INVESTIGATING THE POSSIBILITY OF TARGETING MAJOR DOLERITE INTRUSIVES TO SUPPLEMENT MUNICIPAL WATER SUPPLY IN BLOEMFONTEIN: A GEOPHYSICAL APPROACH

Grace Lebohang Molaba

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Supervisor: Dr François Fourie
Co-supervisor: Dr Saheed Oke

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DECLARATION

I, Grace Lebohang Molaba, 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.

Grace Lebohang Molaba

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INTRODUCTION

1.1 General

The city of Bloemfontein is currently relying on remote surface water sources for its potable water supply, namely the Rustfontein, Mockes, Welbedacht and Knellpoort dams. Water is also released from the Katse dam in Lesotho via the Caledon River to the Rustfontein Water Treatment Works of Bloemwater at the rate of 4 m^3/s. Unfortunately, only 40% of this water reaches the pump station of Bloemwater (Tienfontein pump station) because of evaporation losses and taking of water by farmers. Since Bloemfontein is located in a semi-arid area, surface water resources are unreliable and susceptible to droughts.

The water demand in the Mangaung Metro Municipality (MMM) has increased significantly during recent years due to population increases, agricultural growth and industrial development. It is expected that the surface water resources are soon not going to be adequate to meet the increasing water demand in the MMM.

Recently, interest has been growing in uncovering a viable alternative to overcome the scarcity of water in Bloemfontein. One of the most promising ways to augment the municipal water supply is to utilise the groundwater resources in and around the city. Currently groundwater in Bloemfontein is mostly used by private individuals and companies for irrigation and small-scale agriculture. The potential therefore exists to use this resource to assist in meeting the municipal water demand.

Bloemfontein is located within the central Karoo Basin of South Africa. The city is underlain by rocks of the Karoo Supergroup, which mostly consists of sedimentary rocks characterised by low groundwater potential. However, during the Jurassic age, extensive magmatic activity occurred within the Karoo Basin. Dolerite magmas intruded the sedimentary rocks along fractures and joints, and then solidified to form linear dykes and near-horizontal sills. Due to the high temperatures and pressures that reigned during intrusion, the dolerite magmas significantly altered the host sedimentary rock through fracturing which increases the groundwater potential of the Karoo rocks in the immediate vicinity of the intrusives.

Dolerite structures are ubiquitous in and around the city of Bloemfontein. Since these structures may be associated with prominent aquifers, the detection and delineation of these structures should be considered a primary objective during groundwater exploration programmes. The current study focusses on detection and delineation of a prominent dyke-structure in the industrial area south of the Bloemfontein CBD.

1.2 Historical Background

Bloemfontein (the Dutch word meaning 'flower fountain') is the capital city of the Free State Province in South Africa, and the major urban area within the Mangaung Metropolitan Municipality. The city is named after a strong spring discovered in 1828 by Johannes Nicolas Brits. The beauty and the richness of flowers as well the excellence of water supply in the city led to it being named Bloemfontein.

In 1950, a certain Mr Norman investigated the geological setting of the spring and proposed the theory that the spring was associated with an intrusive ring dyke, which he referred to as the *barrier ridge* (Roberts, 1950).

In 1880, the old spring was providing approximately 100 000 gallons of water per day for the population of some 2 000 Europeans living in the area. The construction of a concrete dam was done along the Barrier Ridge, between Fort Drury and Presidency Hills to supplement the water supply. In 1848, Major Warden desired the fountain water to be transported for half a mile along the south bank for use by the garrison. This was accomplished by the simple means of an open furrow which allowed water to flow across the Presidency garden. A concrete tower was built around the spring to prevent the spring from submerging (Roberts, 1950).

Figure 1 shows the concrete structure that was built around the spring that was discovered by Mr Brits in 1828. The spring is located in a storm water canal which is actually the Bloem Spruit, cladded with concrete to its present state. This unfortunately had an impact on the environment with a reduction in recharge of the spring. Robberts (1950) also described this action as an environment disaster.

Figure 1. The concrete structure that was built around the spring after which the city of Bloemfontein was named

1.3 Problem Statement

Sustainable water supply and the management of water resources are the main challenge encountered by most cities in South Africa. Due to factors such as population growth, industrial development, agricultural demands and climate change, the surface water resources available to many cities cannot meet the growing demand for water. The groundwater resources in the country are therefore currently considered as an alternative source that may be used to augment the water supply to many towns and cities. However, South Africa's groundwater resources mostly occur in fractured hard-rock aquifers, typically characterised by low groundwater potentials. To install successful, high-yielding boreholes, geological structures associated with increased groundwater potential have to be targeted during groundwater exploration programmes.

The current study focuses on the detection and delineation of a prominent dolerite structure in the industrial area south of the Bloemfontein CBD. This structure could potentially be associated with aquifer systems that may be exploited to relieve the water stress faced by the city. The current study not only needs to detect and delineate the dolerite structure, but also has to assess the potential of using potential groundwater resource associated with a major dolerite intrusion to supplement. To achieve this, information on the groundwater quality and aquifer properties related to sustainable abstraction rates needs to be obtained.

1.4 Aim and Objectives

The main aim of the study is to investigate the possibility of using groundwater resources associated with a major dolerite intrusive to supplement the water supply to the Mangaung Metropolitan Municipality (MMM).

To address the aim of this research project, the following objectives were identified:

- To locate and delineate the prominent dolerite structure within the municipal boundaries using geophysical methods.
- To investigate the geometry of the dolerite structure.
- To propose positions for the drilling of production boreholes.
- To assess the suitability of the groundwater resource for municipal use.
- To estimate the abstraction rate from the aquifer that would allow sustainable groundwater use.
- To make recommendation for future utilisation of groundwater resources in the MMM.

1.5 Research Methodology

To achieve the aims and objectives of the study, the following actions were taken:

- The literature on the geology and geohydrology of the Karoo Basin was reviewed to allow insight into the factors that control the occurrence of groundwater within Karoo aquifers.
- A desk-top study was conducted to investigate the geological conditions in and around the city of Bloemfontein. Specific focus was placed on the presence of dolerite intrusives. Satellite images of the area under investigation were studied to identify visible features that may indicate the presence of sub-surface structures. An airborne magnetic map was studied to identify prominent magnetic structures within the study area.
- Ground geophysical surveys were conducted on traverses across the structure identified during the desktop study. The geophysical data were analysed and interpreted to estimate the geometry of the dolerite structure.
- Based on the results of the ground geophysical investigations, positions for the installation of abstraction boreholes were proposed.
- A limited hydrocensus was conducted in selected areas. The purpose of the hydrocensus was to gain information on the aquifer conditions and current groundwater uses at boreholes near dolerite structures similar to the one under investigation. During the hydrocensus parameters

such as the groundwater level, electrical conductivity (EC), and temperature of the water in the boreholes were measured.

- All the gathered information was processed and interpreted to assess the possibility of using groundwater associated with the dolerite structure to augment the municipal water supply.

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 aquifer, as well as sampling of the groundwater from the aquifer. 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. 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: INTRODUCTION

This chapter gives an introduction to the research project providing general and background information on groundwater use in the city of Bloemfontein, as well as describing the aim and objectives of the study. The methodology used to achieve the aim and objectives is described. The structure of the dissertation is explained.

Chapter 2: LITERATURE REVIEW

This chapter summarises the research that was done on the Karoo Basin, Karoo dolerites and their relation to groundwater, as well as the current and future use of water in the Bloemfontein area. The operation principles of the geophysical methods typically used for groundwater exploration in Karoo rocks are discussed. Sources of information included: reports, books and articles relevant to the research project.

Chapter 3: DESCRIPTION OF THE STUDY AREA

This chapter describes the study area in terms of regional setting, geological setting, regional magnetic setting, topography and drainage, geohydrology, climatic conditions and soil types.

