
- Remanently magnetised rocks like the basement rocks that are being affected by multiple stages of deformation and intrusion will therefore produce a magnetic field.
- The non-volcanogenic rocks such as sedimentary rocks do not have a high magnetic susceptibility as opposed to their volcanogenic counterpart rocks.
- In addition to the already mentioned characteristics or principles, the magnetic survey can be used in identifying some structural features that may have developed within the country rocks or even the intrusive rocks such as dolerite dykes and sills within the sedimentary rocks.

2.8.3.8 Magnetic survey instrumentation

Magnetic surveys can be conducted with the use of different instrumentation depending on the type of survey that has to be engaged in. The proton procession magnetometer, Overhauser magnetometer, cesium vapour magnetometer and the SQUID (superconducting quantum interference device) are the different types of magnetometers that can be used in magnetic surveys. The proton procession magnetometer (Figure 26) is the most of all commonly used magnetometers as a result of being more affordable; however it has its own disadvantages as compared to the other types.

Figure 26: Magnetic surveys using Proton Precession Magnetometer during phase 1 of the magnetic survey.

The field investigations carried out during the current study used the GSM-19T magnetometer, manufactured by GEM Systems. This magnetometer is an Overhauser magnetometer and allows the total magnetic field to be recorded at selected sampling rates (GEM, 2008). The GPS coordinates are also measured at the same sampling rate. This allows the system to be used in a continuous mode, where the operator simply walks along the survey lines while the system automatically records magnetic and GPS data, hence why the system is commonly known as *Walkmag* (refer to Figure 27).

Figure 27: Setting and using Walkmag for magnetic survey

2.8.3.9 Advantages and limitations of different magnetic survey instruments

The advantages and limitations of the magnetic survey instruments are displayed in Table 11. The choice on the use of the instrument has to rely on the advantages and the limitations an instrument has as compared with others. The proton precession magnetometer seems to have more of the limitations as compared to the other instruments; however, it was used during the first phase of the magnetic survey as indicated in Figure 26.

Table 11: Advantages and limitations of different magnetic survey instruments (adapted from Reynolds, 1997)

MAGNETIC SURVEY INSTRUMENT	ADVANTAGES	LIMITATIONS
Proton procession magnetometer	Don’t have to align ‘bottle’ with field.	Can’t record continuously
	Fairly lightweight yet rugged.	Can’t measure vector field
	Fairly cheaper as compared to other types	Requires a lot of work and many people for preparations and operation.
SQUID	Allows rapid continuous sampling	Expensive to purchase
Overhauser magnetometer	Can record continuously and survey can be done on a larger scale without much labour with rapid speed of operation (up to 5 readings per second)	Expensive to buy
	Can measure vector field	
	It has a high absolute accuracy.	
	It has exceptionally low power consumption.	
	Can be operated by a single person.	
cesium vapour magnetometer	Do not have to align ‘bottle’ with field.	Cannot measure vector field

CHAPTER 3:
DESCRIPTION OF THE STUDY AREA

3.1 INTRODUCTION

In this chapter the study area of the current investigation is described in detail in terms of the regional setting, geological setting, regional magnetic setting, climatology, topography and drainage, soil and vegetation, geohydrology, structures and transition zones, and recharge.

3.2 REGIONAL SETTING

The study area is located within the central business district (CBD) of the city of Bloemfontein, the capital city of the Free State Province. The location of Bloemfontein within the Republic of South Africa is shown in Figure 28.

3.3 GEOLOGICAL SETTING

The city of Bloemfontein is underlain by rocks of the Karoo Supergroup which are predominantly sandstones, mudrocks and shales. Dolerite intrusions that resulted from the magmatic intrusions during the Jurassic Period (180 Ma) can be observed mostly towards the northern boundaries and within the central part of the study area. The 1:250 000 geological map produced by the Council for Geosciences indicates the presence numerous dolerite outcrops partially underlying the city (refer to Figure 29).

3.4 REGIONAL MAGNETIC SETTING

Figure 30 is an airborne magnetic map covering the city of Bloemfontein, displaying numerous prominent zones of high magnetic field strength, indicated in red colours. These zones are more visible to the north-west, south-west and south-east of the city, and are probably representative of large doleritic intrusions in a form of prominent sill and dykes. Some of these intrusions can be visually observed as prominent dolerite outcrops. A prominent linear magnetic feature with a west/east strike can be observed south-east of the city boundaries. This feature is most probable due to the presence of a large dolerite dyke.

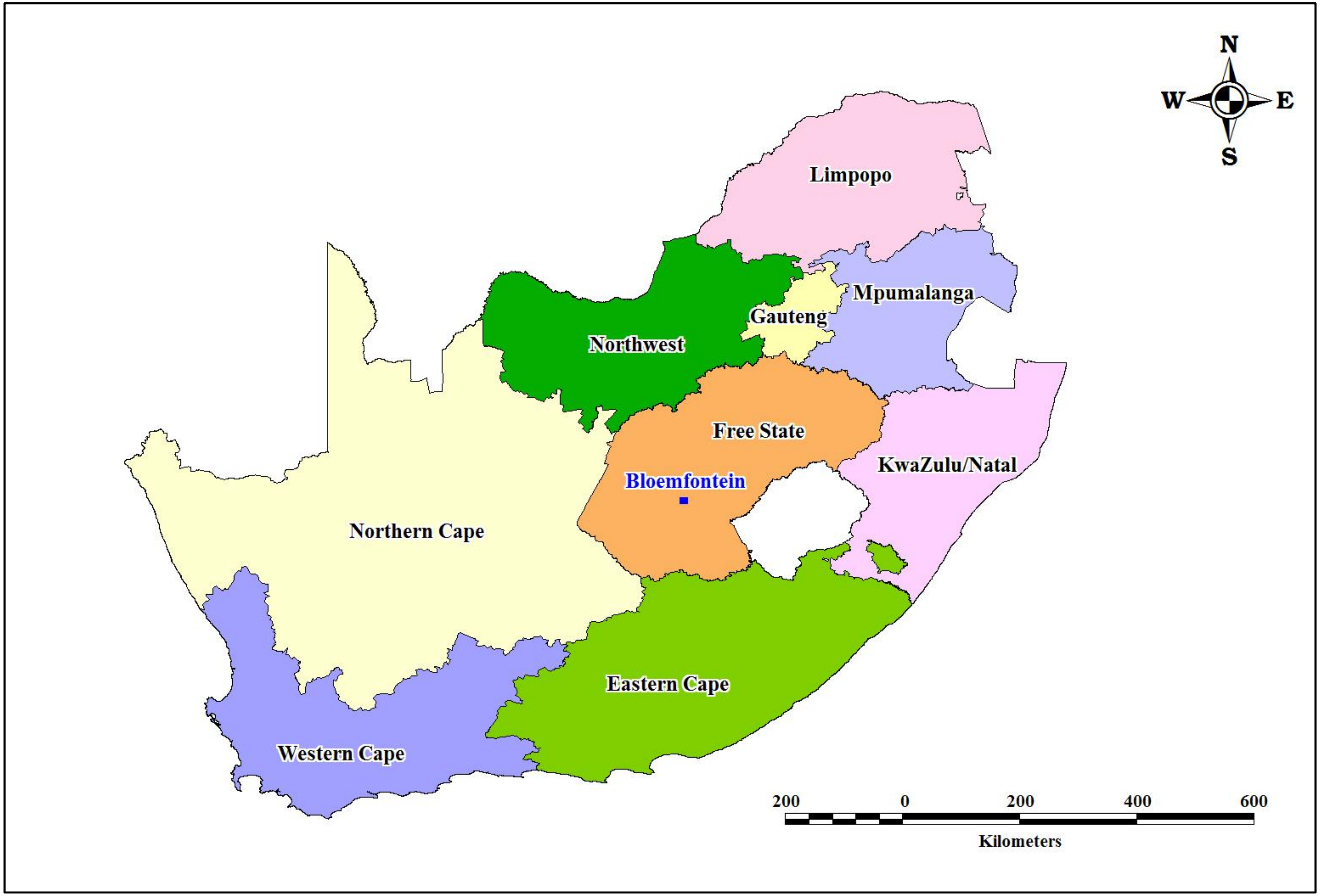

Figure 28: Regional setting of Bloemfontein

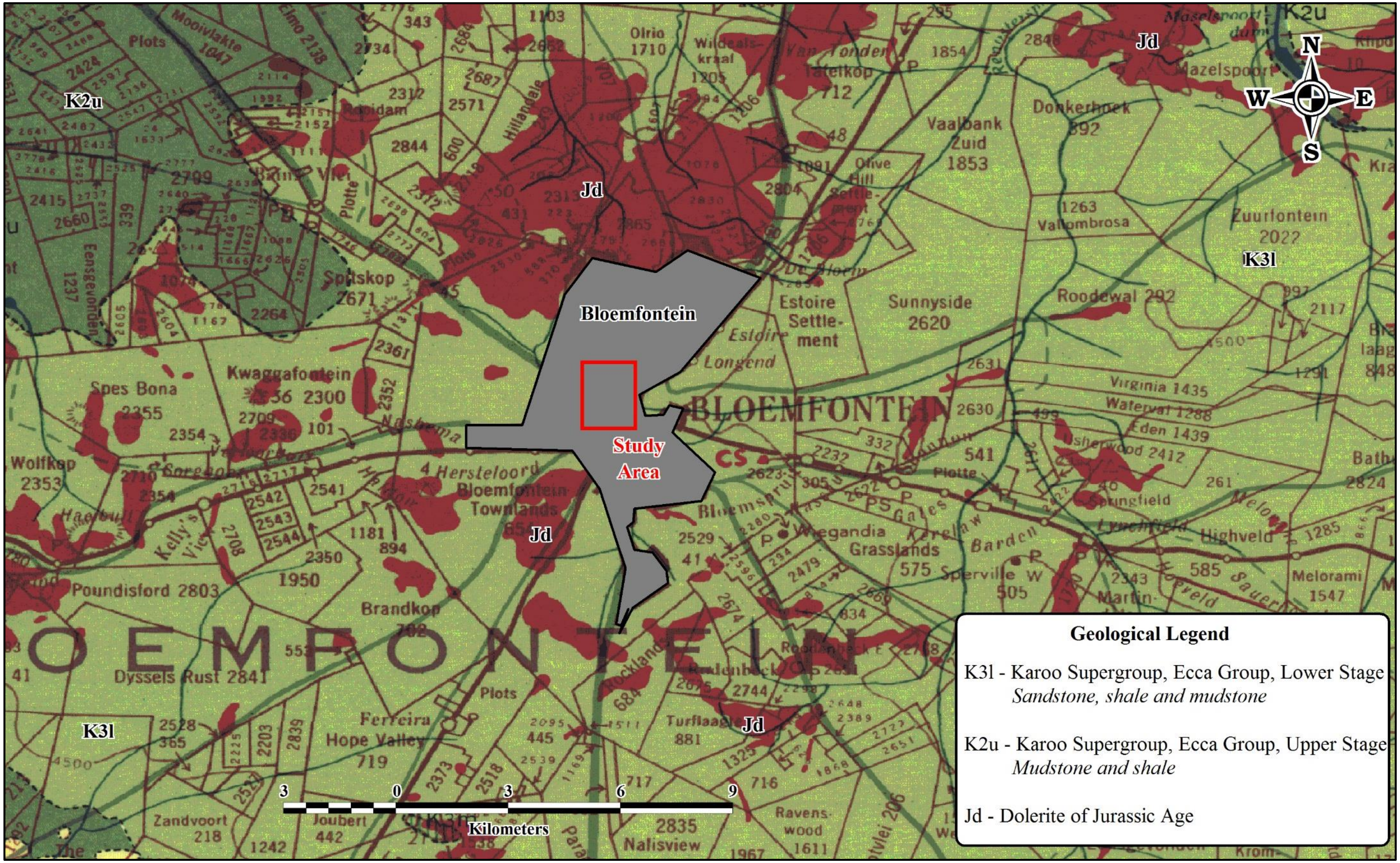

Figure 29: Geological setting of Bloemfontein

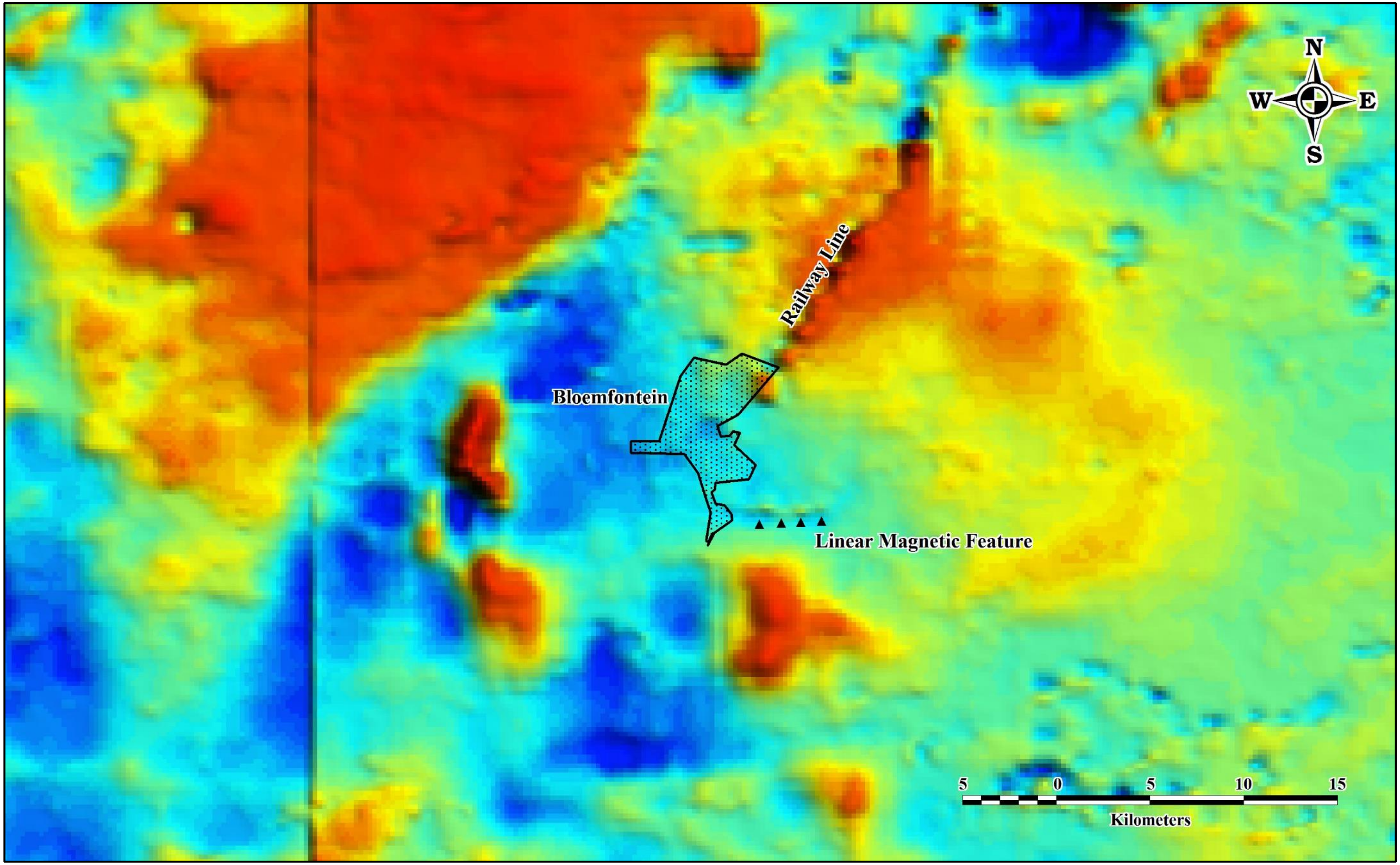

Figure 30: Regional magnetic setting of Bloemfontein

3.5 CLIMATE

3.5.1 Temperature

Bloemfontein experiences a semi-arid to climatic conditions. The summer temperatures are generally high. Hot temperatures are mostly experienced during the day, while cooler temperatures occur at night. The maximum temperatures of approximately 30°C are normally experienced during January and December (Figure 31). During winter months, the temperature becomes uncomfortably cold and reaches minimum values of approximately -1°C. Frost often occurs during the winter months.

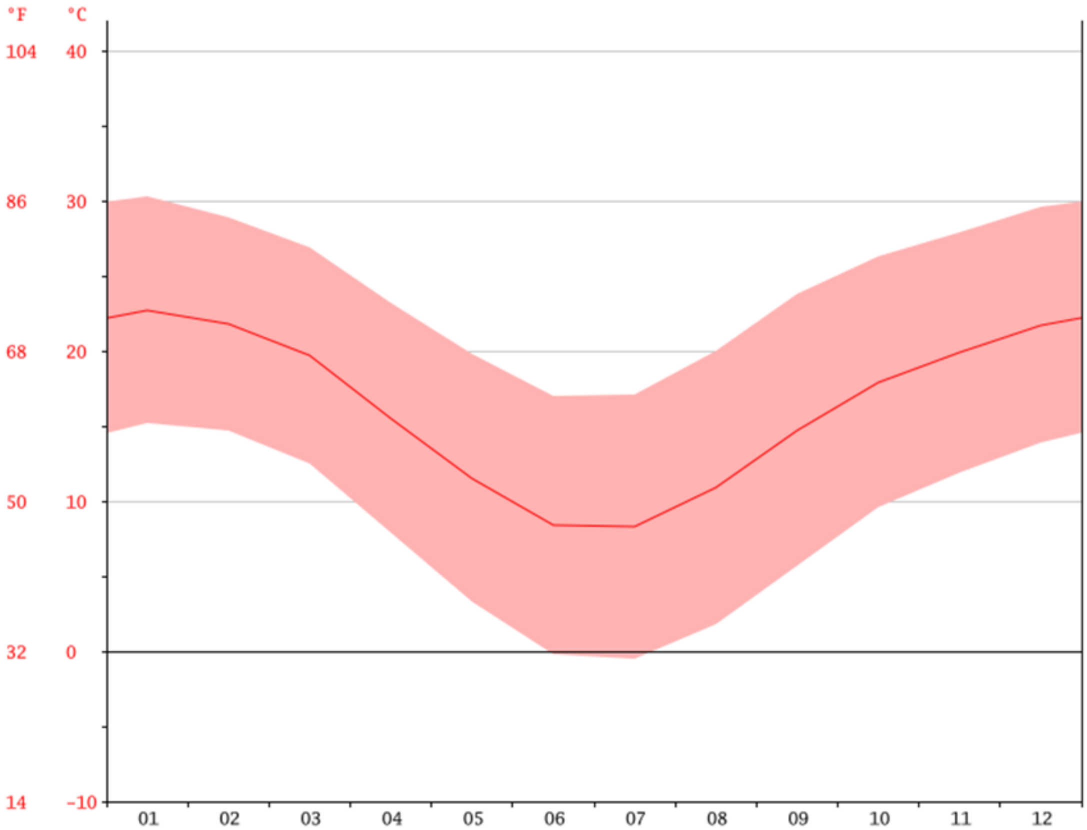

Figure 31: Annual temperatures in Bloemfontein (WeatherSpark, 2017)

3.5.2 Precipitation

The study area lies within a summer rainfall region with a mean annual precipitation (MAP) of approximately 550 mm (refer to Figure 32). The highest rainfall rates are usually experienced from January to March. The lowest rates are typical in June and July, and range from 7 mm/month to 10 mm/month (Figure 33). Snow is not often experienced in Bloemfontein, but occurs as sporadic falls.

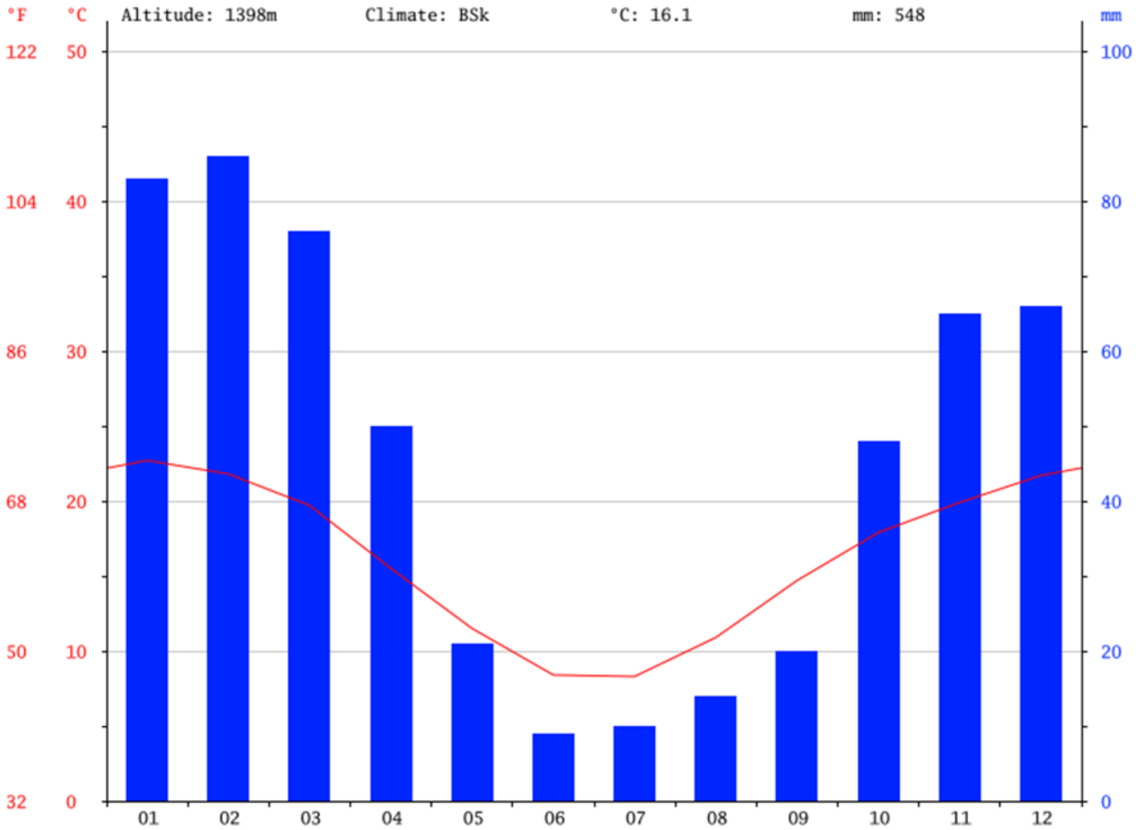

Figure 32: Annual and average rainfall for Bloemfontein (SAWS, 2017)

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Okt	Nov	Dec
mm	83	86	76	50	21	9	10	14	20	48	65	66
°C	22.7	21.8	19.7	15.5	11.5	8.4	8.3	10.9	14.7	17.9	19.9	21.7
°C (min)	15.2	14.7	12.5	7.9	3.3	-0.2	-0.5	1.8	5.7	9.6	11.9	13.9
°C (max)	30.3	28.9	26.9	23.2	19.8	17.0	17.1	20.0	23.8	26.3	27.9	29.6
°F	72.9	71.2	67.5	59.9	52.7	47.1	46.9	51.6	58.5	64.2	67.8	71.1
°F (min)	59.4	58.5	54.5	46.2	37.9	31.6	31.1	35.2	42.3	49.3	53.4	57.0
°F (max)	86.5	84.0	80.4	73.8	67.6	62.6	62.8	68.0	74.8	79.3	82.2	85.3

Figure 33: Estimated annual minimum and maximum rainfall and temperature for Bloemfontein (SAWS, 2017)

3.5.3 Wind

The wind speed varies greatly in Bloemfontein depending on season. The range of wind speeds is typically 0 to 9 m/s. The highest average wind speed of 3 m/s (light breeze) occurs around 22 November when the average daily maximum wind speed is 7 m/s (moderate breeze). The lowest average wind speed of 2 m/s (light breeze) occurs around 14 May, when the average daily maximum wind speed is 4 m/s (gentle breeze) (WeatherSpark, 2017).

According to WeatherSpark (2017), the wind that is experienced at any given location is greatly dependant on the local topography and other factors. Instant wind speed and direction vary more widely than the hourly averages. In Bloemfontein, the average hourly wind speed exhibits mild seasonal variation over the course of the year. The windier part of the year lasts for 5.6 months, from July 25 to January 13 (see Figure 34).

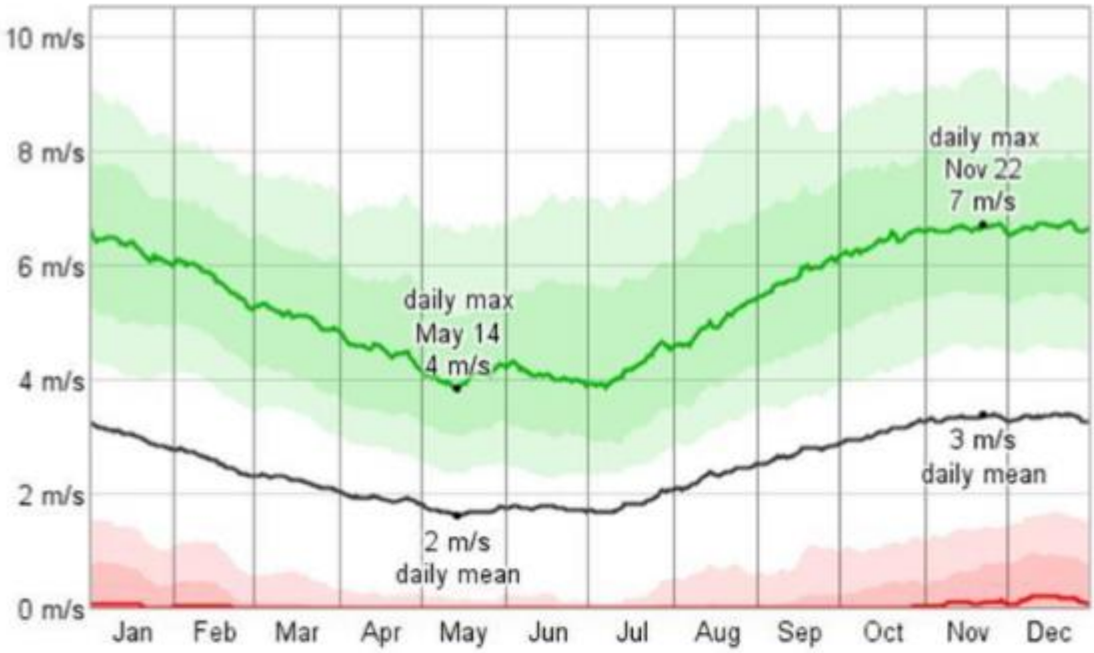

Figure 34: Wind speed averages for Bloemfontein per annum (WeatherSpark, 2017)

The predominant average hourly wind direction in Bloemfontein varies throughout the year. The direction is normally from the west for 1.1 weeks, from 16 to 24 September, with a peak percentage of 33% on the 18 of September (meaning that the wind is from the west for 33% of the day). Over all 12 months of the year, the wind is predominantly from the north, with a peak percentage of 39% on 1 January (refer to Figure 35).

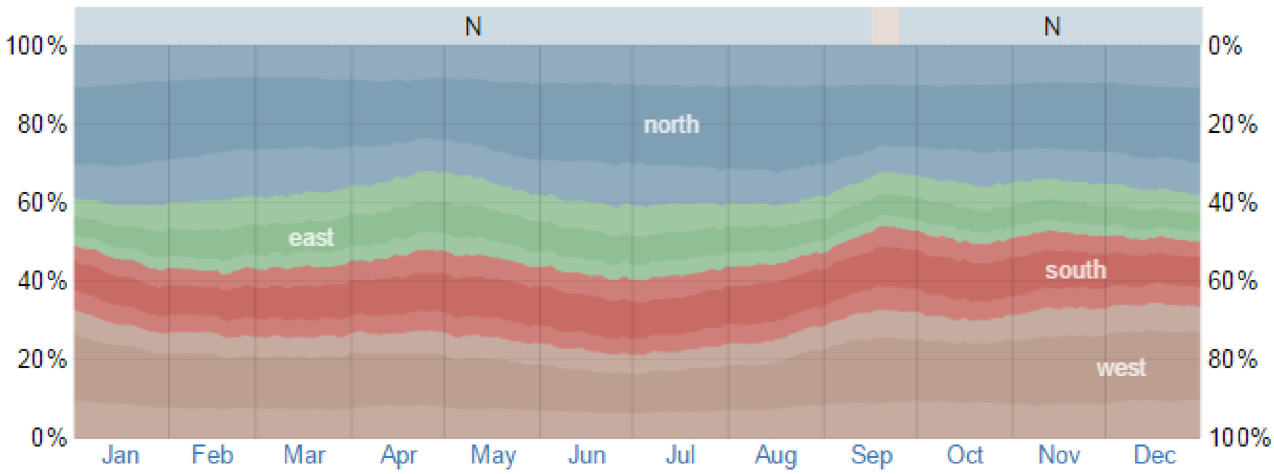

Figure 35: Wind direction in Bloemfontein (WeatherSpark, 2017)

3.5.4 Humidity

The relative humidity typically ranges from 18% (dry) to 92% (very humid) over the course of the year, rarely dropping below 8% (very dry) or reaching values as high as 100% (very humid) (Figure 36). The air is driest around 2 September, at which time the relative humidity drops below 22% (dry) three days out of four. The humidity is the highest around 9 May, exceeding 87% (very humid) three days out of four (WeatherSpark, 2017).

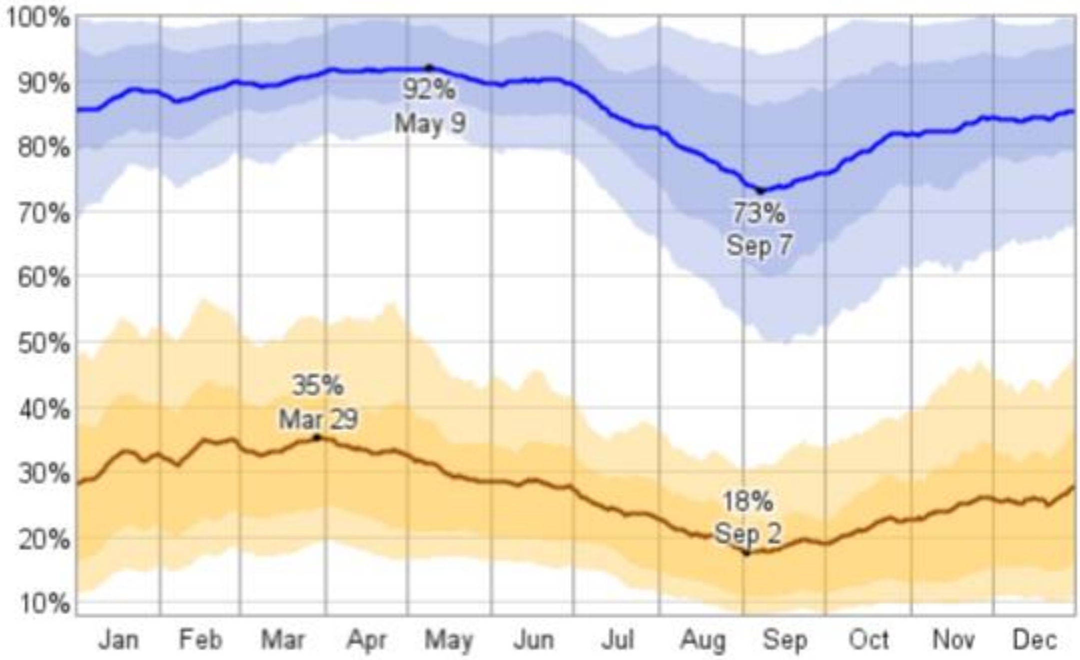

Figure 36: Annual humidity values for Bloemfontein

3.5.5 Dew Point

Dew point is the temperature where condensation begins, or where the relative humidity would be 100% if the air was cooled. Lower levels of dew points feel drier and higher levels of dew points feel more humid (WeatherSpark, 2017). The dew point in Bloemfontein varies over the course of the year, from dry to comfortable, -7ºC to 16ºC respectively (Figure 37). The dew point in Bloemfontein is rarely experienced below -14ºC (dry) or above 18ºC (mildly humid) (WeatherSpark, 2017).

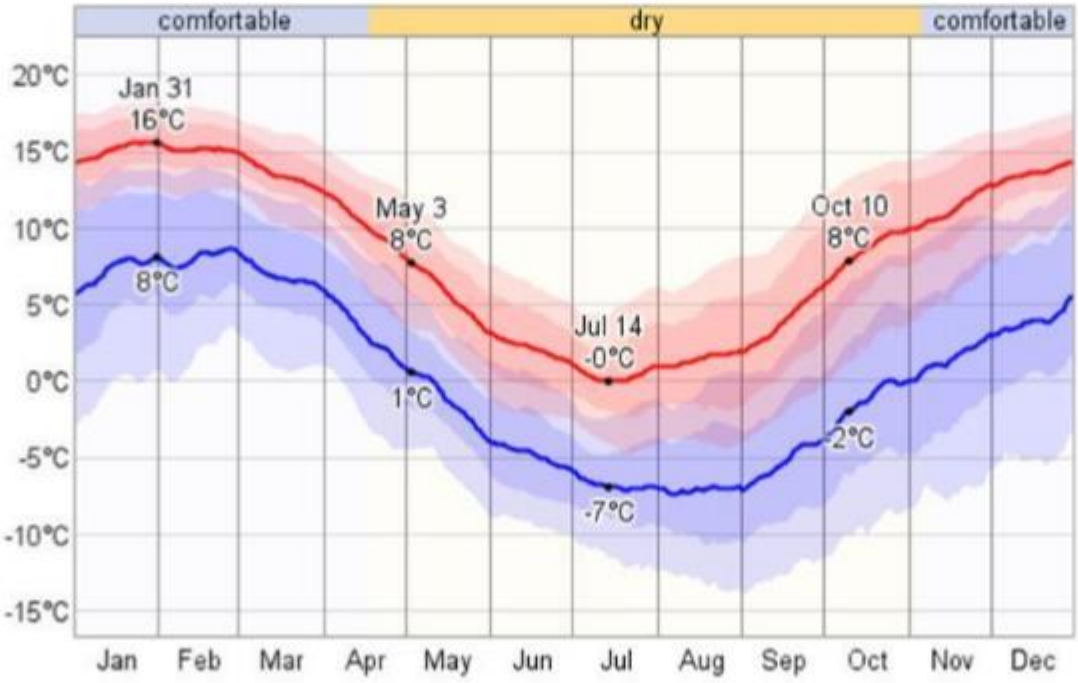

Figure 37: Annual dew point for Bloemfontein

3.5.6 Daylight

The length of the day varies with different seasons throughout the course of the year. According to WeatherSpark (2017), the shorter days in Bloemfontein are experienced in winter months (21st June) and longer days in summer months (21st December).

The determinants of day length are sunrise and sunset. In warmer months (summer), the earliest time for sunrise is 05h08 on 1 December and the latest sunset is on 7 January at 19h20. The latest sunrise is on 3 July (07h10) and the earliest sunset is on the 8 June (17h30) (Figure 38).

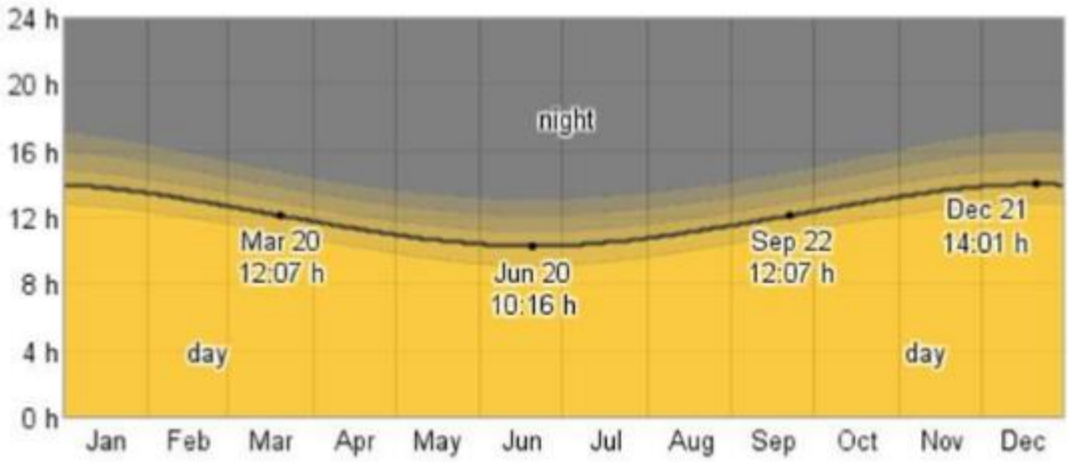

Figure 38: Different annual daylight time for Bloemfontein

3.5.7 Solar Energy

The average daily incident shortwave solar energy experiences significant seasonal variation over the course of the year. The brighter period of the year lasts for 3.2 months, from 4 November to 10 February, with an average daily incident shortwave energy per square meter above 7.6 kWh. The brightest day of the year is 26 December, with an average of 8.6 kWh. The darker period of the year lasts for 3.3 months, from 1 May to 10 August, with an average daily incident shortwave energy per square meter below 4.8 kWh. The darkest day of the year is 18 June, with an average of 3.8 kWh (WeatherSpark, 2017).

3.6 SURFACE HYDROLOGY

The city of Bloemfontein is situated within the Modder River Catchment in the semi-arid Upper Orange Water Management Area (refer to Figure 39). The Modder River basin is a large basin with a total area of 1.73 million hectares (see Figure 40). It is divided into three sub-basins, namely the Upper Modder, the Middle Modder and the Lower Modder River basins. Bloemfontein is located along the middle reaches of the Modder River in quaternary catchment C52F (see Figure 41).

The Modder River is the largest river in the vicinity of Bloemfontein. To the east of Bloemfontein, it flows in a north-westerly direction, before turning west at positions north of Bloemfontein. The Bloem Spruit is the non-perennial tributary of the Renoster Spruit that drains the area in which Bloemfontein is located. It flows in an easterly direction until it reaches the north-flowing Renosterspruit, which is a tributary of the Modder River. The major dams that occur in the Modder River are the Krugersdrift, Mockes and Rustfontein Dams

The Krugersdrift Dam supplies water for irrigation purposes to Lower Modder River Water User Association. More than 50 weirs have been constructed in the Modder River between the dam wall and the confluence with the Riet River. The Rustfontein Dam is located on the Modder River and forms the major storage reservoir in the Modder River. Water is released from the Rustfontein Dam to supplement the Mockes Dam which releases water to the Maselspoort Weir. The latter currently provides 30% of potable water to Mangaung from the Maselspoort Water Treatment Works (DWA, 2012). The Groothoek Dam is located on the Kgabanyane River, a tributary of the Modder River, and supplies water to Thaba Nchu (refer to Figure 41). This dam is operated by Bloemwater and was completely dry at the end of 2016.