Chapter 4: GROUND GEOPHYSICAL INVESTIGATIONS

In this chapter, the ground geophysical surveys conducted within the study area are discussed. The geophysical data are interpreted to determine the geometry of the prominent dolerite intrusive that occurs within the study area.

Chapter 5: HYDROCENSUS

Chapter 5 discusses the results of a limited hydrocensus conducted within a 5 km radius of the study site.

Chapter 6: GROUNDWATER QUALITY

In this chapter, the results of chemical analyses performed on groundwater samples collected during the hydrocensus are discussed in the terms of the groundwater type and quality and the suitability of the groundwater for municipal use.

Chapter 7: CONCLUSION AND RECOMMENDATIONS

In Chapter 7, conclusions are drawn from the results of the study. Definite recommendations for future actions are proposed.

CHAPTER 2:
LITERATURE REVIEW

2.1 Introduction

The current study investigates the possibility of supplementing the municipal water supply to the city of Bloemfontein by using groundwater associated with dolerite intrusives. In this chapter, the literature relevant to the current study is reviewed. First, the current water supply to the city is discussed. Then the current and future water demands are described to illustrate the need for additional water resources to meet the water requirements of the city. Since these additional resources could potentially come from groundwater associated with dolerite intrusives in the Karoo rocks underlying the city, a thorough understanding of the geological and geohydrological conditions of the Karoo Supergroup is required. The literature on the Karoo geology and geohydrology, with specific focus on the influence of dolerite intrusives, is therefore reviewed. Lastly, the principles and applications of three geophysical methods commonly used during groundwater exploration in Karoo rocks are described. These geophysical methods were used in the current study to detect and delineate the intrusive dolerite structures targeted during the groundwater exploration programme.

2.2 Current Water Supply to the City of Bloemfontein

The current water supply to the city of Bloemfontein is shown in Figure 2. The Caledon-Bloemfontein Transfer Scheme transports purified water along the 107 km-long Caledon-Bloemfontein pipeline from the Welbedacht Dam to the Bloemwater reservoir at Brandkop and from there to certain municipal reservoirs of the Mangaung Metro Municipality.

Modder and Caledon River Region

The Caledon-Modder Transfer Scheme was put into active service at the end of 1999. This scheme is referred to as direct transfer scheme, which pumps unprocessed water from the Caledon River to the Knellpoort Dam and from there to the upper reaches of the Modder River, upstream of the Rustfontein Dam near Thaba Nchu. The above two schemes are operated by Bloemwater, the Bulk Water Service Provider and provides 70% of the MMM's water supply. The municipality provides approximately 30% of the water supply from its Water Treatment Works at Maselspoort in the Modder River.

The water supply schemes are located within the Greater Bloemfontein Supply System (GBSS). The GBSS provides most of the water required by the towns located within the Mangaung

Metropolitan Municipality, namely Bloemfontein, Thaba Nchu, Botshabelo, Dewetsdorp, Reddersburg, Wepener, Edenburg and Excelsior (DEA, 2013). Water for the rural villages, approximately 36 in total, in the Thaba Nchu area, are supplied by boreholes. The boreholes are maintained and operated by BloemWater (DWA, 2010).

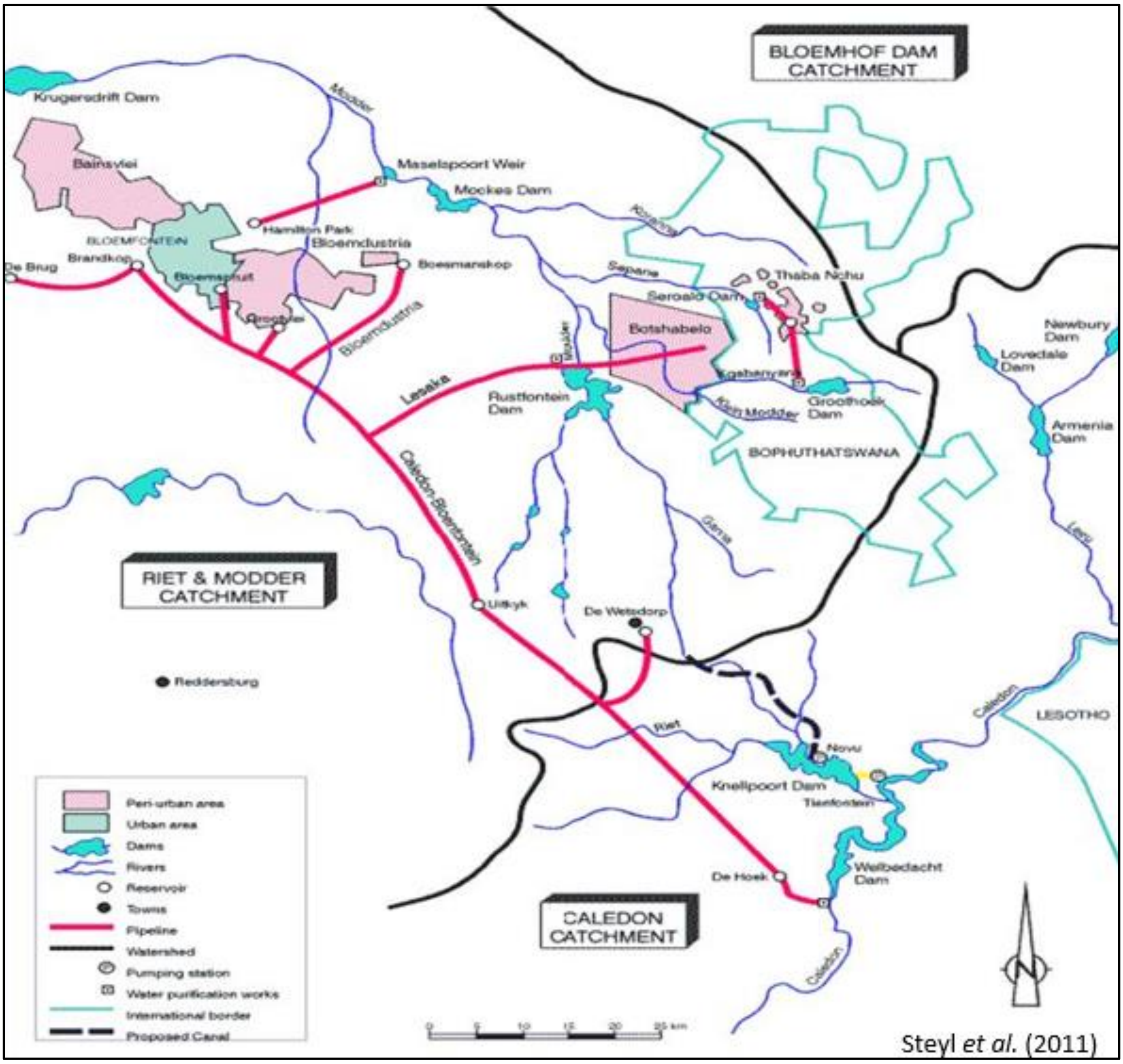

Figure 2. Water supply to Bloemfontein along the water transfer schemes

The Modder River region scheme is BloemWater's middle-sized scheme and is made up of two water treatment works, namely: Rustfontein, which supplies 100 ML/day, and Groothoek which supplies 18 ML/day (DWA, 2010). The Rustfontein Water Treatment Works is situated at the Rustfontein Dam, 12 km west of Botshabelo and 25 km south of Bloemfontein. The Rustfontein Dam receives most of its water from the Knelpoort/Novo transfer scheme, and acts as a buffer for the Mockes Dam.

Water is released from the Rustfontein Dam into the Mockes Dam where it is released to the Maselspoort Water Treatment Works. Maselspoort is owned and operated by the Mangaung Metropolitan Municipality (DWA, 2010). This plant has a design capacity of 110 ML/day and supplies water to the northern parts of Bloemfontein (DWA, 2010). The average daily production rates of the Rustfontein Water Treatment Works' are outlined below:

- Botshabelo: 55 ML/day,
- Thaba Nchu (including 36 villages) :17 ML/day,
- Excelsior: 4 ML/day, and
- Bloemfontein 27 ML/day.

The Groothoek Water Treatment Works is situated 17 km from Thaba Nchu near the Maria Moroka Game Reserve. Besides supplying water to the villages south of Thaba Nchu, the system acts as an augmentation scheme for the Rustfontein Water Supply System (DWA, 2010). The average production rate of the Groothoek Water Treatment Works is 12 ML/day. This dam is currently at 0% (January 2017), because of the severe draught and this puts a high risk on the area's water supply.

The Caledon River region scheme is BloemWater's largest scheme and comprises the Welbedacht Water Treatment Works, which supply 145 ML/day. The scheme supplies the most of its water to Bloemfontein with take-off to Wepener, Dewetsdorp, Edenburg, Reddersburg and surrounding farmers (DWA, 2010). The water treatment plant is situated 110 km south-east of Bloemfontein at the Welbedacht dam.

The average volumes of water delivered from the Welbedacht Water Treatment Works to the towns in the GBSS are as follows (DWA, 2010):

- Wepener: 3.73 ML/day
- Dewetsdorp: 4 ML/day
- Reddersburg-Edenburg: 3 ML/day
- Bloemfontein: 113 ML/day

Orange River Region

The Orange River region scheme is Bloem Water's small-sized scheme and comprises four water treatment works, namely (DWA, 2010):

- Bethulie: 6 ML/day (currently being increased to 12 ML/day),

- Gariep: 2.8 ML/day,
- Phillippolis: 1.2 ML/day, and,
- Jagersfontein: 2 ML/day.

The Bethulie Water Treatment Works is situated in Bethulie, which receives water from a pump station at the Steyn Bridge in the Orange River from approximately 33 million cubic meter to approximately 80 million cubic meter and supplies water to the towns of Bethulie, Springfontein and Trompsburg. The Gariep Water Treatment Works is situated at the Gariep Dam and supplies water to the town of Gariep. The Phillippolis Water Treatment Works is situated 50 km from the Orange River (Tolhuis), in the town of Phillippolis, and supplies water to this town.

2.3 Current and Future Water Demand in the Bloemfontein Area

2.3.1 Historical water consumption in Bloemfontein

In Figure 3, the annual volumes of water supplied from the GBSS are shown for the period 1993 to 2011. From the figure it can be seen that the water demand has steadily increased during this period, from approximately 33 ML/annum on 1993 to approximately 80 ML/annum in 2011, although the demand did show a decrease during the period of high rainfall experienced in 2002.

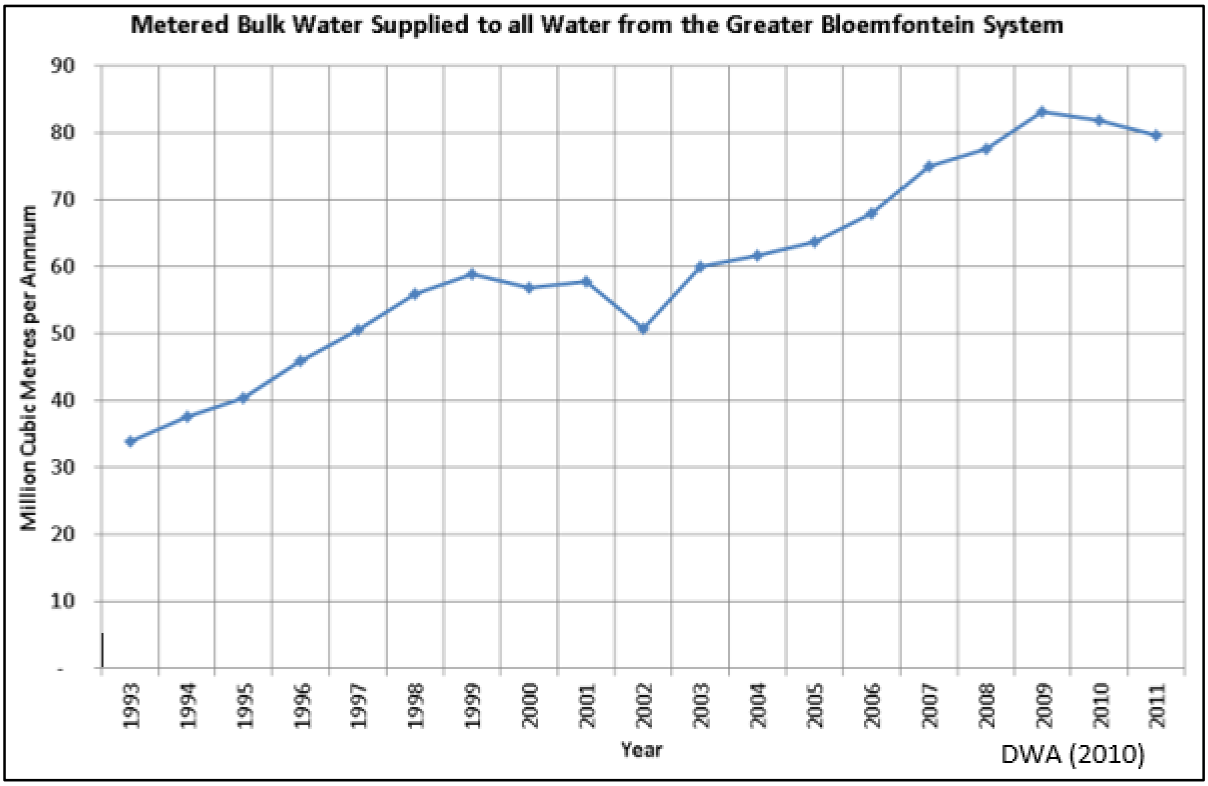

Figure 3. Metered bulk water supply from the Greater Bloemfontein Supply System

2.3.2 Current water demand

BloemWater is the main supplier of bulk potable water to the urban centres in the Modder/Riet River sub-catchment and currently supplies approximately 100 million m^3/a to about 580 000 people. Unaccounted water use which in the Bloemfontein area has reached more than 39% of the total annual consumption (DWA, 2012).

The Greater Bloemfontein area currently utilises surface water from three primary sources, namely the Welbedacht/Knellpoort system, the Rustfontein Dam and Maselspoort Weir. The total current capacity of reservoirs serving the Greater Bloemfontein is 425 ML (this includes Mangaung Municipality reservoirs) (BloemWater, 2015). The capacity of BloemWater's bulk reservoirs is 278 ML.

2.3.3 Future water demand

Estimates of the future water requirements for the Bloemfontein area are based on more than population growth and local economic growth. Other factors affecting the water demand include (DEA, 2013):

- Changes in the level of service with improvements in water services, sanitation, and health awareness
- Impact of HIV/AIDS on population numbers, with the highest occurrence in the rural areas.

Three population growth scenarios, namely low, medium and high growth, have been used considered to estimate the future water demand (refer to Figure 4).