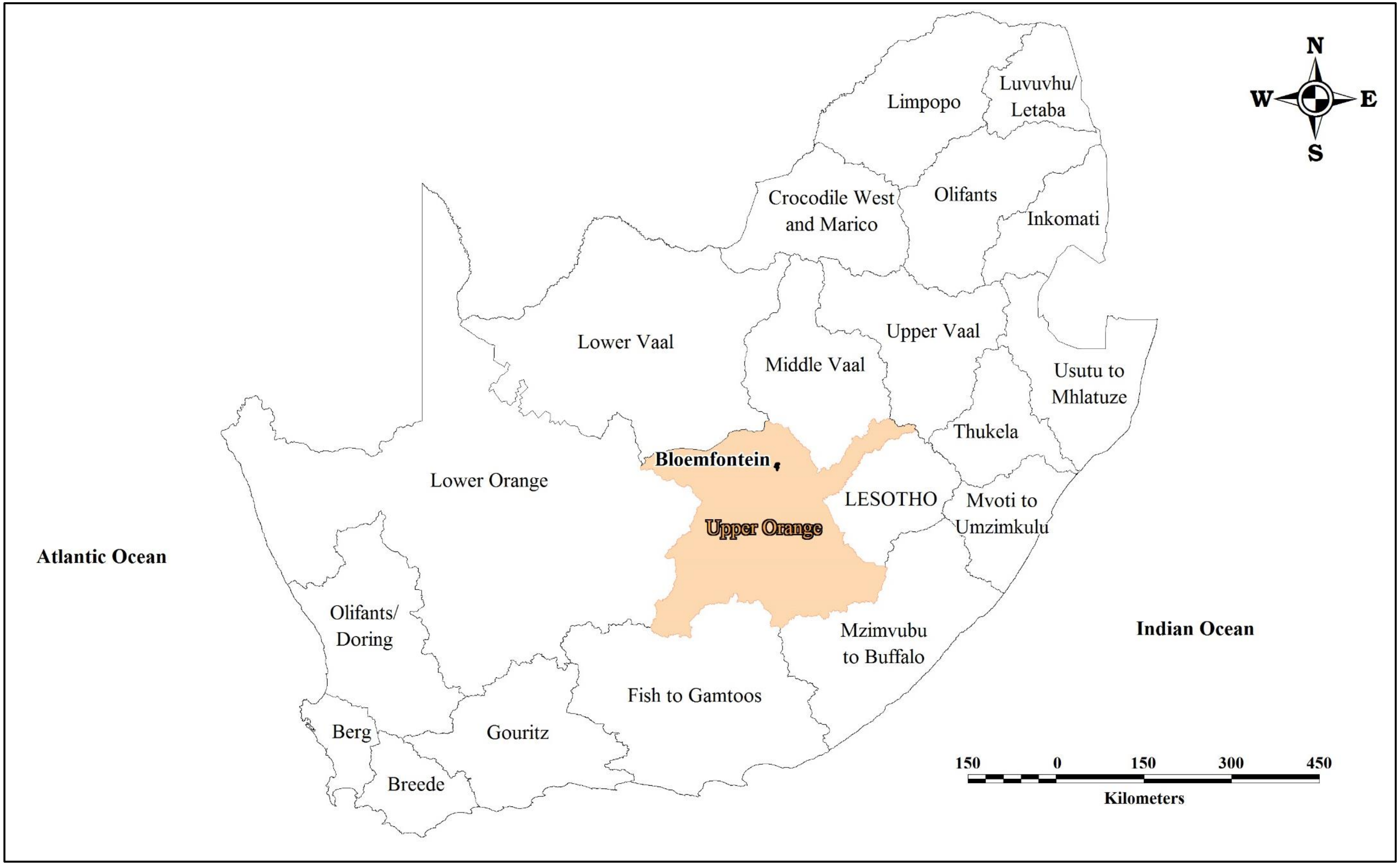

Figure 39: Upper Orange Catchment Management Area (redrafted from Bloemwater, 2012)

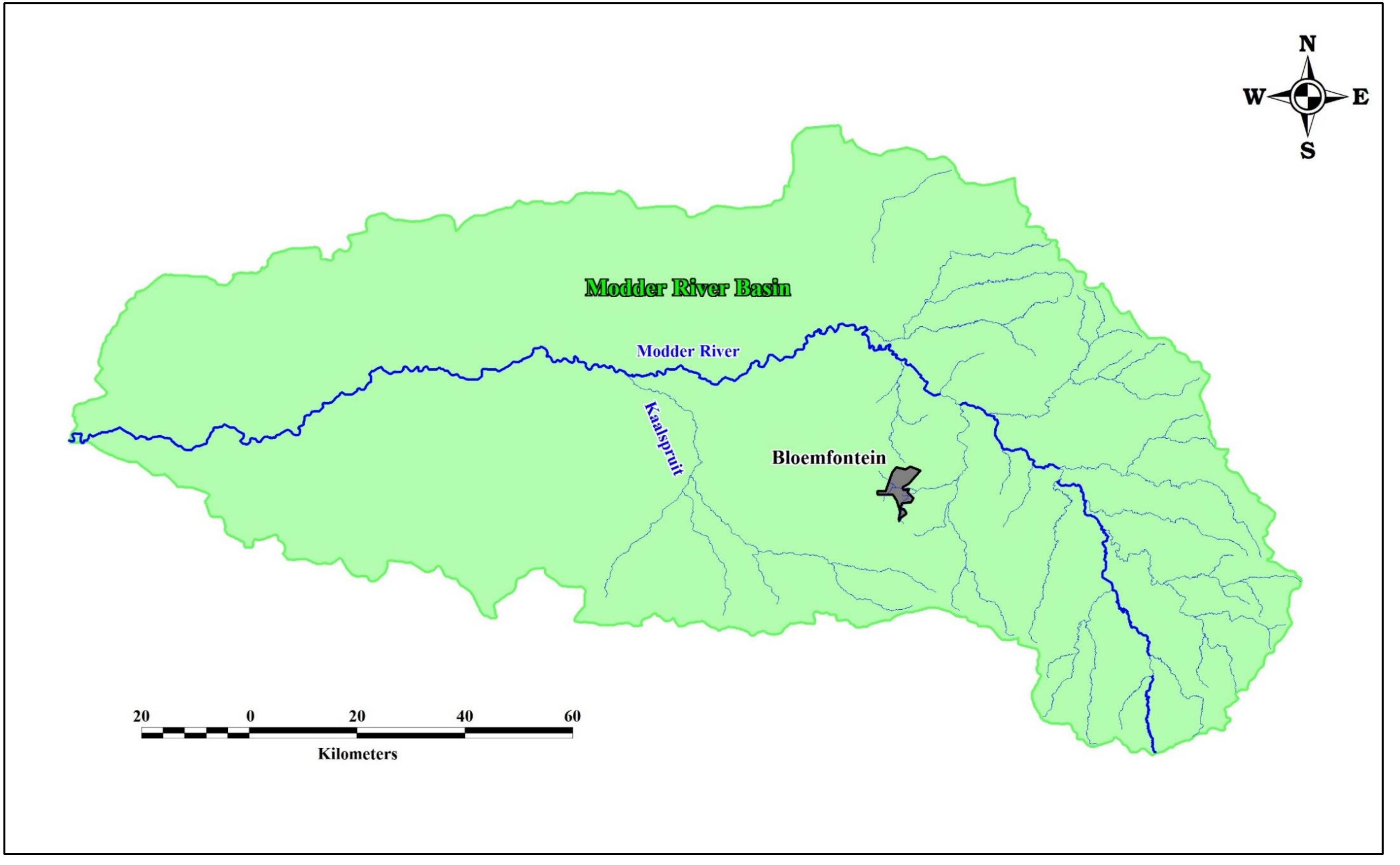

Figure 40. Location of Bloemfontein within the Modder River Basin

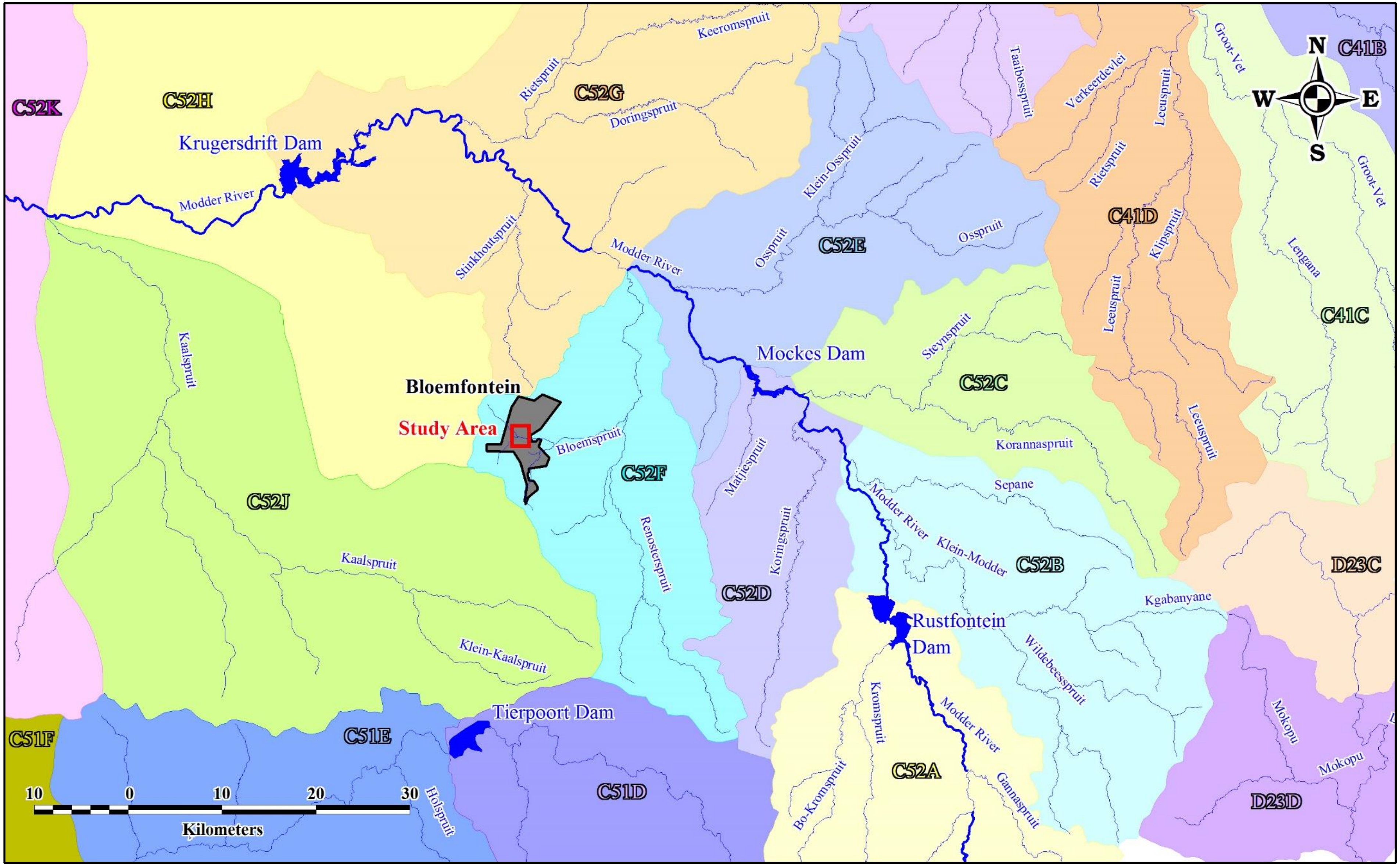

Figure 41. Quaternary sub-catchments and major surface water bodies in the area surrounding Bloemfontein

3.7 TOPOGRAPHY AND DRAINAGE

Bloemfontein is located in central South Africa on the southern edge of the Highveld, and occurs at an elevation of approximately 1 400 metres above mean sea level (mamsl) (Bloemwater, 2012). The surface topography is generally flat with occasionally dotted dolerite hills mostly laying in the northern part of the city. In the southern parts of the study area there are flat doleritic structures and sedimentary outcrops that have been resistant to erosion.

A seasonal stream flows approximately 0.5 km from the study area in a north-easterly direction following the surface topography. This stream is confluent with the Bloemspruit in the south-eastern part of Bloemfontein (Figure 42). Although the stream is non-perennial, there is a possible artificial water discharge into it from the spring located in the basement at Loch Logan Mall.

3.8 GEOHYDROLOGY

The city of Bloemfontein is underlain by sedimentary rocks belonging to the Beaufort Group of the Karoo Supergroup. These sedimentary rocks were extensively intruded by dolerite magmas during the Jurassic Age. The geohydrology of the study area is closely related to these geological features.

The type of aquifer present in the study area is mostly fractured, hard rock, with low storage coefficients, ranging from 0.001-0.1 (Steyl *et al.*, 2011). Water storage is predominantly in the fractured sedimentary rocks in which secondary porosity was developed by processes such as fracturing and weathering (Steyl *et al.*, 2011). These formations typically have very low primary porosities and permeabilities. Groundwater flow, on the other hand, mostly takes place through the fractures, which are associated with much higher permeabilities. The fractures may form complex interconnected networks.

The fractured contact zones of dolerite sills, and especially dykes, represent favoured targets for the siting of drilling positions for water supply boreholes since these zones are typically associated with higher permeabilities.

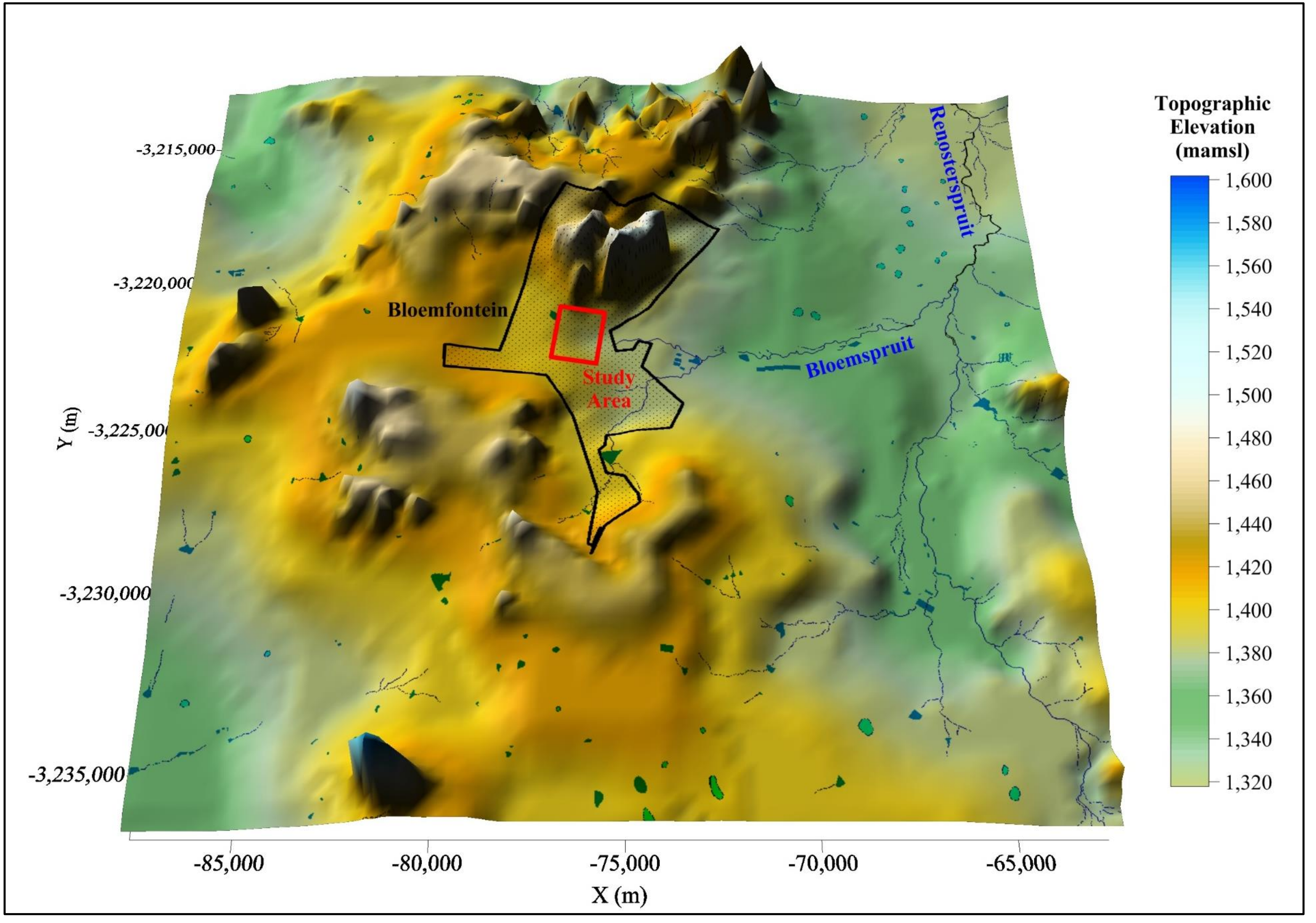

Figure 42: Topography and drainage in the area surrounding Bloemfontein with the study area indicated with a red polygon

3.9 STRUCTURES AND TRANSITION ZONES

The study area contains outcrops of various rock types. Fractures and joints in these rocks were observed during the investigations. These secondary features are of importance to the current study since they can serve as pathways for groundwater recharge. Major fracture zones are often considered as targets during groundwater exploration.

The columnar joints and fractures observed in the different rocks of the study area (Figure 43) are the result of different mechanisms, such as the contraction of the cooling magmas, and the pressure on the host rock during intrusion.

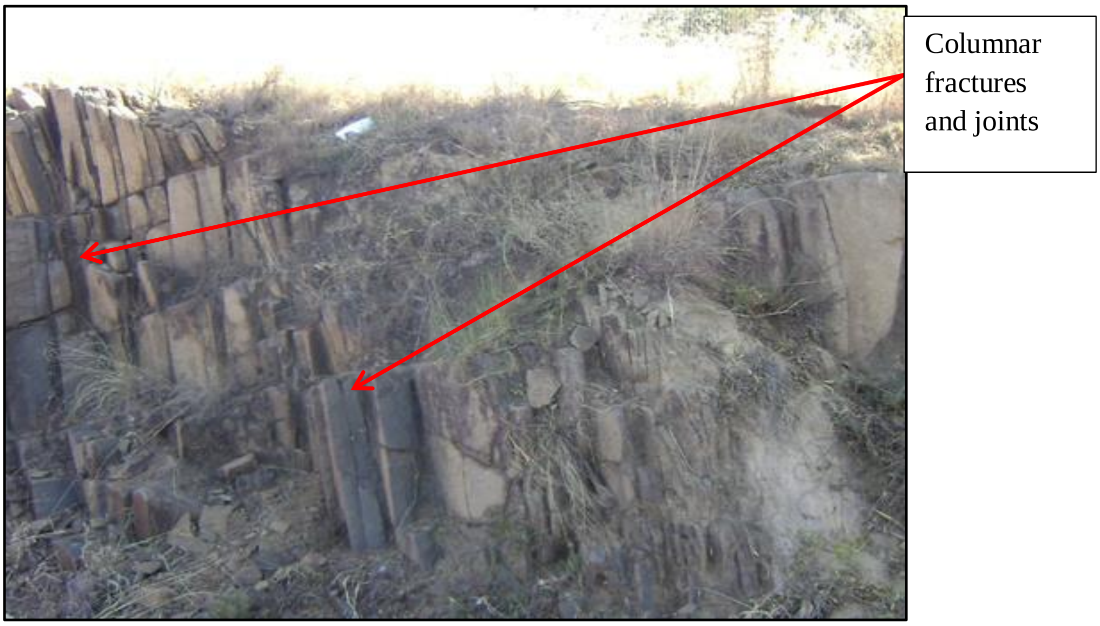

Figure 43: Columnar fractures and zones along the Old Cemetery

The exfoliation and weathering patterns on the dolerite rocks were also identified in the north-western part of the South African Armour Museum (Figure 44). The rocks exfoliate as a result of experiencing different temperatures which possibly trigger the peeling of rocks. The material of the peels from the rocks forms some of the targets for groundwater exploration as they are associated with fractures or lineaments. The accumulation of secondary minerals (calcite veins) along the intrusive bodies was also observed (Figure 45). These veins could possibly have formed as a result to alteration of primary minerals as the parent rock cooled.

Figure 44: Weathered outcrop at the northern part of the SA Armour Museum

Figure 45: Calcite veins along the dolerite outcrop at CUT

3.10 SOIL AND VEGETATION

The general vegetation in the Mangaung Metro Municipality is Highveld Grassland Ecoregion (Bloemwater, 2012); however, the study area is sparsely vegetated due to the fact that most of the surface area is covered by roads, pavements, buildings and other infrastructure. The aridity of the area, as well as the occurrence of frost, has also limited the presence of tree species which are rare in the landscape and restricted to river banks, protected slopes and valleys of doleritic hills. However, trees that have been planted along the streets and roads within the city of Bloemfontein. These trees probably prevent soil erosion and contribute to soil conservation, while contributing to rainfall infiltration (Bloemwater, 2012).

3.11 RECHARGE

The presence of dolerite intrusions in the Karoo Basin has enhanced the possibility for aquifer recharge through fractures, joints and weathered zones along the contact zones with the country rocks. The type of formations found in this basin also contributes to aquifers recharge because the porosities of the rocks are sufficient to allow infiltration of meteoric and surface water into the aquifers. Woodford and Chevallier (2002) stated that there are two different mechanisms through which recharge by meteoric water into a porous matrix can occur:

- Direct, vertical infiltration through the layers of soil, and,
- Through vertical fractures which are exposed at the surface and regarded as preferential pathways.

Vertical fractures enhance the rate at which water initially enters the fracture system, after which it flows from the fracture system into the matrix by means of an induced pressure gradient between the two systems (Woodford and Chevallier, 2002).

Groundwater recharge is not easily determined in arid and semi-arid areas (such as the Karoo Basin) due to variations in the precipitation period. Other contributing factors influencing recharge in the Karoo Basin aquifers include: topography, soil cover, vegetation and land use (Lerner *et al.*, 1990). Since Bloemfontein occurs in a semi-arid area, these factors should be taken into consideration when estimating recharge.

In order to exploit and manage Karoo aquifers, Woodford and Chevallier (2002) suggested that reliable methods have to be used to estimate the long-term sustainable yields. The most important factors to consider include: the recharge rate, the storativity of the aquifer as well as surface inflow and outflow from and into the aquifer system. Scanlon *et al.* (2002) emphasised that appropriate methods should be used for recharge estimation in order to estimate the sustainable yield.

Figure 46 shows a recharge map of South Africa (Dennis and Dennis, 2012). According to this map, the recharge rate around Bloemfontein is approximately 40 mm/a which translates into a recharge percentage of approximately 7.3% of the MAP. However, Vegter (1995) suggested a much lower recharge percentage of 3.6% of the MAP.

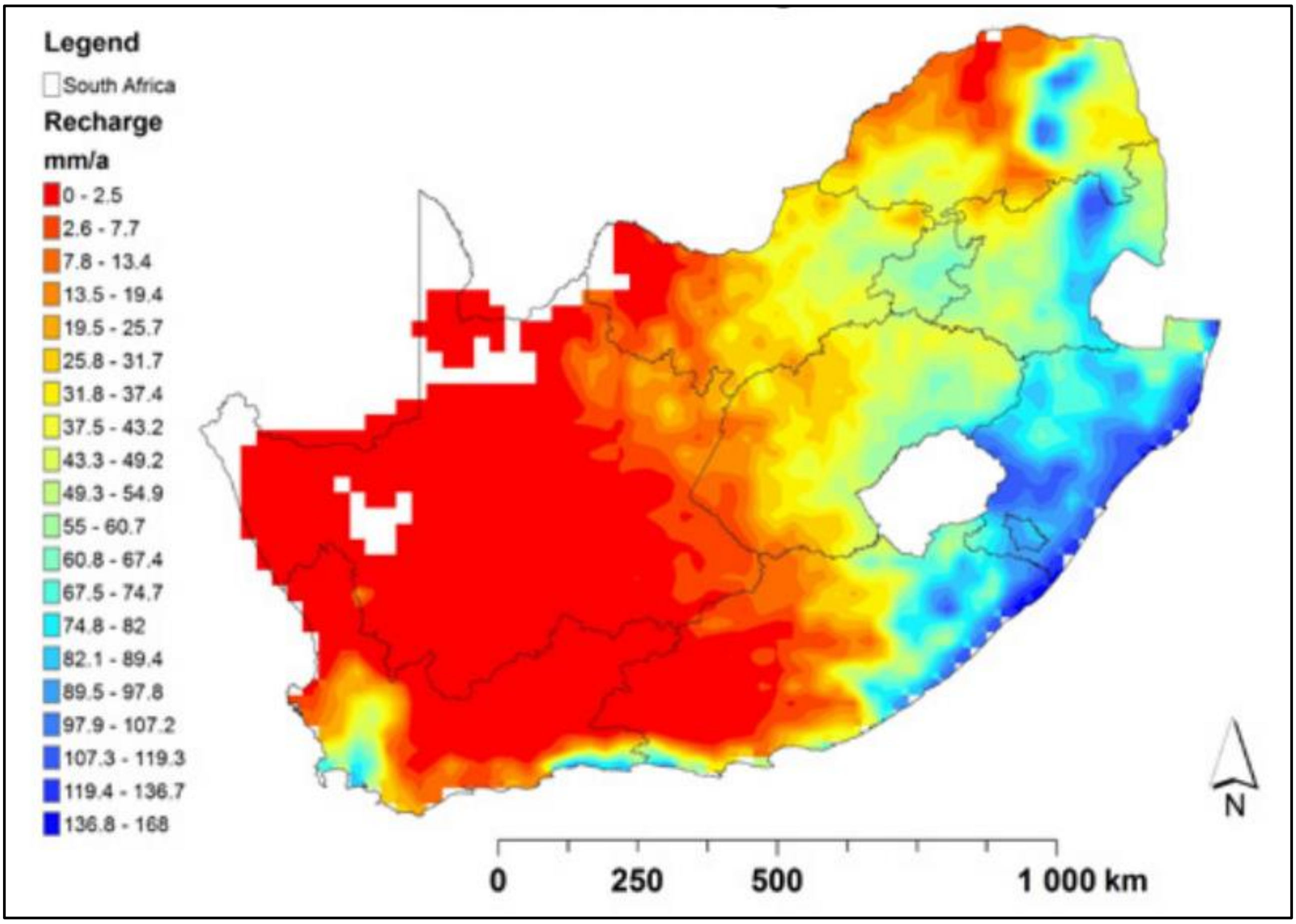

Figure 46: Recharge map of South Africa (Dennis and Dennis, 2012)

CHAPTER 4:
GROUND GEOPHYSICAL INVESTIGATIONS

4.1 INTRODUCTION

The primary purpose of the ground geophysical surveys was to detect and delineate the prominent dolerite ring-dyke known to occur within the limits of the Bloemfontein CBD. The exact location and orientation of this geological structure are not known, since surface infrastructure in the form of roads, buildings, sports grounds and drainage canals covers the parts of the CBD underlain by the ring-dyke. However, some land features visible at surface do still provide an indication of the presence of the dyke. Dolerite outcrops observed at the cricket field and along a fence of the CUT clearly show the presence of a dolerite structure. An example of such an outcrop at the cricket field is shown in Figure 47.

Figure 47: Dolerite outcrop encountered within the study area at CUT

During the geophysical investigation, two techniques were employed to detect and delineate the dolerite intrusions, namely the magnetic method and the 2D resistivity method (also known as electrical resistivity tomography, ERT). The magnetic method is well suited to the detection of dolerite bodies, since dolerite is generally much more magnetic than the sedimentary rocks of the Karoo Supergroup. Large resistivity contrasts are also generally observed between dolerite (more resistive) and the sedimentary Karoo rocks (less resistive), making the ERT method appropriate for the detection of intrusive dolerites.

One of the main limitations of applying geophysical methods in urban and industrial environments is the presence of noise that could influence the quality of the recorded data. The magnetic method is sensitive to both the presence of metallic infrastructure at surface or in the shallow subsurface and to the presence of electromagnetic noise generated where electrical currents flow. Since urban and industrial environments are characterised by such sources of noise, the magnetic survey was severely restricted in terms of the locations available for the recording of reliable data. Although the ERT method is not as sensitive to noise from EM radiation or metallic objects at surface, current flows in the subsurface from poorly insulated current-carrying wires could introduce noise to the recorded resistivity data. Such electrical current leaks are not peculiar to industrial settings.

The approximate position and orientation of the prominent ring-dyke are shown in Figure 48 relative to the surface infrastructure of the Bloemfontein CBD. The ground geophysical surveys were conducted at five locations within the CBD where the surface infrastructure allowed access, namely:

- Within an open display area at the Queens Fort Military Museum,
- At the President Brand Cemetery,
- On the cricket and soccer fields of the Central University of Technology (CUT),
- In an open area along one of the storm water canals channelling runoff to the Bloemspruit, and,
- In open areas along the railway line in the eastern parts of the CBD.

The GSM-19W magnetometer manufactured by GSM Systems was used for all the magnetic surveys conducted during the current investigations. Magnetic data and GPS coordinates were recorded at a sampling rate of 2 s during all the surveys.

The Lund Imaging System manufactured by ABEM was used for all the ERT surveys. The standard electrode spacings varied from one survey area to the next, depending on the space available for the surveys. The smallest electrode spacing used was 1.5 m while the largest was 5 m. The maximum depths of investigation also varied accordingly from site to site. The Wenner (α) geometry was used for all ERT surveys.

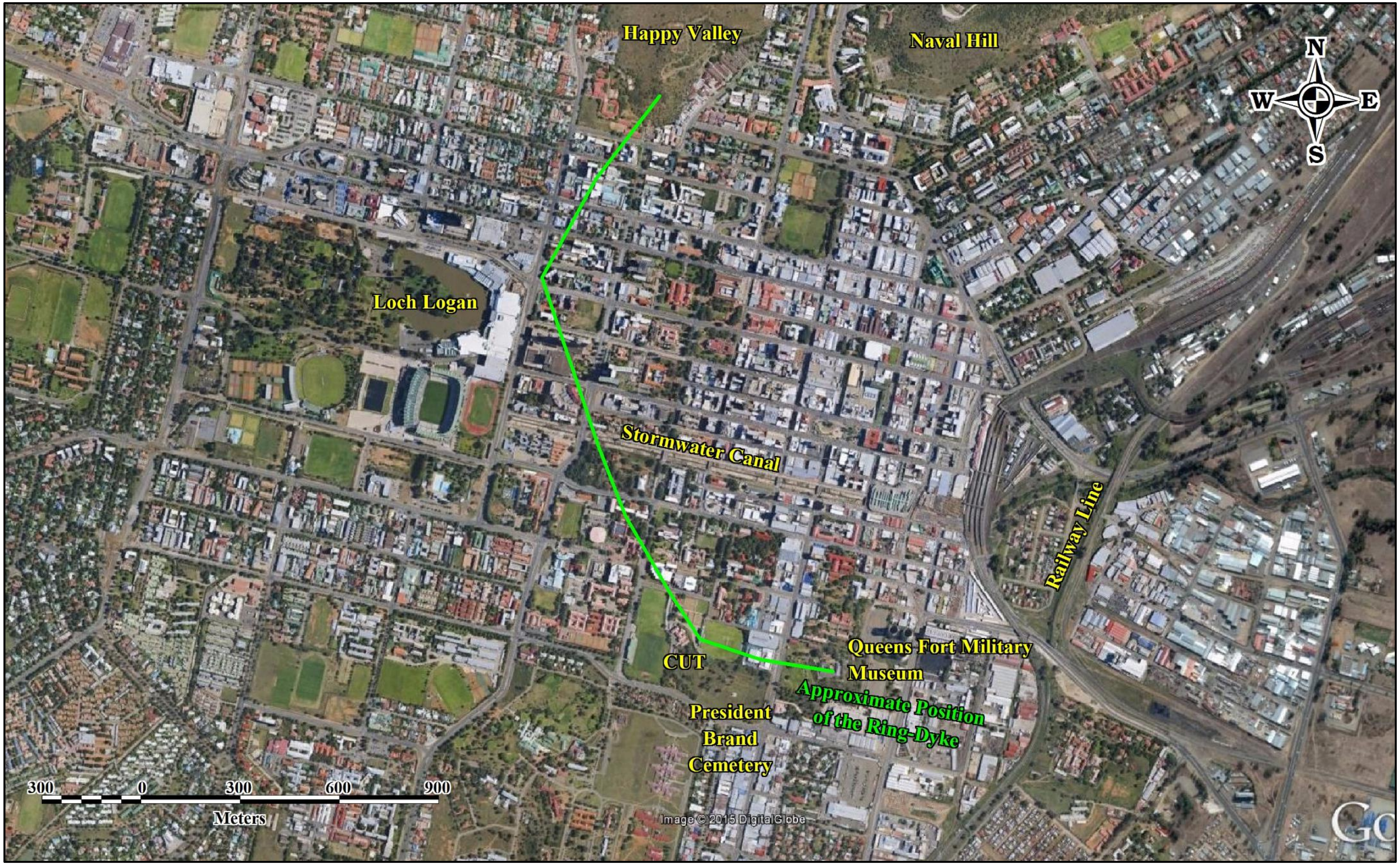

Figure 48: Approximated position and orientation of the ring-dyke underlying Bloemfontein

4.2 APPROACH TO THE GEOPHYSICAL INVESTIGATIONS

As part of the geophysical investigations, the following actions were taken:

- Previous publications were studied to gain insight into the possible position of the ring-dyke partially underlying the city of Bloemfontein.
- Satellite images of the city and surrounds were studied to identify surface features that may be indicative of changes in the geological conditions.
- A geological map covering the area under investigation was obtained from the Council for Geoscience and studied to determine the geological conditions that can be expected and to ascertain whether any large-scale geological features have been mapped.
- Large-scale magnetic features within the study area that may be indicative of changes in the subsurface geological conditions were identified using an airborne magnetics map that was purchased from the Council for Geoscience.
- Various sites within the city limits were visited to examine the surface infrastructure and to determine the possibility of using different geophysical techniques to gain insight into the subsurface conditions.
- Where infrastructure allowed, magnetic data were recorded on several traverses at selected sites with the central business district (CBD) of Bloemfontein where dolerite outcrops are known to occur.
- Where infrastructure allowed, two-dimensional resistivity data were recorded at selected sites within the CBD where the magnetic survey had confirmed the presence of a prominent dolerite structure.
- All the geophysical data recorded during the investigations were processed and interpreted in terms of the local geological and hydrogeological conditions.

4.3 GEOPHYSICAL SURVEYS AT THE QUEENS FORT MILITARY MUSEUM

4.3.1 Introduction

The Queens Fort Military Museum is located in the south-eastern parts of the Bloemfontein CBD (see Figure 48). The museum is located near the position where surface manifestations of the ring-dyke disappears. The geophysical surveys conducted at the museum attempted to detect and delineate the ring-dyke to see whether it extends as far as the museum.

4.3.2 Survey Geometry

Magnetic data were recorded on seven traverses of which six had approximate west/east strikes and one had an approximate south/north strike (refer to Figure 50). The positions and orientations of the traverses were severely restricted by the presence of armoured vehicles on display within the study area. These large metal objects were significant sources of magnetic noise that had to be avoided during the survey.

Resistivity data were recorded on a single ERT profile with a south/north strike (see Figure 50). The orientation of the ERT profile was chosen so as to run approximately perpendicular to the expected strike of the ring-dyke at this position.

4.3.3 Results and Discussion

Profiles of the magnetic data recorded on Traverses 01 to 07 are presented in **Appendix A**. Due to the presence of large metal objects, large magnetic gradients exist on site. These large gradients led to the sensor of the magnetometer reaching saturation while data were recorded along Traverse 04. No data could therefore be recorded on Traverses 05 and 06, while data could only be recorded on the northernmost parts of Traverse 07.

Although the surface infrastructure had a strong influence on the magnetic data recorded at the SA Armour Museum, some anomalies do suggest the presence of a large dolerite intrusive. The broad magnetic anomaly (with an amplitude of approximately 200 nT) observed near the eastern parts of Traverse 02, for example, could be due to the ring-dyke occurring at this position (see Figure 49).

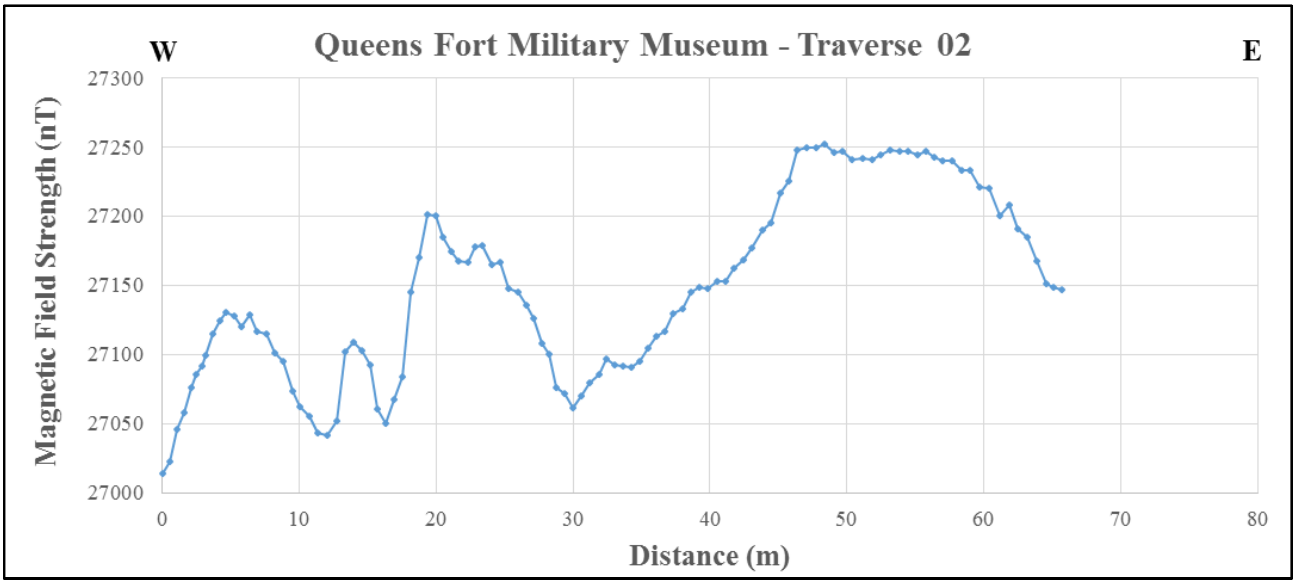

Figure 49: Profile of the total magnetic field recorded along Traverse 02 at the Queens Fort Military Museum

A contour map of the total magnetic field recorded across the site is presented in Figure 51. The large positive anomaly (red colour) observed near the north-eastern corner of the surveyed area is possibly due to the ring-dyke. Localised anomalies near the south-western corner of the surveys area are probably due to surface infrastructure.

The inverse resistivity model along the ERT profile shows large variability in the subsurface resistivity distribution (refer to Figure 52). Some of this variability may be due to subsurface infrastructure. For example, the near-surface resistivity lows (blue colours) seen near positions 114 m and 154 m could be due to underground pipes. However, the high resistivities (red to purple colours) observed north of position 114 m could represent real changes in the subsurface geology and could due to the presence of the ring-dyke. The near-vertical zone of low resistivities (green colours) between positions 100 m and 114 m could be indicative of a contact zone along the southern boundary of the ring-dyke. This zone could potentially be targeted for the installation of a production borehole.

4.4 GEOPHYSICAL SURVEYS AT THE PRESIDENT BRAND CEMETERY

4.4.1 Introduction

The President Brand Cemetery is located in the south-eastern parts of the Bloemfontein CBD (see Figure 49). Localised topographic highs in the northern parts of the cemetery indicate the presence of rock materials more resistant to weathering. The topographic highs correspond to the positions of dolerite outcrops observed at the cricket field of the CUT (adjacent to the cemetery), and hence indicated the possible surface manifestation of the ring-dyke. The geophysical surveys conducted at the cemetery were intended to detect the ring-dyke and delineate its southern contact with the Karoo host rock.

4.4.2 Survey Geometry

Ground magnetic data were recorded on 11 traverses across the cemetery. The positions and orientations of the traverses were restricted by the presence of surface infrastructures in the form of graves and metal fencing. ERT data were recorded on two profiles with approximate south-west/north-east orientations, approximately perpendicular to the expected strike of the ring-dyke.

Figure 50: Positions and orientations of the traverses and profiles on which ground geophysical data were recorded at the Queens Fort Military Museum

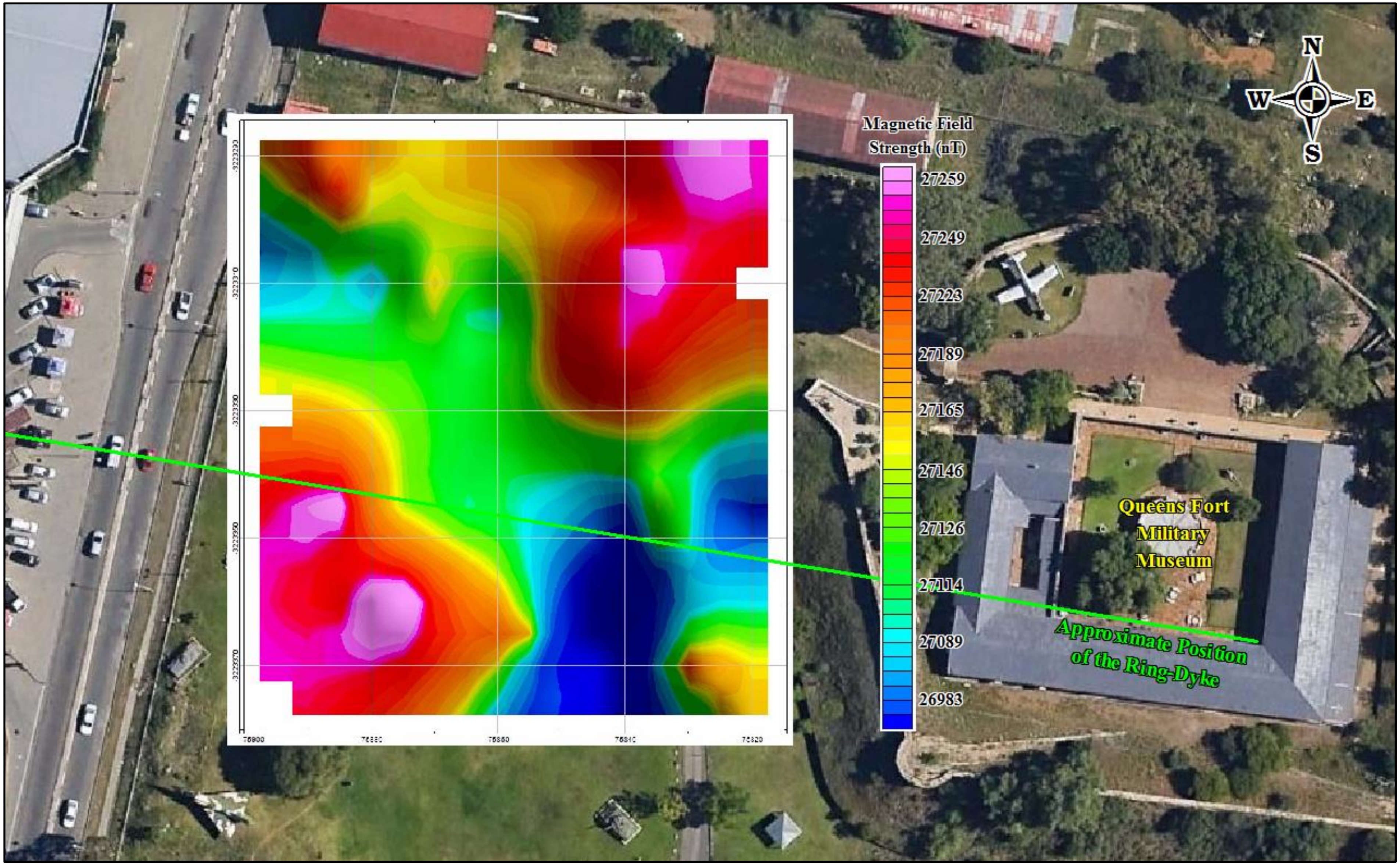

Figure 51: Contour map of total magnetic field recorded at Queens Fort Military Museum

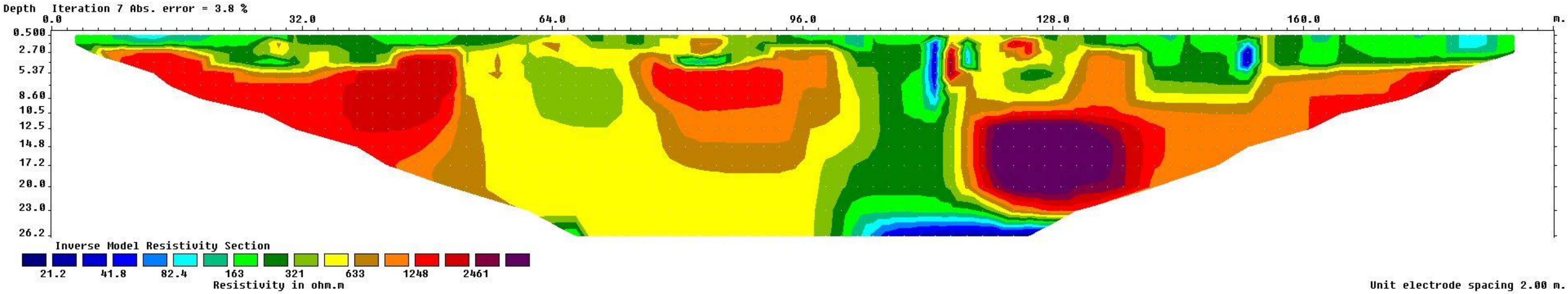

Figure 52: Modelled resistivity section along the ERT Profile at the Queens Fort Military Museum (S to N)

Figure 53: Positions and orientations of the traverses and profiles on which ground geophysical data were recorded at the President Brand Cemetery

4.4.3 Results and Discussion

The ground magnetic survey was detrimentally influenced by the presence of metallic infrastructure in the form of graves, fences and buried piping which caused localised anomalies (see the magnetic profiles in **Appendix A**). However, the contour map of the total magnetic field (Figure 54) shows a zone of prominent positive magnetic anomalies (red colours) near the northern parts of the cemetery. This zone coincides with an area of higher topographic elevations where dolerite outcrops occur. It can therefore be concluded that observed magnetic anomaly is in all likelihood due to the presence of the ring-dyke.