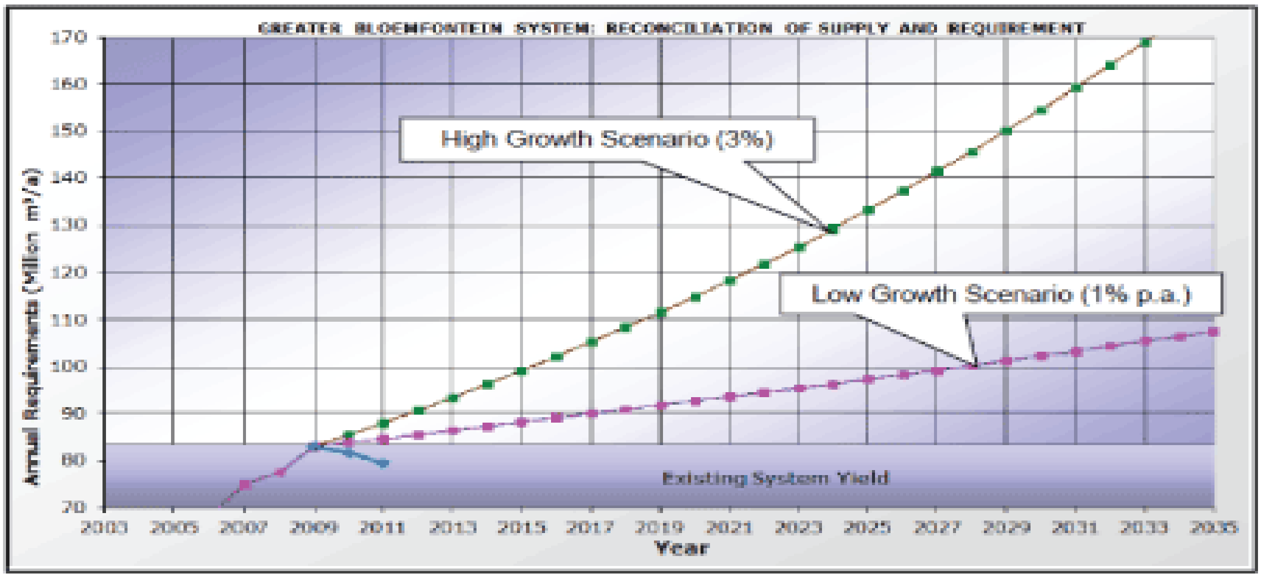

Figure 4. The Greater Bloemfontein Study graph of future scenarios of water supply

In the **low-growth scenario**, anticipated growth in existing population is mainly attributed to a higher mortality rate as a result of HIV/Aids, a lack of urbanisation in the smaller towns, a decline in development within Bloemfontein, as well as higher emigration rates from the rural areas due to a stagnant and declining local economy and a low immigration rate for Bloemfontein (DEA, 2013).

In the **medium-growth scenario**, anticipated growth in the existing population is more or less in line with the average between the low and high growth scenarios. In this scenario it is assumed that there will be a lack of urbanisation in the smaller towns, but more positive growth for development within Bloemfontein, as well as higher emigration rates from the rural areas due to a declining local economy, with the assumption that these residents will migrate to Bloemfontein and Botshabelo in seek of employment opportunities (DEA, 2013).

In the **high-growth scenario**, it is anticipated that growth in existing population will be attributed to a lower mortality rate and a longer life expectancy as a result of a successful HIV/Aids treatment programme (supported by improved health services), an increase in urbanisation in the smaller towns, and further development within Bloemfontein (DEA, 2013). Emigration rates from the rural areas will decline, specifically to other provinces such as Gauteng, as well as a more positive immigration rate to Bloemfontein, specifically from other provinces, such as the Northern Cape and Kwazulu-Natal (DEA, 2013).

The current situation in South Africa as far as water supply is concerned, is that a large fraction of the population does not have an adequate water supply. As an example of the influence of population increases on the water demand, it has been estimated that the 1995 increase in the South Africa population of approximately 1 million people, projected to the year 2015 when newborns reach adulthood, will result in an increase in the water demand of approximately 638 ML/day. This indicates the tremendous pressure on water resources as a direct consequence of the high current levels of population growth (Schutte and Pretorius, 1997). It is expected that the water demand in Bloemfontein will experience similar pressures, especially under the high-growth scenario described above.

2.4 The Karoo Supergroup

The rocks of the Karoo Supergroup were deposited in glacial, deep marine, shallow marine, deltaic, fluvial, lacustrine as well as, aeolian environments, and the deposition took place during the Late Carboniferous until the Early Jurassic eras (Johnson *et al.*, 2006). Deposition took place in a number of basins during the formation and breakup of Pangea. The Main Karoo Basin covers an approximate area of 700 000 km^2, but during the period of Late Carboniferous to Permian it was more extensive with an area of approximately 1 500 000 km^2 (Selley, 1997). The basin is made up of sedimentary strata aged between Late Carboniferous to Middle Jurassic, and has a maximum thickness of approximately 12 km in the southern portion of the basin towards the eastern end of the Karoo trough (Woodford and Chevallier, 2002). According to McCarthy and Rubidge (2005) the rocks which are found at the lower parts of the Karoo Basin depict a time during which climatic conditions were changing in southern Gondwana.

Figure 5 shows a schematic cross-section through the Main Karoo Basin from George in the south-west to Johannesburg in the north-east. It is seen that the Karoo deposits are thicker in the south-west than in north-east. Karoo sedimentary rocks in the south-eastern and southern parts of the basin display extensive deformation due to the influence of the Cape orogeny. The Karoo Supergroup is subdivided into different groups, depending on the depositional environments that reigned during deposition of the sediments. These groups are: the Dwyka, Ecca, Beaufort and Stromberg Groups. The Drakensberg Group consists of basaltic lavas erupted during a period of extensive lava outflows in the basin (see figure 5). The outpouring of lava brought the Karoo sedimentation to an end (Woodford and Chevallier, 2002).

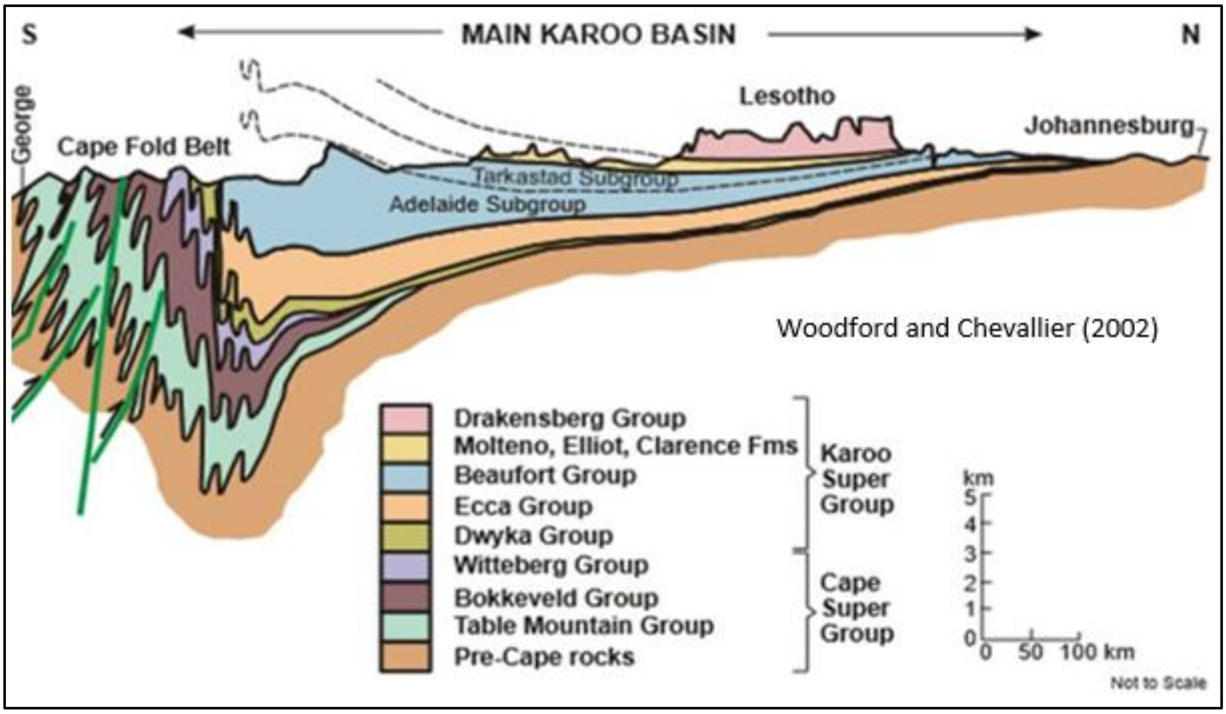

Figure 5. Cross-section through the Main Karoo Basin

2.4.1 The Dwyka Group

The Dwyka Group is the oldest deposit in the Karoo; its sediments were deposited during the Late Carboniferous to Early Permian period by glacial processes and underlying rocks, more especially in the northern part, displaying well-developed striated glacial pavements in places. This particular group is made up of mainly diamictite (tillite) which is generally massive with little jointing, but it may be stratified in places. Other associate rocks are conglomerate, sandstone, rhythmite and mudrock (both with and without dropstones) (McCarthy and Rubidge, 2005).