The modelled resistivity section along ERT Profile 01 indicates the presence of a zone of high resistivities near the northern parts of the profile. These high resistivities are probably due to the presence of the ring-dyke. Immediately to the south of the zone of high resistivities, areas of low resistivities are observed. These areas could be targeted during a groundwater exploration programme.

However, the modelled resistivity section along ERT Profile 02 does not show a significant lateral change in resistivities that could be attributed to a dolerite intrusive intersecting Karoo sedimentary rocks. It is possible that ERT Profile 02 occurs too far to the south and west and does not extend across the contact with the ring-dyke.

4.5 GEOPHYSICAL SURVEYS AT THE CUT

4.5.1 Introduction

The Central University of Technology (CUT) is located in the southern parts of the study area where the ring-dyke is thought to occur (refer to Figure 48). The ground geophysical investigations were conducted in order to investigate the presence of the ring-dyke in the vicinity of the rugby, soccer and the cricket fields of the CUT.

4.5.2 Survey Geometry

Magnetic surveys were done on two grids at the CUT; one grid on the cricket field, and another on the soccer field (see Figure 57). The magnetic surveys were detrimentally impacted on by surface and subsurface infrastructure in the form of fences, metal score boards and underground piping. Resistivity data were also recorded on a single profile extending across the soccer and rugby fields (Figure 57).

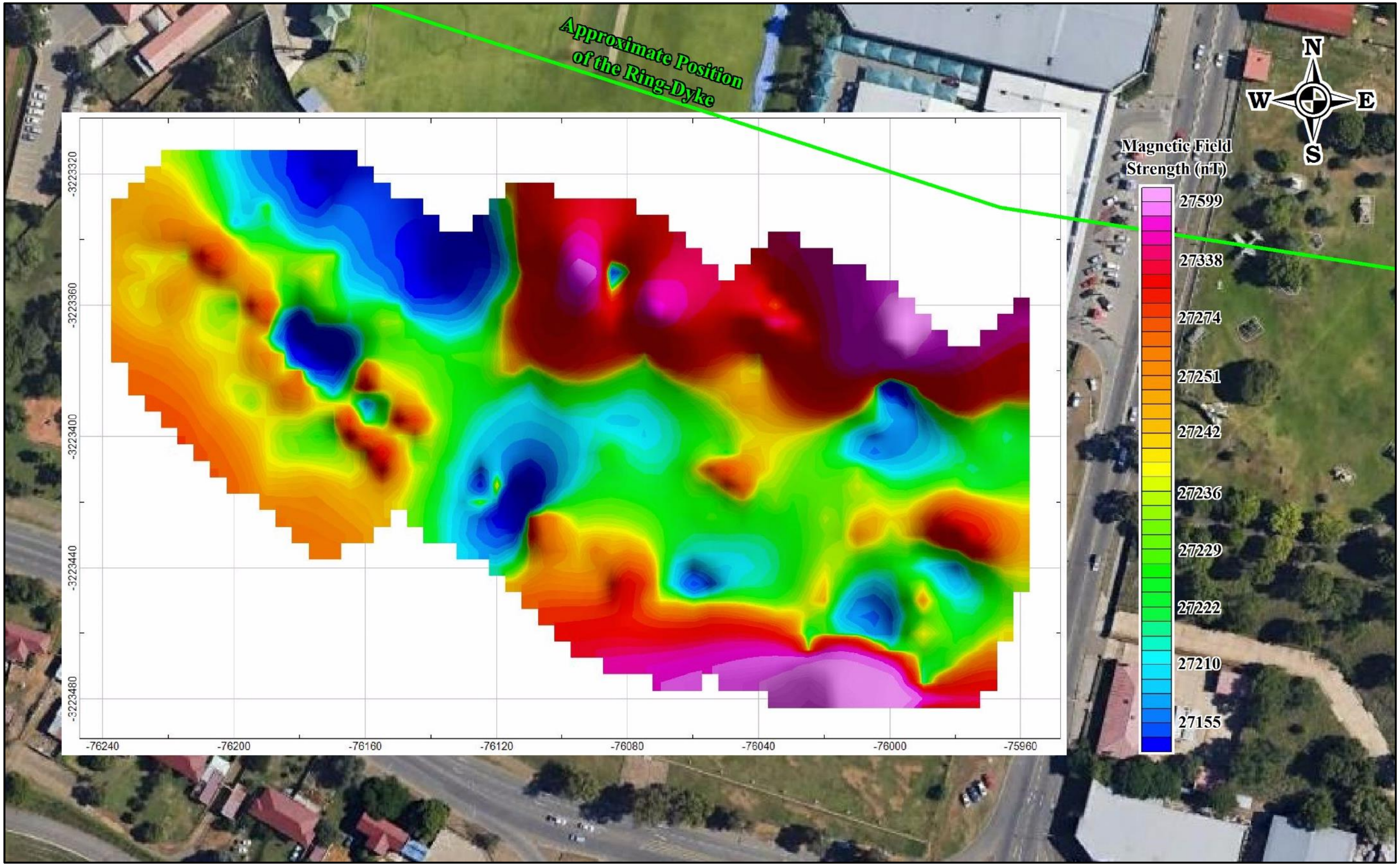

Figure 54: Contour map of the total magnetic field recorded at the President Brand Cemetery

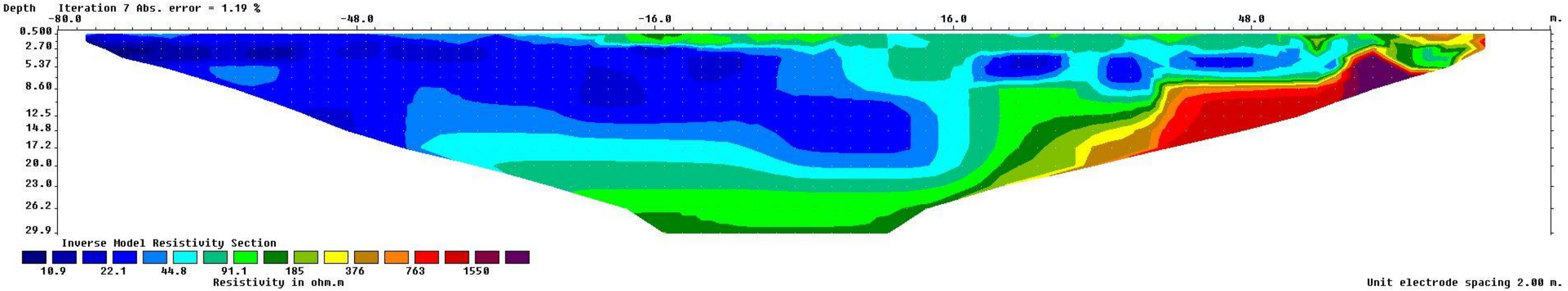

Figure 55: Modelled resistivity section along ERT Profile 01 at the President Brand Cemetery (SW to NE)

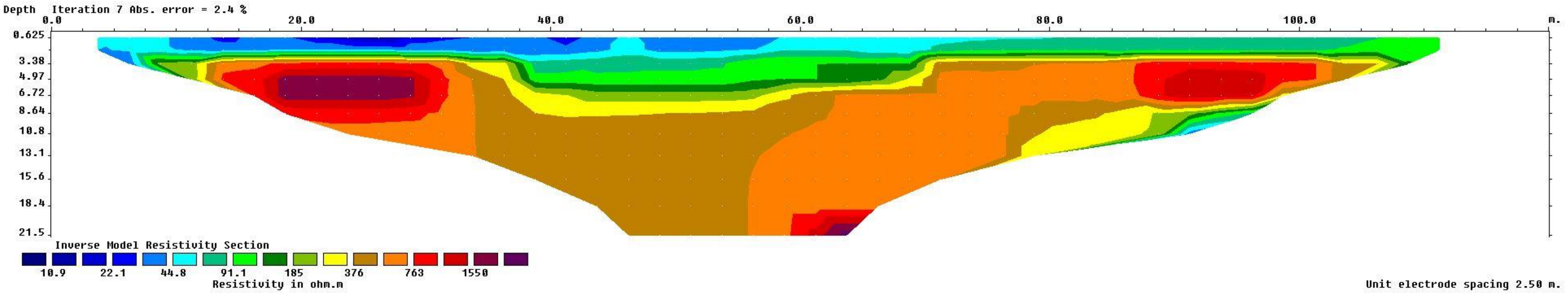

Figure 56: Modelled resistivity section along ERT Profile 02 at the President Brand Cemetery (SW to NE)

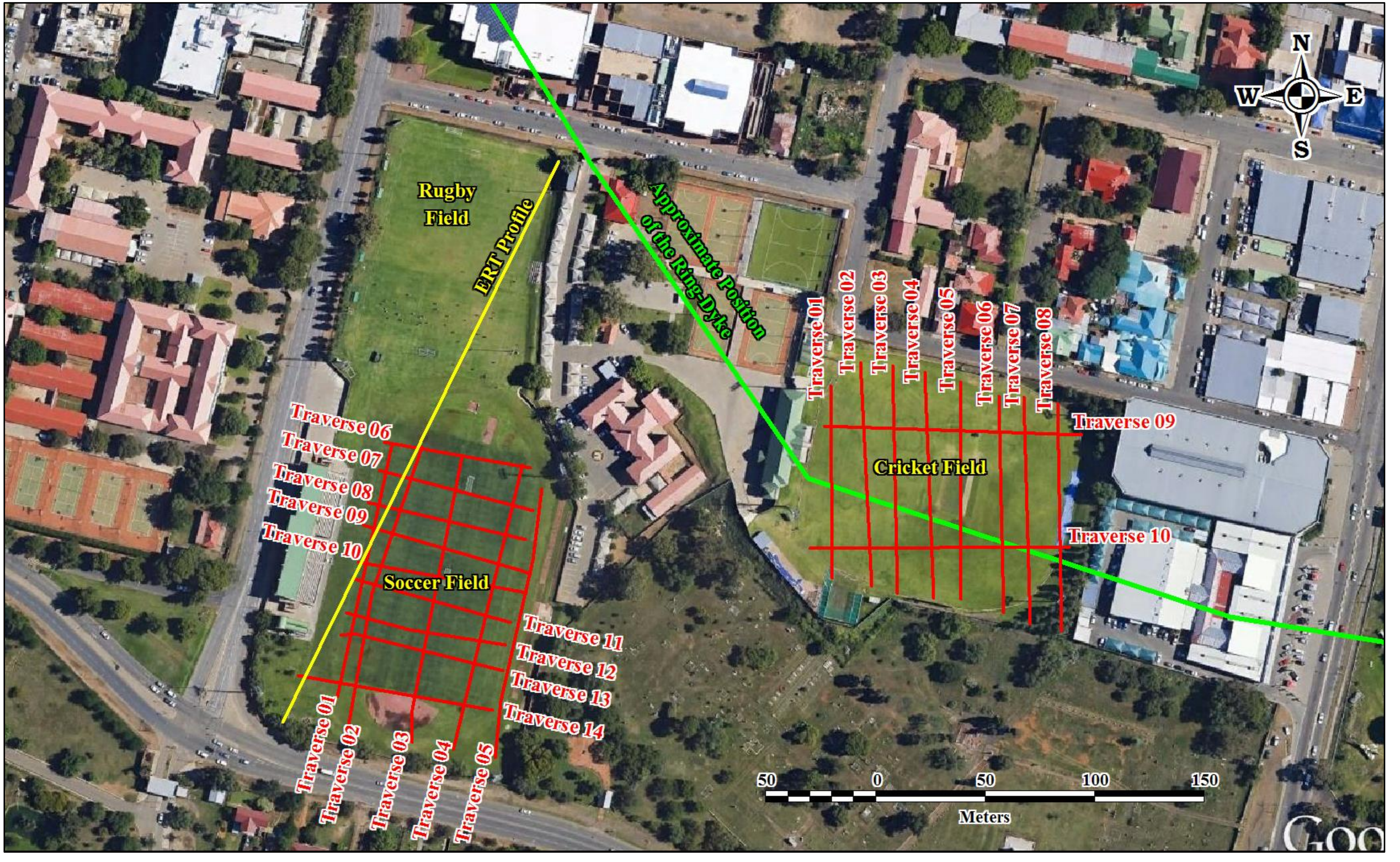

Figure 57: Positions and orientations of the traverses and profiles on which ground geophysical data were recorded at the CUT

4.5.3 Results and Discussion

The results of the magnetic survey are presented as profiles plots in **Appendix A**. Prominent broad magnetic anomalies were observed on some of the traverses across the cricket field. For example, an anomaly with an amplitude of almost 200 nT was recorded near the central parts of Traverse 07 (refer to Figure 58).

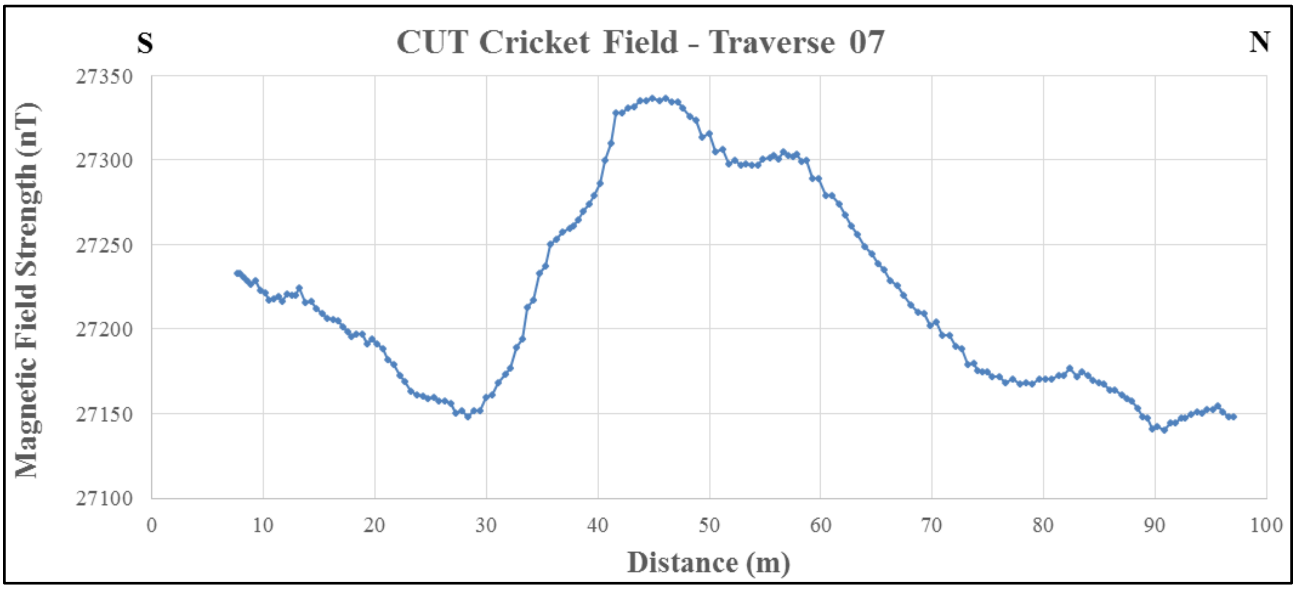

Figure 58: A profile of the magnetic field recorded along Traverse 07 across the cricket field at the CUT

Contour maps of the total in magnetic field recorded across the cricket field and soccer field are shown in Figure 59 and Figure 60, respectively. The contour map of the total magnetic field on the cricket field displays a broad anomaly near the central part of the surveyed area. This anomaly roughly coincides with the inferred positions of the ring-dyke. The contour map of the total magnetic field recorded on the soccer field shows the presence of localised magnetic anomalies. These anomalies are thought to be due to surface and subsurface infrastructure, and not due to geological structures of relevance to the current investigations.

The modelled resistivity section along the ERT profile displays two near-surface zones of low resistivities (Figure 61). These zones are most probably due to buried pipes. A zone of high resistivities near the northernmost parts of the profile could be due to the ring-dyke thought to occur near this position.

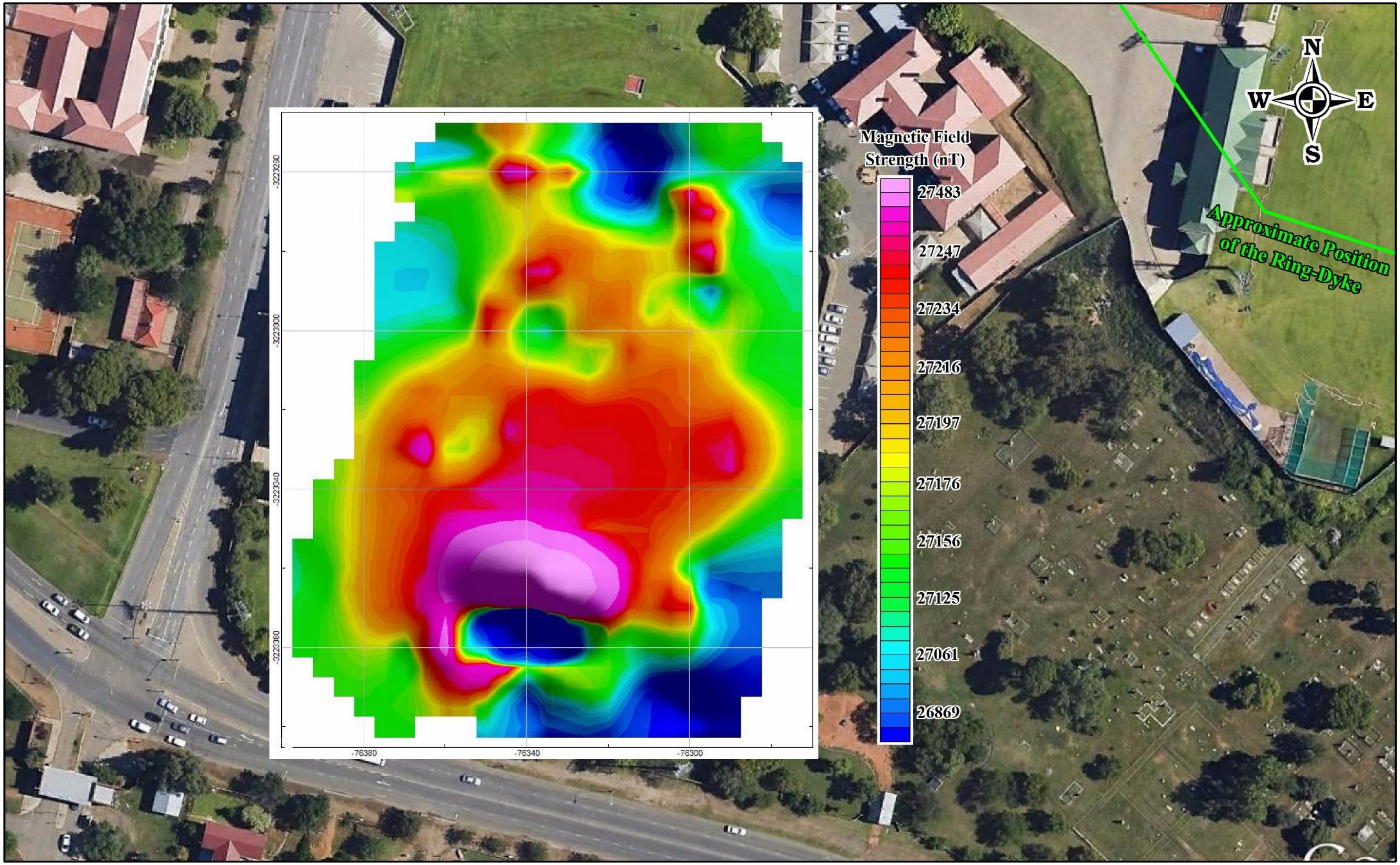

Figure 59: Contour map of the total magnetic field recorded at the CUT soccer field

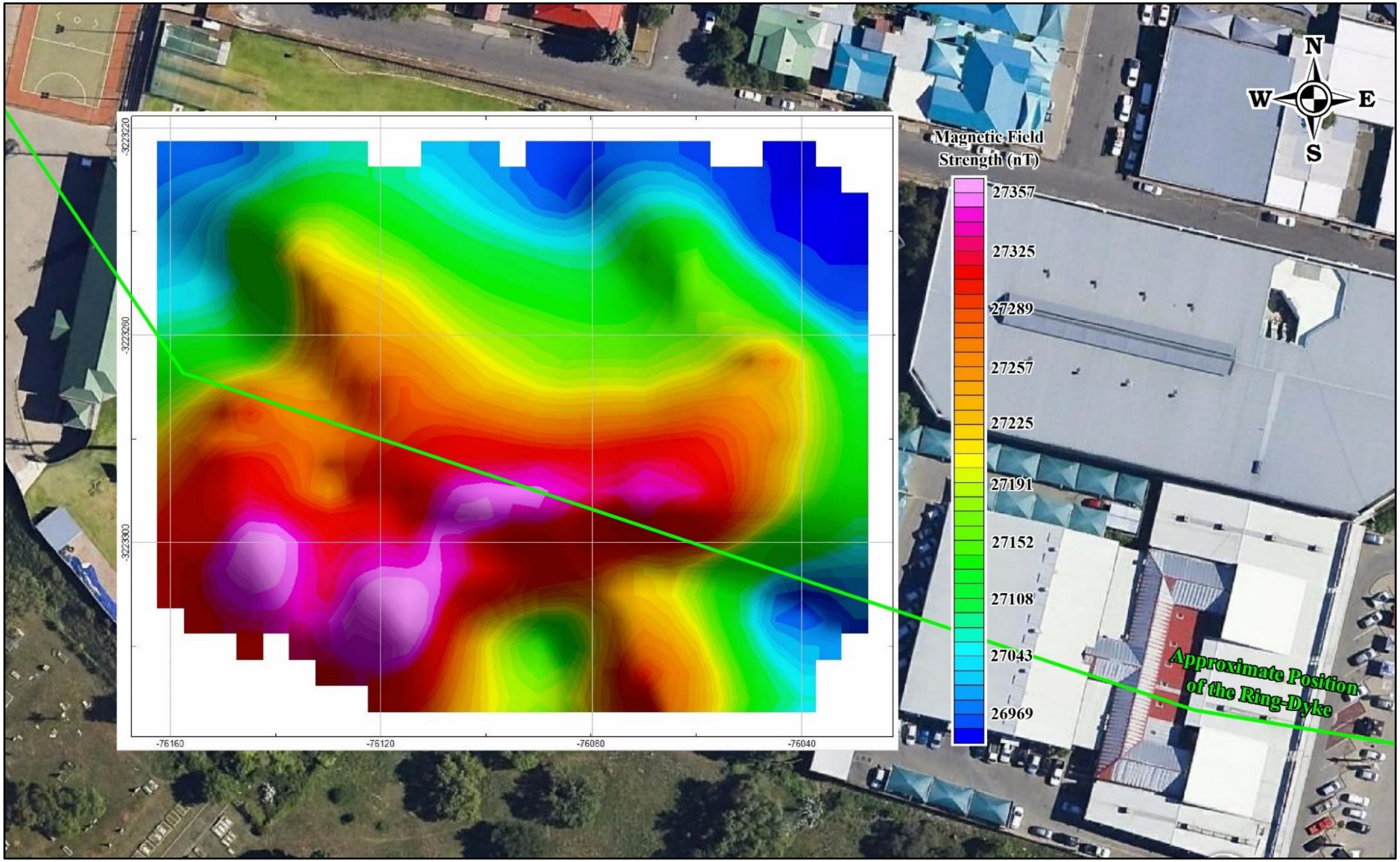

Figure 60: Contour map of the total magnetic field recorded at the CUT cricket field

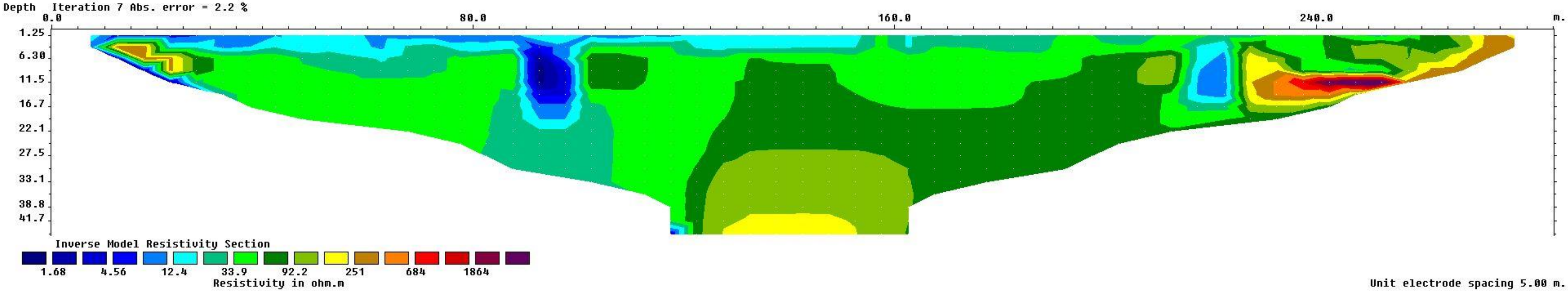

Figure 61: Modelled resistivity section along the ERT Profile across the soccer and rugby fields of the CUT (SW to NE)

4.6 GEOPHYSICAL SURVEYS AT THE STORM WATER CANAL

4.6.1 Introduction

The storm water canal is located in the western part of the study area in the CBD of Bloemfontein (see Figure 48). An open area along the canal allowed an ERT survey to be conducted. However, this open area occurs to the east of the expected position of the ring-dyke. The survey at the storm water canal was nevertheless conducted to determine whether the ring-dyke extended as far to the east as this position.

4.6.2 Survey Geometry

Resistivity data were recorded on a single ERT profile along the storm water canal (see Figure 62) at a position where the surface infrastructure (fences, concrete slabs) allowed. As such, the ERT profile occurred to the east of the inferred position of the ring-dyke. No magnetic data were recorded due to the presence of a metal fence and other metal infrastructure near the survey position.

4.6.3 Results and Discussion

The inverse resistivity model along the storm water canal is shown in Figure 63. The model indicates a shallow near-surface layer of low resistivities overlying material of high resistivity. Lateral changes in the subsurface resistivity distribution that could be indicative of an intrusive dyke are absent along this profile. It can therefore be concluded that this profile did not intersect the ring-dyke, and was probably located too far to the east.

4.7 GEOPHYSICAL SURVEYS ALONG THE RAILWAY LINE

4.7.1 Introduction

The railway line is located in the south-eastern parts of the study area. The presence of several dolerite outcrops along the railway line suggested that the ring-dyke may extend as far as this position. The geophysical surveys conducted along the railway line were intended to investigate whether these outcrops were indeed due to the ring-dyke.

4.7.2 Survey Geometry

The resistivity data was recorded along the two ERT profiles that were approximately parallel to the railway line (refer to Figure 64). During the survey, the surface infrastructure that could affect the survey included the railway line itself, concrete slabs, fences, buildings and roads.

4.7.3 Results and Discussion

The results of the ERT surveys on Profiles 01 and 02 are shown in Figure 65 and Figure 66, respectively. Although prominent lateral changes in the subsurface resistivities are observed, particularly along Profile 02, these lateral changes do not bear the signature of an intrusive dolerite structure. From the surveys at the Queens Fort Military Museum, the President Brand Cemetery and the CUT soccer and rugby fields it was noted that the dolerite can be expected to have resistivities in the order of thousands of Ohm.meters (Ωm), while the resistivities along Profiles 01 and 02 are generally lower than 500 Ωm. It can therefore be concluded that the two ERT profiles did not traverse the ring-dyke. Either the ring-dyke does not extend as far the east as the railway line, or locally it occurs at depths beyond the maximum depth of investigation of the ERT survey.

4.8 PROPOSED INVESTIGATIVE, PRODUCTION AND MONITORING BOREHOLES

4.8.1 Introduction

The aim of the current study was to investigate the possibility of using groundwater associated with a known dolerite ring-dyke that underlies the city of Bloemfontein to augment the water supply to the MMM. Objectives of the study included a) the investigation of the association of the ring dyke with groundwater resources, b) the investigation of the hydraulic properties of the aquifers to determine the quantities of water that can be sustainably abstracted from the aquifers, and c) the investigation of the quality of the groundwater associated with the ring-dyke to assess its suitability for human consumption and other municipal applications. For these objectives, it was foreseen that a number of boreholes would be drilled at suitable locations as determined from the geophysical surveys. These boreholes would then be used as investigative boreholes that could also have served as monitoring and production boreholes (if adequate groundwater resources were encountered). However, due to delays resulting from disagreements between the MMM and Bloemwater, the boreholes have not yet been drilled. This is a major shortcoming of the current study, but is beyond the control of the researcher.

Nevertheless, from the interpretation of the geophysical data, it is still possible to make recommendation for future drilling projects aimed at augmenting the municipal water supply and to monitor the aquifers utilised in terms of the groundwater quantity and quality. In this section, recommendations are made for the installation of investigative, monitoring and production boreholes at the various sites studied during the geophysical surveys.

Figure 62: Position and orientation of the profile on which ERT data were recorded along the storm water canal

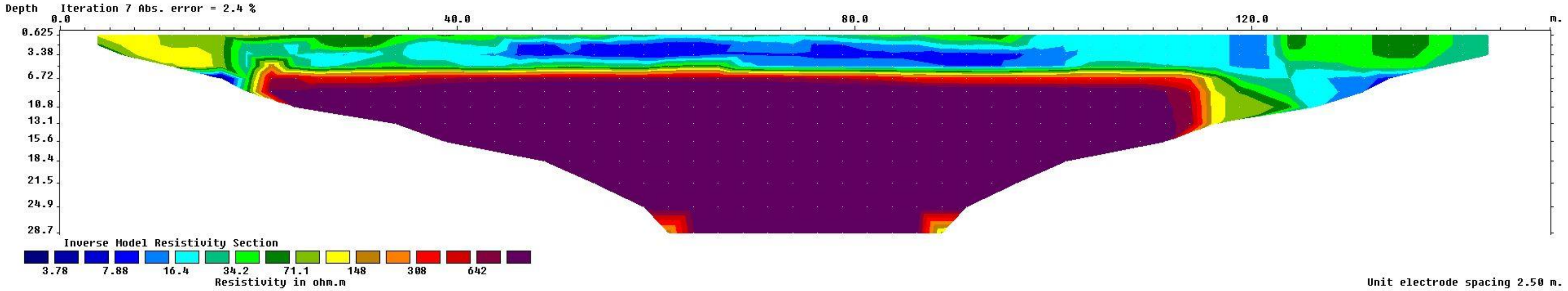

Figure 63: Modelled resistivity section along the ERT Profile along the storm water canal (WNW to ESE)

Figure 64: Position and orientation of the profile on which ERT data were recorded along the storm water canal

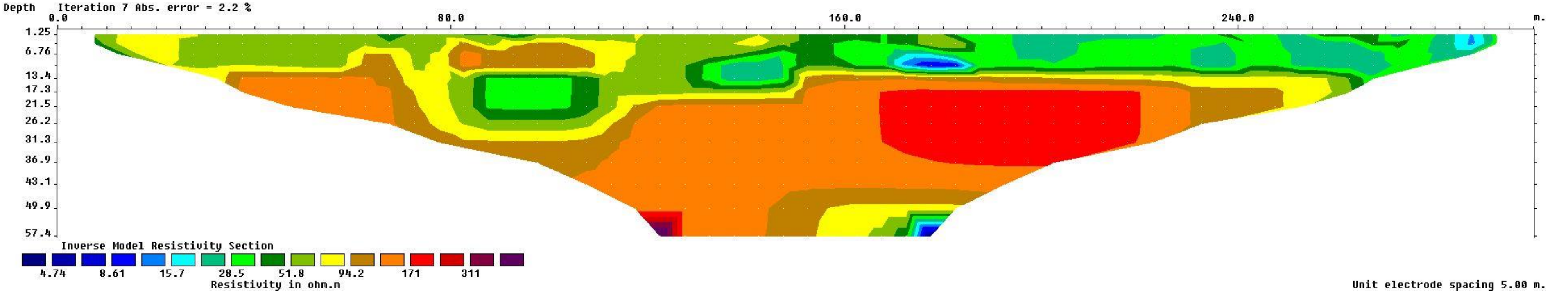

Figure 65: Modelled resistivity section along ERT Profile 01 along the railway line (S to N)

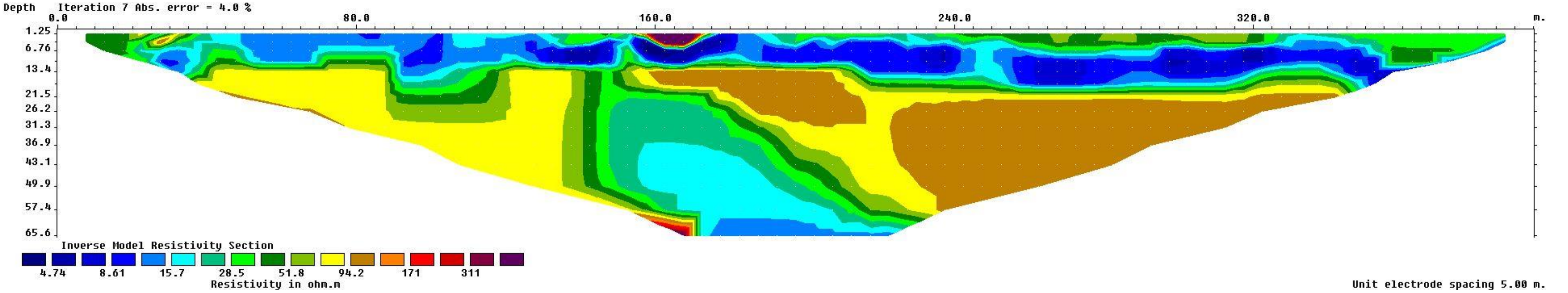

Figure 66: Modelled resistivity section along ERT Profile 02 along the railway line (SSW to NNE)

4.8.2 The Queens Fort Museum

Since the results of both the magnetic and ERT surveys suggest the presence of a dolerite body in the northern parts of the surveyed area, it is recommended that a borehole be drilled along the southern contact with this intrusive body. The modelled resistivity section along the ERT profile revealed the presence of a near-vertical zone of low resistivities immediately south of the possible ring-dyke. This zone should be targeted during drilling. The position of the proposed borehole (PB01) is shown in Figure 67, while its coordinates are listed in Table 12.

4.8.3 The President Brand Cemetery

The magnetic and ERT surveys conducted at the President Brand Cemetery revealed the presence of a magnetic and resistive body along the northern boundary of the cemetery. This body is in all likelihood the ring-dyke known to underlie the Bloemfontein CBD. The ERT data furthermore indicated the presence of a zone of low resistivities immediately south of the ring-dyke. This contact zone is likely to be extensively fractured and associated with high permeabilities, making it a good target for a groundwater exploration programme. Taking the surface and subsurface infrastructure into account, the position of the proposed borehole (PB02) is shown in Figure 68, while its coordinates are listed in Table 12.

Since the proposed borehole is situated within a cemetery, it is unlikely that this borehole will be used as a production borehole. However, the borehole could still be used for investigative and monitoring purposes.

4.8.4 The Central University of Technology

The magnetic survey on the cricket field of the CUT showed a broad linear magnetic anomaly running across the field. This anomaly is thought to be due to the ring-dyke. The curvature of the mapped ring-dyke (refer to Figure 48) indicates that the dyke dips to the north-east in the vicinity of the CUT. It is therefore recommended that a borehole (PB03) be drilled north of the broad magnetic anomaly to intersect the contact zone of the down-dip side of the ring-dyke. Since this borehole will be drilled on the cricket field, it will have to be constructed with no collar or casing protruding above surface.

The ERT data recorded on the soccer and rugby fields also revealed the possible presence of the ring-dyke in the northern parts of the rugby field. It is recommended that a borehole (PB04) be drilled immediately south of the zone of high resistivities thought to be due to the dyke. Again the borehole infrastructure will have to be installed below ground surface.

The positions of the proposed drilling sites are shown in Figure 69, while their coordinates are listed in Table 12.

4.8.5 The storm water canal

The only position available for the geophysical survey along the storm water canal was to the east of the mapped ring-dyke. The ERT survey conducted at this position did not show any lateral changes in the subsurface resistivities that could be attributed to the dyke. However, it may still be advisable to install an investigative and monitoring borehole. Once groundwater abstraction commences from other production boreholes, this borehole could serve to monitor the response of the aquifer system to the withdrawal of groundwater. The position of a proposed borehole (PB05) is shown in Figure 70. The coordinates for this borehole are listed in Table 12.

4.8.6 The railway line

Although the ERT survey conducted along the railway line did not show significant resistivity anomalies that could be attributed to the ring-dyke, it is still recommended that investigative and monitoring boreholes be installed in this area to monitor the aquifer response to groundwater abstraction from the other production borehole(s) drilled to augment the municipal water supply. The recommended positions of such a boreholes (PB06 and PB07) are indicated in Figure 71 while their coordinates are given in Table 12.

Table 12: Coordinates of the proposed boreholes near the ring-dyke

Borehole #	Longitude (^oE)	Latitude (^oS)	X (m)	Y (m)
PB01	26.22062	29.12452	-75 851.98	-3 223 321.49
PB02	26.21873	29.12522	-76 035.41	-3 223 400.52
PB03	26.21842	29.12403	-76 066.36	-3 223 269.26
PB04	26.21610	29.12312	-76 292.54	-3 223 169.78
PB05	26.21546	29.11885	-76 357.99	-3 222 696.56
PB06	26.22933	29.12361	-75 004.54	-3 223 215.15
PB07	26.22885	29.12562	-75 050.18	-3 223 438.92

WGS84 LO27

Figure 67: Proposed borehole at the Queens Fort Military Museum

Figure 68: Proposed borehole at the President Brand Cemetery

Figure 69: Proposed boreholes at the CUT

Figure 70: Proposed borehole along the storm water canal

Figure 71: Proposed boreholes along the railway line

4.9 DISCUSSION

The aim of the geophysical surveys was to detect and delineate the prominent dolerite ring-dyke known to occur within the limits of the Bloemfontein CBD. However, since the CBD is characterised by the presence of urban and industrial developments, the presence of surface and subsurface infrastructure was a constraint which severely limited the application of geophysical methods. The geophysical surveys were therefore restricted to a few open areas in the vicinity of the ring-dyke.

Despite the above limitations, the geophysical surveys were able to identify magnetic and resistive structures in some of the investigated areas, which indicated the possible presence of the ring-dyke. Based on the results of the geophysical investigations, recommendations for the installation of investigative, monitoring and potential production boreholes were made. Although the initial scope of the research project included the drilling of boreholes, funding for the drilling was not received in time due to delays resulting from disagreements between the MMM and Bloemwater. This was another limitation of the current project, but was beyond the control of the researcher.

CHAPTER 5:
HYDROCENSUS

5.1 INTRODUCTION

As part of the investigations into the potential of using groundwater associated with the ring-dyke underlying the Bloemfontein CBD for municipal water supply, a limited hydrocensus was conducted in the vicinity of the dyke. The purpose of the hydrocensus was to locate points of groundwater abstraction near the ring-dyke in order to obtain information on the use and quality of the groundwater, as well as to investigate the aquifer system(s) hosting the groundwater. Information gathered during the hydrocensus included: the type of site (borehole, spring), the location of the sites (GPS coordinates), the construction of the borehole sites (diameter of the boreholes, depths of drilling, types of casing installed, the equipment installed at the borehole sites (types of pumps), the groundwater levels within the boreholes, the current use of the groundwater abstracted from the boreholes, the estimated yield of the boreholes, the groundwater quality as reflected by field measurements of pH and EC, and olfactory observations regarding the groundwater quality (taste and smell).

Apart from the boreholes and springs near the ring-dyke, the hydrocensus also included a number of boreholes located remotely from the dyke (at distances greater than 1 km). The hydrocensus included these boreholes to allow the groundwater conditions at remote locations to be compared to the groundwater conditions close to the ring-dyke. Such a comparison could allow the characterisation of the groundwater conditions near the ring-dyke against the background groundwater conditions.

5.2 RESULTS OF THE HYDROCENSUS

During the hydrocensus, several boreholes were located within 300 m from the estimated position of the ring-dyke. Of these boreholes, access to only three could be obtained as the owner of the properties on which the remaining boreholes were located would not allow access to these boreholes. The positions of the three boreholes near the ring-dyke (BH4 to BH6) are shown in Figure 72. Also shown is the position of the lake at the Loch Logan Waterfront. This lake is fed by a spring from the aquifer system thought to be associated with the ring-dyke. Of these three boreholes, BH6 is the closest to the ring-dyke (<100 m) and is likely to give the best representation of aquifer conditions near the dyke. The positions of three background boreholes (BH1 to BH3) are also shown in Figure 72. These boreholes are located in the suburb Willow at a distance of approximately 1.6 km from the estimated position of the ring-dyke. Another borehole (BH7) located at a distance of approximately 400 m from the ring-dyke could also represent background conditions.

Figure 72: Locations of the boreholes and spring identified during the hydrocensus relative to the estimated position of the ring-dyke

The three boreholes in the vicinity of the dyke are located at 1) the Sasol Garage near the main entrance of the CUT (BH4), 2) the Sasol Garage near the athletics track south of Loch Logan (BH5), and 3) the soccer field at the CUT (BH6). Borehole BH7 is located at the Free State Psychiatric Complex.

Some of the data gathered during the hydrocensus are listed in Table 13 (hydrocensus sheets containing all the field data are presented in **Appendix B**). All the boreholes located during the hydrocensus were equipped with steel casings and submersible pumps. Groundwater from these boreholes was generally clear with no odour. However, muddy water occurred at BH 6 while murky water was observed at BH 2.