2.4.2 The Ecca Group

The Ecca Group was deposited during the Permian period onto the Dwyka Group. The Ecca Group consists of 16 formations, representing the lateral facies changes that characterise this succession (Johnson *et al*., 2006). The basal sediments in the southern, western and north-western zones of the basin which are the Prince Albert and Whitehill Formations, will first be described, followed by the southern Collingham, Vischkuil, Laingsburg, Ripon, Fort Brown and Waterford Formations.

The remaining western and north-western sediments of the Tierberg, Skoorsteenberg, Kookfontein and Waterford Formations and the north-eastern Pietermaritzburg, Vryheid and Volksrust Formations will then be considered.

The Prince Albert 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 Pietermarizburg Formations (Johnson *et al.*, 2006). It 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. The southern facies is characterised by the predominance of dark-grey, pyrite-bearing, splintery shale and the presence of dark-coloured chert and phosphatic nodules and lenses.

The mudrock of Whitehill Formation weathers white on surface, making it a very useful marker unit. In fresh outcrops and in the subsurface, the predominant facies is black, carbonaceous, pyrite-bearing shale. The shale is very thinly laminated and contains up to 17% organic carbon (Johnson *et al*., 2006). The thickness of the Whitehill Formation varies from 10 to 80 m towards the north-east. Its lower parts comprise siltstone and very fine-grained sandstone.The outcrops of the Collingham Formation are mainly found in the southern and western margins of the Main Karoo Basin. The thickness of this particular formation ranges between 30 and 70 m. The formation is made up of a rhythmic alteration of thin, continuous beds of hard, dark-grey siliceous mudrocks and very thin beds of softer yellowish tuff (Johnson *et al.*, 2006).

The Vischkuil Formation is mainly argillaceous and overlies the Collingham Formation in the southern part of the basin. The Vischkuil Formation has a thickness which ranges from 200 to 400 m, becomes more arenaceous towards the east and grades into the Ripon Formation (Johnson *et al*., 2006). The formation comprises dark shales, alternating with subordinate sandstone, siltstones and minor yellow tuff. The formation Laingsburg is made up of four sandstone-rich intervals separated by shale units, and has a thickness of 400 m. A vertical cut-off is located in the east where the underlying Vischkuil Formation merges with Ripon Formation (Johnson *et al*., 2006). Massive thick sandstones are fine-to medium-grained and are parallel-sided with sharp upper and lower contacts. The Ripon Formation has a thickness of 600 to 700 m, but towards the eastern parts of its outcrop, it is approximately 1 000 m thick. It consists of poorly sorted, fine- to medium-grained lithofeldspathic sandstone alternating with dark-grey clastic rhythmite and mudrock (Johnson *et al*., 2006).

Rhythmite and mudrock are the main constituents of the Fort Brown Formation with minor sandstone intercalations. These sedimentary units display an overall upwards-coarsening tendency. Outcrops are confined to the southern margin of the basin (Johnson *et al.*, 2006). The average thickness is approximately 1 000 m, with values ranging from 500 to 1 500 m. Sand/silt layers display a general upward increase in thickness within the formation. The Waterford Formation is arenaceous and it overlies the Fort Brown Formation west of 26°E. Its thickness varies from 200 to 800 m. The formation is made up of alternating very fine-grained, lithofeldspathic sandstone and mudrock or clastic rhythmite units (Johnson *et al*., 2006). The Britskraal Shale Member in the upper part of the Waterfort Formation in the eastern outcrop area averages 100 m in thickness and essentially consists of dark-grey mudrock and rhythmite.

The Tierberg Formation is a mainly argillaceous succession which is approximately 700 m in thickness along the western margin of the basin. Towards the north-east it thins to approximately 350 m. It rest with a sharp contact on the Collingham or Whitehill Formations and grade upwards into the arenaceous Waterford Formation or, where the latter is absent, into the Adelaide Subgroup of the Beaufort Group (refer to Section 2.4.3). The Skoorsteenberg Formation is a lens shaped; arenaceous unit located between the Tierberg and Kookfontein Formations in the south-western part of basin. The Skoorsteenberg Formation has a thickness of approximately 250 m and comprises up to five sandstone-rich units with shale units separating them (Johnson *et al.*, 2006).

The Kookfontein Formation overlies the Skoorsteenberg Formation with a sharp contact and grades upwards into the Waterford Formation. It is the same size as the upper part of the Tierberg Formation and is approximately 350 m in thickness (Johnson *et al.*, 2006). The lower part of the formation comprises horizontal laminated dark-grey shales alternating with clastic rhythmite, which form minor upward-thickening cycles. The Waterford Formation overlies the Kookfontein and Tierberg Formations with a gradational contact. It has a thickness of 130 m along the western flank of the basin. The major rock types are fine- to medium-grained sandstone, siltstone, shale and rhythmite (Johnson *et al*., 2006). The Pietermaritzburg Formation is the lower-most unit of the Karoo Supergroup in the north-eastern part of the basin and generally overlies the Dwyka Group with a sharp contact. It is made up of dark silty mudrock, which coarsens upwards, with heavily bioturbated and penecontemporaneously deformed sandy and silty beds appearing near the top

(Johnson *et al*., 2006). Fossils, such as invertebrate traces, are found on bedding planes of carbonate cemented mudrock.

The Vryheid Formation has a maximum thickness of approximately 500 m and thins towards the north, west, and south. Thinning and pinch-out towards the south-west and south is due to a facies gradation of its lower and upper parts into shales of the Pietermaritzburg and Volksrust Formations. Lithofacies of the Vryheid Formation are arranged in upward-coarsening cycles; these cycles are 80 m thick and originate from deltaic deposition (Johnson *et al.*, 2006). The deltaic cycle in the eastern part of the formation consists of dark-grey, muddy siltstone resulting from shelf suspension deposition in anoxic water of moderate depth.

The Volksrust Formation is a predominantly argillaceous unit which interfingers with the overlying Beaufort Group and underlying Vryheid Formation. Drilling results revealed that it reaches a thickness of 380 m approximately 120 km north-east of Bloemfontein, thinning to 250 m towards the northern margin of the basin (Johnson *et al*., 2006). The formation consists of grey to black silty shale with thin, usually bioturbated, siltstone or sandstone lenses and beds, particularly towards its upper and lower boundaries.

2.4.3 The Beaufort Group

The rocks of the Beaufort Group were deposited by large, northward-flowing meandering rivers in which sand accumulated, flanked by extensive floodplains where periodic floods deposited mud (McCarthy and Rubidge, 2005). The Beaufort Group of the Karoo Supergroup is subdivided into the Lower Adelaide, Upper Tarkastad Subgroups, and six formations which are the Koonap, Middleton, Balfour, Abrahamskraal, Teekloof and Normandien Formations. Of these formations, the Koonap, Middleton, Balfour Formations belong to the Adelaide Subgroup, and the Abrahamskraal, Teekloof and Normandien Formations belong to the Tarkastad Subgroup (see Figure 6).

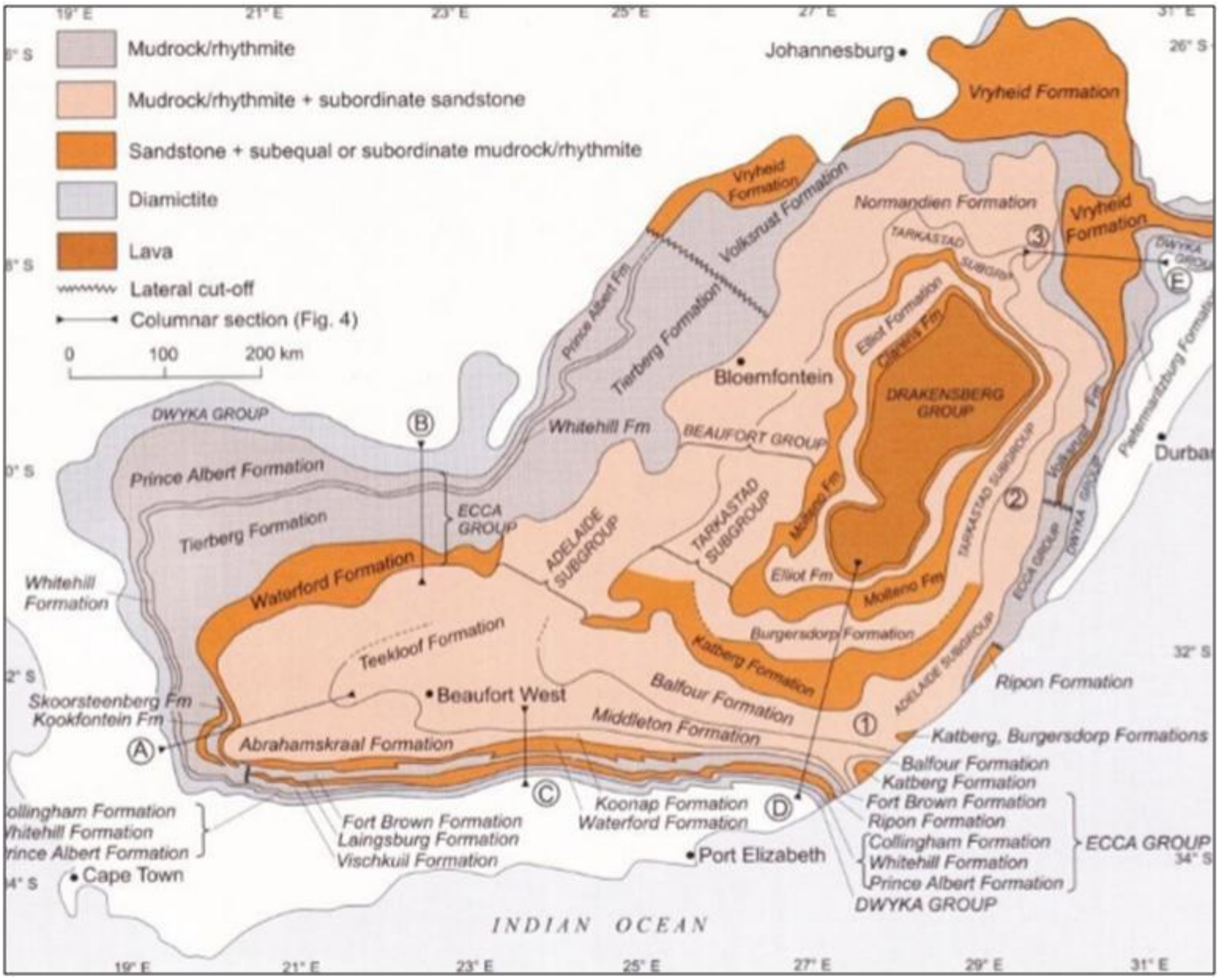

Figure 6. Schematic plan of the main Karoo Basin showing the geographic and stratigraphic relationship of the formations of the Beaufort Group (modified from Johnson *et al.,* 2006)

The Adelaide Subgroup, of late Permian age (i.e. 260 Ma), has a maximum thickness of 5 000 m in the south-east of the basin, which decreases rapidly to about 800 m in the extreme north (Woodford and Chevallier, 2002). The Koonap Formation has a maximum thickness of approximately 1 300 m, while the Middleton and Balfour Formations have thicknesses of approximately 1 600 and 2 000 m, respectively. Towards the southern and in the central parts of the basin, the Adelaide Subgroup consists of the older Abrahamskraal and younger Teekloof Formations, which form alternating bluish-grey mudstone and grey, very fine- to medium-grained and lithofeldspathic sandstone (Woodford and Chevallier, 2002).

The Tarkastad Subgroup was formed during the early Triassic period and it is characterized by abundance of both sandstone and mudstone in contrast with Adelaide Subgroup. In the western parts of the Beaufort Group, the Abrahamskraal and Teekloof Formations are up to 2 500 and 1 400 m in thickness, and the Normandien Formation has a thickness of about 320 m. (Woodford and Chevallier, 2002). The subgroup comprises of the lower Katberg and upper Burgersdorp

Formation, whereby according to Woodford and Chevallier (2002), Katberg Formation is sandstone rich and Burgersdorp Formation is mudstone rich.

Woodford and Chevallier (2002) postulated that the Katberg Formation of the Tarkastad Subgroup was deposited in a braided stream environment, because the sandstone and mudstone units of the Tarkastad Subgroup tend to form fining-upwards cycles in contrast with those of the Adelaide Subgroup. The Subgroup has a maximum thickness of about 2000 m in the southern part of the Basin, and a decrease of 800 m occur in the mid-basin as well as 50 m or less in far northern extremity of the Basin.

Burgersdorp Formation sandstones are greenish grey to light brownish grey and are fine grained. In the central part of the Formation, the average thickness of sandstone is 2 m in the main outcrop area, (Woodford and Chevallier, 2002). The Katberg Formation sandstones are light brownish grey to greenish grey, fine to medium-grained and consist of scattered pebbles up to 15 cm in diameter within the coastal outcrops, (Woodford and Chevallier, 2002). Oval and spherical calcareous concretions of about 3-10 cm in diameter are also common. The Beaufort is rich in reptilian and amphibian remains, first discovered in the fifties of the last century by Andrew Geddes Bain, the father of geology in this country and these remains have permitted a subdivision into six biostratigraphical zones (Truswell, 1970).

Following the deposition of Beaufort Group and Karoo Sediments, during the break-up of Gondwanaland, these sedimentary rocks were extensively intruded by dolerite magmas which resulted in dolerite sills, dykes and even inclined sheets which are present in the study area (Woodford and Chevallier, 2002).

2.4.4 The Stormberg Group

This particular group is made up of three formations which are the Molteno, Elliot and Clarence Formations. The sediments of these formations were deposited in different periods and by different processes. The lithology of the Stormberg Group reflects a gradual change to increasingly more arid conditions. The rocks of the Molteno Formation were deposited by large braided rivers and they formed 600 m of sandstones that can be seed in the cliff faces of the Bamboesberg, as well as the Stormberg Mountains in the Eastern Cape. The deposition of this particular formation took place during the Triassic period (Johnson et al., 2006).

The Elliot Formation, which overlies the Molteno Formation, was deposited by meandering rivers with an oxidised nature of sediments, and the change in climate conditions is well reflected in the floodplain (Johnson *et al.*, 2006). The lithology of the Elliot Formation provides evidence that there was another global mass extinction which took place during the Triassic to Jurassic periods.

Towards the end of the deposition of the Elliot Formation, warming and aridity increased. The overlying rocks of the Clarence Formation attest to desert conditions, but there is still evidence for river activity.