Boreholes near the ring-dyke are currently mostly used for irrigation, while the groundwater from the spring at Loch Logan is used for recreational purposes on the lake. The borehole at the psychiatric complex (BH 7) is used for fish ponds and irrigation of a golf course. Boreholes remote from the ring-dyke are used for both irrigation and domestic water supply.

Table 13: Summary of hydrocensus results

Borehole #	Long (°E)	Lat (°S)	Borehole depth (m)	Water level (mbgl)	Pump type	Casing type	Water use	Colour	Odour
BH1	26.19694	29.12136	41	9.52	Submersible	Steel	Domestic	Clear	None
BH2	26.19763	29.12085	N/A	8.20	Submersible	Steel	Not operational	Murky	None
BH3	26.19729	29.12076	34	N/A	Submersible	Steel	Irrigation	Clear	None
BH4	26.21215	29.12226	40	N/A	Submersible	Steel	Irrigation and car wash	Clear	None
BH5	26.21133	29.11825	40	N/A	Submersible	Steel	Irrigation and car wash	Clear	None
BH6	26.21557	29.12317	N/A	9.46	Submersible	Steel	Irrigation	Muddy	None
BH7	26.21377	29.12557	N/A	N/A	Submersible	Steel	Golf course & fish ponds	Clear	None
Spring	26.20958	29.11572	N/A	N/A	N/A	N/A	Recreation	Clear	None

Due to surface infrastructure covering the boreholes, borehole depths could be recorded at only four boreholes, while the depth of the groundwater table could be measured at only three boreholes. From the available data it appears that the groundwater table near the ring-dyke is at a similar depth as at the remote boreholes (8.20 to 9.52 mbgl).

Photographs of some of the boreholes and the spring located during the hydrocensus are presented in Figure 73 to Figure 78.

Figure 73: Borehole BH1 at Mr. Coetzer's premises

Figure 74: Borehole BH2 at the Close to Home Agency (student accommodation)

Figure 75: Borehole BH3 at the premises of GHT Consulting

Figure 76: Borehole BH4 at the Sasol Garage at the main entrance of CUT

Figure 77: Borehole BH5 located at the Sasol Garage near Loch Logan

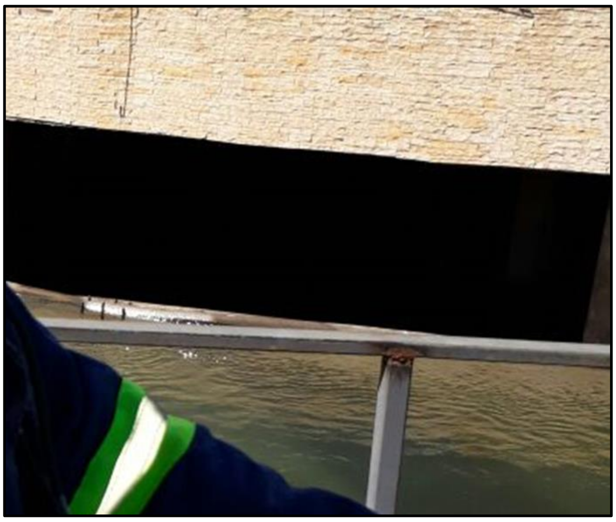

Figure 78: The basement at the Loch Logan Waterfront where the spring is located

5.3 FIELD PARAMETER MEASUREMENTS

The presence of some infrastructure prohibited the recording of electrical conductivity and temperature profiles in most of the boreholes located during the hydrocensus. However, borehole BH3 (at GHT Consulting) was accessible for such recordings. Figure 79 illustrates the results of the EC profiling done on this borehole, while the results of the temperature profiling are shown in Figure 80.

From Figure 79 it can be seen that the EC values increase gradually with depth until the bottom of the borehole is reach where large EC values are observed. The slowly increasing EC values are most likely due to the combined influence of salts gravitating downwards and recharge replenishing the aquifer in the shallower parts of the borehole. The temperature profile is seen to be nearly constant along the entire length of the borehole. Both the EC and temperature profiles give no indication of the presence of zones of preferential flow that could indicate the presence of fracture zones.

Borehole BH3 is one of the background boreholes located during the hydrocensus and occurs at a distance of more than 1.5 km from the ring-dyke. The conditions within this borehole should therefore not be seen as representative of conditions in the aquifer system associated with the ring-dyke. Unfortunately, none of the boreholes near the ring-dyke was accessible for profiling.

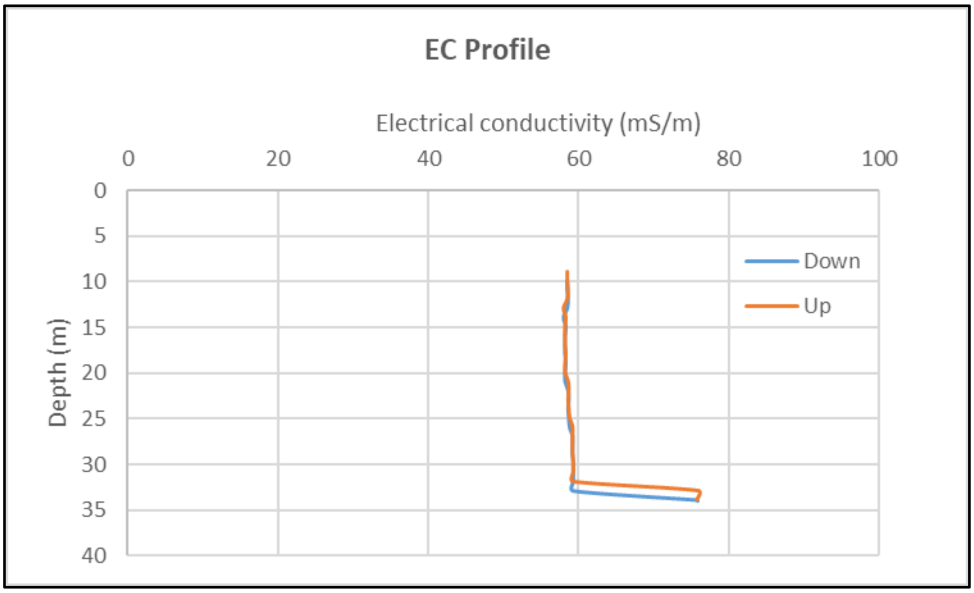

Figure 79: EC Profiling of BH3

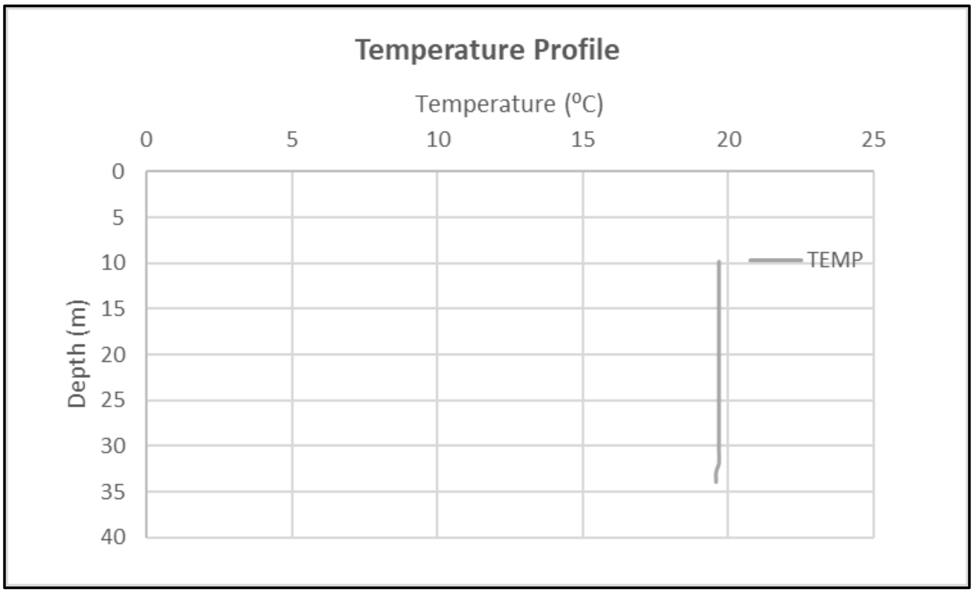

Figure 80: Temperature profile of BH3

CHAPTER 6:
AQUIFER HYDRAULIC PARAMETER

6.1 INTRODUCTION

To estimate the volumes of groundwater that can sustainably be abstracted from the aquifer system associated with the ring-dyke, information on the hydraulic properties of the aquifer system is required. This information can be obtained by performing hydraulic tests on boreholes intersecting the aquifer system. The initial scope of the current research project included the drilling of a number of investigative and production boreholes at suitable positions along the ring-dyke. These boreholes would have allowed investigation of the groundwater conditions and aquifer hydraulic parameters. Unfortunately, the drilling component of the current investigations never realised due to factors beyond the control of the researcher. This absence of a drilling programme severely restricted the current investigations.

Since no new boreholes could be drilled during the research project, it was decided to perform hydraulic tests on existing boreholes in the vicinity of the ring-dyke. Unfortunately, only one such borehole was located during the investigations. This borehole is located on the property of the Central University of Technology (CUT), and was not discovered during the hydrocensus (refer to Chapter 5), but was only found months after the hydrocensus. Although the results of a single hydraulic test on a single borehole are unlikely to be representative of the hydraulic properties of the larger aquifer system, it was thought that these results would provide at least an indication of the hydraulic properties that could be expected for the aquifer system. The absence of a comprehensive set of pumping test data from several boreholes along the ring-dyke should be viewed as a severe limitation of the current investigations.

6.2 THE PURPOSE OF CONDUCTING PUMPING TESTS

Pumping tests are performed in order to investigate the aquifer parameters. Gomo *et al.* (2014) stated that in South Africa, the main aim of pumping tests is to estimate the sustainable yield of a borehole. The sustainable yield is defined as the rate at which the borehole can be operated for a long time (e.g. two years) without reaching a specified drawdown level (in other words, the position of the main water strike in a fractured-rock aquifer), including the influence of boundaries and other boreholes. This practice is done engaging different steps in which an aquifer is stressed by pumping out water for a certain period of time, which is determined by the strength of an aquifer.

According to Abdel-Ghafour (2005), pumping test is conducted for the following reasons:

- Pumping tests are the principal part in many projects and studies dealing with groundwater exploitation, protection and remediation,
- Pumping tests aim to regulate and optimise the extraction of groundwater without adversely impacting an aquifer system, and,
- Pumping tests give the best information on the drawdown level, flow rates and unforeseen factors generated in the aquifer system upon pumping.

Van Tonder *et al.* (2001) stated that main objectives of pumping tests are:

- To understand an aquifer system better,
- To quantify the aquifer hydraulic properties and characteristics, and,
- To assess both the sustainable yield and the condition or efficiency of the borehole.

In this study the objective of the pumping test was to evaluate the hydraulic parameters of the aquifer system associated with the ring-dyke underlying the Bloemfontein CBD, and to estimate the long-term sustainable yield of the aquifer system.

6.2.1 Principles of pumping tests

Applying stress to an aquifer by extracting groundwater from a pumping well and measuring the response of an aquifer to such stress by monitoring drawdown as a function of time, is one of the principles of pumping test. The measurements that are recorded are then incorporated into an appropriate well-flow equation to calculate the hydraulic parameters of the aquifer. According to Van Tonder *et al.* (2001), in South Africa pumping tests are performed for mainly two reasons: to determine the long-term sustainable yield of a borehole and to estimate aquifer parameters.

In general, there are three types of pumping test, namely: step tests, constant rate tests, and recovery tests. These tests and their purposes are briefly described below:

6.2.1.1 Step tests

A step test (step drawdown test) is a single-well pumping test that is designed to investigate the performance of a pumping well under controlled variable discharge conditions. The discharge rate in a pumping well is increased from an initially low constant rate through a sequence of pumping steps of gradually higher constant rates. In a step test each step is typical of equal duration, lasting from approximately 30 minutes to 2 hours (Kruseman and de Ridder, 1994).

The purpose of conducting a step test is to evaluate the performance of a well criterion such as well loss, well efficiency, wellbore skin factor and effective well radius.

6.2.1.2 Constant rate tests

A constant rate test is a type of pumping test in which a control well is pumped at a constant rate and water-level response is measured in one or more surrounding observation wells or boreholes and sometimes be measured on the control well (pumped borehole). The purpose of conducting a constant rate test is to estimate the hydraulic properties of an aquifer system such as the transmissivity, hydraulic conductivity and storativity.

6.2.1.3 Recovery tests

The recovery test is a controlled field experiment that is performed at the end of a pumping test (constant-rate or step-drawdown). This is conducted immediately after pumping in the pumped (control) well has ended. Water-level response (residual drawdown) is measured after pumping has stopped in one or more surrounding observation wells and can optionally be recorded in the control well itself.

The purpose of conducting a recovery test just like in any aquifer tests is, to estimate hydraulic properties of an aquifer system such as transmissivity, hydraulic conductivity and storage coefficient (Kruseman and de Ridder, 1994).

6.3 PUMPING TEST

6.3.1 Introduction

A pumping test was conducted on a borehole owned by the Central University of Technology (CUT). This borehole is located at 29º07′12,72″S, 26º12′49,01″E within the proximity of the investigated ring dyke (refer to Figure 81). A constant rate test was performed for a period of 8 hours and 50 seconds. Previous hydraulic tests on the borehole had been done on this borehole prior to the current investigations. Unfortunately, the results of these hydraulic tests were not available to the researcher during the current investigations. However, these tests had indicated that the borehole was high yielding. A high pumping rate of 13.3 L/s was therefore employed during the constant rate test of the current investigations. Recovery data were also recorded after completion of the constant rate test. Unfortunately, groundwater level monitoring in observation boreholes could not be performed as access to other boreholes on the premises was denied.

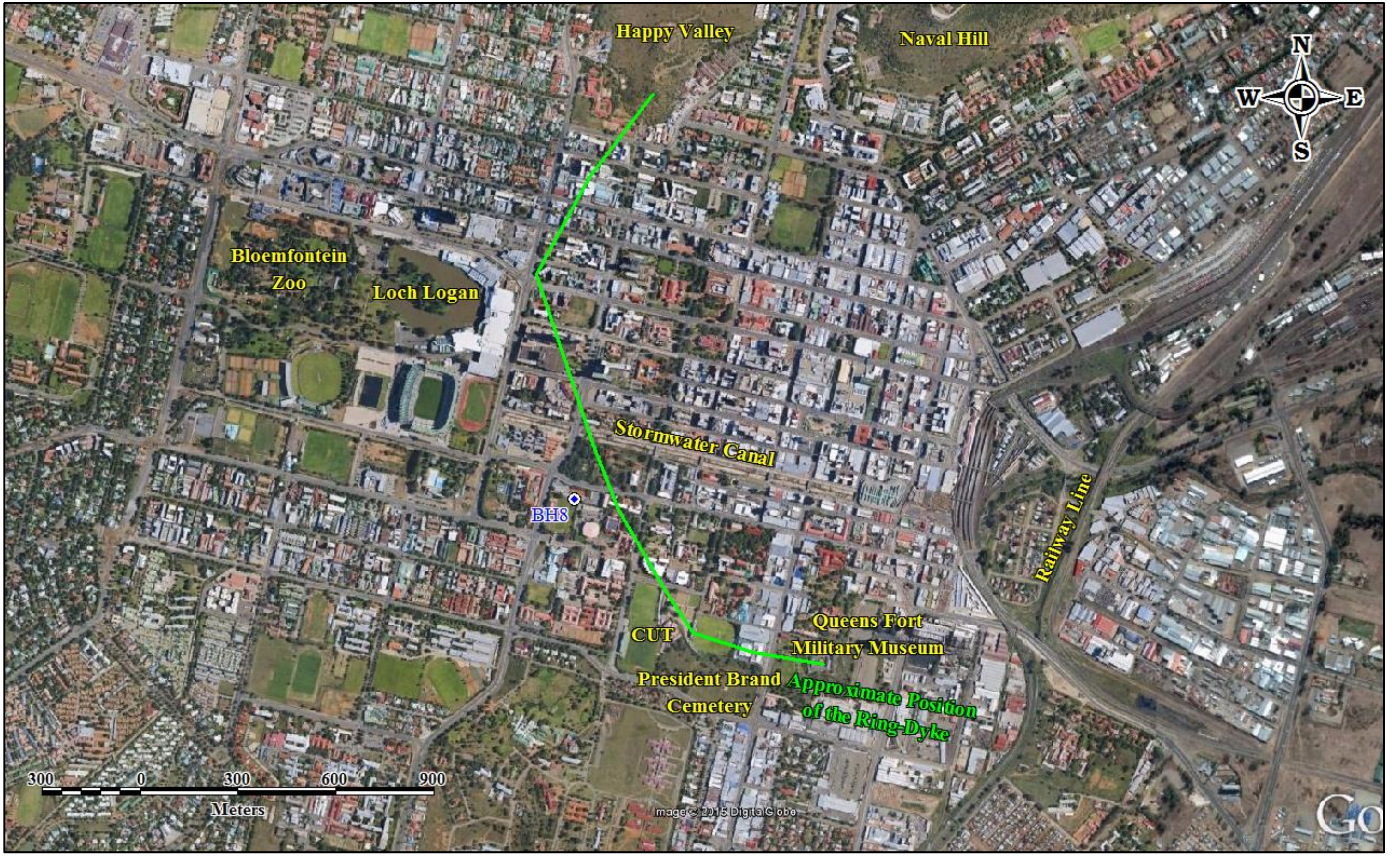

Figure 81: Location of the borehole (BH8) on which a pumping test was performed

6.3.2 Results of the pumping tests

Figure 82 is a log-log plot of the drawdown data recorded against time during the constant rate pumping test performed on borehole BH8 (Figure 81). The pump inlet was positioned at a depth of 25 metres below surface (mbs), 1 m above the main water strike of the borehole. A total drawdown of almost 2.5 m was observed after 481 minutes of pumping.

The recovery data are plotted in Figure 83. A rapid recovery rate was observed for borehole BH8 with the groundwater level recovering to 90% of its undisturbed value in less than 120 minutes. The high pumping rate employed during the constant rate test and the rapid recovery rate show that borehole BH8 intersect a high-yielding aquifer system.

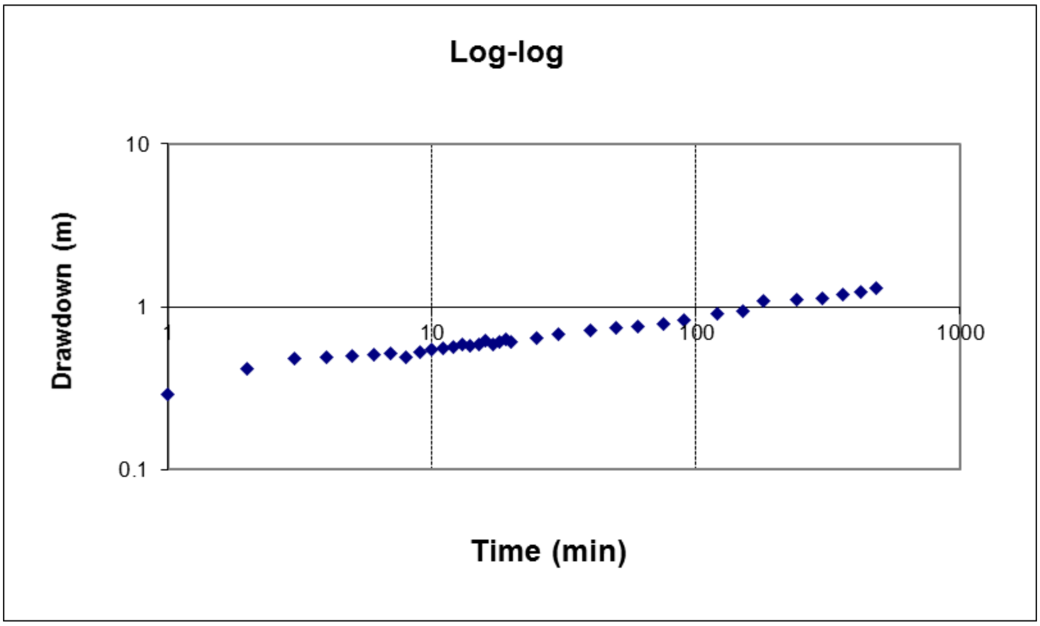

Figure 82: Diagnostic log-log plot displaying the drawdown versus time of the pump tested borehole

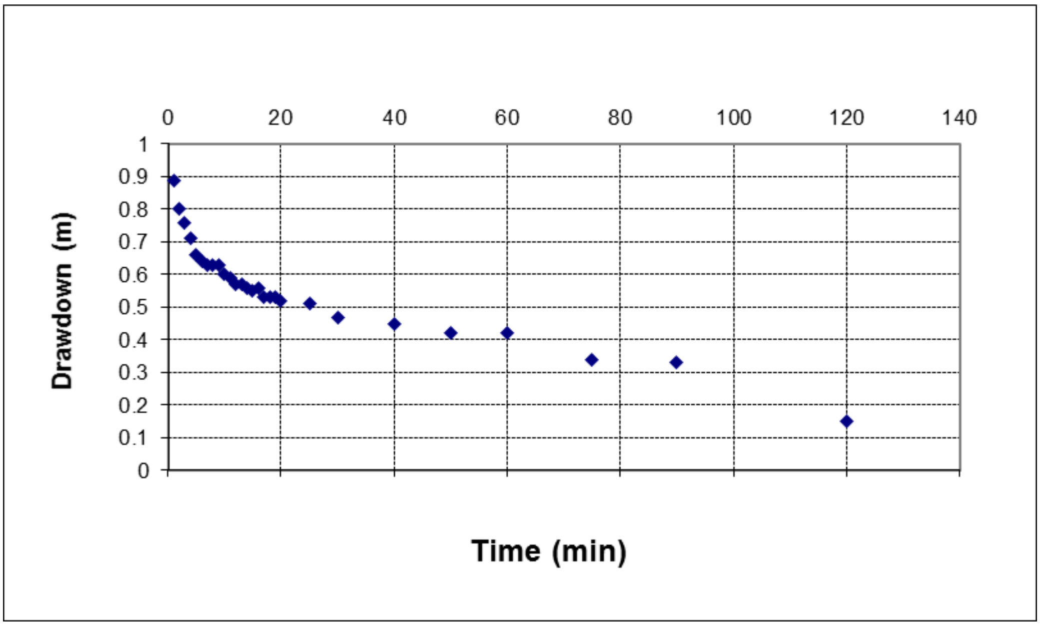

Figure 83: Remaining drawdown versus time during the recovery test

6.3.3 Interpretation

To estimate the hydraulic parameter values and the sustainable yield of the borehole, the Flow Characteristic (FC) programme developed by the Institute for Groundwater Studies (IGS) was used. This programme allows the calculation of a sustainable yield by taking into account factors such as: a) the hydraulic parameter values, b) the flow characteristics of the aquifer system, and c) boundaries affecting the flow.

A derivative plot of the drawdown data versus time is shown in Figure 84. This plot may be used to characterise the flow regimes encountered during the pumping test. Multiple dips in the derivative plot suggest that multiple fracture zones are contributing to the groundwater flow towards the borehole (refer to Figure 84). However, there is also an indication of a single no-flow boundary encountered approximately 100 minutes after pumping started, while radial flow is observed some time before this boundary is reached.

Estimates of the transmissivity (*T*-) values were obtained by applying the Cooper-Jacob Method to the data recorded during the constant rate test, and by analysing the data recorded during the recovery test. s well as the data. A late-time *T*-value of 265 m^2/day was calculated using the Cooper-Jacob Method (see, while a higher *T*-value of 709 m^2/day was found for the recovery data. Although the difference between these T-values is significant, both methods show that *T*-values in the order of hundreds of metres squared per day can be expected for the aquifer system. These high *T*-values show that the aquifer systems associated with the ring-dyke is high-yielding. Using the FC method with the information obtained from the diagnostic plot, a sustainable yield of approximately 22.5 L/s over a 24-hour period was calculated for borehole BH8.

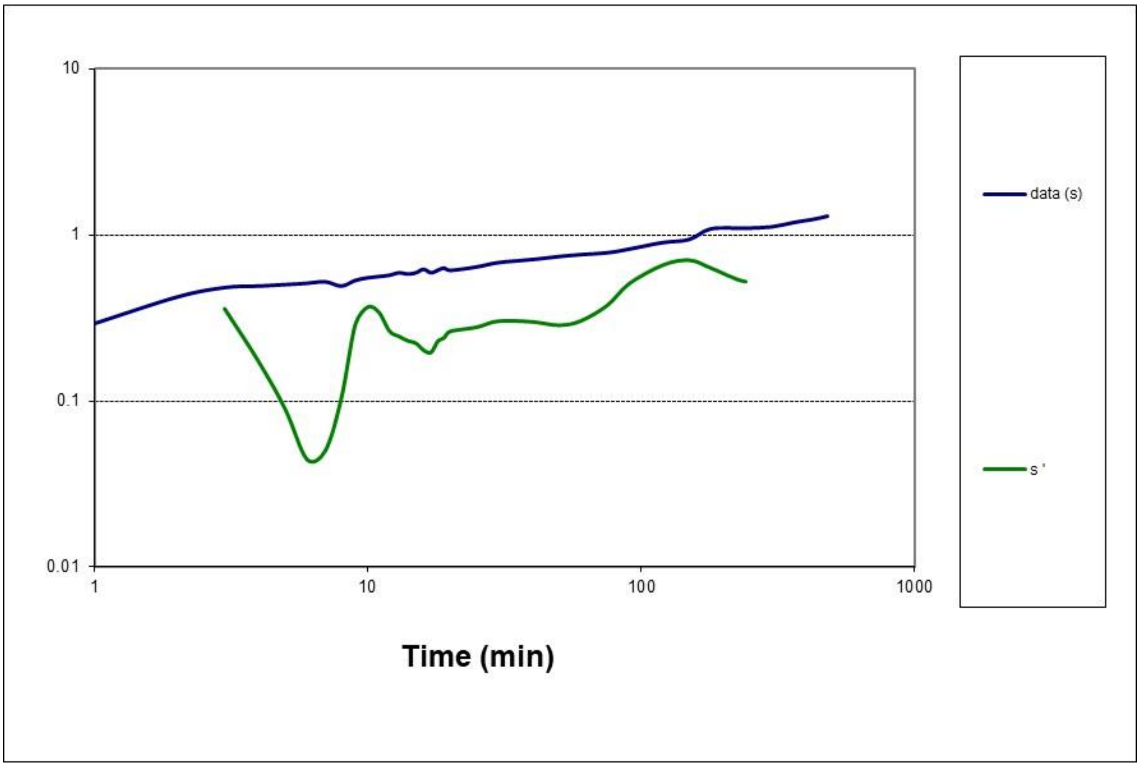

Figure 84: Derivative graph displaying the derivative and data with time (where the derivative declines is fracture dewatering and the incline is after dewatering of a fracture)

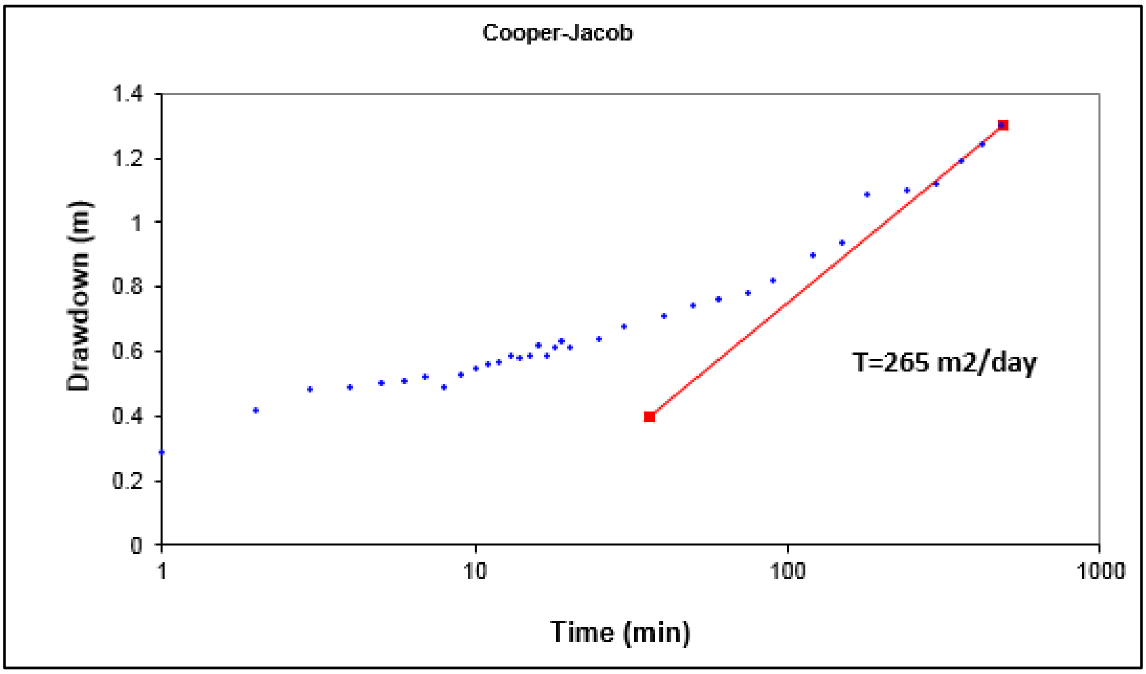

Figure 85: Estimation of the *T*-value using the Cooper-Jacob Method

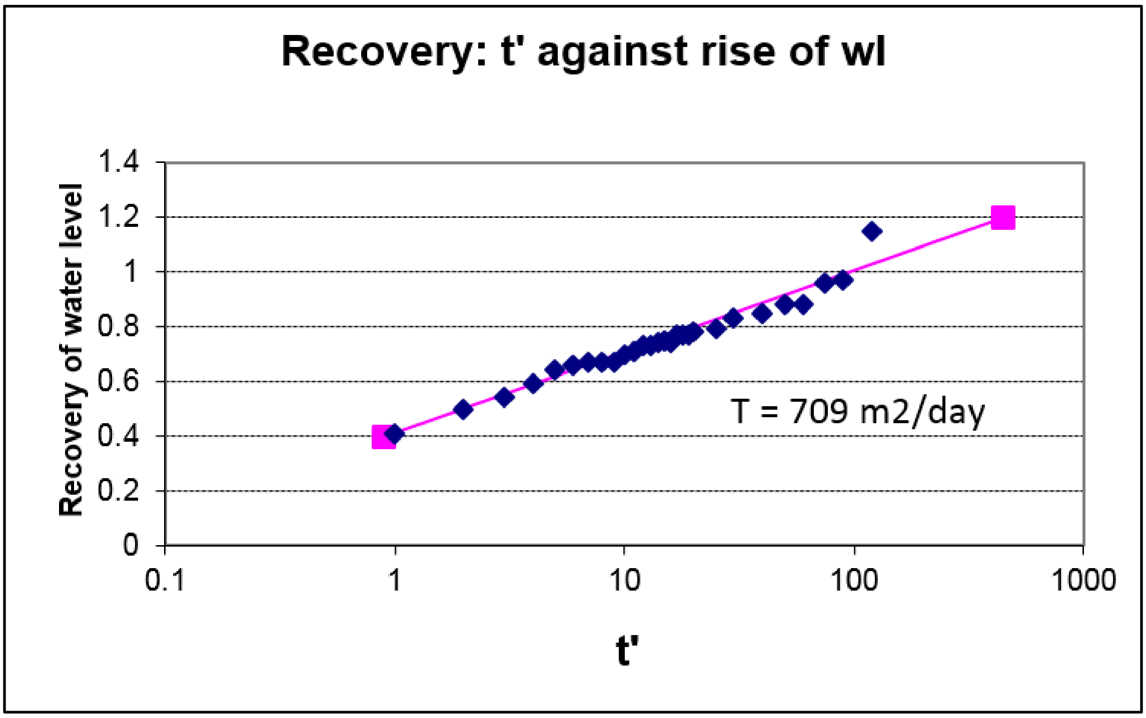

Figure 86: Estimation of the *T*-value from the recovery data

6.4 CONCLUSIONS

Although only a single borehole was tested during the current investigations, the results of the pumping tests performed on borehole BH8 show that the aquifer system associated with the ring-dyke is high-yielding. This observation suggests that the groundwater resource may make a significant contribution to the volumes of water supplied to the MMM.

To assess the aquifer properties with a greater deal of certainty, additional pumping tests should be performed on other boreholes located within the aquifer system. These boreholes could possibly be existing boreholes not located during the hydrocensus, or boreholes drilled as part of future drilling programmes aimed at installing investigative and production boreholes.

CHAPTER 7:
Groundwater Quality

7.1 INTRODUCTION

Since the current research project focusses on the possible use of groundwater to augment the municipal water supply in the MMM, information on the groundwater quality is required. This information is particularly important considering the fact that the aquifer system underlies an area of urban development in which various sources could contribute to groundwater contamination.

Information on the groundwater quality and hydrochemical characteristics will also be essential when evaluating the various possible uses of the groundwater within the municipality. If, for example, the water quality is found to be unacceptable for human consumption, then treatment options could be considered. Alternatively, the groundwater could be used for other applications with less stringent quality requirements, such as irrigation or industrial use.

This chapter describes the results of the chemical analyses that were performed on groundwater samples from the boreholes and spring that were identified during the hydrocensus (refer to Chapter 5). The main aim of the chemical analyses was to gain insight into the groundwater characteristics, and to evaluate its suitability for different applications. A secondary aim was to investigate whether the groundwater from the aquifer system associated with the ring-dyke has a different hydrochemical signature than the groundwater at positions remote from the ring-dyke.

7.2 GROUNDWATER SAMPLING

Groundwater samples were collected from the seven boreholes and one spring identified during the hydrocensus (refer to Figure 72). Pumped water samples were collected all the boreholes, except for boreholes BH1, BH2 and BH6. Groundwater samples from these latter boreholes were collected using a depth-specific bailer. A water sample from the spring at the Loch Logan Mall was collected from the discharge point where the spring is diverted into the lake. All groundwater samples were submitted to the laboratory of the Institute for Groundwater Studies (IGS) for chemical analyses.

No bacteriological analyses were performed on the groundwater samples during the current investigations. However, bacteriological analyses will have to form part of a routine groundwater monitoring programme if the groundwater is to be used for municipal water supply in future. This is particularly true if the water is to be used for domestic water supply.

7.3 HYDROCHEMICAL ANALYSES

The results of the hydrochemical analyses performed on the groundwater samples are listed in Table 14 (and in **Appendix C**). All parameters values are measured in milligrams per litre (mg/L) except for EC which is in milli-Siemens per metre (mS/m). Table 14 makes use of colour-coded cells to indicate whether the particular parameter value falls within the quality standards set by the Department of Water Affairs purposely for domestic water supply (DWA, 1998) (no standards exist for uncoloured cells). The legend shown in Table 15 shows the quality representation of each colour.

From the hydrochemical results listed in Table 14, the following observations can be made:

- All water samples have qualities that fall within the range of ideal to fair water quality, the only exception being borehole BH3, which displays almost ideal water quality (only the EC value is slightly elevated).
- The pH values of all the groundwater sample reflect near-neutral to neutral water samples.
- The trace elements concentrations in all the boreholes are very low, often lower than the detection limits of the equipment used in the laboratory for chemical analyses.
- Boreholes BH1, BH5 and BH6 display higher concentrations of total dissolved solids (TDS) and electrical conductivity (EC) values than the other boreholes.
- Low nitrate values are observed at all boreholes, but particularly at borehole BH3.
- The calcium concentration is lower in BH3 than in the other water samples.
- The chloride and sulphate concentration are slightly elevated in boreholes BH1, BH5 and BH6.

An important observation is that there is no significant difference between the water chemistries at boreholes near the ring-dyke as compared to the water chemistries in boreholes remote from the ring-dyke (refer to Table 14). This observation suggests that the aquifer system associated with the ring-dyke has a similar recharge source than the aquifer(s) at positions remote from the ring-dyke, and that the groundwater is exposed to similar geochemical conditions. There is no evidence that the aquifer near the ring-dyke has been exposed to higher levels of contamination that the remote aquifer(s).

Table 14: Results of the chemical analyses performed on groundwater samples

PARAMETERS	BOREHOLES NEAR THE DYKE				BOREHOLES REMOTE FROM THE DYKE			
	BH4	BH 5	BH 6	Spring 1	BH1	BH 2	BH 3	BH 7
pH	6.98	6.96	7.01	7.09	7.05	7.13	7.61	6.96
EC	94.5	185	190	89.9	113	94.6	18.8	96.4
Ca	108	166	239	91.74	132	106	21	98
Mg	49	79	127	58.16	57	47	6	48
Na	61	205	65	43.59	78	60	12	74
K	5.12	4.56	3.71	2.33	5.88	5.19	2.57	2.85
PAlk	0	0	0	0	0	0	0	0
MAlk	342	542	515	346	387	339	77	308
F	0.25	0.46	0.13	0.2719	-0.1	0.22	0.15	0.42
Cl	77	163	240	59.38	111	78	13	88
NO2(N)	<0.01	<0.1	<0.1	-0.01	<0.1	<0.01	<0.01	<0.01
Br	0.38	0.50	0.47	0.2007	-0.4	0.38	0.08	0.45
NO3(N)	5.16	4.81	8.25	7.82	6.12	5.56	0.39	7.10
PO4	<0.1	<1	<1	<0.1	<1	<0.1	<0.1	<0.1
SO4	88	346	263	75.28	109	85	14	97
CA Hard.	269	416	596	229	329	264	52	246
Mg Hard.	201	325	521	238	235	193	24	195
Tot. Hard.	470	740	1117	468	564	457	76	441
TDS (sum)	753	1527	1488	711	905	744	146	749
Al	<0.020	<0.020	0.032	0.029	<0.020	0.023	0.035	<0.020
As	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
B	0.063	0.521	0.073	0.073	0.091	0.068	<0.040	0.081
Ba	0.083	0.074	0.080	0.038	0.144	0.139	0.039	0.033
Cd	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003	<0.003
Co	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Cr	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Cu	<0.005	0.050	0.025	0.015	0.126	0.010	0.017	0.010
Fe	<0.020	<0.020	0.037	<0.020	<0.020	<0.020	<0.020	<0.020
Mn	<0.020	<0.020	<0.020	0.024	<0.020	<0.020	<0.020	<0.020
Mo	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Ni	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
Pb	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015	<0.015
S	77.672	292.112	224.277	0.000	92.190	79.881	15.574	86.957
Si	18.230	16.942	20.502	19.338	16.963	17.844	5.614	17.676
U	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020	<0.020
V	0.013	0.013	<0.010	0.015	0.010	0.013	<0.010	0.012
Zn	0.059	0.022	0.031	<0.020	0.060	0.020	<0.020	<0.020

Table 15: Colour-coding used in Table 14

	Ideal water quality
	Good water quality
	Fair water quality

7.4 HYDROCHEMICAL CHARACTERISTICS

The hydrochemical characteristics of each source of groundwater can be displayed by the use hydrochemical diagrams in order to illustrate the absolute or relative abundance of major cations and anions per water samples. The SI units that are used to express the concentration of these components is milli-equivalents per litre (denoted by meq/L), with the purpose to avoid dominance of heavier parameters over the lighter parameters. In this section, the hydrochemical results for the groundwater samples are displayed on four hydrochemical diagrams used to visualise the groundwater characteristics. These diagrams are: the Piper, Durov, Stiff and SAR (Sodium Absorption Rate) diagrams.

7.4.1 The Piper Diagram

In the Piper diagram the hydrochemistry of water samples is displayed in a form of ternary plots in which the cation and anion concentrations are shown. In this ternary plot of the cations, the apexes correspond to the calcium, magnesium and sodium-plus-potassium concentrations. The apexes of the ternary plot of the anions correspond to the sulphate, chloride and carbonate-plus-bicarbonate concentrations. These two ternary plots are projected onto a diamond structure that is a matrix transformation of a graph of the anions and cations. The central diamond plot is generally divided into four zones, corresponding to four different water types, namely: calcium-sulphate waters, calcium-bicarbonate waters, sodium-chloride waters, and sodium-bicarbonate waters.

In Figure 87 the groundwater samples that were collected in all seven boreholes and a spring are projected on a Piper diagram. It is seen that all the groundwater samples are of the calcium-bicarbonate type, except for water samples that was drawn from BH5 and BH6, which plot in the calcium-sulphate section.

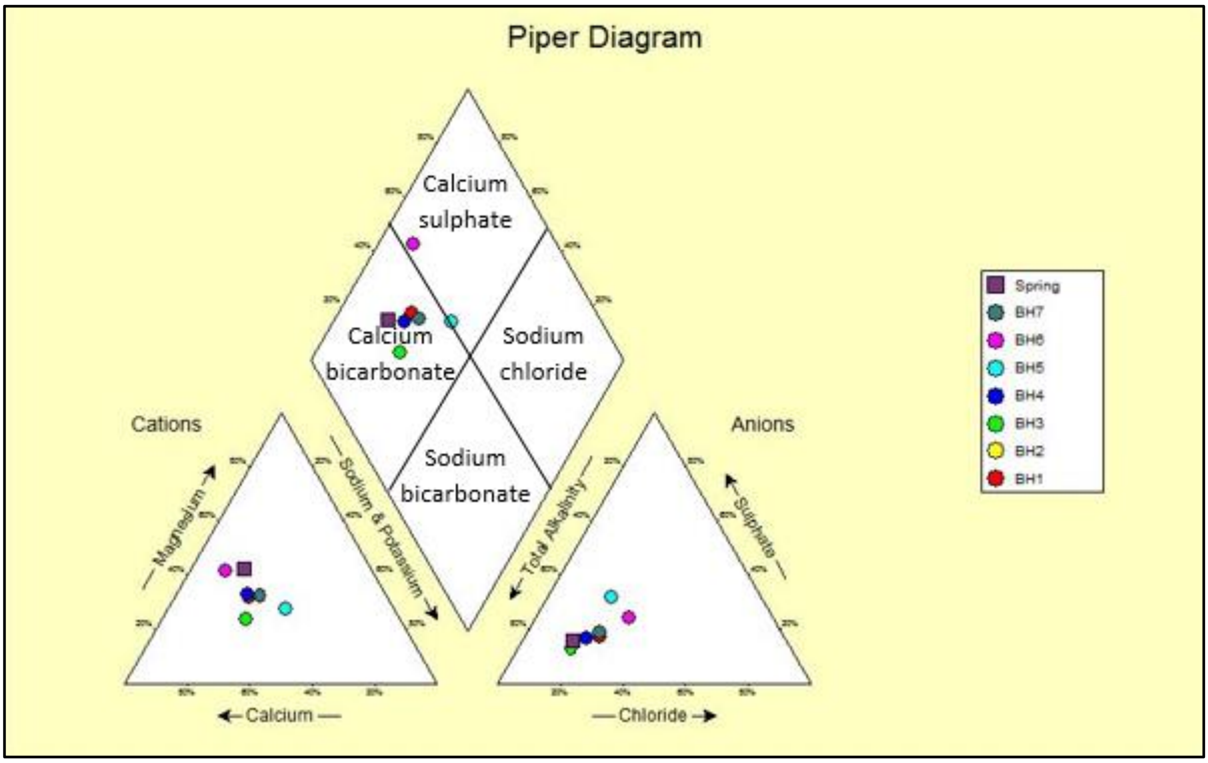

Figure 87: Piper diagram of the groundwater samples

7.4.2 The Durov Diagram

The Durov diagram can be used to compare relative anion and cation concentration in water samples. The Durov diagram is used to visualise the cation and anion concentrations relative to the pH and the TDS values. This diagram offers the advantage of graphical visualisation of almost all the major ion concentrations of water samples.