2.4.5 The Drakensberg Group

The rocks of the Drakensberg Group consist of basaltic lavas, and were laid down during a period of intense magmatic activity with lava outburst. The eruptions occurred mostly from long, crack like fissures through the Earth's crust up which magma welled. The lava flows were between 10 and 20 m thick, and over 1 600 m thick lava piled up forming the mountainous areas of Lesotho. A lot of magma was injected under pressure into the horizontal sedimentary layers of the Karoo Basin, where dolerite sills were formed and other magma solidified in the conduits, producing dolerite dykes (Johnson *et al.*, 2006). Dolerite rocks are resistant to erosion; they protect underlying sedimentary rocks from erosion. This is particularly true for dolerite sills. The Drakensberg Group volcanic rocks are well preserved in the high Drakensberg and Maluti Mountains and in Lesotho.

2.5 Karoo Dolerite

The Karoo dolerite is made up of an interconnected network of dykes and sills and it is difficult to identify a particular intrusion or tectonic event. From the geometry of the sills and dykes, it would seem that various fractures were intruded by magma at the same period. The dolerite intrusion signifies the beginning of a volcanic system; as a result, they are said to be the same age as the extrusive lava (Woodford and Chevallier, 2002).

There are different dolerite dyke swarms forming three major structural domains in the Karoo, namely: the Western Karoo Domain, the Eastern Karoo Domain, and the Transkei-Lesotho-Northern Karoo Domain (refer to Figure 7).

The Western Karoo Domain

It extends from Calvinia to Middelburg and is characterised by two distinctive structural features which are: the E-W Dyke Intrusion and the NNW Dyke Intrusion. In the E-W Dyke Intrusion, some of these dykes are extensive and continuous and can be followed over 500 km. They were intruded along a major right lateral E-W dislocation or shear zone and are accompanied by NW Riedel shears and NE-P type fractures (Woodford and Chevallier, 2002). Dykes of the NNW Dyke Intrusion are also extensive structures and are regularly spaced from east to west across the domain. The trend of these dykes differs along their trajectory, curving from WNW in the south to NS in the north (Woodford and Chevallier, 2002). Two dyke systems are specifically well developed, namely:

the Middelburg Dyke delimiting the Western Karoo Domain in the east, and the Loxton Fracture Zone in the centre of the delimiting boundary to the west.

The Eastern Karoo Domain

It extends from East London to Middleburg and comprises two major dyke swarms. The first is an arcuate swarm of extensive dykes diverging from a point offshore of East London. They display a strong curvy-linear pattern, trending approximately E-W along the coast and curving NNW to NS inland (Woodford and Chevallier, 2002). It seems likely that the Middleburg dyke was fed from one of these diverging intrusive systems. The dykes have a very thick width of up to 300 m. The second is minor trending dykes represent the extension and probably the termination of the Lesotho NE trend.

The Transkei-Lesotho-Northern Karoo Domain

It consists of two major swarms which are NW-trending dykes and NE-trending dykes. NW-trending dykes occur in the Transkei region, curving to EW in the Free State Province (Woodford and Chevallier, 2002). However, some of these dykes or intrusives do not curve and may form part of an extensive swarm which is 1 000 km long. NE-trending dykes mainly occurring within and alongside the Lesotho basalts and seem to converge towards the Limpopo-Lebombo Triple Junction.

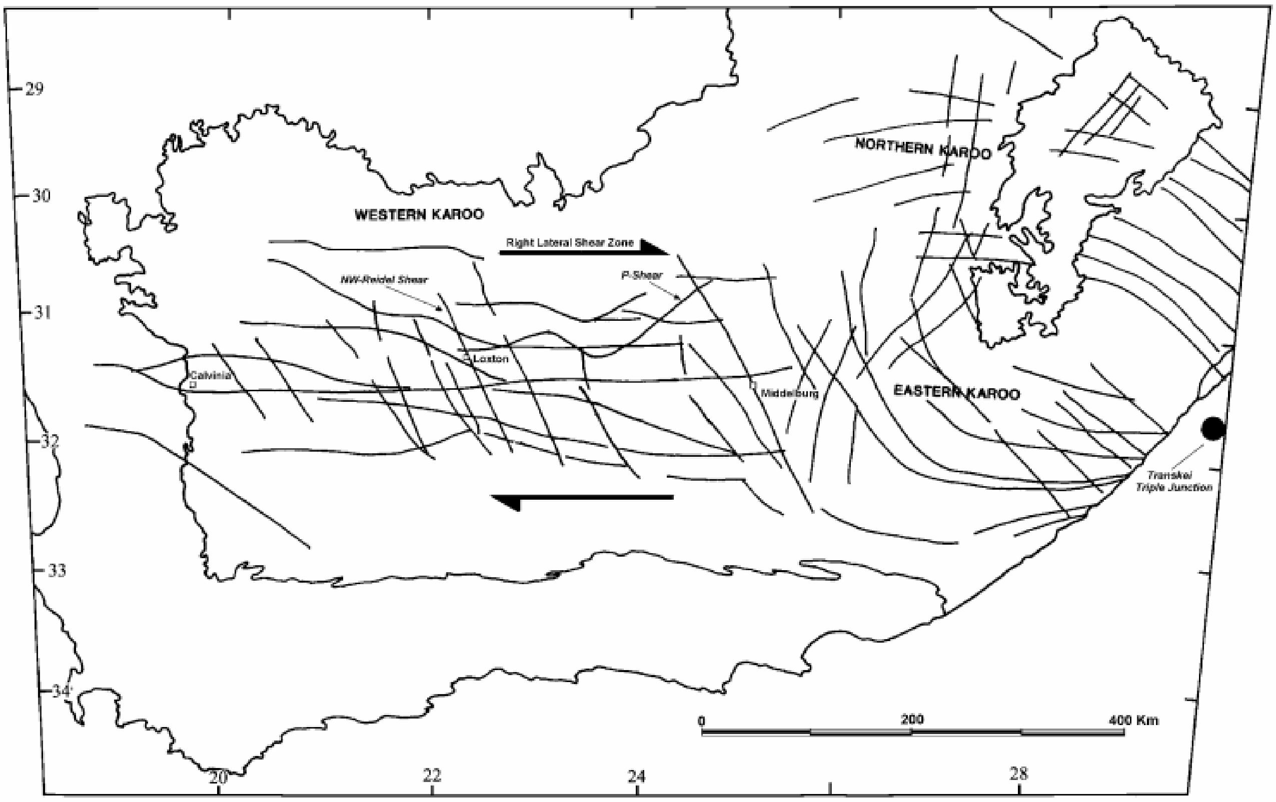

Figure 7. Dolerite dykes of the main Karoo Basin (Woodford and Chevallier, 2002)

2.5.1 Sills and ring complexes

The dolerite sills and rings have the same geographical distribution than the dykes and are by far the most common tectonic style in the Karoo Basin, controlling the geomorphology of the landscape to a large extent (Chevallier *et al*., 2001). The most common geometry in the Upper Ecca and Beaufort Groups is sub-circular saucer-like shape, the inclined rims of which are commonly exposed as topographical highs that form ring-like outcrops (Chevallier *et al.*, 2001).

The geometry becomes very complex at the regional scale since the rings form large coalescing, cross-cutting, circular, oval or kidney-shaped structural units. Each unit is in itself composed of several sub-units of smaller size which in turn are made of even smaller units and so forth, resulting in the so called "ring-within-ring" patterns. This suggests inherent structural control in the intrusive event; perhaps by jointing associated with initial uplift just prior to the magmatic intrusions (Chevallier *et al.*, 2001)

Many near vertical dykes branch onto the sill and ring complexes or cut through them. The relationship between the dykes and sill/ring complexes is very intricate (Chevallier *et al*., 2001). In the Western Karoo, many of the dykes can be seen feeding into the inclined sheet and controlling the shape of the ring, sometimes resulting in a jagged rim. Some of the dykes can also branch out of one ring into another ring (Chevallier *et al*., 2001).