Figure 88 is a graphical presentation of the major ions relative to the pH and the TDS concentrations of the water sample collected from all the groundwater sources. It is seen that all the water samples plot closely together in the central square of the Durov diagram, suggesting that these water samples have a very similar hydrochemistry. Only boreholes in BH5 and BH6 plot at positions slightly displaced from the cluster.

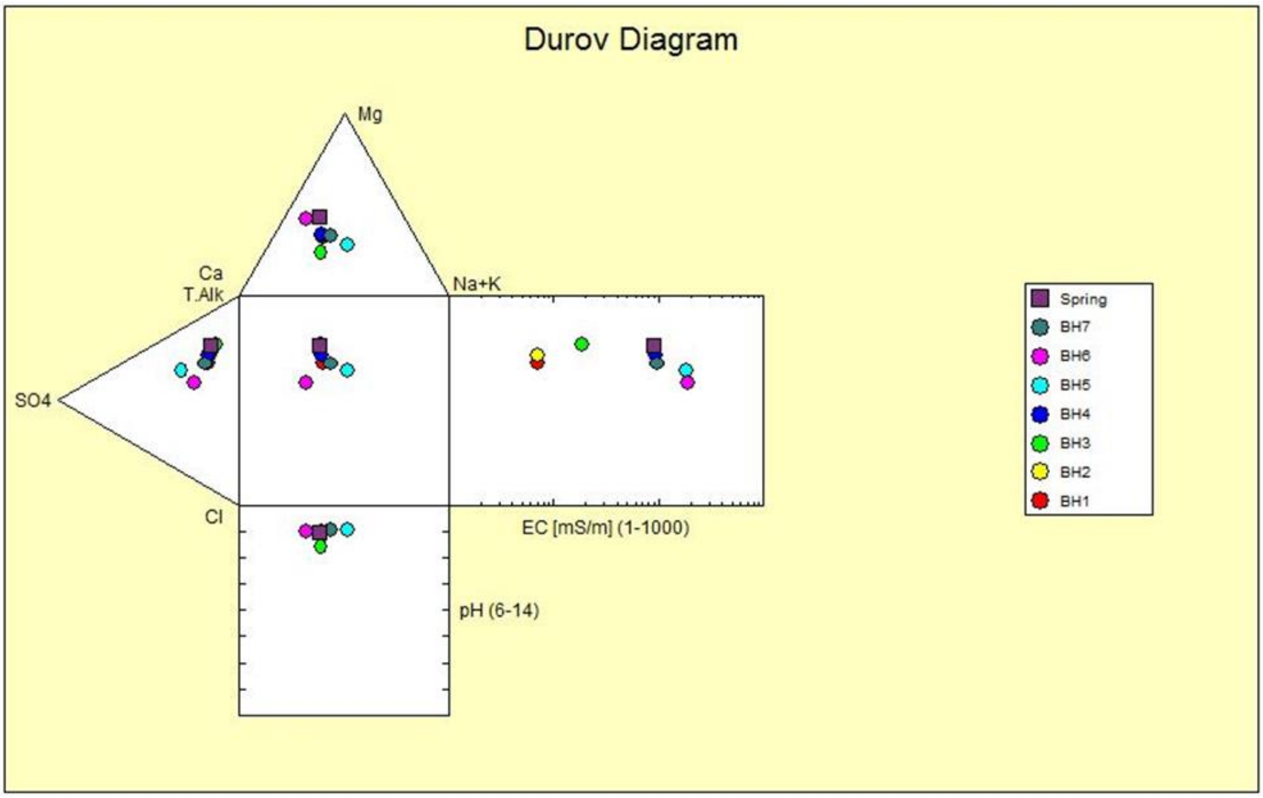

Figure 88: Durov diagram of the groundwater samples

7.4.3 The Stiff Diagram

The Stiff Diagram is mostly used to demonstrate the concentrations of anions and cations in water sample and it is useful for visually differentiating between water from different sources. The concentrations of the major anions and cations are plotted as milli-equivalents per litre (meq/L) on horizontal axes. In this way, polygons are created which give visual representations of the relative ions concentrations.

The Stiff diagram for the groundwater samples collected during the hydrocensus is shown in Figure 89. It is seen that all the water samples yield very similar shapes, except for boreholes BH3, BH5 and BH6. This observation suggests that the water chemistries at these boreholes are different than at the other boreholes.

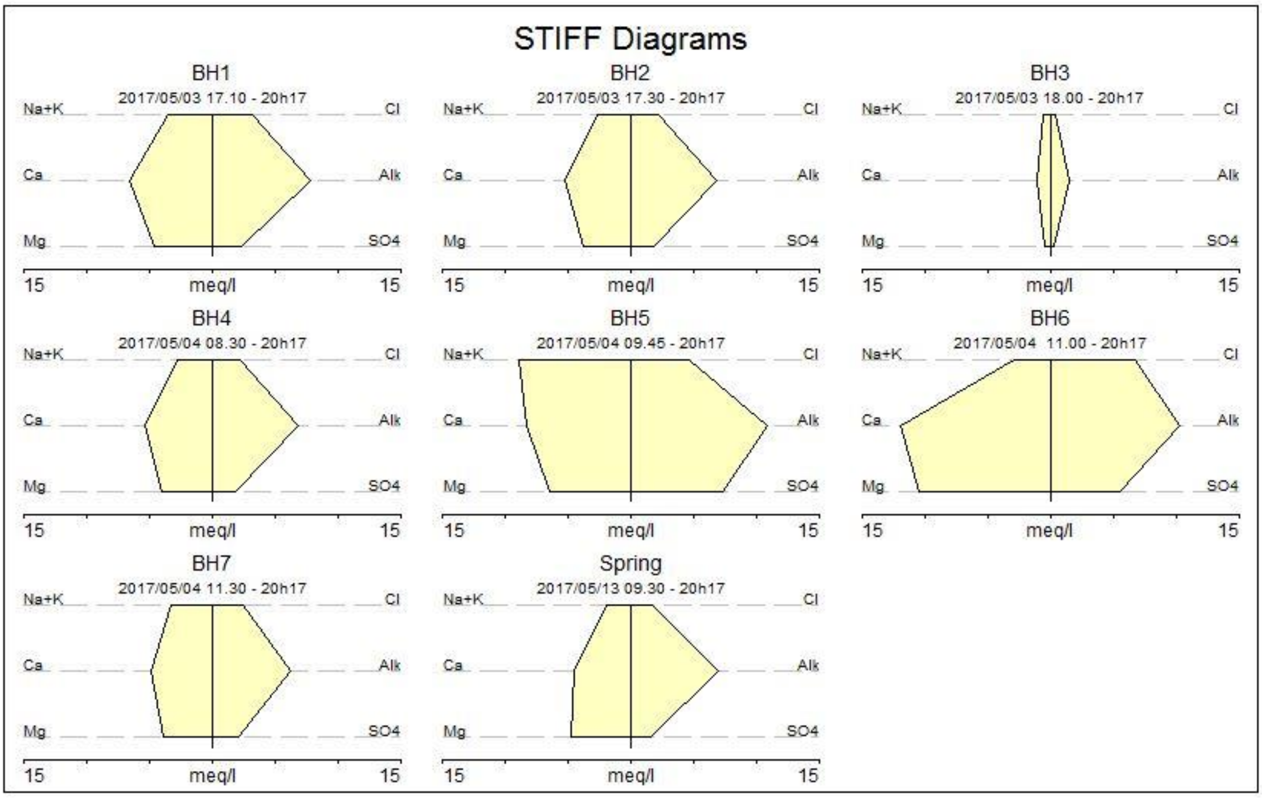

Figure 89: Stiff diagram of the groundwater samples

7.4.4 The SAR (Sodium Adsorption Rate) Diagram

The Sodium Absorption Rate (SAR) diagram is used to evaluate if water is suitable for irrigation purposes. The SAR diagram of all water samples is presented in Figure 90. It is seen that although all the groundwater samples are associated with low sodium hazards, boreholes BH5, BH6 and BH7 and the spring have high salinity hazards. These latter groundwater sites all occur in the vicinity of the ring-dyke, suggesting that groundwater from the aquifer system associated with the ring-dyke may pose a salinity hazard if the water is used for irrigation on poorly-drained soils. Irrigating plants with water that has a high salinity hazard could affect the intake of nutrients, which could result in poor crop/plant production, particularly during the early developing stages (Hathaway *et al*., 1981).

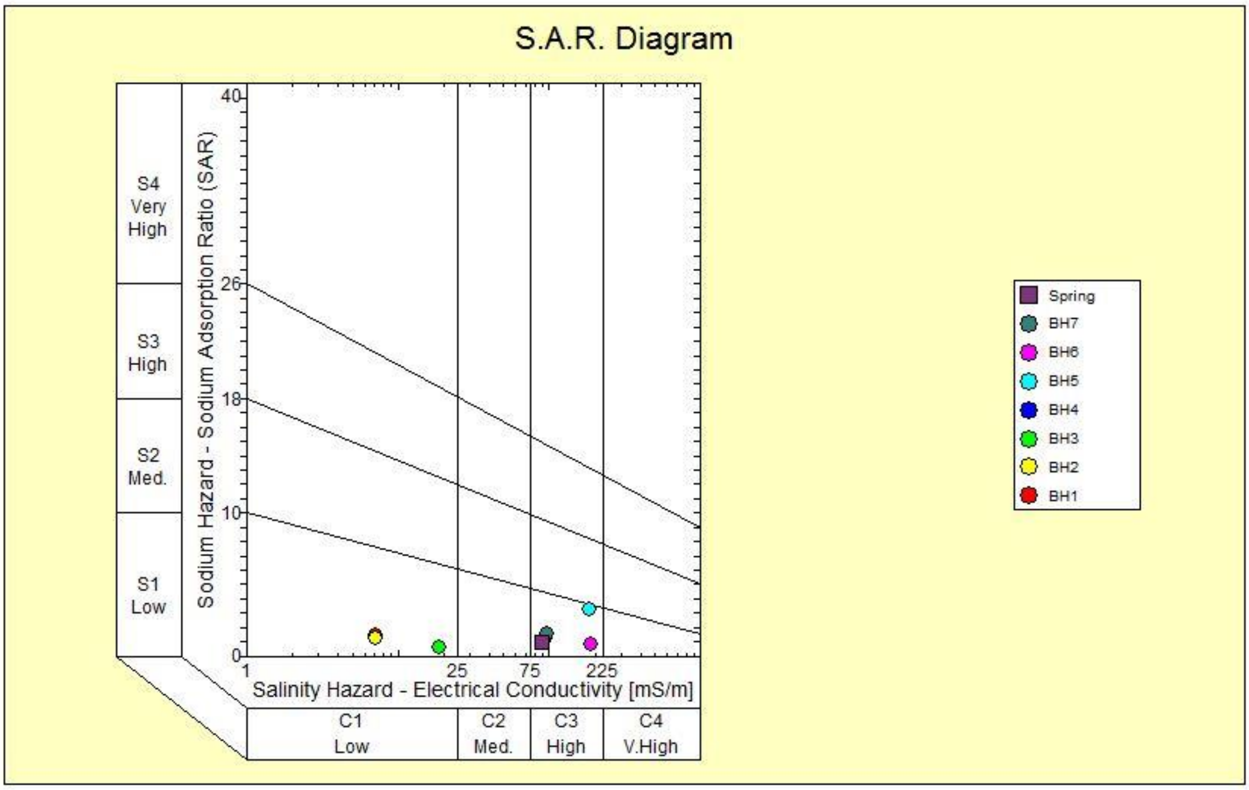

Figure 90: SAR diagram of the groundwater samples

CHAPTER 8:
MONITORING AND MANAGEMENT PROGRAMMES

8.1 INTRODUCTION

This research project focusses on investigating the possibility of using groundwater associated with a prominent ring-dyke underlying the Bloemfontein CBD to augment the municipal water supply. The results of the investigation indicate that the aquifer system associated with the ring-dyke is high-yielding and that the current water quality ranges from good to ideal when measured against the drinking water standards set by the Department of Water Affairs (DWA, 1998).

To ensure the safe and sustainable use of the groundwater resource, a groundwater monitoring and management programme should be implemented. Such a programme will aim to ensure that the volumes of groundwater abstracted do not exceed the long-term capacity of the aquifer system to deliver water, while ensuring that the quality of the water delivered to the municipal supply system is of a suitable quality for the its intended purpose.

The groundwater abstracted from the aquifer system could potentially be used for different purposes within the municipality, including: drinking and domestic water, irrigation, and industrial use. For each of these different applications of the abstracted groundwater, different monitoring and management options should be considered. Monitoring and management programmes relevant to the different groundwater uses are described in this chapter.

8.2 DISCUSSION

The results of the investigations into the groundwater quality and characteristics show that the groundwater from all the sampled sites is generally of good to ideal quality, although high salt concentrations occur at some boreholes (BH1, BH5 and BH6). There is no prominent difference between the groundwater characteristics and groundwater qualities at boreholes close to the ring-dyke as compared to boreholes remote from the ring-dyke. The groundwater in the aquifer system associated with the ring-dyke therefore appears to have the same source and exposure than the groundwater in the aquifer(s) at a distance. No clear evidence for contamination is visible in the results of the inorganic analyses.

The good quality of the groundwater suggests that it can be incorporated into the municipal water supply without requiring too much treatment. However, the investigations into the groundwater quality did not consider hydrocarbon or bacteriological contamination of the groundwater. No conclusions can therefore currently be drawn on the groundwater quality in terms of possible organic and bacteriological contaminants. If the groundwater is to be included in the municipal water supply, routine monitoring of the water quality should be done to detect possible contamination with organic compounds and bacteria.

8.3 PROPOSED GROUNDWATER MONITORING PROGRAMME

8.3.1 Introduction

The aim of the groundwater monitoring programme will be to ensure the safe and sustainable use of the groundwater for its intended purpose. The monitoring programme should therefore include monitoring of both the groundwater quality and the groundwater levels in the abstraction boreholes (and observation boreholes, if available). Since different water quality criteria are applicable to different water uses, and since different water uses are associated with different risks, the monitoring programme should be tailor-made for the specific water use.

8.3.2 Proposed monitoring programme: domestic and drinking water

Water used for domestic purposes is associated with the highest risks of contaminant impacts. The monitoring programme for domestic use should therefore be the most comprehensive and should be based on the most stringent criteria for water quality. It should also be kept in mind that the groundwater is abstracted from aquifers underlying industrial and urban developments, and that a wide variety of pollutants could potentially impact on the groundwater resource. New contaminant sources can also be introduced as new industries are established in the Bloemfontein CBD. This implies that groundwater sampling and testing should be done on regular basis and that the range of chemical and physical parameters included in the groundwater analyses should be extensive.

Considering the different industries found within the Bloemfontein CBD, various industry-specific contaminants could potentially impact on the groundwater system. Some of these contaminants may not be detected by the organic and inorganic analyses routinely performed in the investigations of groundwater quality. These contaminants could include new and emerging contaminants, as well as specialised hydrocarbon compounds used by specific industries. It will therefore be necessary to conduct as census of the industries in the CBD and to identify the industry-specific contaminants that could pose a health risk. Groundwater monitoring will then have to include analyses aimed at detecting the identified industry-specific contaminants. The industry census will have to be repeated at least annually to ensure that new industries are included in the database.

It will also be advisable to do contaminant fingerprinting on groundwater samples. During fingerprinting, comprehensive analyses should be done to detect any contaminants not identified during the industry census. Routine monitoring for such contaminants should then form part of the groundwater monitoring programme.

The proposed monitoring programme for domestic use of the groundwater is summarised in Table 16. Although a weekly monitoring frequency is recommended, daily measurements of parameters such as pH, EC, Eh, dissolved oxygen, turbidity and temperature using handheld instruments should be done to allow early detection of any changes in the groundwater conditions that may be related to contamination.

Apart from the water quality monitoring, monitoring of the water levels in the abstraction boreholes (and possible observation boreholes) should be done on a weekly basis. The water levels in the boreholes should not exceed the recommended maximum available drawdowns, as determined by qualified geohydrologists (refer to Section 8.4).

8.3.3 Proposed monitoring programme: irrigation

At present, purified domestic water is mostly used for irrigation within the MMM. This is an unnecessary waste of costly purified water. Groundwater abstracted from the aquifer associated with the ring-dyke could potentially be used for irrigation. In this case, the groundwater quality will be of lesser concern, since the health risks associated with groundwater ingestion will be avoided. A smaller range of parameters to be analysed, a lower monitoring frequency, and less stringent water quality criteria will therefore suffice for the monitoring programme.

Since the municipality does not at present have separate infrastructure to handle irrigation water, the use of groundwater for irrigation will initially be restricted to areas close to the abstraction boreholes. If the long-term benefit of using groundwater for irrigation is determined to outweigh the costs associated with the installation of new infrastructure, it may be feasible to install separate reservoirs and piping for irrigation water.

The proposed monitoring programme for groundwater used as irrigation water is summarised in Table 17. Weekly water level monitoring of the abstraction boreholes should also form part of the monitoring programme.

8.3.4 Proposed monitoring programme: industrial use

As is the case for irrigation, the water monitoring programme for industrial use of the groundwater should be less stringent in terms of the range of parameters, the monitoring frequency and the water quality criteria. A similar monitoring programme for industrial groundwater use than for irrigation should be followed (refer to Table 17). The water levels in the abstraction boreholes should again be monitored on a weekly basis.

8.4 ADAPTIVE MANAGEMENT PROGRAMME

To manage the aquifer system from which groundwater is abstracted, a groundwater abstraction (pumping) strategy should be developed before the groundwater resource is used to augment the municipal water supply. This pumping strategy should be developed in close consultation with qualified geohydrologists, using information obtained from hydraulic tests performed on the abstraction boreholes. The sustainable abstraction rates and maximum allowable drawdowns should be determined for each borehole included in the abstraction network. The mutual influence of the different abstraction boreholes should be incorporated in the calculation of the sustainable yield from the aquifer system.

Table 16: Proposed groundwater monitoring programme: domestic use

Parameters					Monitoring frequency	Quality criteria
Inorganic		Organic	Bacteriological	Industry-specific		
Major	Minor					
pH	Al	Benzene	Biochemical oxygen demand	As identified from the industry census and contaminant fingerprinting	Weekly	The South African Water Quality Guidelines - Domestic Use Standards relevant to industry-specific contaminants (if available)
EC	As	Toluene	Heterotrophic plate count			
Ca	B	Ethyl-benzene	E. coli			
Na	Ba	Xylene	Total coliform bacteria			
Mg	Cd	Naphthalene	Faecal coliform bacteria			
PAlk	Co	Total petroleum hydrocarbons				
MAlk	Cr	Methyl tertiarybutyl ether				
F	Cu	Tertiary amyl methyl ether				
Cl	Fe	Volatile organic compounds				
$NO_2(N)$	Mn	Total organic carbon				
Br	Mo	Chlorinated hydrocarbons				
$NO_3(N)$	Ni	Diesel-range organics				
PO_4	Pb					
SO_4	S					
CA Hard.	Si					
Mg Hard.	U					
Tot. Hard.	V					
TDS (sum)	Zn					

Table 17: Proposed groundwater monitoring programme: irrigation and industrial use

Parameters					Monitoring frequency	Quality criteria
Inorganic		Organic	Bacteriological	Industry-specific		
Major	Minor					
pH	Al				Monthly	The South African Water Quality Guidelines - Agricultural Use: Irrigation
EC	As					
Ca	B					
Na	Ba					
Mg	Cd					
PAlk	Co					
MAlk	Cr					
F	Cu					
Cl	Fe					
NO_2(N)	Mn					
Br	Mo					
NO_3(N)	Ni					
PO_4	Pb					
SO_4	S					
CA Hard.	Si					
Mg Hard.	U					
Tot. Hard.	V					
TDS (sum)	Zn					

The information gained from the monitoring programme will inform the management programme. The management programme should be flexible and adaptive to allow quick responses to changes in the groundwater conditions revealed by the monitoring programme. For example, if the groundwater level monitoring indicates groundwater level declines that approach the maximum allowable drawdowns in the different boreholes, then the pumping strategy should be updated, again in close consultation with qualified geohydrologists. Similarly, if significant changes in the groundwater quality are observed, then management decisions will have to be taken to decide whether these changes warrant additional actions, such as identifying the contaminant source and changing the pumping strategy. Input from qualified geohydrologists will again be required in the decision-making

If groundwater is to be used to augment the domestic water supply, then the management programme could also include possible treatment options. Water treatment is currently done at the Rustfontein and Maselspoort Water Treatment Plants. These treatment plants are distant from the Bloemfontein CBD. It would therefore be a costly exercise to pump groundwater from the abstraction boreholes to the water treatment plants. Establishing a new dedicated water treatment plant closer to the city with the specific aim of treating the groundwater is clearly not a viable option since the development costs would be enormous.

The most feasible water treatment option appears to be mixing the abstracted groundwater with the treated water received from the water treatment plants. In this case, groundwater could simply be pumped to nearby reservoirs where mixing with treated water can take place. This option will require careful monitoring and management to ensure that the mixture of treated water and groundwater is still of acceptable quality for domestic use. This option will also require the development of some infrastructure in the form of pumps and pipes from the boreholes to the reservoirs.

8.5 DISCUSSION

The water monitoring and management programme described in this chapter was developed using only very limited information on the aquifer conditions and groundwater quality associated with the ring-dyke. Hydraulic information from pumping tests conducted on only a single borehole was available. The proposed monitoring and management programmes should therefore be updated when new information becomes available that sheds new light on the aquifer conditions and groundwater quality.

CHAPTER 9:
CONCLUSIONS AND RECOMMENDATIONS

The current study focussed on investigating the potential of using groundwater resources associated with a prominent dolerite ring-dyke underlying the city of Bloemfontein to augment the current water supply to the Mangaung Metro Municipality. To achieve this aim, the following objectives were:

- To detect and delineate the dolerite ring-dyke known to underlie the city of Bloemfontein.
- To investigate the association of the ring dyke with groundwater resources.
- To investigate the current use of groundwater from aquifers associated with the ring-dyke.
- To investigate the hydraulic properties of the aquifers to determine the quantities of water that can be sustainably abstracted from the aquifers.
- To investigate the quality of the groundwater associated with the ring-dyke to assess its suitability for human consumption and other municipal applications.
- To suggest water treatment options to render the groundwater suitable for its intended municipal use,
- To estimate and recommend the abstraction rate from the aquifers for sustainable use of the groundwater associated with the ring-dyke.
- To develop a monitoring programme for early detection of changes in the hydraulic heads and groundwater quality.
- To make recommendations for adaptive management practices to ensure the sustainable use of the groundwater resource associated with the ring-dyke.

Many challenges were encountered in addressing the stated objectives. Firstly, the geophysical surveys used to detect and delineate the dolerite structure were affected by the presence of surface and subsurface infrastructure in the form of metal objects and sources of electromagnetic radiation. Such sources of noise are ubiquitous in urban and industrial environments. Secondly, access to only a limited number of existing boreholes near the ring-dyke could be obtained. Although more boreholes are known to exist in the vicinity of the ring-dyke, the owners of the properties on which the boreholes occur would not allow access to the boreholes. Other boreholes could not be accessed due to the presence of infrastructure at surface.

A third challenge to the current investigations was the fact that, due to factors beyond the control of the researcher, no boreholes were drilled along the ring-dyke as was originally envisaged for the project. Furthermore, access could be obtained to only a single existing borehole near the ring-dyke to perform hydraulic tests. The estimates of the aquifer hydraulic parameters obtained from this borehole may therefore not be representative of the aquifer conditions at other positions along the ring-dyke. This lack of a comprehensive set of information on the aquifer hydraulic parameters made the estimation of a sustainable yield from the aquifer system impossible. Since the aquifer hydraulic parameters and sustainable yield need to be known with great certainty to effectively manage groundwater abstraction from the aquifer system, the proposed management programme is also at present limited by this lack of information.

Groundwater quality information was also only available for a small number of existing boreholes near the ring-dyke. Reliable conclusions regarding the quality of the groundwater in the aquifer system can at present not be made.

Despite the above limitations of the current investigations, the initial assessment of the aquifer system associated with the ring-dyke suggests that the aquifer system is high-yielding and that the groundwater quality ranges from good to ideal. The results of the investigation therefore suggest that groundwater associated with the ring-dyke could successfully be used to augment the municipal water supply. Depending on the quality of the groundwater, it may find different applications in the municipality, including: domestic water, irrigation, and industrial use. However, each of these applications comes with its own challenges in terms of monitoring, aquifer management, water treatment and infrastructural requirements. Monitoring and managing the water quality is of particular concern since a host of known and emerging contaminants may contribute to groundwater contamination in an urban and industrial environment.

Based on the results of the current investigations a number of future actions are recommended:

- The drilling programme that would have formed part of the current investigations should go ahead. Boreholes should be drilled on the positions sited from the results of the geophysical investigations.
- Hydraulic test should be performed on all the newly-drilled boreholes to assess the hydraulic properties of the aquifer system and to estimate the sustainable abstraction rate. The mutual influence of all the abstraction boreholes should be taken into account when estimating the sustainable yield.
- Groundwater sampling should be done from all the newly-drilled boreholes to expand the water quality dataset.

- An industry census should be conducted with the Bloemfontein CBD to create a database of the industries and the potential contaminants originating from each industry. A database containing the census data should be created. This database should be updated on at least an annual basis.
- Groundwater analyses should be performed on all the samples collected from the newly-drilled and existing boreholes. The analyses should include analyses for those potential contaminants identified during the industry census.
- Contaminant fingerprinting should be done on the groundwater samples. During fingerprinting, comprehensive analyses should be done to detect any contaminants not identified during the industry census. Analyses for these contaminants should also be included in future water quality assessments.
- The monitoring and management programmes proposed in the current investigations should be updated if and when new information becomes available that allows different insights into the aquifer conditions and groundwater quality.

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ABSTRACT

This study investigates the potential of using groundwater resources associated with an intrusive dolerite ring-dyke underlying the central business district (CBD) of Bloemfontein to augment the current water supply to the Mangaung Metro Municipality (MMM). The current water supply to the municipality is wholly dependent on surface water sources, which have proved to be unreliable and insufficient to meet the increasing water demand in the municipality.

During the investigations, ground geophysical methods were used to detect and delineate the ring-dyke in areas within the CBD where the surface infrastructure allowed the geophysical surveys. The magnetic and electrical resistivity (ERT) methods were used during the surveys. The magnetic method is sensitive to both the presence of metallic infrastructure at surface or in the shallow subsurface and to the presence of electromagnetic noise generated where electrical currents flow. Since urban and industrial environments are characterised by such sources of noise, the magnetic survey was severely restricted in terms of the locations available for the recording of reliable data. The ERT survey, in turn, was severely restricted in terms of the space available within the CBD, as well as the presence of hard surface covering (roads, pavements, concrete slabs) prohibiting the installation of electrodes into the ground. Despite these limitations, the geophysical surveys were successful in detecting the presence of the ring-dyke at certain positions within the CBD.

Based on the results of the geophysical investigations, positions for the drilling of investigative and production boreholes were proposed. The drilling of these boreholes was to form part of the current investigations, but due to factors beyond the control of the researcher, these boreholes are yet to be drilled. These boreholes would have allowed the researcher access to the aquifers system associated with the ring-dyke in order to perform hydraulic tests and assess the groundwater quality. The fact that these boreholes were not drilled in time should be seen as a significant limitation of the current study.

A limited hydrocensus was conducted in the vicinity of the ring-dyke. The purpose of the hydrocensus was to locate points of groundwater abstraction near the ring-dyke in order to obtain information on the use and quality of the groundwater, as well as to investigate the aquifer system(s) hosting the groundwater. During the hydrocensus, several boreholes were located within 300 m from the ring-dyke. Of these boreholes, access to only three could be obtained as the owner of the properties on which the remaining boreholes were located would not allow access to these boreholes. The hydrocensus revealed that the boreholes near the ring-dyke are currently mostly used for irrigation.

No hydraulic tests could be performed on the boreholes identified during the hydrocensus due to the presence of infrastructure. Hydraulic tests were, however, performed on a single borehole located on

the premises of the Central University of Technology (CUT). Analyses of the results of the hydraulic tests indicated transmissivity values in the order of hundreds of metres squared per day, indicating that the aquifer system associated with the ring-dyke can be expected to be high-yielding.

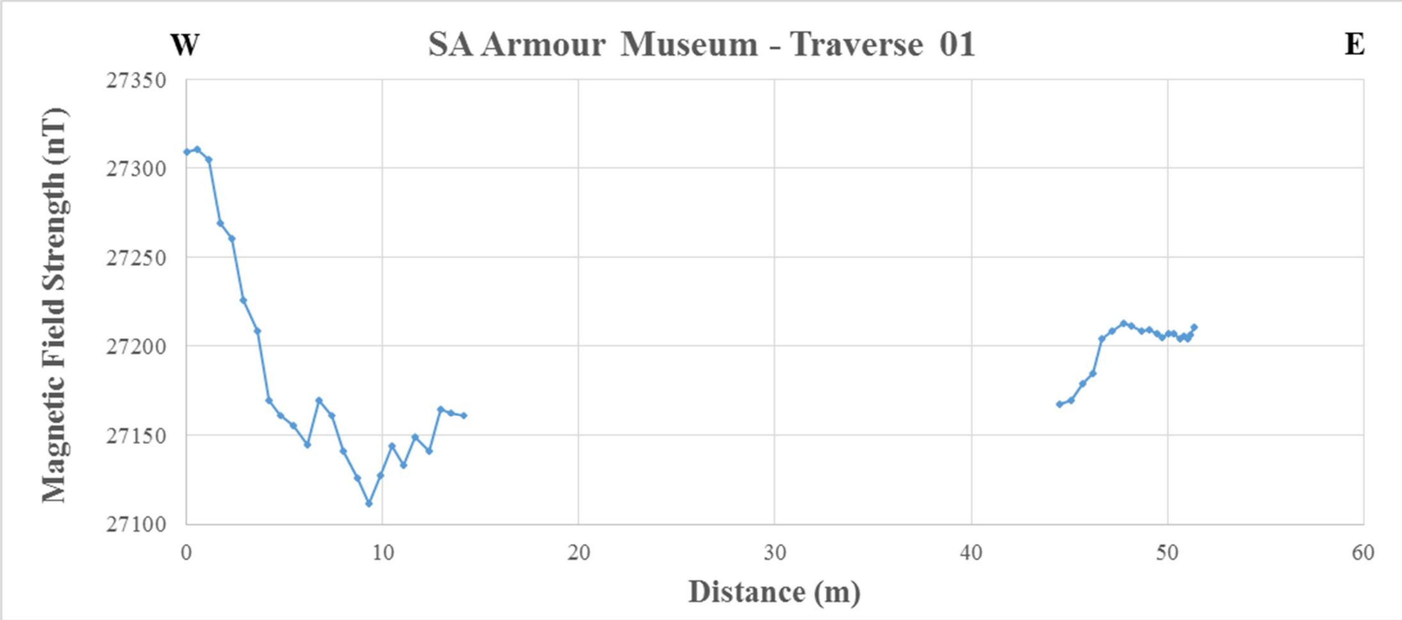
Hydrochemical analyses of the groundwater samples collected from the boreholes identified during the hydrocensus showed that the groundwater quality ranges from good to ideal. No clear evidence for contamination was visible in the results of the inorganic analyses. The good quality of the groundwater suggests that it can be incorporated into the municipal water supply without requiring too much treatment. However, the investigations into the groundwater quality did not consider hydrocarbon or bacteriological contamination of the groundwater. No conclusions can therefore be drawn on the groundwater quality in terms of possible organic and bacteriological contaminants.

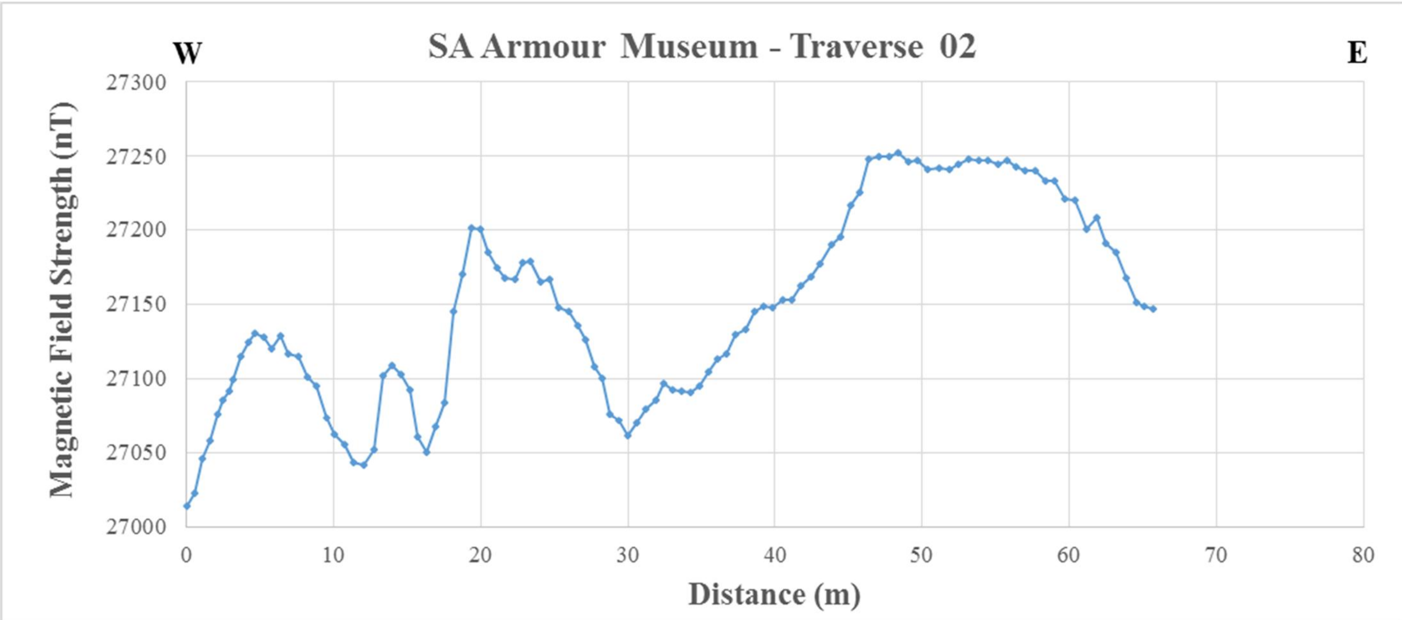
The results of the investigations indicate that that groundwater associated with the ring-dyke could successfully be used to augment the municipal water supply. Depending on the quality of the groundwater, it may find different applications in the municipality, including: domestic water, irrigation, and industrial use. However, each of these applications has its own challenges in terms of monitoring, aquifer management, water treatment and infrastructural requirements. To ensure the safe and sustainable use of the groundwater resource, a groundwater monitoring and management programme should be implemented. Such a programme will aim to ensure that the volumes of groundwater abstracted do not exceed the long-term capacity of the aquifer system to deliver water, while ensuring that the quality of the water delivered to the municipal supply system is of a suitable quality for the its intended purpose. Routine monitoring of the water quality should be done to detect possible contamination with organic compounds and bacteria, as well as industry-specific contaminants.

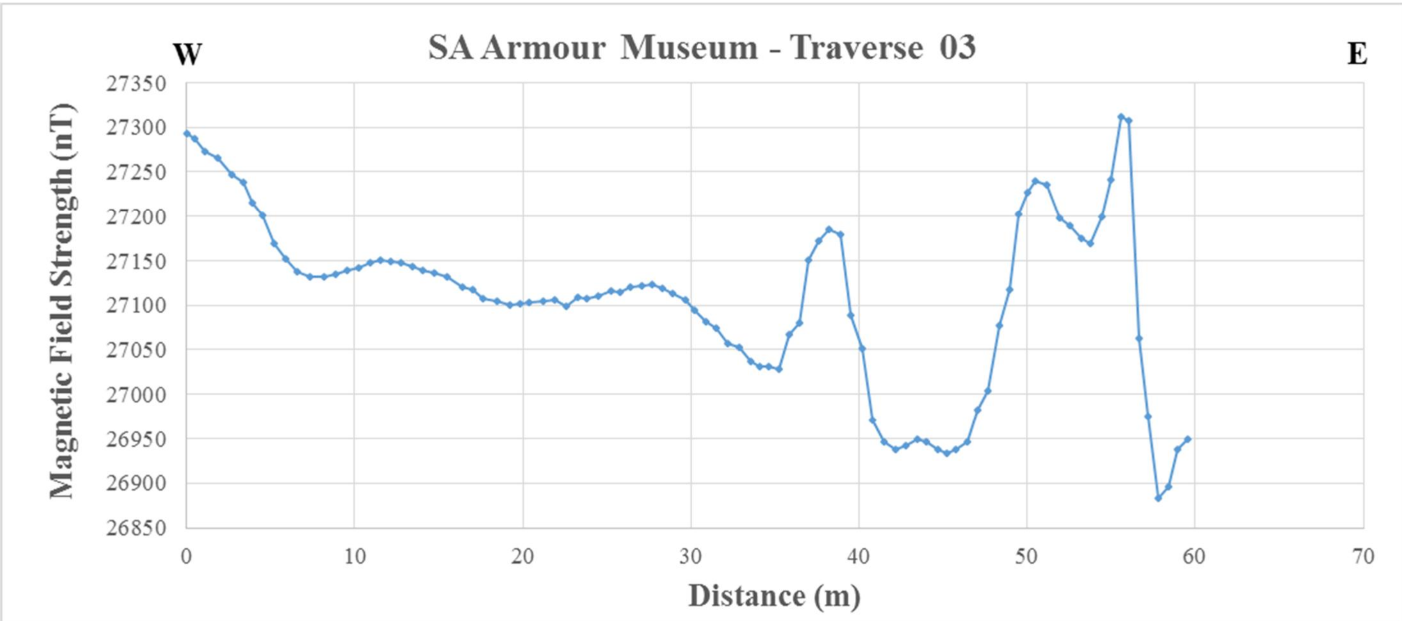
APPENDIX A

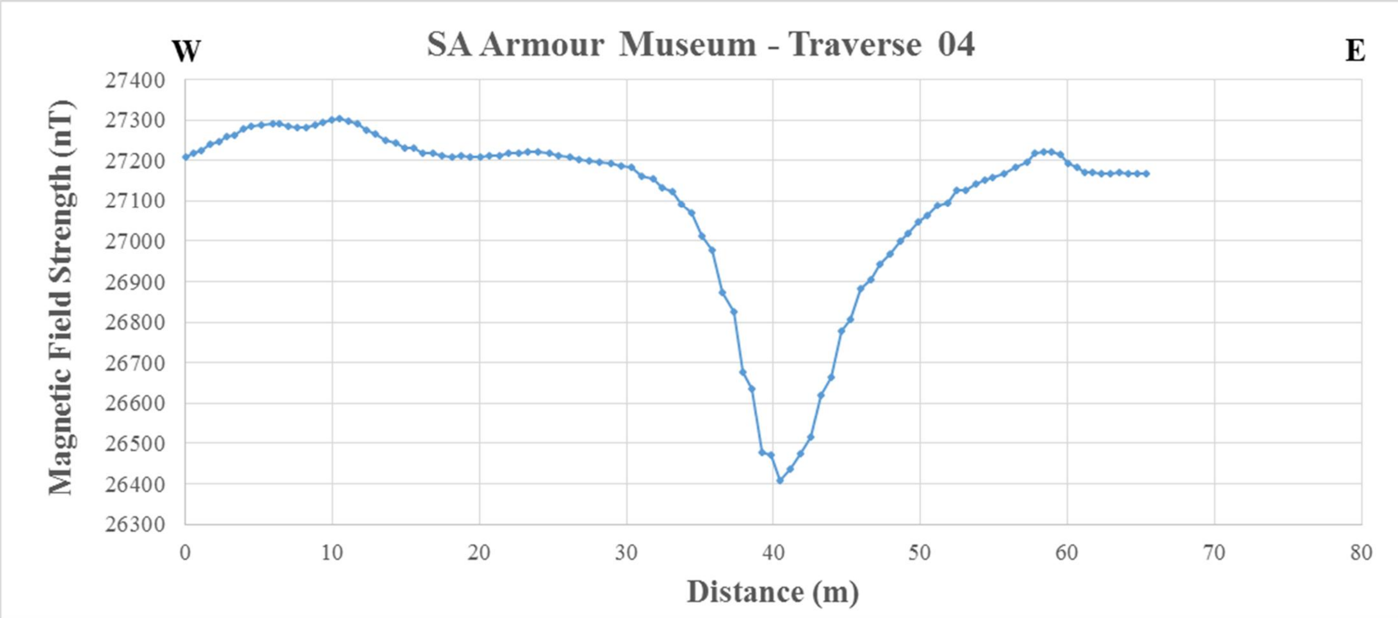
Magnetic Data

SA Armour Museum

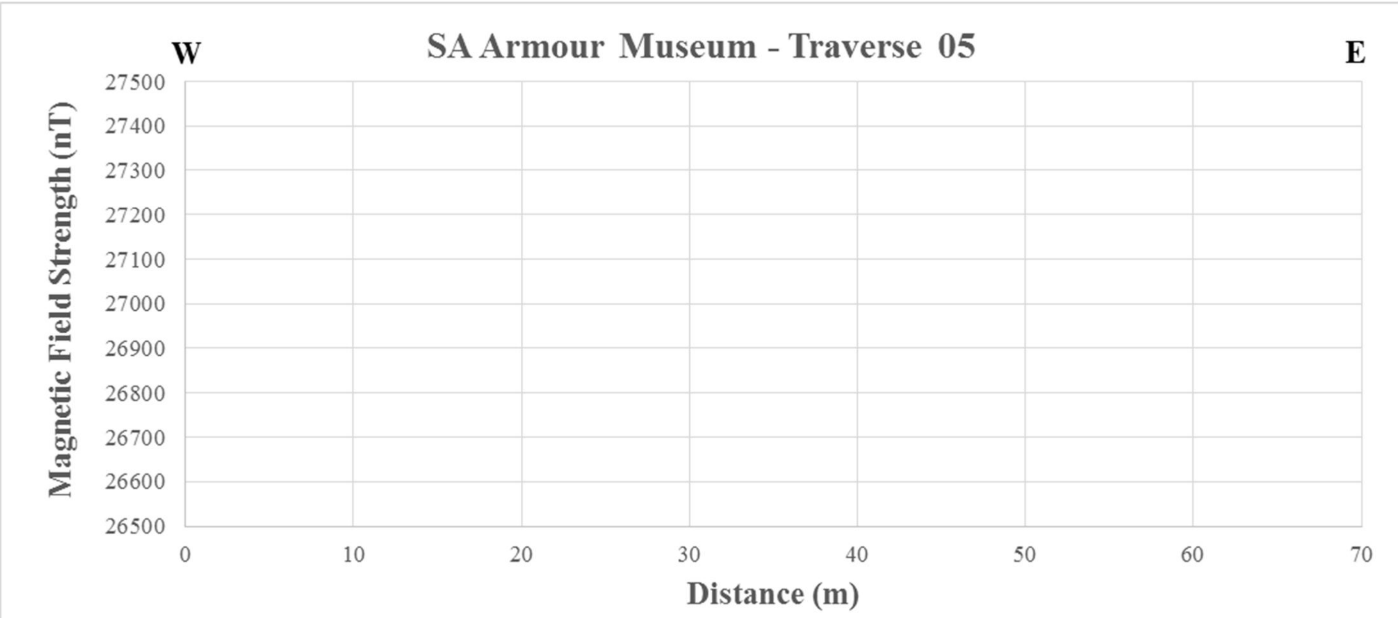




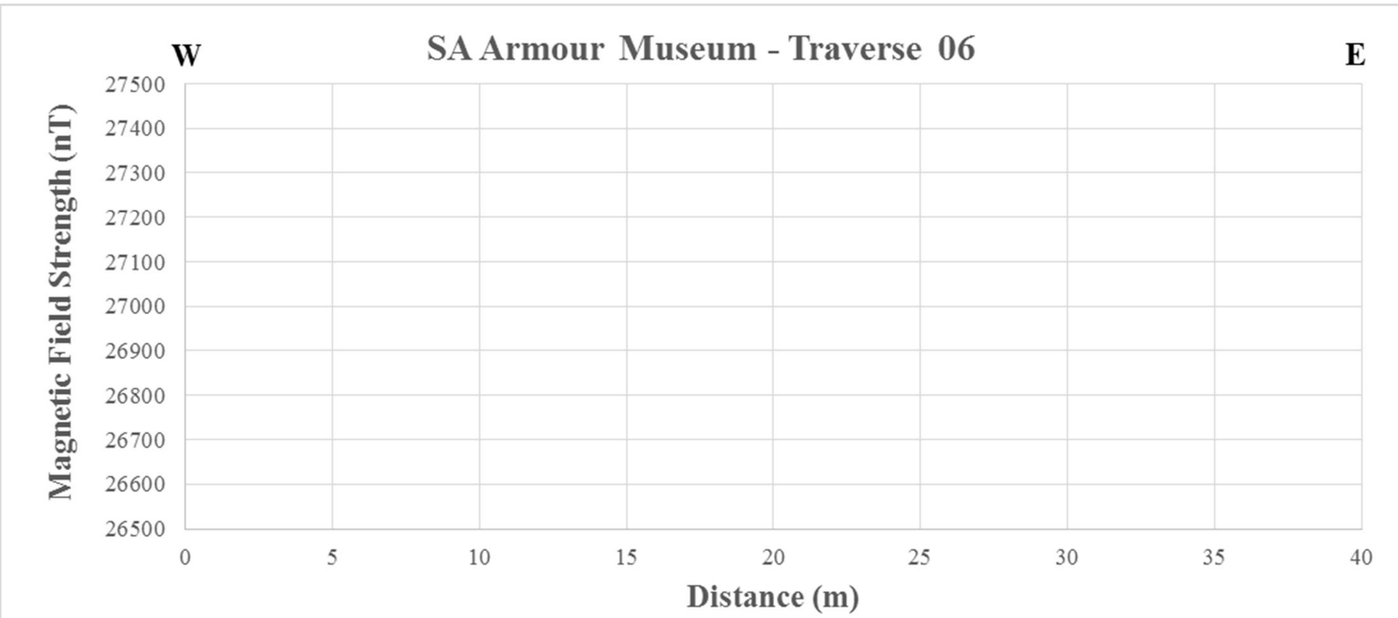




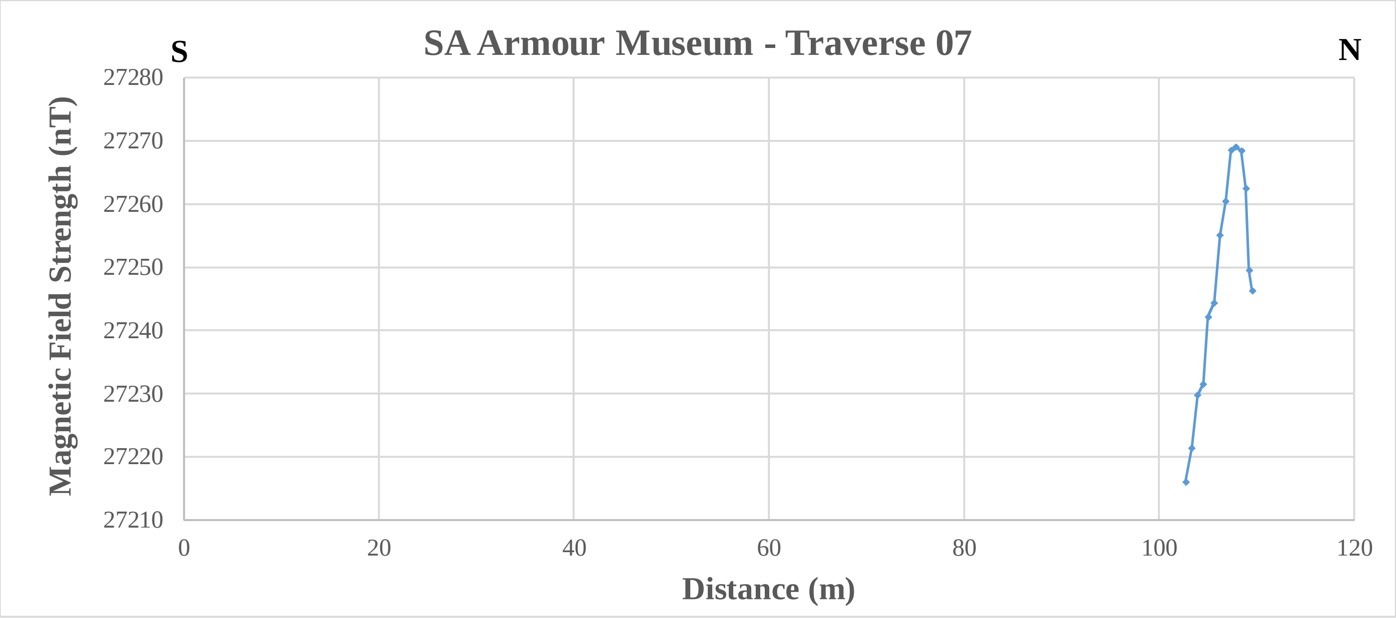
SA Armour Museum - Traverse 04
W
E
Magnetic Field Strength (nT)
27400
27300
27200
27100
27000
26900
26800
26700
26600
26500
26400
26300
0
10
20
30
40
50
60
70
80
Distance (m)



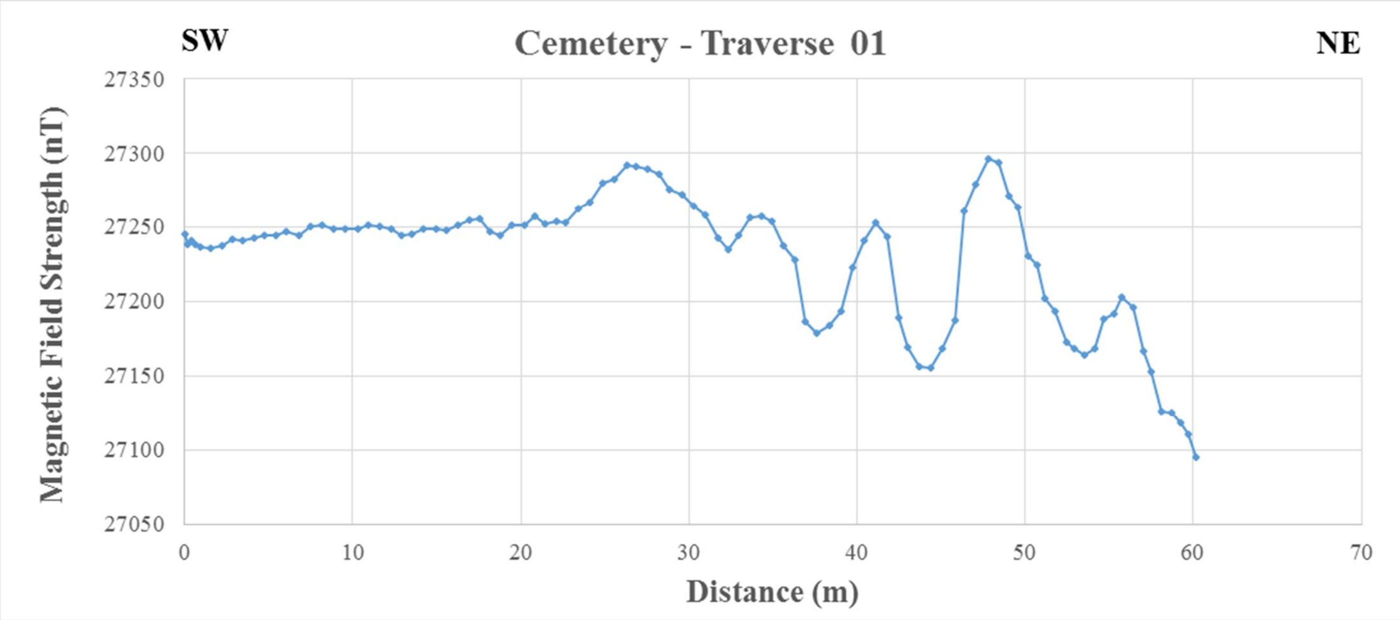
SA Armour Museum - Traverse 05
W
E
Magnetic Field Strength (nT)
27500
27400
27300
27200
27100
27000
26900
26800
26700
26600
26500
0
10
20
30
40
50
60
70
Distance (m)

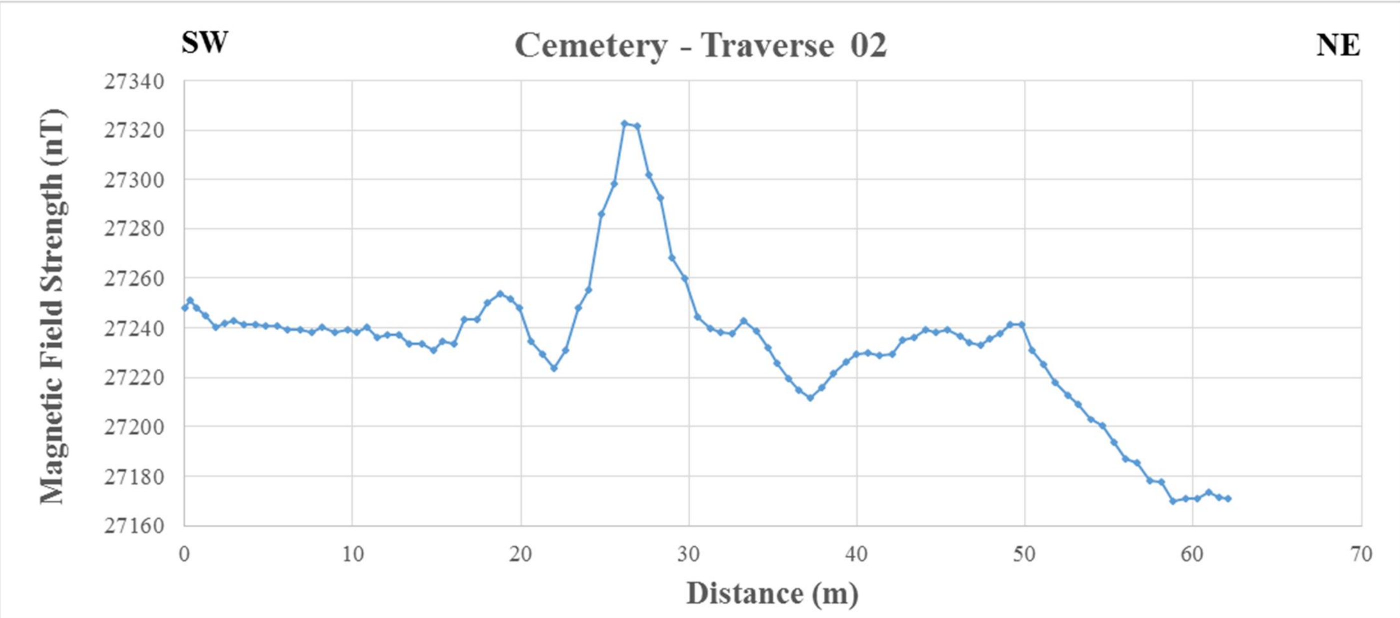


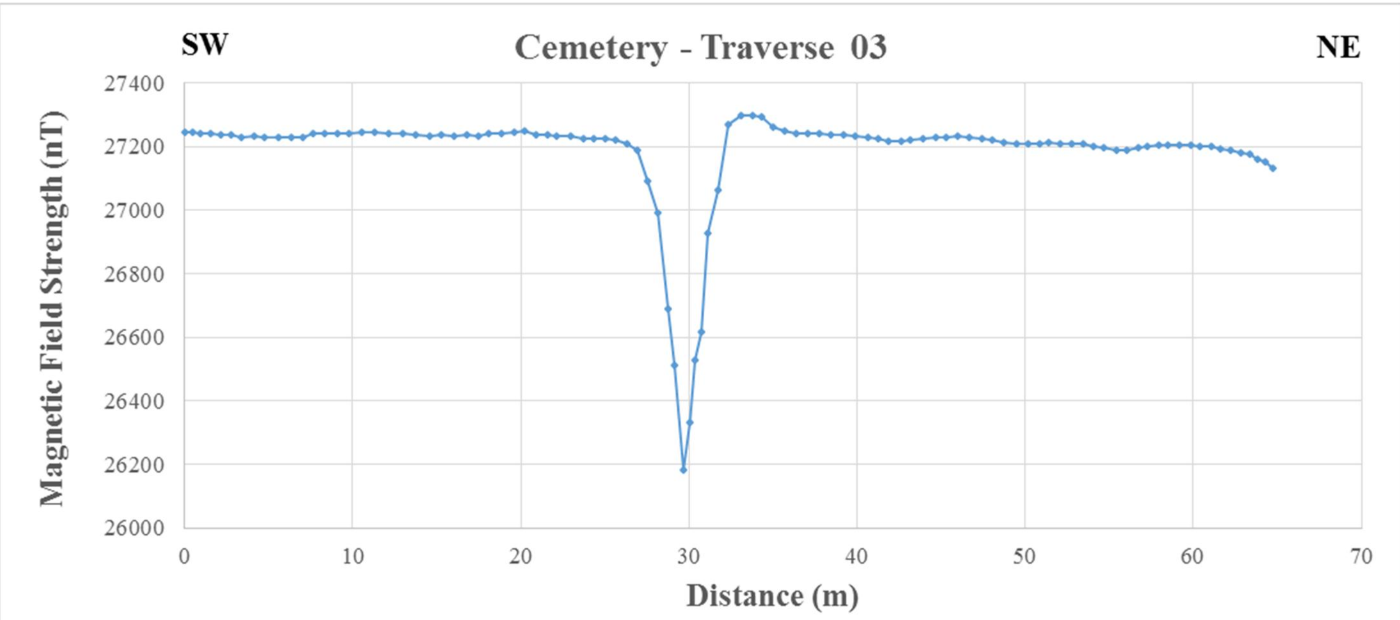
SA Armour Museum - Traverse 06
W
E
Magnetic Field Strength (nT)
27500
27400
27300
27200
27100
27000
26900
26800
26700
26600
26500
0
5
10
15
20
25
30
35
40
Distance (m)

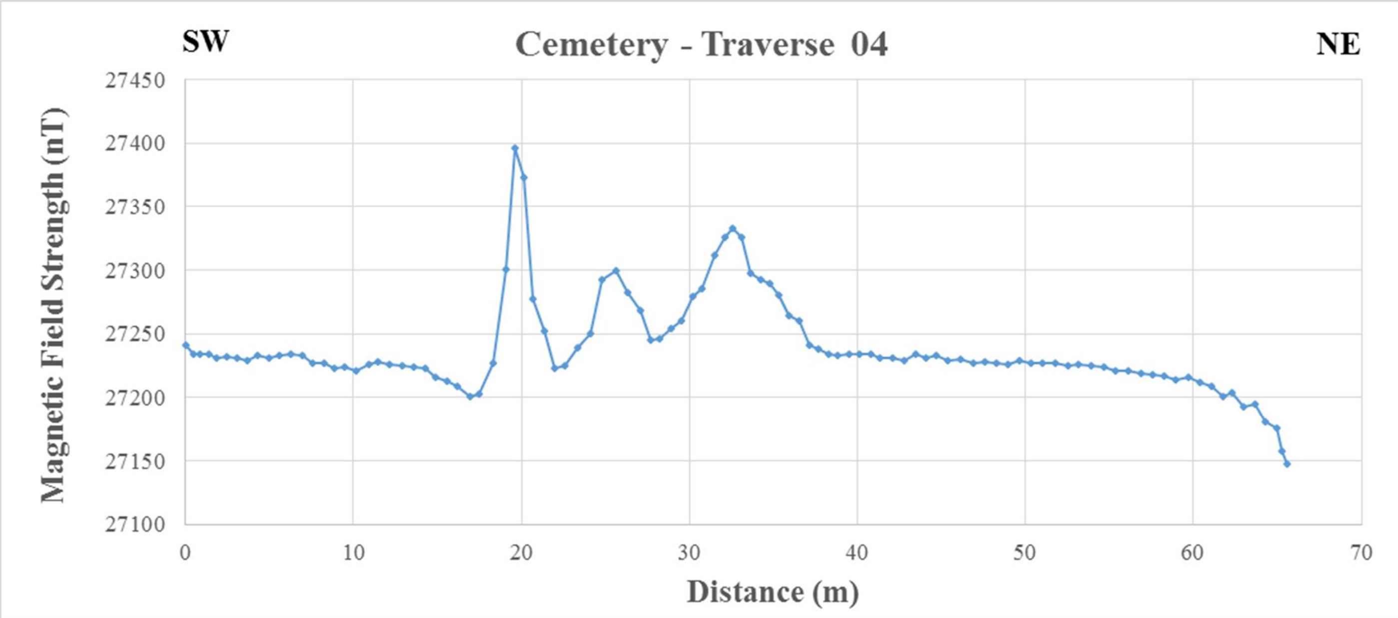

SA Armour Museum - Traverse 07
S
N
Magnetic Field Strength (nT)
27280
27270
27260
27250
27240
27230
27220
27210
0
20
40
60
80
100
120
Distance (m)

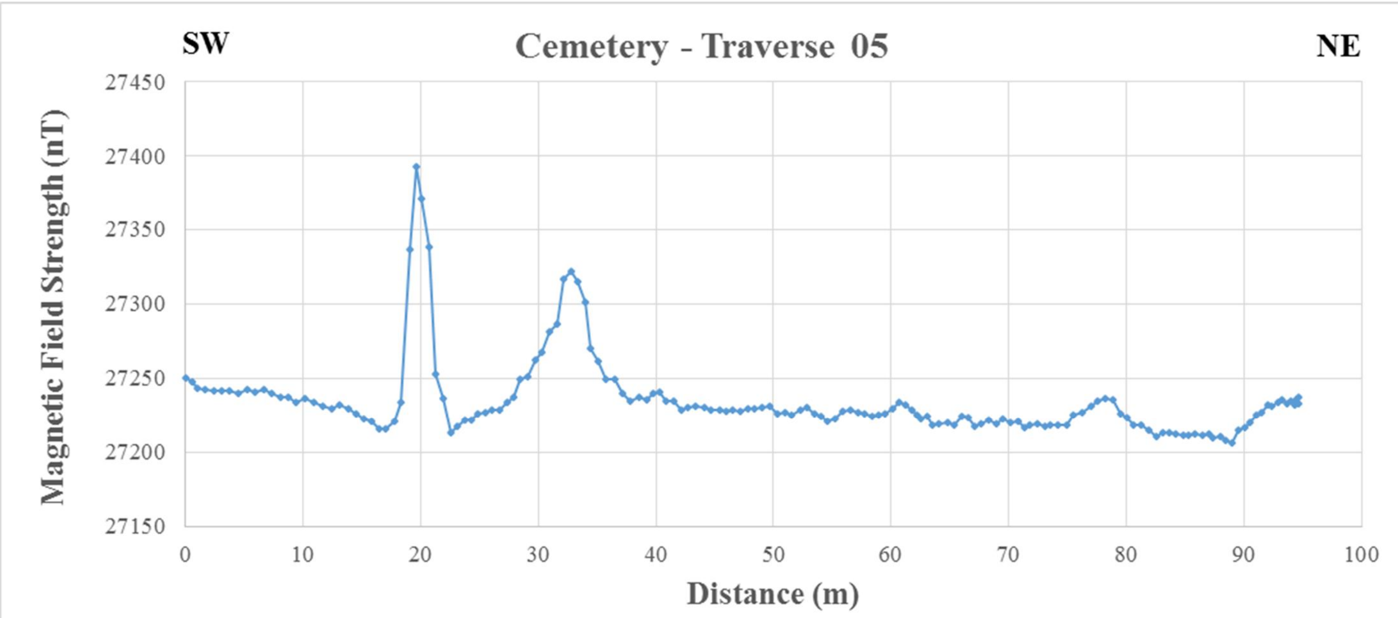
Cemetery

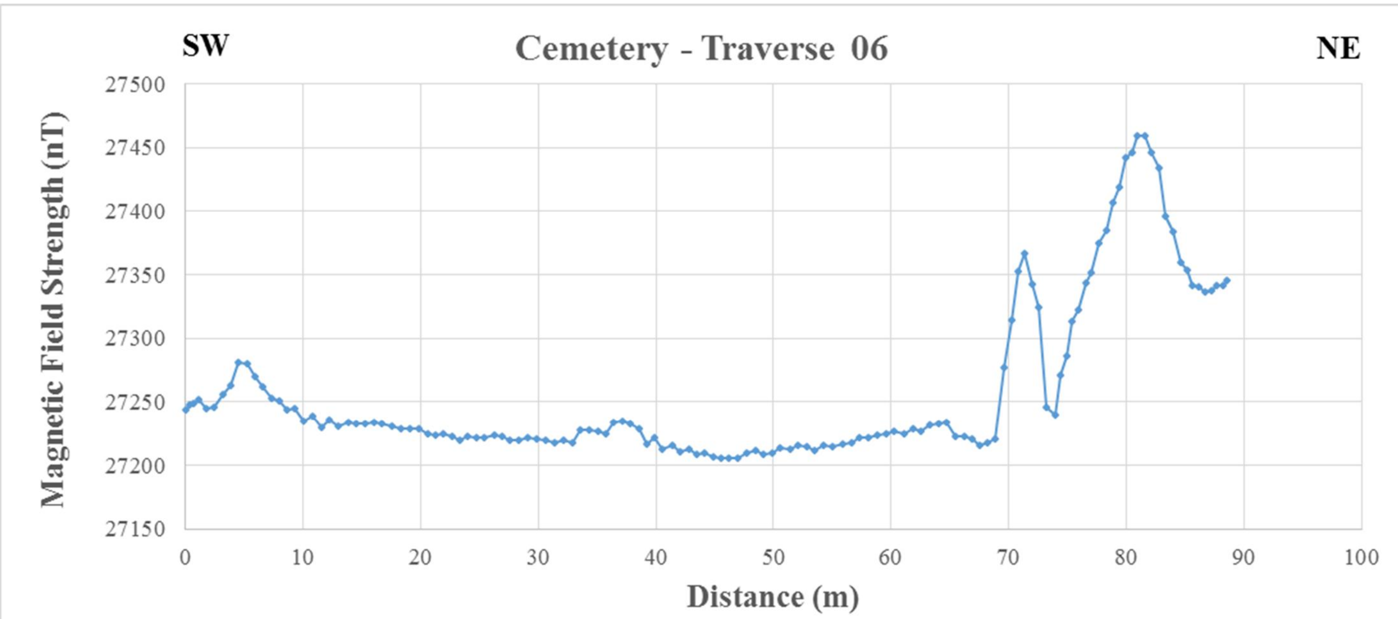

SW
Cemetery - Traverse 01
NE
Magnetic Field Strength (nT)
27350
27300
27250
27200
27150
27100
27050
0
10
20
30
40
50
60
70
Distance (m)


SW
Cemetery - Traverse 02
NE
Magnetic Field Strength (nT)
27340
27320
27300
27280
27260
27240
27220
27200
27180
27160
0
10
20
30
40
50
60
70
Distance (m)

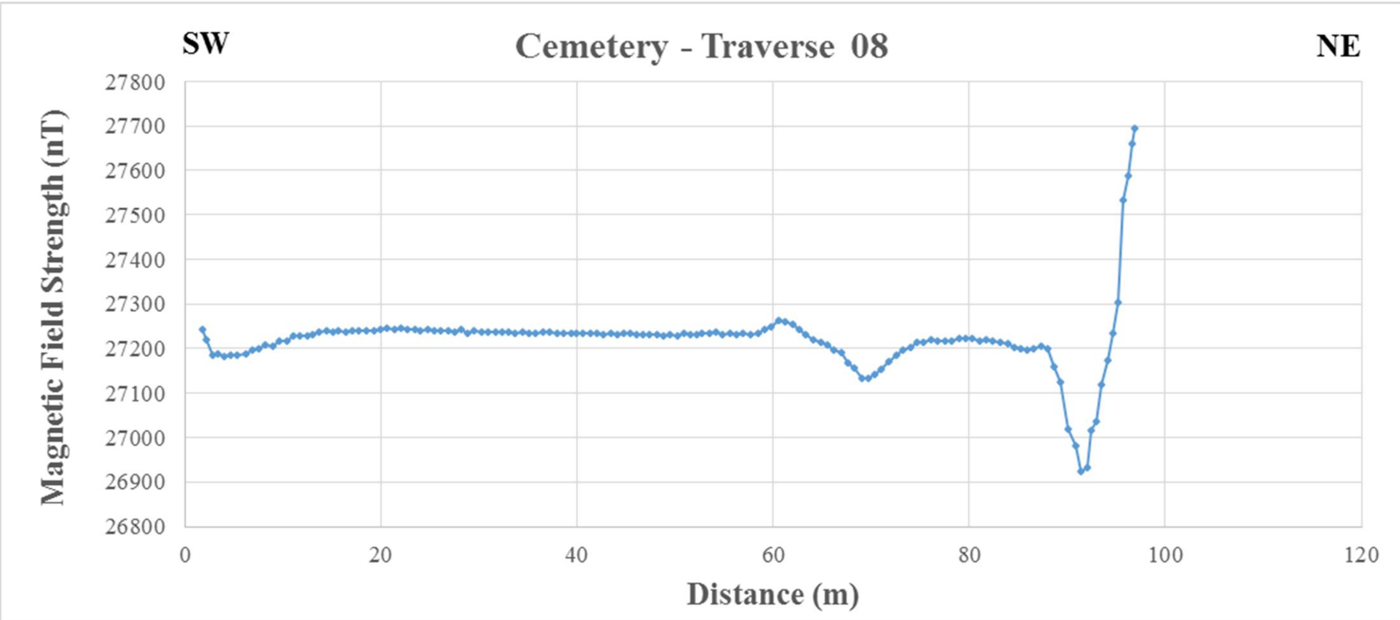

SW
Cemetery - Traverse 03
NE
Magnetic Field Strength (nT)
27400
27200
27000
26800
26600
26400
26200
26000
0
10
20
30
40
50
60
70
Distance (m)

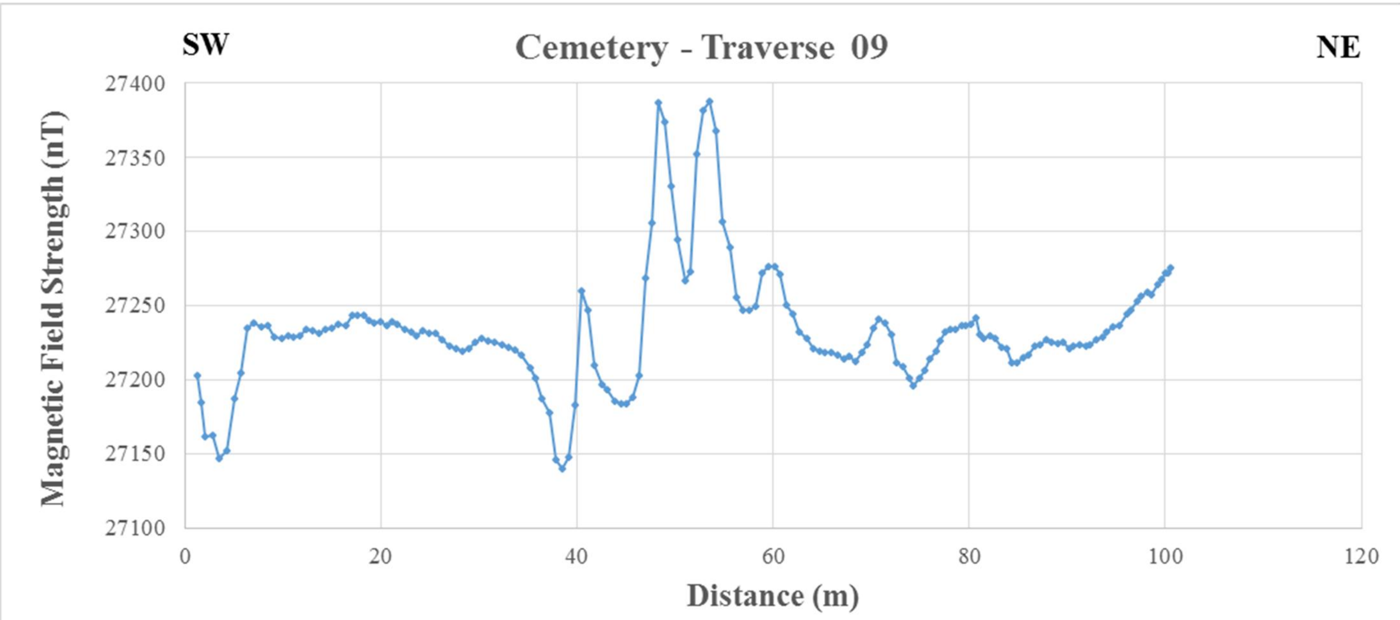

SW
Cemetery - Traverse 04
NE
Magnetic Field Strength (nT)
27450
27400
27350
27300
27250
27200
27150
27100
0
10
20
30
40
50
60
70
Distance (m)

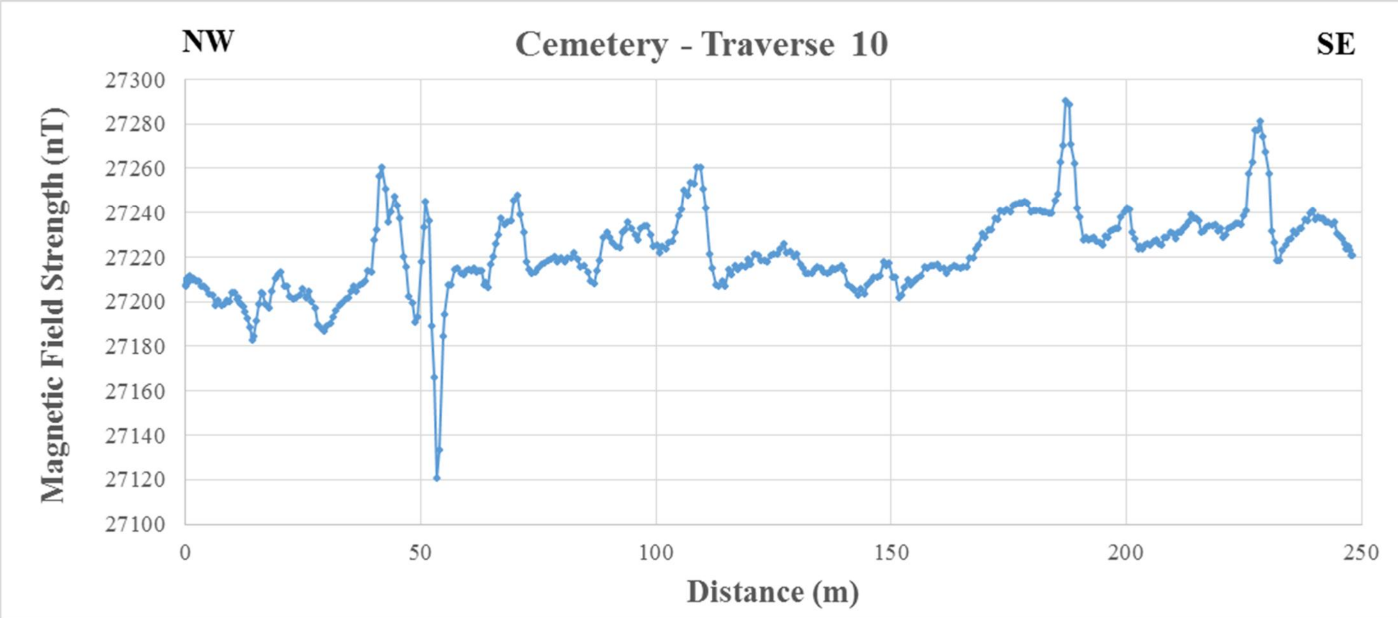

SW
Cemetery - Traverse 05
NE
Magnetic Field Strength (nT)
27450
27400
27350
27300
27250
27200
27150
0
10
20
30
40
50
60
70
80
90
100
Distance (m)


SW
Cemetery - Traverse 06
NE
Magnetic Field Strength (nT)
27500
27450
27400
27350
27300
27250
27200
27150
0
10
20
30
40
50
60
70
80
90
100
Distance (m)

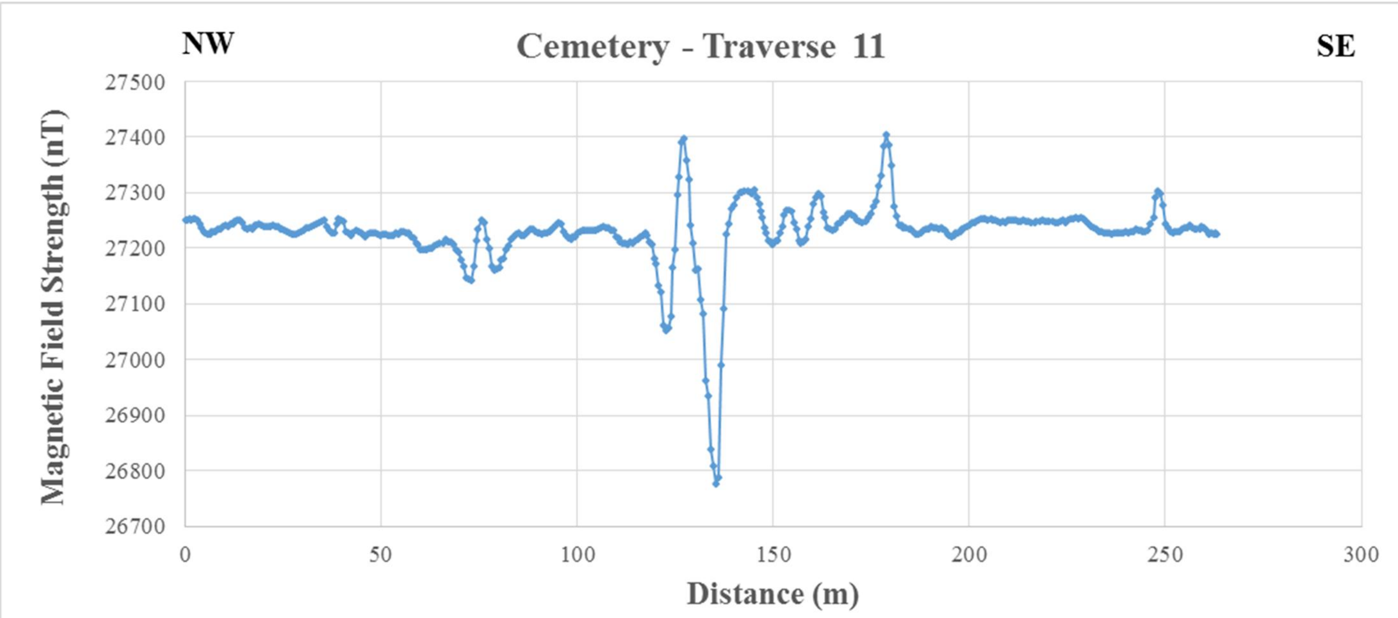

SW
Cemetery - Traverse 07
NE
Magnetic Field Strength (nT)
27450
27400
27350
27300
27250
27200
27150
27100
27050
0
20
40
60
80
100
120
Distance (m)


SW
Cemetery - Traverse 08
NE
Magnetic Field Strength (nT)
27800
27700
27600
27500
27400
27300
27200
27100
27000
26900
26800
0
20
40
60
80
100
120
Distance (m)


SW
Cemetery - Traverse 09
NE
Magnetic Field Strength (nT)
27400
27350
27300
27250
27200
27150
27100
0
20
40
60
80
100
120
Distance (m)

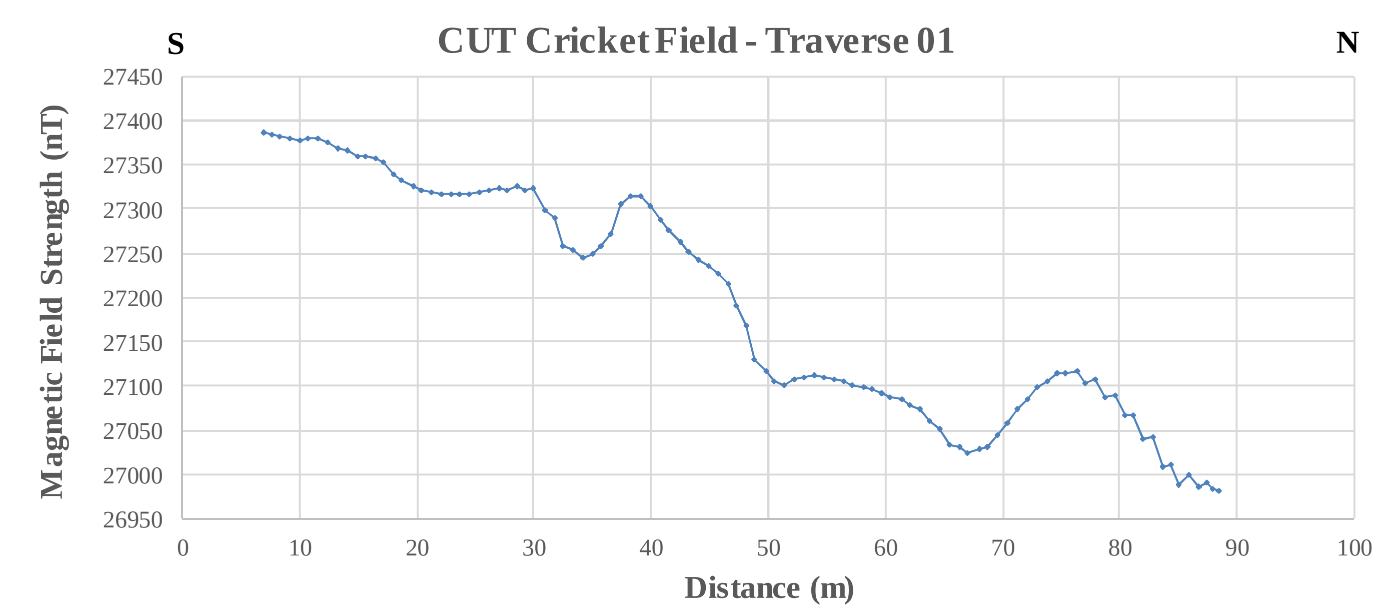


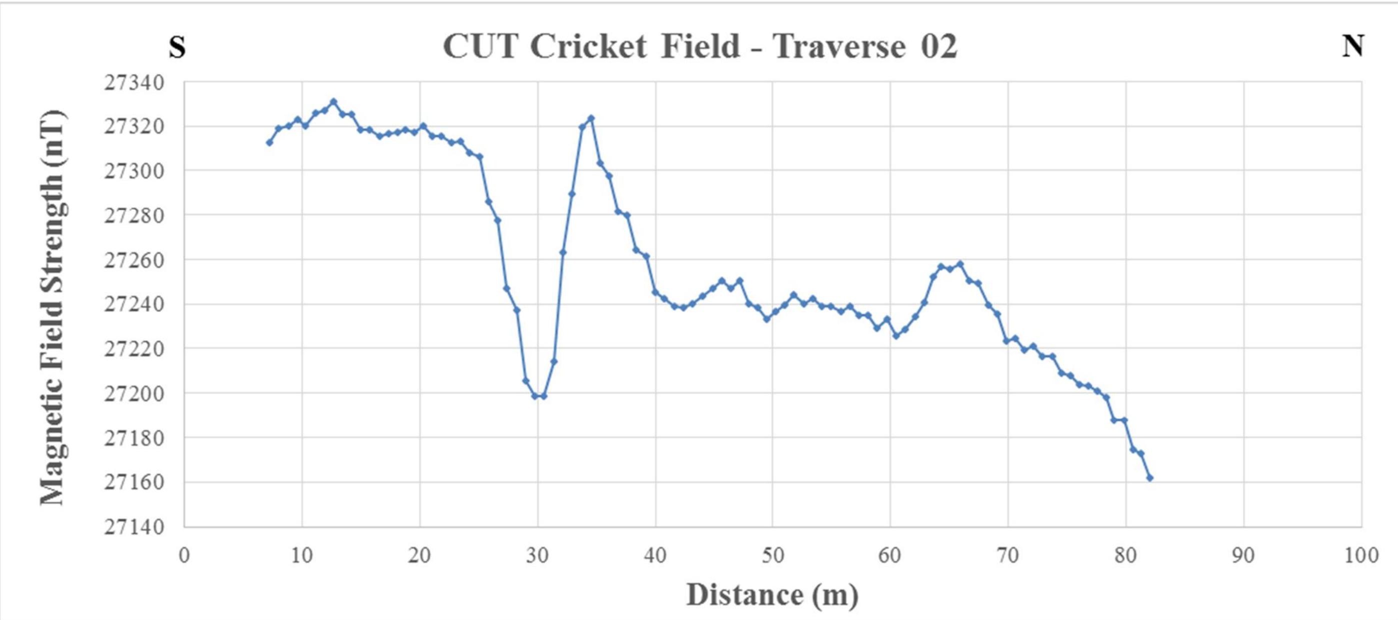
NW
Cemetery - Traverse 10
SE
Magnetic Field Strength (nT)
27300
27280
27260
27240
27220
27200
27180
27160
27140
27120
27100
0
50
100
150
200
250
Distance (m)

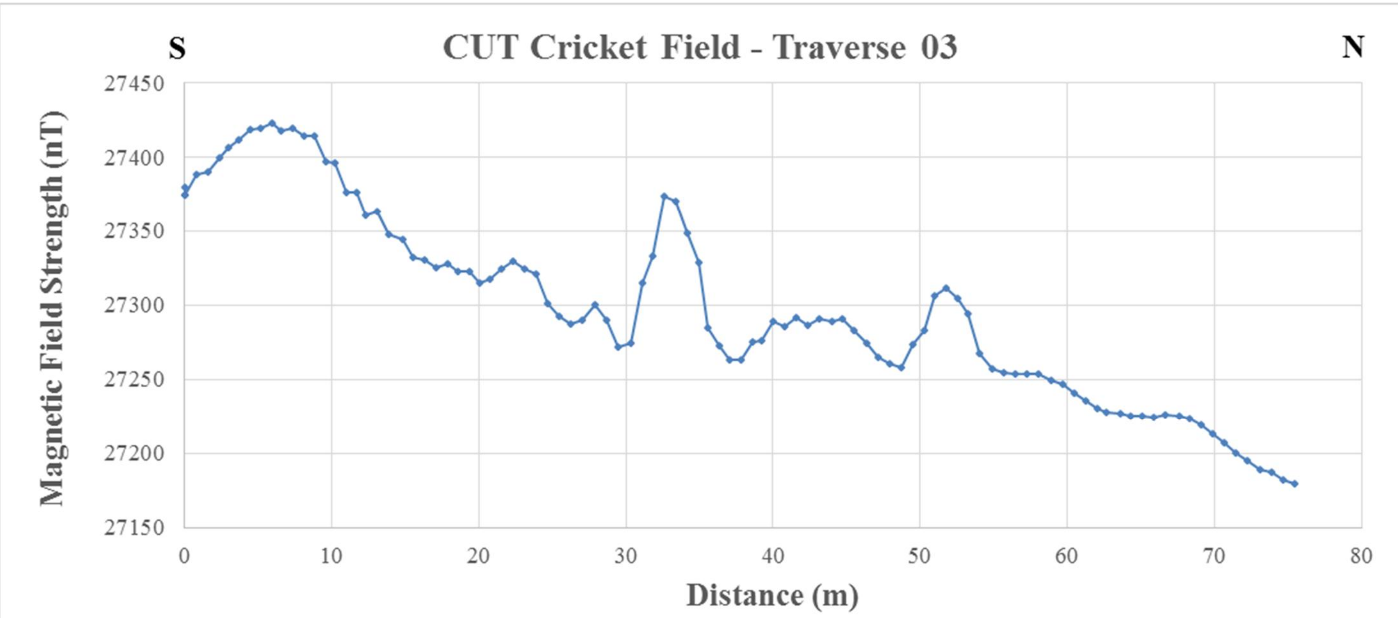


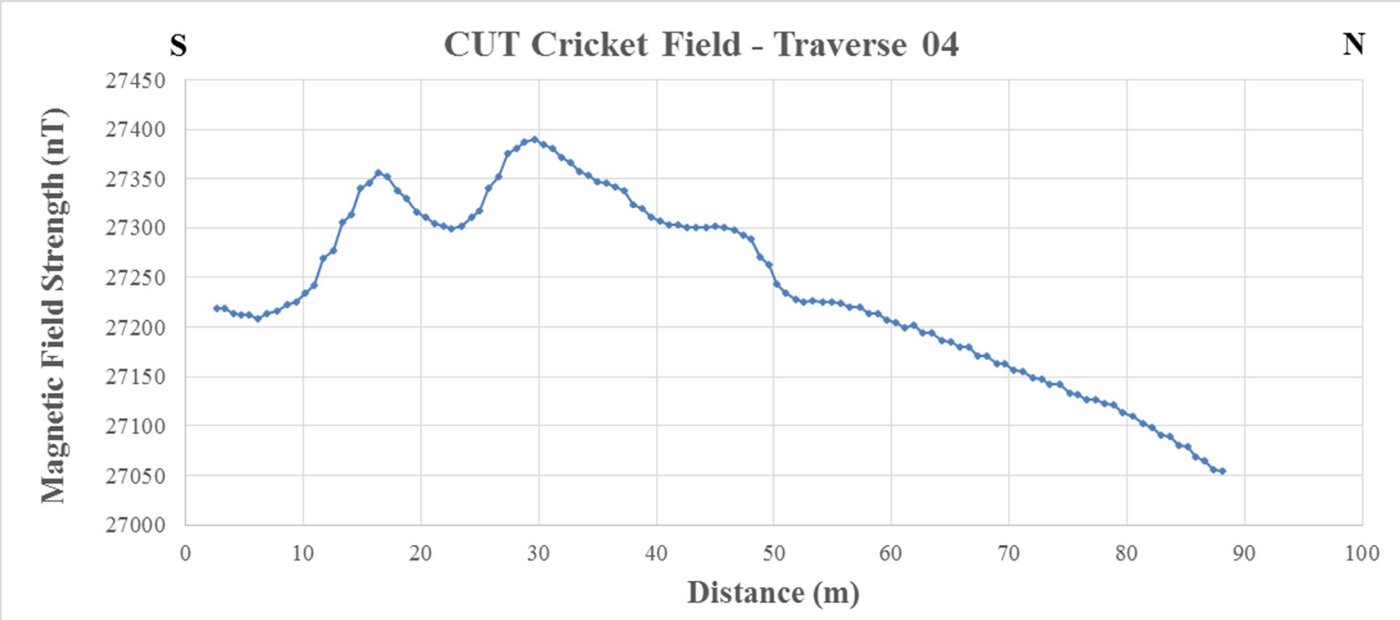
NW
Cemetery - Traverse 11
SE
Magnetic Field Strength (nT)
27500
27400
27300
27200
27100
27000
26900
26800
26700
0
50
100
150
200
250
300
Distance (m)

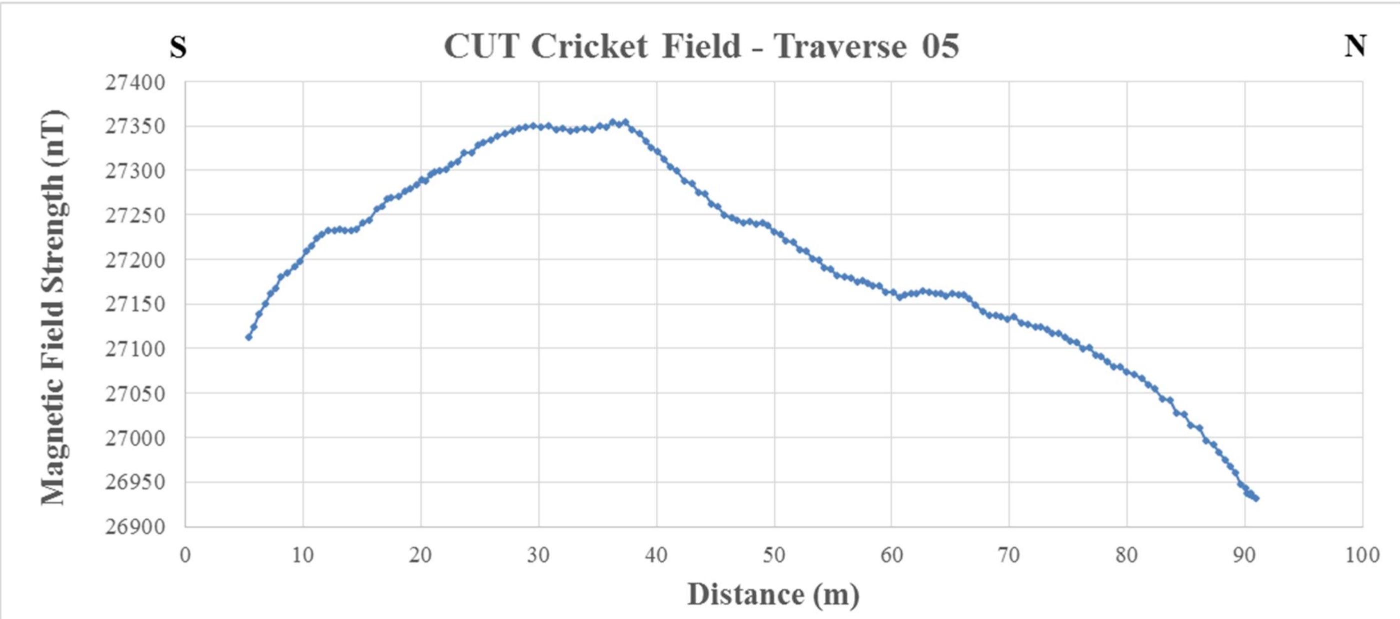
CUT – Cricket Field

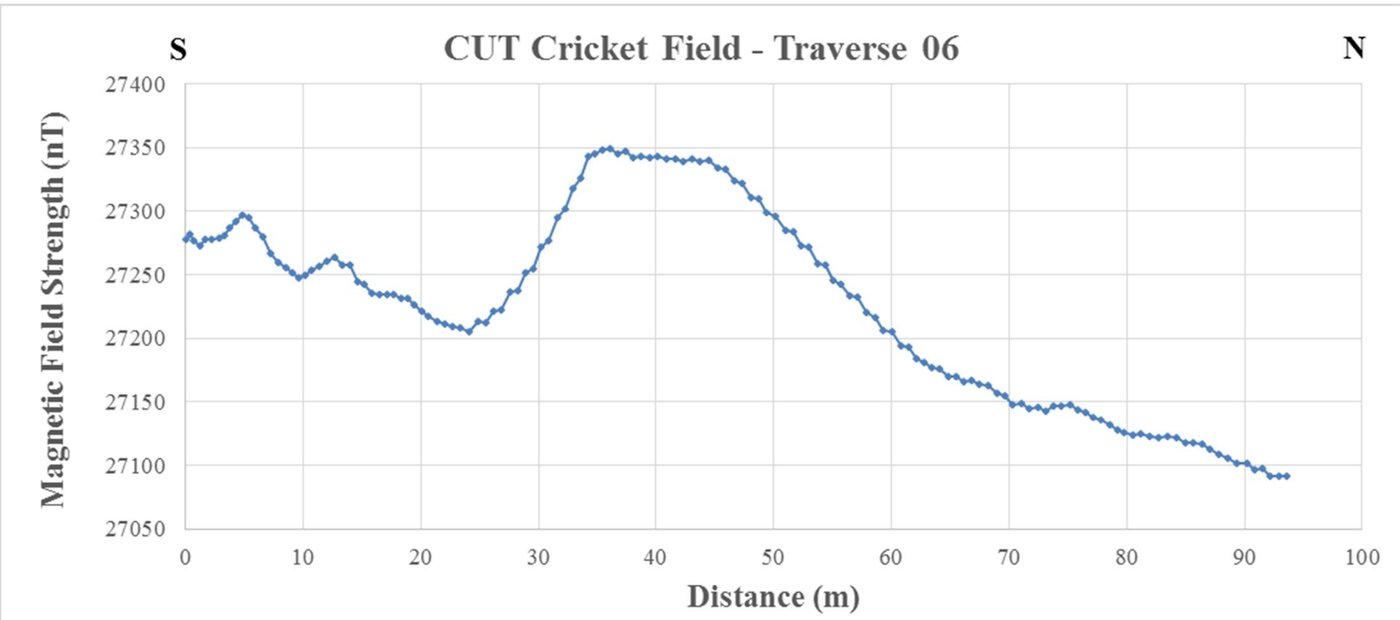


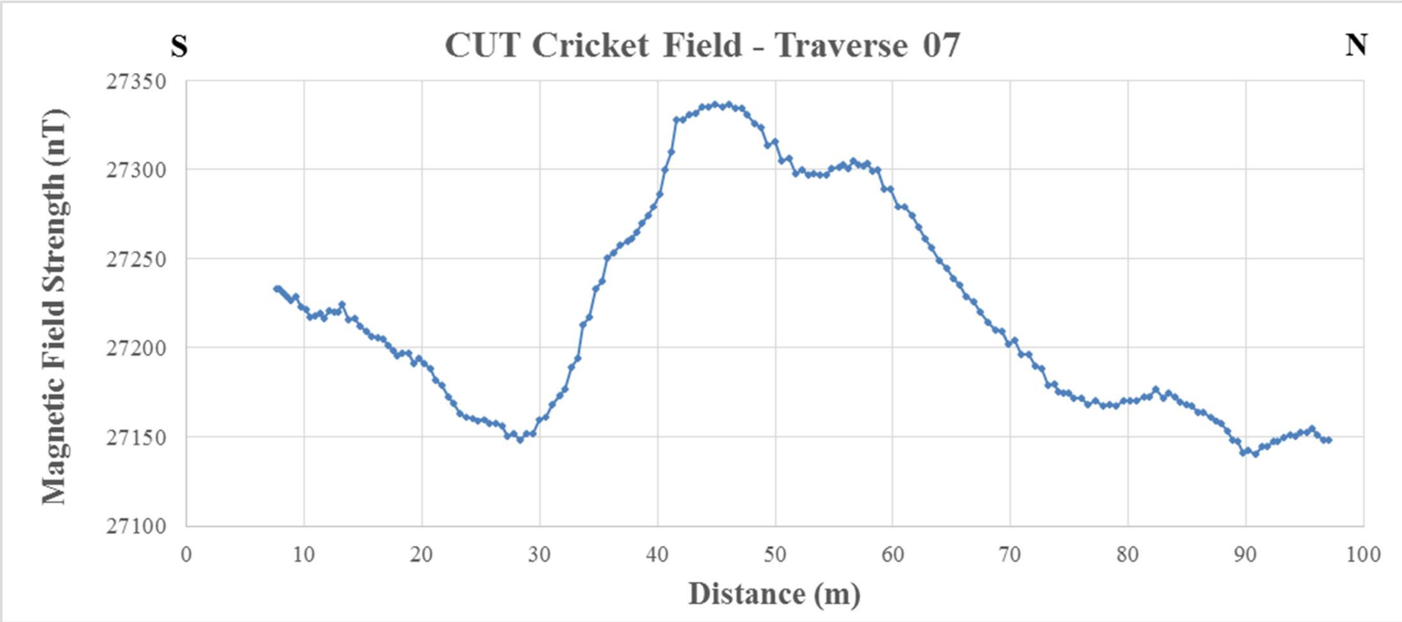


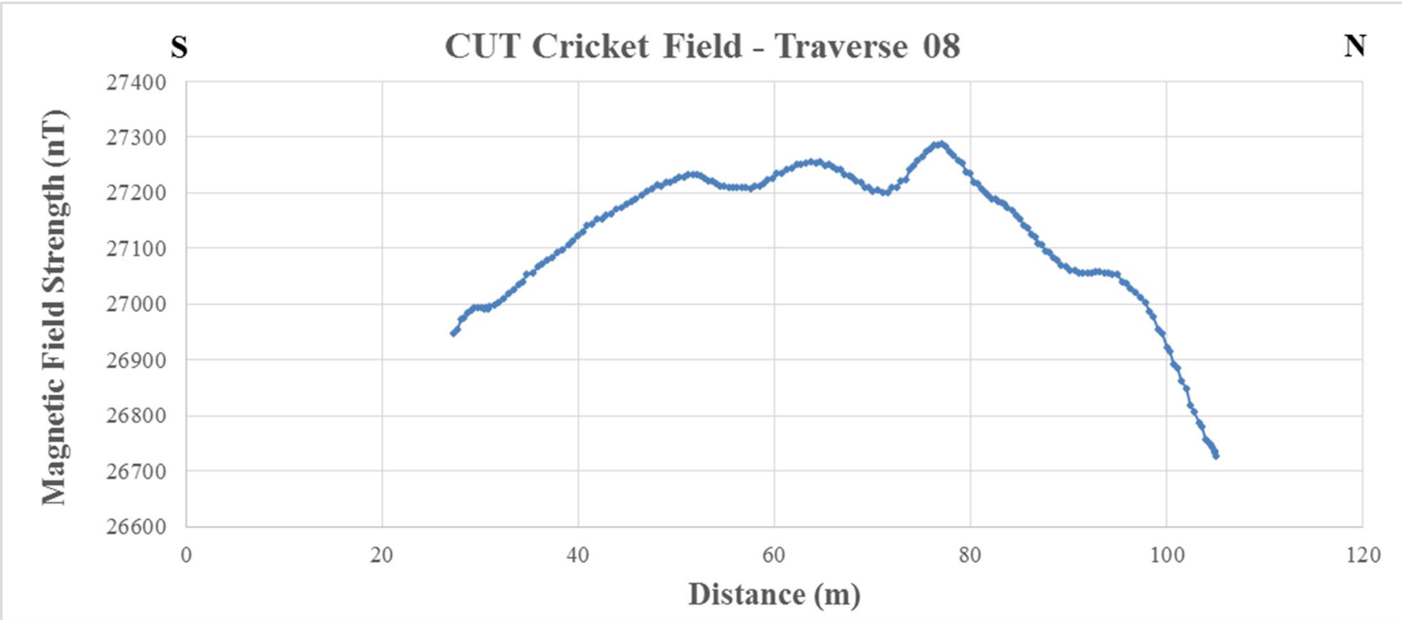


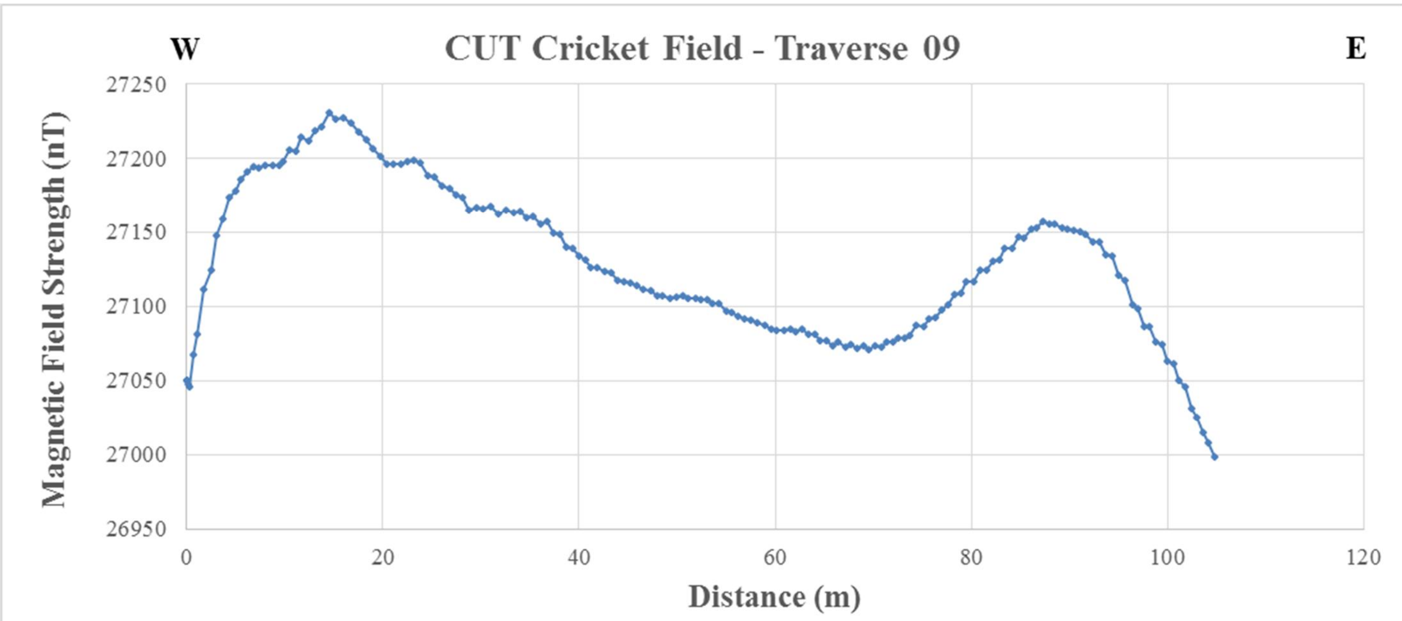

S
CUT Cricket Field - Traverse 04
N
Magnetic Field Strength (nT)
Distance (m)

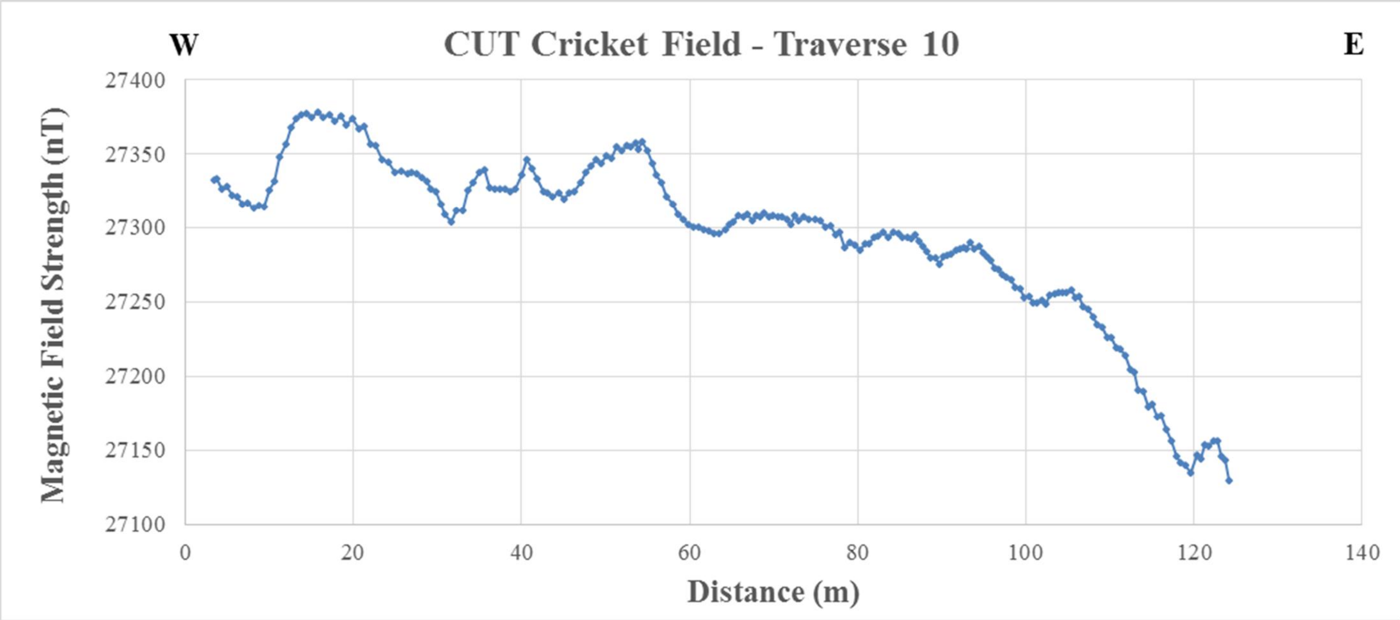

S
CUT Cricket Field - Traverse 05
N
Magnetic Field Strength (nT)
Distance (m)


S
CUT Cricket Field - Traverse 06
N
Magnetic Field Strength (nT)
Distance (m)

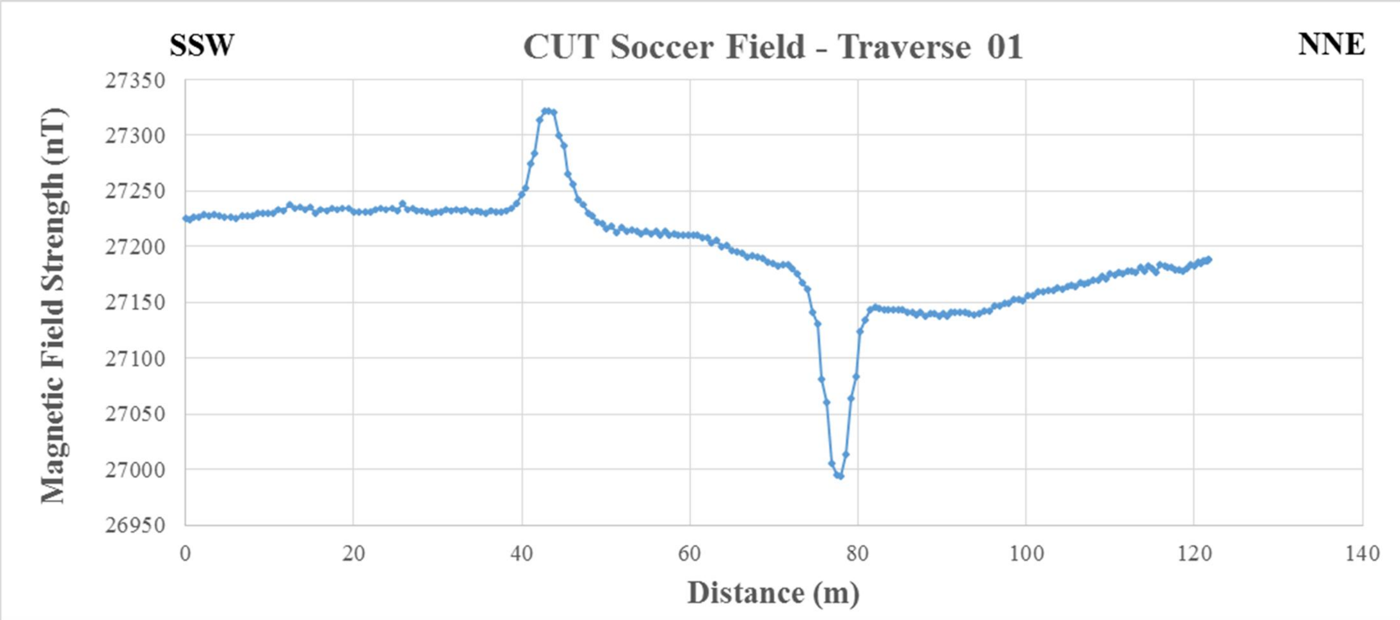

S
CUT Cricket Field - Traverse 07
N
Magnetic Field Strength (nT)
27350
27300
27250
27200
27150
27100
0
10
20
30
40
50
60
70
80
90
100
Distance (m)

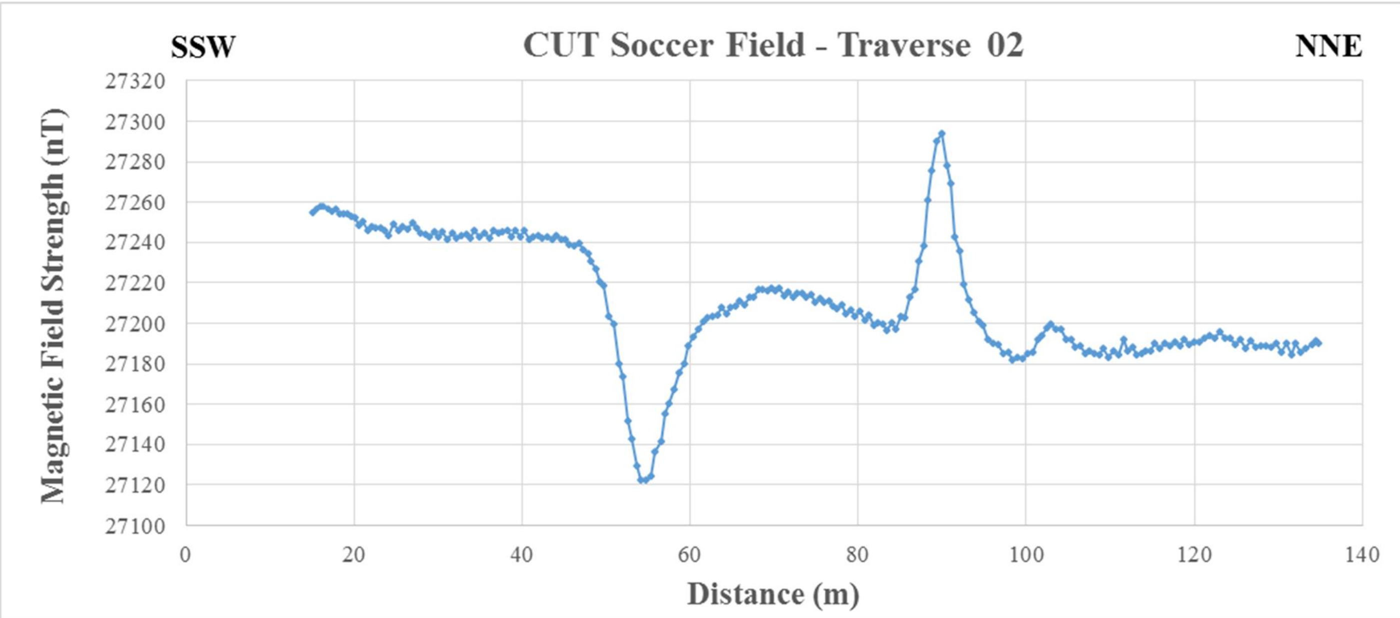

S
CUT Cricket Field - Traverse 08
N
Magnetic Field Strength (nT)
27400
27300
27200
27100
27000
26900
26800
26700
26600
0
20
40
60
80
100
120
Distance (m)

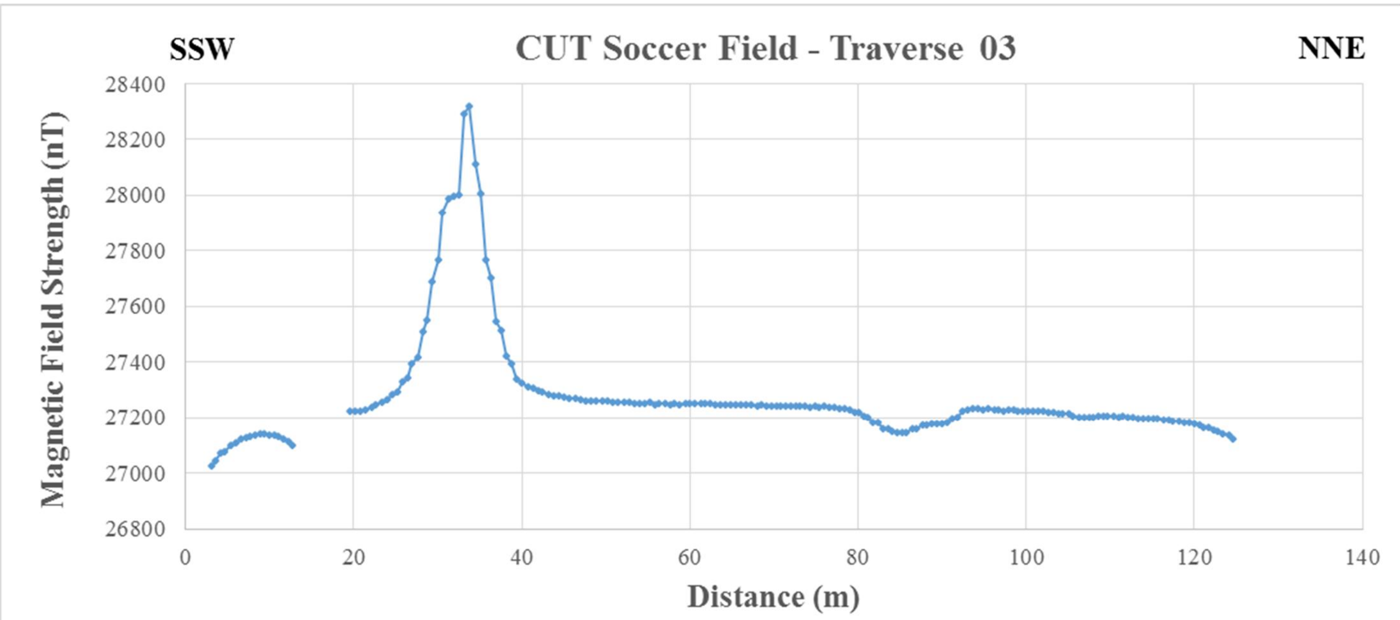

W
CUT Cricket Field - Traverse 09
E
Magnetic Field Strength (nT)
27250
27200
27150
27100
27050
27000
26950
0
20
40
60
80
100
120
Distance (m)

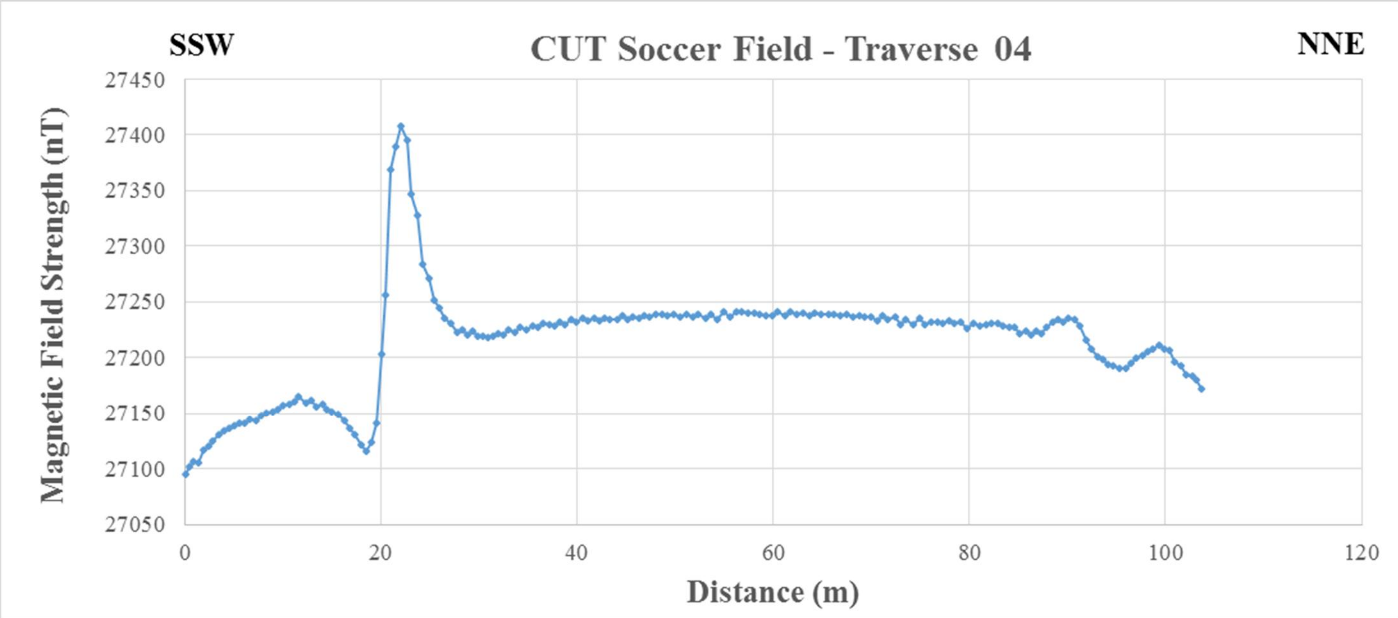

W
CUT Cricket Field - Traverse 10
E
Magnetic Field Strength (nT)
27400
27350
27300
27250
27200
27150
27100
0
20
40
60
80
100
120
140
Distance (m)

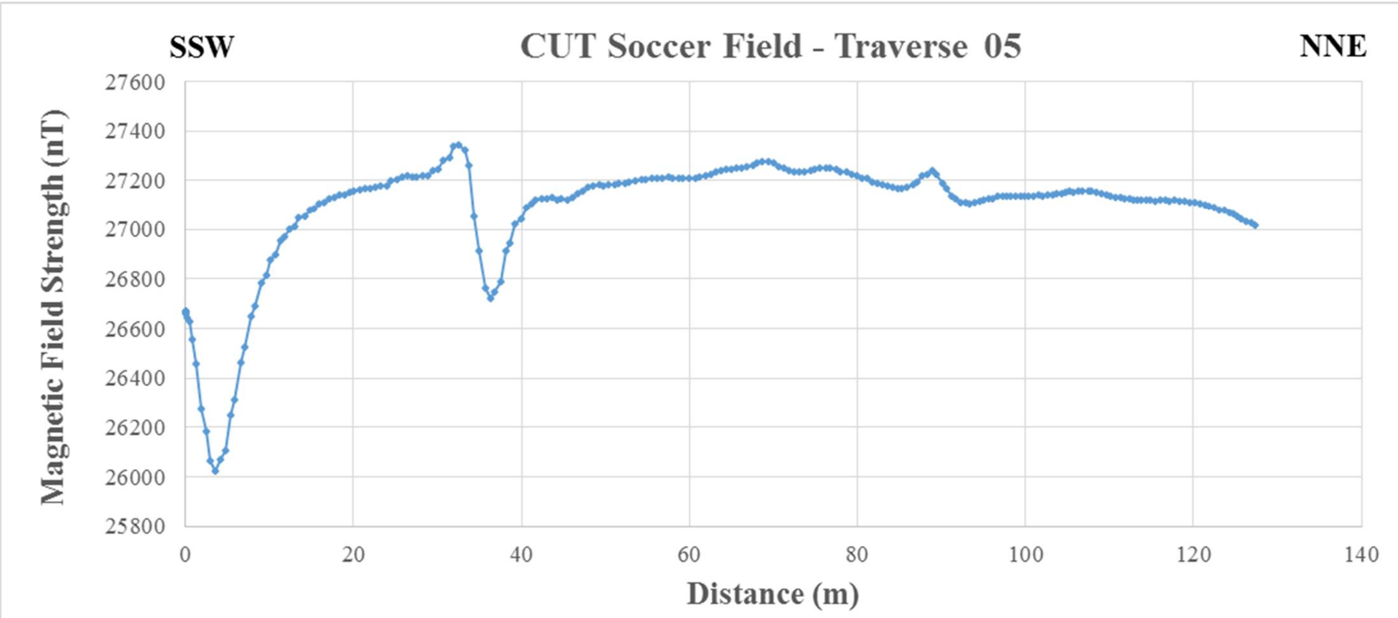
CUT – Soccer Field

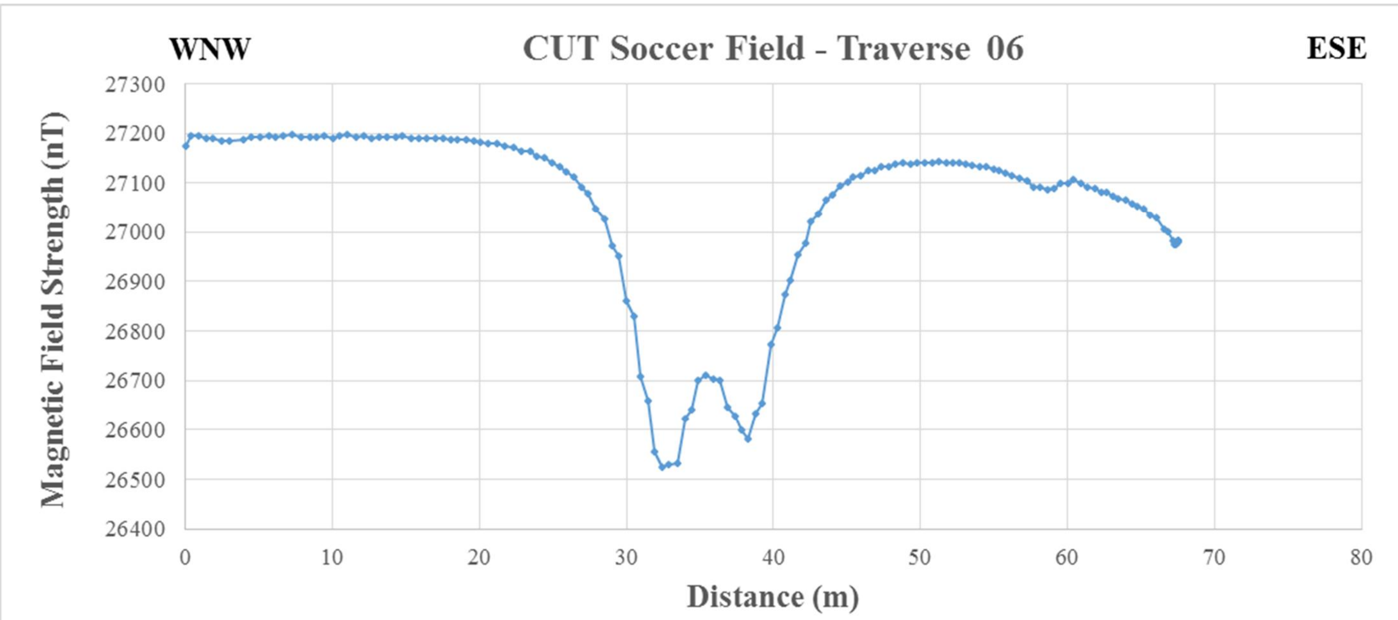


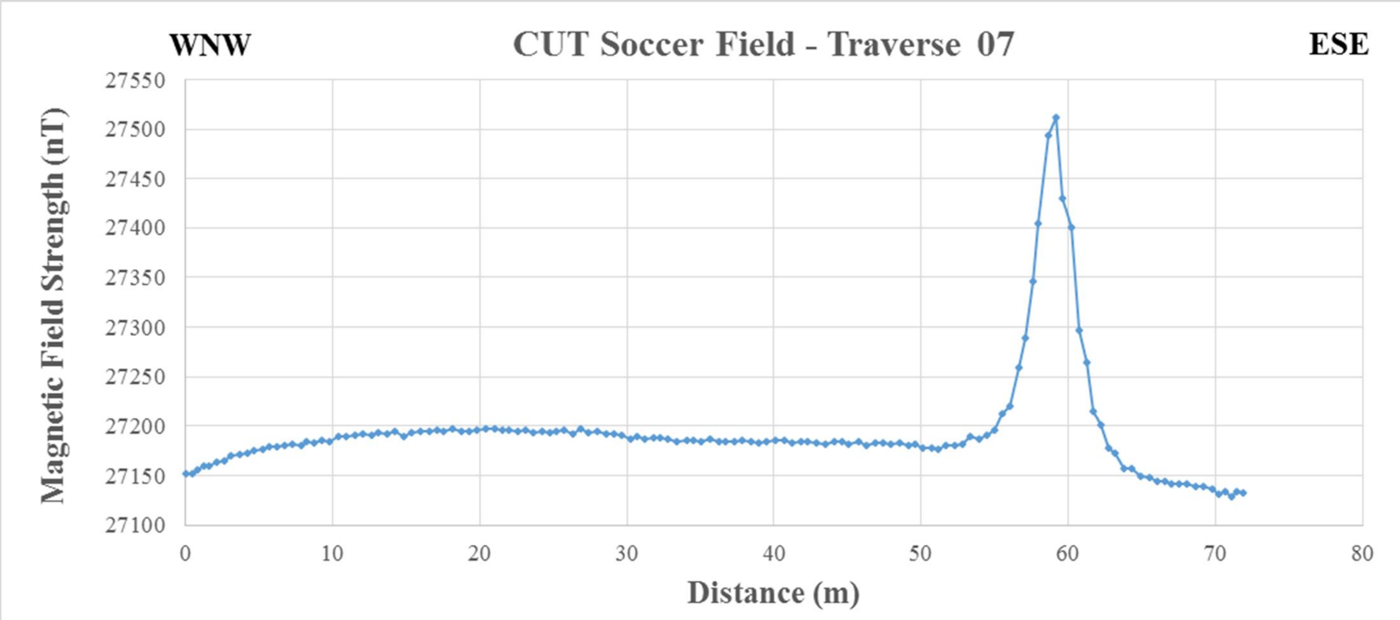




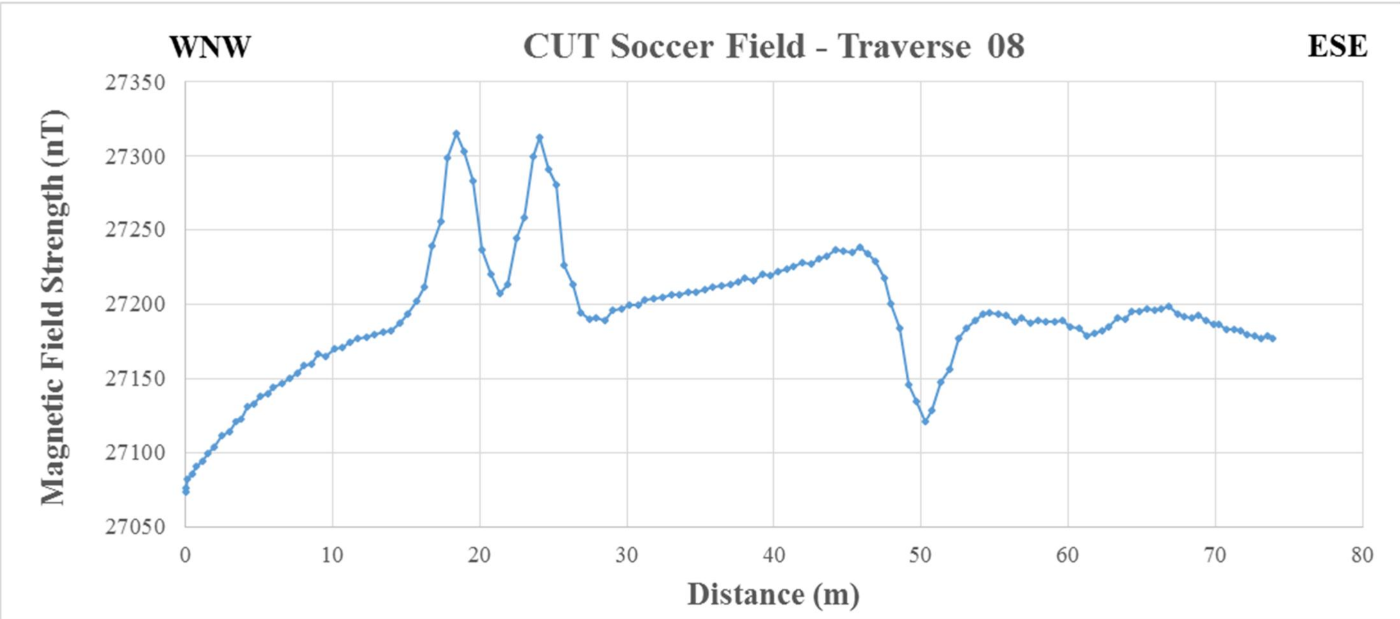

SSW
CUT Soccer Field - Traverse 04
NNE
Magnetic Field Strength (nT)
Distance (m)
27450
27400
27350
27300
27250
27200
27150
27100
27050
0
20
40
60
80
100
120


SSW
CUT Soccer Field - Traverse 05
NNE
Magnetic Field Strength (nT)
Distance (m)
27600
27400
27200
27000
26800
26600
26400
26200
26000
25800
0
20
40
60
80
100
120
140

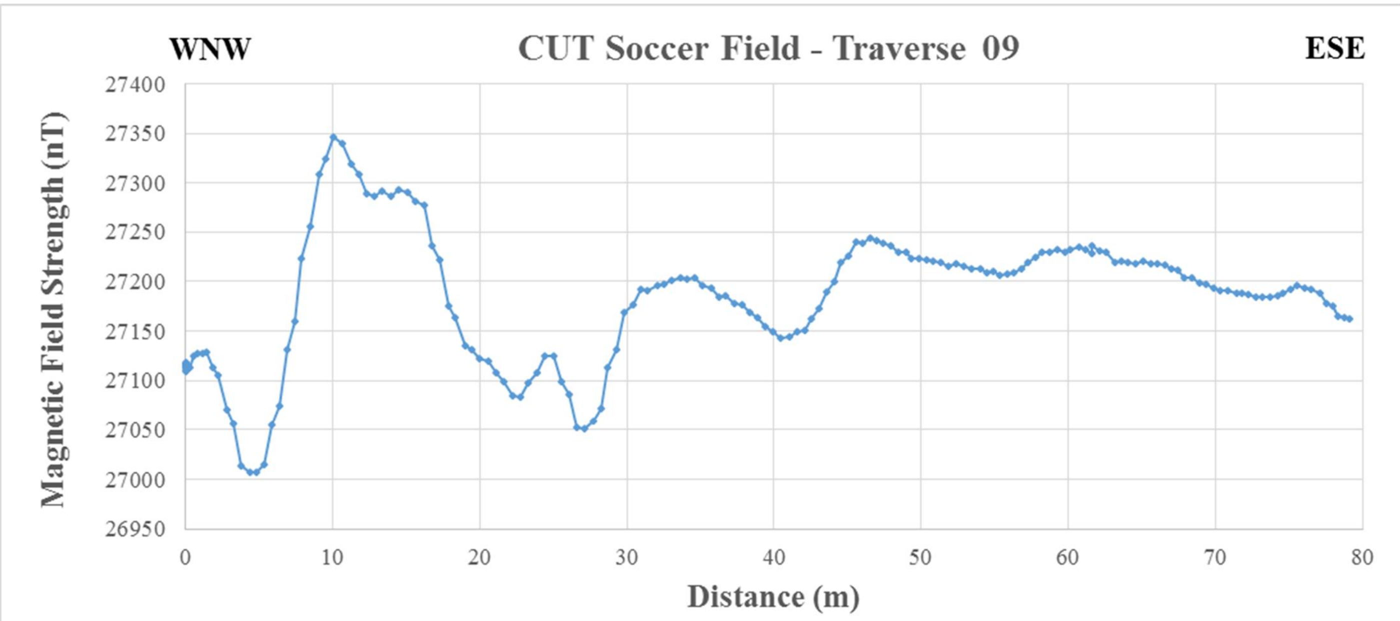

WNW
CUT Soccer Field - Traverse 06
ESE
Magnetic Field Strength (nT)
Distance (m)
27300
27200
27100
27000
26900
26800
26700
26600
26500
26400
0
10
20
30
40
50
60
70
80



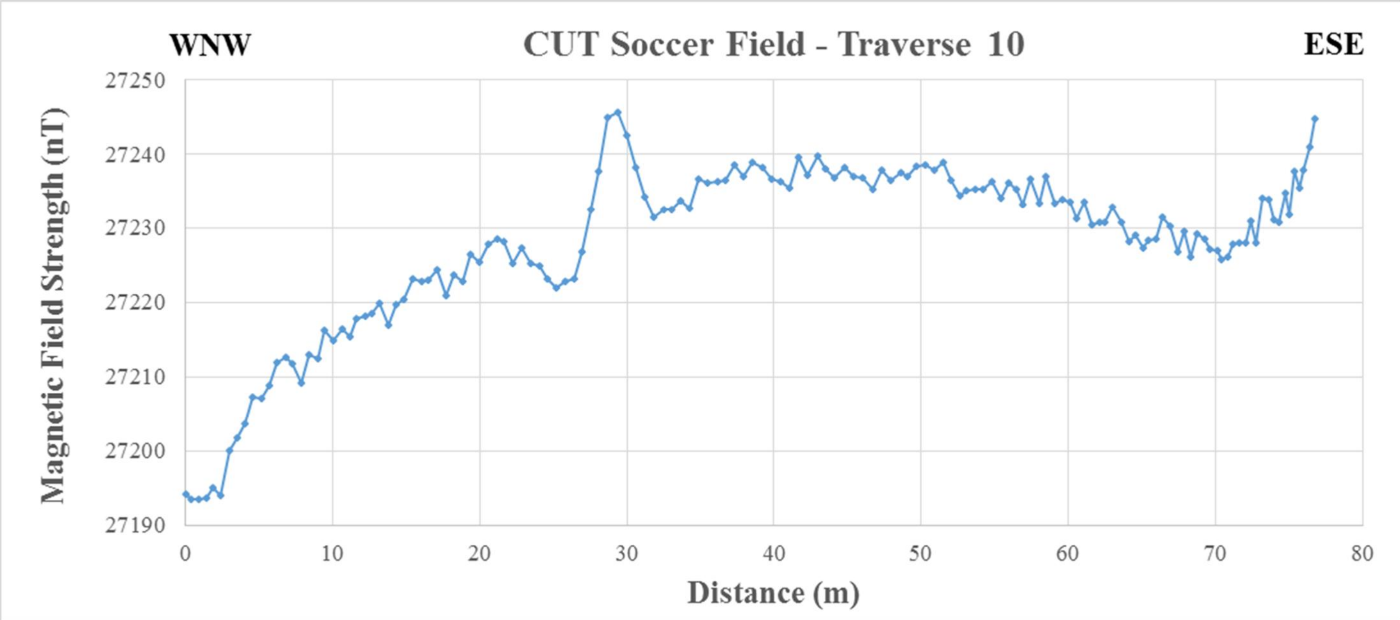
WNW
CUT Soccer Field - Traverse 07
ESE
Magnetic Field Strength (nT)
27550
27500
27450
27400
27350
27300
27250
27200
27150
27100
0
10
20
30
40
50
60
70
80
Distance (m)

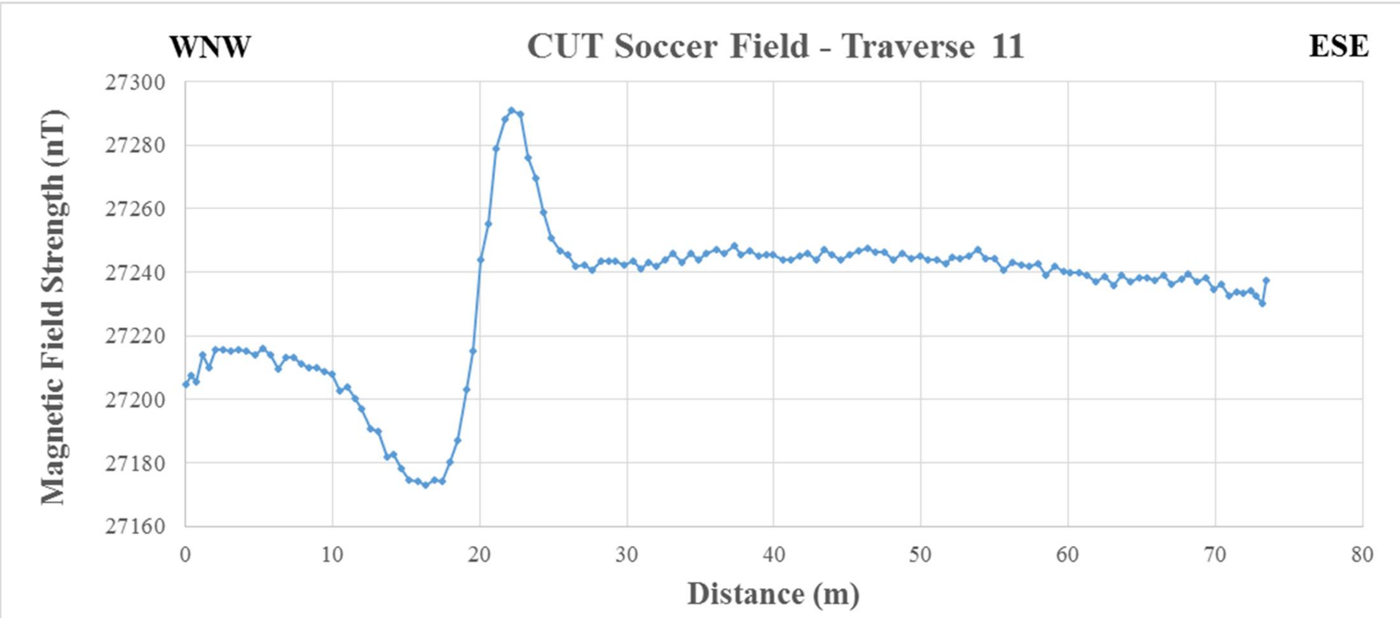


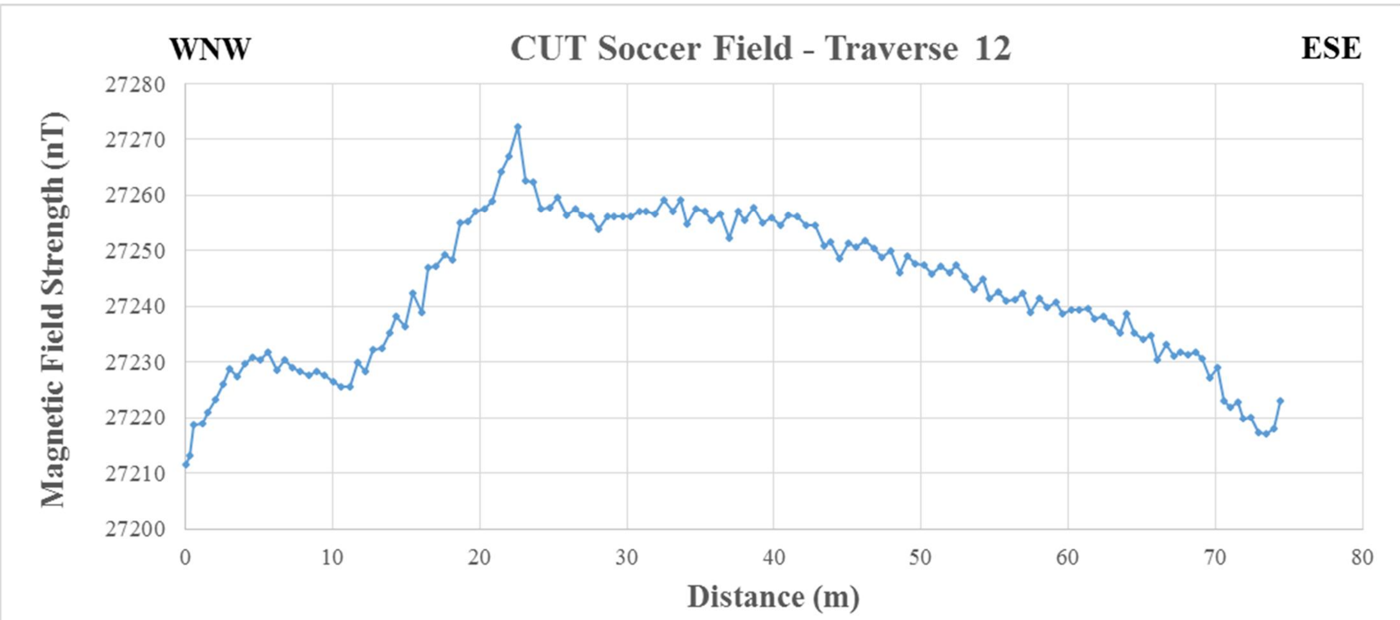
WNW
CUT Soccer Field - Traverse 08
ESE
Magnetic Field Strength (nT)
27350
27300
27250
27200
27150
27100
27050
0
10
20
30
40
50
60
70
80
Distance (m)

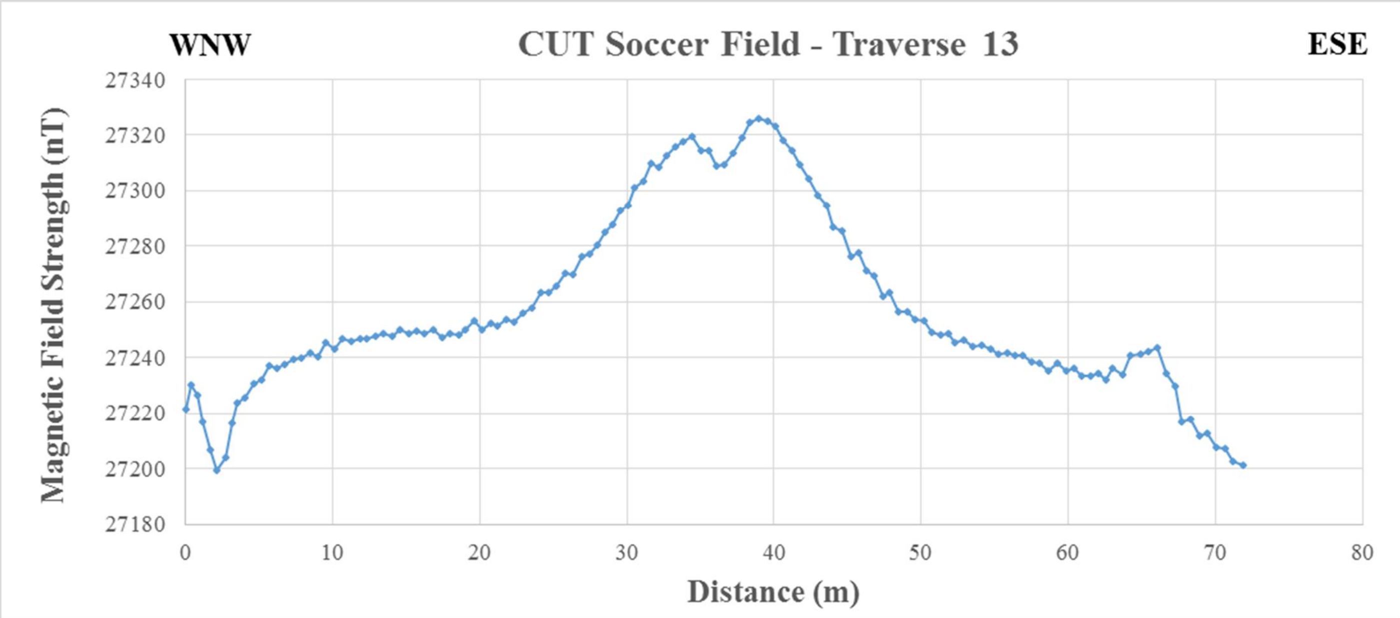


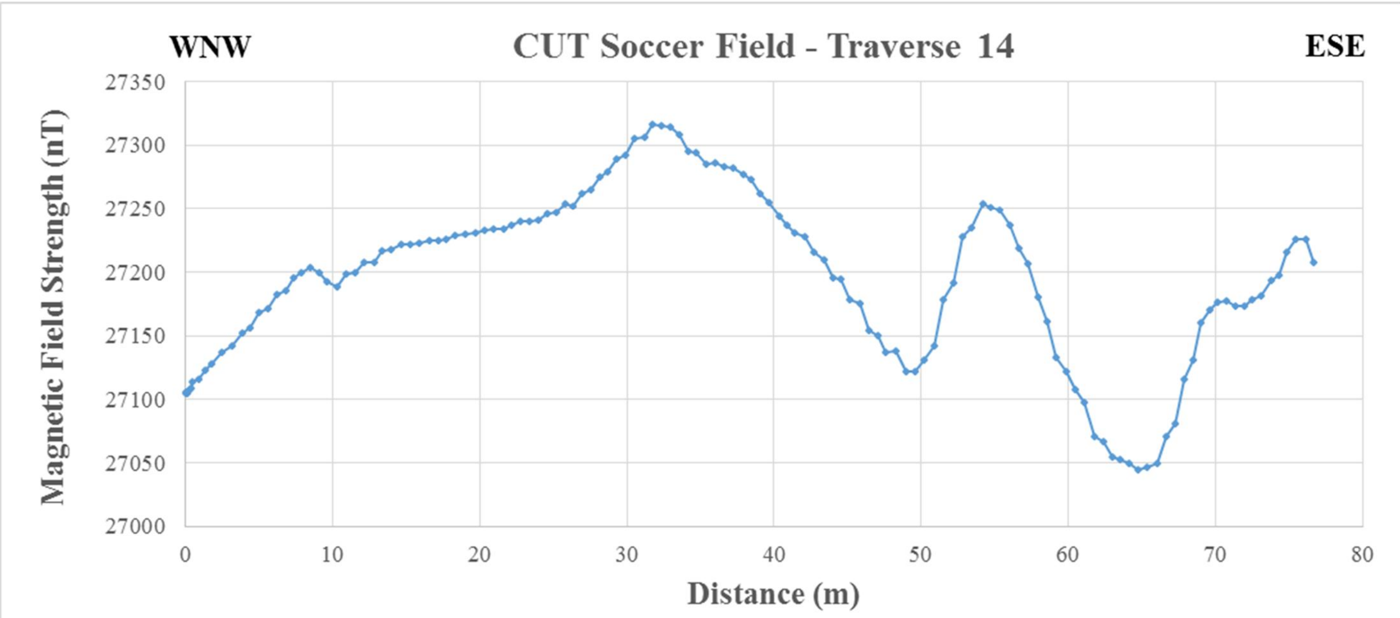
WNW
CUT Soccer Field - Traverse 09
ESE
Magnetic Field Strength (nT)
27400
27350
27300
27250
27200
27150
27100
27050
27000
26950
0
10
20
30
40
50
60
70
80
Distance (m)


WNW
CUT Soccer Field - Traverse 10
ESE
Magnetic Field Strength (nT)
27250
27240
27230
27220
27210
27200
27190
0
10
20
30
40
50
60
70
80
Distance (m)


WNW
CUT Soccer Field - Traverse 11
ESE
Magnetic Field Strength (nT)
27300
27280
27260
27240
27220
27200
27180
27160
0
10
20
30
40
50
60
70
80
Distance (m)


WNW
CUT Soccer Field - Traverse 12
ESE
Magnetic Field Strength (nT)
27280
27270
27260
27250
27240
27230
27220
27210
27200
0
10
20
30
40
50
60
70
80
Distance (m)


WNW
CUT Soccer Field - Traverse 13
ESE
Magnetic Field Strength (nT)
27340
27320
27300
27280
27260
27240
27220
27200
27180
0
10
20
30
40
50
60
70
80
Distance (m)


WNW
CUT Soccer Field - Traverse 14
ESE
Magnetic Field Strength (nT)
27350
27300
27250
27200
27150
27100
27050
27000
0
10
20
30
40
50
60
70
80
Distance (m)

APPENDIX B

Hydrocensus Data

UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

UFS·UV
NATURAL AND AGRICULTURAL SCIENCES
NATUUR- EN LANDBOUWETENSKAPPE
INSTITUTE FOR GROUNDWATER STUDIES (IGS)
INSTITUUT VIR GRONDWATERSTUDIES (IGS)

HYDROCENSUS of GROUNDWATER

Project Details									
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District			Number:	1					
Site information									
Owner: PETER COETZER			Dialing Code:						
Farm/plot Name/number:	97		Tel:						
Street/Box: VICTORIA ROAD			Fax:						
Place: PARKWEST			Cell: 082 876 3141						
Area Code: 9301									
Borehole information									
Borehole number: 01			Casing type:			Steel	X	Plastic	
Y-coordinate: S29.12136°		°S	Depth of casing:						
X-coordinate: E 26.19694°		°E	Length of Perforated:						
Z-coordinate: 1397		mamsl	Depth of water strikes:						
Borehole depth: 40		m	Pump type	Sub	X	Wind		Mono	
Date drilled: N/A			Pump k Watt:						
Diameter:	165mm	mm	Yield:						
Collar height: 0.35M	Level	mm	In use:	Yes	X	No			
			Reservoir:	Yes		No			
Water application **Current use**			**Planned or possible future use**						
If irrigation - crop and irrigated area:									
If livestock watering	Horses		Sheep / Goats			Game		Exotic	
no of.....									
If Domestic - number of people:									
Other uses:									
Sampling									
Operator: OWNER			Purge time: 16.15 (03/05						
Date sampled: 03/05/2017			When last pumped:			**18.00 (02/05/2017)**			
Sample taken			How often pumped:			**TWICE A DAY**			
Depth to water table (SWL):		mbgl	Water quality information:				Odor:		
Floating/pumped sample:			Turbidity:	Clear	X	Murky		Muddy	
			Color:	**CLEAR**					
Field measurements (if applicable)									
Diss. Oxygen (mg/L)	Temp (°C)	pH	EC (mS/m)			Other 1			
	19.7		572						
Notes:			Photo:						
WATER SEEMS TO HAVE A BIT HIGH CALCIUM QUANTITY									

Figure B-1: hydrocensus data for borehole BH1

BH UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

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NATURAL AND AGRICULTURAL SCIENCES
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INSTITUTE FOR GROUNDWATER STUDIES (IGS)
INSTITUUT VIR GRONDWATERSTUDIES (IGS)

HYDROCENSUS of GROUNDWATER

Project Details									
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District					Number:	2			
Site information									
Owner: CLOSE TO HOME AGENC					Dialing Code:				
Farm/plot Name/number:	89				Tel:				
Street/Box: DONALD MURRAY					Fax:				
Place: PARKWEST					Cell:				
Area Code: 9301									
Borehole information									
Borehole number: 02					Casing type:		Steel	X	Plastic
Y-coordinate: S 29.12085°				°S	Depth of casing:				
X-coordinate: E 26.19763°				°E	Length of Perforated:				
Z-coordinate: 1384				mamsl	Depth of water strikes:				
Borehole depth: N/A				m	Pump type	Sub	X	Wind	Mono
Date drilled:					Pump k Watt:				
Diameter:	165mm		225mm	mm	Yield:				
Collar height: 0.35 M	Level	X	8.2	mm	In use:	Yes	No	X	
					Reservoir:	Yes	No		
Water application Current use					**Planned or possible future use**				
If irrigation - crop and irrigated area:									
If livestock watering	Horses		Poultry	Cattle	Sheep / Goats		Game		Exotic
no of.....									
If Domestic - number of people:									
Other uses:									
Sampling									
Operator:					Purge time:		**15.30 PM (03/05/2017)**		
Date sampled: 03/05/2017					When last pumped:		**14.00 PM (03/05/2017)**		
Sample taken		Yes	X	No	How often pumped:				
Depth to water table (SWL):		8.2		mbgl	Water quality information:			Odor:	
Floating/pumped sample:		Float		Pump	Turbidity:	Clear	Murky	X	Muddy
					Color:	**NOT CLEAR**			
Field measurements (if applicable)									
Diss. Oxygen (mg/L)	Temp (°C)		pH		EC (mS/m)		Other 1		Other 2
	19.7								
Notes:					Photo:				
THE HOUSE IS AN AGENCY HOUSE OCCUPIED BY STUDENTS									

Figure B-2: Hydrocensus data for borehole BH2

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INSTITUUT VIR GRONDWATERSTUDIES (IGS)

HYDROCENSUS of GROUNDWATER

Project Details							
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District				Number:	3		
Site information							
Owner: KOBUS HATTING				Dialing Code:			
Farm/plot Name/number:	1			Tel:	051 448 877		
Street/Box: PRESIDENT BOSHC				Fax:			
Place: WILLOWS BLOEMFONTI				Cell:			
Area Code: 9330							
Borehole information							
Borehole number: BH3				Casing type:		Steel	X
Y-coordinate: S 29.12226°			°S	Depth of casing:			m
X-coordinate: E 26.21215°			°E	Length of Perforated:			m
Z-coordinate: 1381			mamsl	Depth of water strikes:			m
Borehole depth: 40			m	Pump type	Sub X	Wind	None
Date drilled: 2003				Pump k Watt:			kW
Diameter:	165mm	225mm	mm	Yield:			l/h
Collar height: N/A	Level		mm	In use:	Yes X	No	
				Reservoir:	Yes	No	
Water application Current use				**Planned or possible future use**			
If irrigation - crop and irrigated area:							m²
If livestock watering	Horses	Poultry	Cattle	Sheep / Goats		Game	Other
no of.....							
If Domestic - number of people:							
Other uses: FOR CAR W							
Sampling							
Operator:				Purge time: 17.30 (03/05/2017)			
Date sampled: 03/05/201				When last pumped:		**17.10 (03/05/2017)**	
Sample taken		Yes X	No	How often pumped:		**EVERYDAY**	
Depth to water table (SWL):	**N/A**		mbgl	Water quality information:			Odor:
Floating/pumped sample:		Float	Pump	Turbidity:	Clear X	Murky	
				Color:	**Clear**		
Field measurements (if applicable)							
Diss. Oxygen (mg/L)	Temp (°C)	pH		EC (mS/m)		Other 1	Other 2
	N/A			N/A			
Notes:				Photo:			
THE BOREHOLE IS NOT ACCESSIBLE,SAMPLE WAS TAKEN							

Figure B-3: Hydrocensus data for borehole BH3

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HYDROCENSUS of GROUNDWATER

Project Details

Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District

Number: 4

Site information

Owner: GHT CONSULTANTS	Dialing Code: 51
Farm/plot Name/number: :	Tel: 002751444000 2
Street/Box:	Fax:
Place:	Cell:
Area Code:	

Borehole information

Borehole number:					Casing type:		Steel	X	Plastic	
Y-coordinate: 29.12076				°S	Depth of casing:				m	
X-coordinate: 26.1979				°E	Length of Perforated:				m	
Z-coordinate:				mamsl	Depth of water strikes:				m	
Borehole depth: 34				m	Pump type	Sub	X	Wind	Mo	None
Date drilled:					Pump k Watt:				kW	
Diameter:	165mm	225mm		mm	Yield:				/h	
Collar height:	Level			mm	In use:	Yes	X	No		
					Reservoir:	Yes		No		

Water application

Current use | **Planned or possible future use**

If irrigation - crop and irrigated area:								m²	
If livestock watering	Horses	Poultry	Cattle	Sheep / Goats		Game		Ex	Other
no of.....									
If Domestic - number of people:									
Other uses:									

Sampling

Operator:					Purge time:		09.30 AM (04/0		
Date sampled: 04/05/201					When last pumped:		9.20 AM (04/05/2017		
Sample taken	Yes	X	No		How often pumped:		DAILY		
Depth to water table (SWL):			N/A	nbgl	Water quality information:			Od	NO
Floating/pumped sample:	Float		Pump	X	Turbidity:	Clear	X	Murky	Muddy
					Color:				

Field measurements (if applicable)

Diss. Oxygen (mg/L)	Temp (°C)	pH	EC (mS/m)	Other 1	Other 2
	19.7	7	95		

Figure B-4: Hydrocensus data for borehole BH4

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HYDROCENSUS of GROUNDWATER

Project Details												
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District							Number:	5				
Site information												
Owner: Kobus Hatting							Dialing Code:		51			
Farm/plot Name/number:							Tel: 0027514303492					
Street/Box: Cnr 1st Ave & St. Ge							Fax:					
Place: Willows, Bloemfontein							Cell:					
Area Code: 9301												
Borehole information												
Borehole number: 5							Casing type:			Steel	X	Plastic
Y-coordinate: 29.11854						°S	Depth of casing:		N/A			m
X-coordinate: 26.21133						°E	Length of Perforated:		N/A			m
Z-coordinate:						mamsl	Depth of water strike		N/A			m
Borehole depth: 40						m	Pump type	Sub	X	Wind		None
Date drilled: 2003							Pump k Watt:					kW
Diameter:	165mm		225mm			mm	Yield:					l/h
Collar height: N/A	Level					mm	In use:	Yes	X	No		
							Reservoir:	Yes		No		
Water application Current use							**Planned or possible future use**					
If irrigation - crop and irrigated area:												m²
If livestock watering	Horses		Poultry		Cattle		Sheep / Goats			Game		Other
no of.....												
If Domestic - number of people:												
Other uses: Car Wash												
Sampling												
Operator:							Purge time:	11.30 AM (04/05/2017				
Date sampled: 04/05/201							When last pumped:			**11.25 AM (04/05/2017)**		
Sample taken			Yes	X	No		How often pumped:		DAILY			
Depth to water table (SWL):		N/A				mbgl	Water quality information:				Odor:	
Floating/pumped sample:			Float		Pump	X	Turbidity:	Clear	X	Murky		Muddy
							Color:					
Field measurements (if applicable)												
Diss. Oxygen (mg/L)	Temp (°C)		pH				EC (mS/m)			Other 1		Other 2
	19.8		7				195					

Figure B-5: Hydrocensus data for borehole BH5

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HYDROCENSUS of GROUNDWATER

Project Details									
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business				Number:	6				
Site information									
Owner: CUT				Dialing Code:		51			
Farm/plot Name/number:		20		Tel:		27515073911			
Street/Box: PRESIDENT BRAND STREET				Fax:					
Place: WESTDENE, BLOEMFONTEIN SOUTH AFRICA				Cell:					
Area Code: 9300									
Borehole information									
Borehole number: 06				Casing type:		Steel	X	Plastic	
Y-coordinate:29.12317			°S	Depth of casing:		N/A			m
X-coordinate: 26.21540			°E	Length of Perforated:			N/A		m
Z-coordinate:			mamsl	Depth of water strikes:			N/A		m
Borehole depth:			9.46 m	Pump type	Sub	X	Wind	Mono	None
Date drilled:	N/A			Pump k Watt:					kW
Diameter:	165mm	225mm	mm	Yield:					l/h
Collar height: N/A	Level		mm	In use:	Yes	X	No		
				Reservoir:	Yes		No		
Water application Current use				**Planned or possible future use**					
If irrigation - crop and irrigated area:									m²
If livestock watering	Horses	Poultry	Cattle	Sheep / Goats		Game		Exotic	Other
no of…..									
If Domestic - number of people:									
Other uses:									
Sampling									
Operator:				Purge time:		12.00 AM (04/05/2017)			
Date sampled: 04/05/201				When last pumped:		10.30 AM (04/05/2017)			
Sample taken		Yes	No	How often pumped:		DAILY			
Depth to water table (SWL):		4.5	mbgl	Water quality information:			Odor:		
Floating/pumped sample:		Float	Pump X	Turbidity:	Clear	Murky		Muddy	X
				Color:	BROWNISH				
Field measurements (if applicable)									
Diss. Oxygen (mg/L)	Temp (°C)		pH	EC (mS/m)		Other 1		Other 2	
	19.7		7	190					

Figure B-6: Hydrocensus data for borehole BH6

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HYDROCENSUS of GROUNDWATER

Project Details	
Name: Investigating the Possibility of Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business	Number: 7

Site information			
Owner: ORANJE PSYCHATRIC HOSPITAL		Dialing Code:	51
Farm/plot Name/number:	: 35	Tel:	27514079260
Street/Box:	NICO VAN DER MERWE AVE	Fax:	
Place:	ORANJESIG, BLOEMFONTEIN	Cell:	
Area Code:	9301		

Borehole information											
Borehole number:	7		Casing type:		Steel	X	Plastic				
Y-coordinate:	29.12557		Depth of casing:		N/A						m
X-coordinate:	26.21377		Length of Perforated:				N/A				m
Z-coordinate:			Depth of water strikes:				N/A				m
Borehole depth:	N/A		Pump type	Sub	X	Wind		Mono		None	
Date drilled:	N/A		Pump k Watt:	N/A							kW
Diameter:	165mm	X	Yield:	N/A							l/h
Collar height: N/A	Level		In use:	Yes	X	No					
			Reservoir:	Yes		No					

Water application									
Current use		Planned or possible future use							
If irrigation - crop and irrigated area:									m²
If livestock watering	Horses	Sheep / Goats		Game		Exotic		Other	
no of.....									
If Domestic - number of people:									
Other uses: FISH POND									

Sampling								
Operator:		Purge time:	15.00 PM (04/05/2017)					
Date sampled:	4/5/2017	When last pumped:	14.59 PM (04/05/2017)					
Sample taken		How often pumped:						
Depth to water table (SWL):	N/A	Water quality information:			Odor:			
Floating/pumped sample:		Turbidity:	Clear	X	Murky		Muddy	
		Color:	N/A					

Field measurements (if applicable)				
Diss. Oxygen (mg/L)	Temp (°C)	EC (mS/m)	Other 1	Other 2
	19.7	96		

Figure B-7: Hydrocensus data for borehole BH7

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HYDROCENSUS of GROUNDWATER

Project Details	
Using Groundwater Associated with Dolerite Structures to Augment the Municipal Water Supply to the City of Bloemfontein – Investigations in the Central Business District	Number: 8

Site information				
Owner: WATERFRONT MALL			Dialing Code:	51
Farm/plot Name/number:	105		Tel:	27514483607
Street/Box: HENRY & 1ST AVE			Fax:	
Place: WILLOWS, BLOEMFONTEIN			Cell:	
Area Code: 9301				

Borehole information												
Borehole number: 08					Casing type:		Steel		Plastic			
Y-coordinate: 29.11572				°S	Depth of casing:							m
X-coordinate: 26.20958				°E	Length of Perforated:				N/A			m
Z-coordinate:				mamsl	Depth of water strikes:				N/A			m
Borehole depth: N/A				m	Pump type	Sub	X	Wind		Mono		None
Date drilled: N/A					Pump k Watt:							kW
Diameter: N/A	165mm	225mm		mm	Yield:							l/h
Collar height: N/A	Level			mm	In use:	Yes	X	No				
					Reservoir:	Yes		No				

Water application										
Current use					**Planned or possible future use**					
If irrigation - crop and irrigated area:										m²
If livestock watering	Horses	Poultry	Cattle		Sheep / Goats		Game		Exotic	Other
no of.....										
If Domestic - number of people:										
Other uses: RECREATIONAL PURPOSES										

Sampling												
Operator:						Purge time:	10.30 AM (17/05/2017)					
Date sampled: 17/05/2017						When last pumped:	10.29 AM (17/05/2017)					
Sample taken	Yes	X	No			How often pumped:	DAILY					
Depth to water table (SWL):					mbgl	Water quality information:				Odor:		
Floating/pumped sample:	Float		Pump	X		Turbidity:	Clear	X	Murky		Muddy	
						Color:						

Field measurements (if applicable)					
Diss. Oxygen (mg/L)	Temp (°C)	pH	EC (mS/m)	Other 1	Other 2
	19.7	7	90		

Figure B-8: Hydrocensus data for the spring

APPENDIX C

Pumping Test Data

Table C-1: Pumping test data for BH8

General Information						
Borehole No:	BH1					
Site Name:	CUT					
Farm Name:	Bloemfontein					
Latitude:	29º07′12,72″S					
Longitude:	26º12′49,01″S					
Pumping Borehole Information						
Depth of Pump (m):	24					
Collor Height (m):	0					
BH diameter (m):	0.165					
Depth of BH (m):	39					
Static W/L (m):	5.03					
Time (min)	Water lev	Drawdown s (m)	Yield (l/s)	Time (min)	Water lev	Recovery s' (m)
1	5.32	0.29	13.3	1	6.18	0.15
2	5.45	0.42	13.3	2	6	0.33
3	5.51	0.48	13.3	3	5.99	0.34
4	5.48	0.45	13.3	4	5.91	0.42
5	5.47	0.44	13.3	5	5.91	0.42
6	5.47	0.44	13.3	6	5.88	0.45
7	5.5	0.47	13.3	7	5.7	0.63
8	5.52	0.49	13.3	8	5.86	0.47
9	5.56	0.53	13.3	9	5.82	0.51
10	5.58	0.55	13.3	10	5.77	0.56
15	5.62	0.59	13.3	15	5.77	0.56
20	5.64	0.61	13.3	20	5.81	0.52
25	5.67	0.64	13.3	25	5.8	0.53
30	5.71	0.68	13.3	30	5.8	0.53
40	5.74	0.71	13.3	40	5.73	0.6
50	5.77	0.74	13.3	50	5.67	0.66
60	5.79	0.76	13.3	60	5.62	0.71
75	5.81	0.78	13.3	75	5.57	0.76
90	5.85	0.82	13.3	90	5.53	0.8
120	5.93	0.9	13.3	120	5.44	0.89
150	5.97	0.94	13.3	150		
180	6.12	1.09	13.3	180		
240	6.13	1.1	13.3	240		
300	6.15	1.12	13.3	300		
360	6.22	1.19	13.3	360		
420	6.27	1.24	13.3			
480	6.33	1.3	13.3			