2.5.2 Dolerite intrusions in the Beaufort Group

Steyl *et al.* (2011) described the results of a groundwater potential assessment conducted within the Mangaung Metropolitan Municipality in areas underlain by the Beaufort Group of the Karoo Supergroup. The authors discussed the role of dolerite intrusives in the groundwater potential of the area 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. Steyl *et al.* (2011) further stated that contact zones between dolerite intrusions and sedimentary rocks, as well as related tensional stresses, fault zones and fractures, are potentially rich targets for groundwater development.

Dolerite sills that are situated in low-lying and well drained areas experience more extensive weathering (below the aquifer table) (Steyl *et al*., 2011). These confined, shallow intergranular aquifers are capable of storing large volumes of groundwater, even though abstraction from these compacted and very big structures is only possible where extensive weathering has occurred (Steyl *et al.*, 2011).

2.6 Geohydrology of the Karoo Basin

2.6.1 Aquifers of the Main Karoo Basin

Karoo aquifers are classified as the multi-layered, multi-porous aquifers in which bedding parallel fractures form the main conduits of water. The opening and the extent of the fractures are limited flow (Botha *et al*, 1998*)*. Woodford and Chevallier (2002) concluded that the behaviour of aquifers in the Karoo Basin is determined by their bizarre geometry, more especially where horizontal, bedding-parallel fractures are present. The sandstone containing the most horizontal fractures also forms the main water-carrying formation, while the fractures operate as pathways for groundwater to boreholes in the Karoo aquifers. These fractures are also play an important role in the interactions between the aquifer. Fractures are therefore not able to store large quantities of water, with the result that their piezometric pressures drop rapidly when a borehole that intersects them is pumped. This drop in piezometric pressure will cause water to leak from the matrix to the fracture. There are thus two types of flow present in a Karoo aquifer: bedding-parallel fracture flow and matrix flow (Botha *et al.*, 1998*)*.

Fracture flow is the flow in a fully fractured medium is largely controlled by the fracture dimension, orientation and connectivity (Botha *et al*, 1998). The bedding-parallel fractures in Karoo aquifers are mainly horizontally orientated and evenly distributed. Since no large-scale vertical or sub-vertical fractures were observed in these aquifers, multiple bedding-parallel fractures will only be weakly connected through the intermediate rock matrix. The ability of a Karoo aquifer to transmit water will therefore be determined mainly by the apertures of bedding-parallel fractures, if present.

The matrix of Karoo rocks consists mainly of fine-grained mudstones, siltstones and shales, with interbedded sandstones, whose grain size can vary from fine to coarse. The rocks therefore originally had a very high primary porosity, but this porosity was considerably reduced by cementation and compaction. Matrix flow is when there is always a flux of water from the matrix to the fracture, as long as the piezometric pressure gradient exists from the rock matrix towards the fracture, because the matrix is the main storage unit. Although this flux may be small, the flow over a large area can be considerable. The matrix can thus supply large quantities of water to a bedding parallel fracture with a large areal extent. The result is that the pores and micro-fractures in the rocks are usually very small (Botha *et al.*, 1998).

2.6.2 Hydraulic properties of Karoo rocks

Sandstones found in the southern part of the Karoo Basin, south of latitude 29^{o}S, have an extremely low primary porosity and permeability (Woodford and Chevallier, 2002). The permeability and porosity of the Middle Ecca sandstones to the north of latitude 29^{o}S improve from south to north.

This trend relates to the general decrease in diagenesis from south to north over the Main Karoo Basin.

According to Woodford and Chevallier (2002), the porosity of Karoo sediments tends to be higher near the Earth's surface, perhaps because of weathering and leaching of the rocks within the upper 30 m. In the same way, the primary porosity of the sediments is expected to decrease with depth due to an increasing lithostatic pressure and temperatures. The average porosities of the sedimentary rocks tend to decrease from approximately 0.1 north of latitude 28°S to less than 0.02 in the southern and southern-eastern parts of the Main Karoo Basin, while their bulk densities increase from approximately 2 000 to more than 2 650 kg.m^{-3} (Botha *et al.*, 1998).

Figure 8 shows a map of the estimated average transmissivities in South Africa, Swaziland and Lesotho (Dennis and Wentzel, 2007). Although localised occurrences of transmissivities in excess of 500 m^2/day are observed, the transmissivity values generally below 60 m^2/day with an average of approximately 44 m^2/d. Kirchner *et al.* (1991) reported on pumping tests that had been carried out in different locations within the Karoo. The authors calculated transmissivity values varying between approximately 7 m^2/d and 286 m^2.

As storativity involves a volume of water per volume of aquifer, it is a dimensionless quantity. Its values in confined aquifers generally range from 5×10^{-5} to 5×10^{-3} (Kruseman and de Ridder, 1990). Kirchner *et al.* (1991) and Botha *et al.*, (1996) found estimates for the storativities of Karoo sedimentary rocks at two sites in Bloemfontein and Philippolis. The storativities for different rock units that ranged from values as low as 1×10^{-10} to 6.9×10^{-5}. Kirchner *et al.* (1991) also reported storativity values for Karoo rocks varying between approximately 1×10^{-7} and 2×10^{-1}. It is therefore seen that, although some exceptions occur, Karoo sedimentary rocks are generally characterised by low storativities.

As an example of the hydraulic parameters values of Karoo rocks, the aquifer on the campus 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 1. 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).

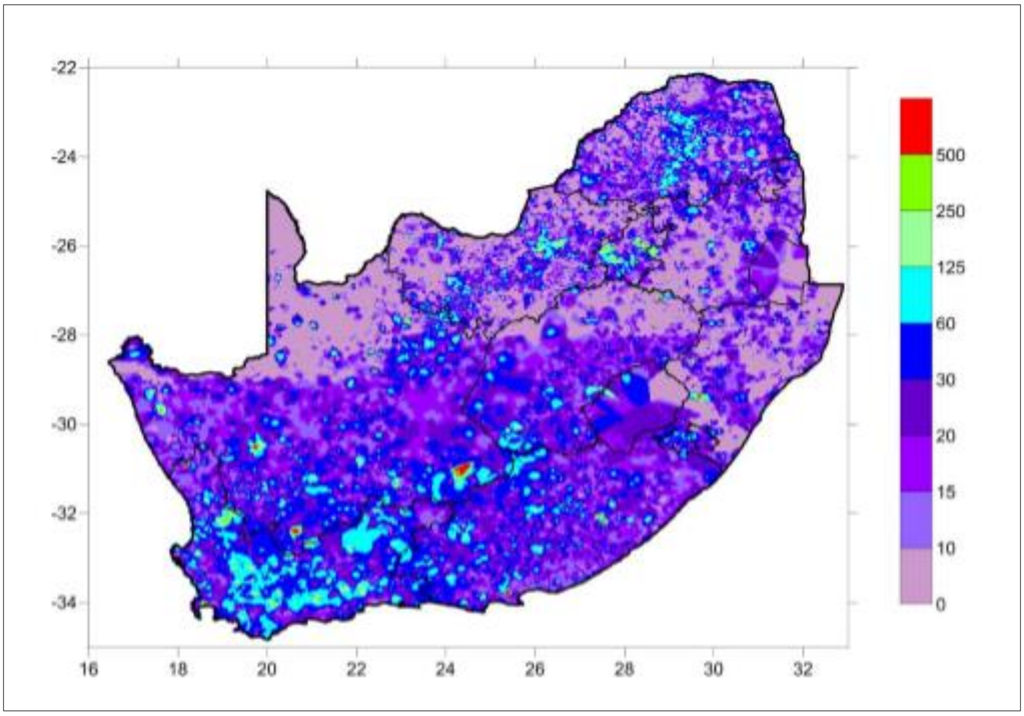

Figure 8. Estimated transmissivity values (m^2/d) for South Africa. Data points are from the Groundwater Resource Directed Management (Dennis and Wentzel, 2007)

Table 1. Estimated transmissivity and storativity values for the campus aquifer (Riemann *et al.*, 2002)

Parameter	Estimated value
K_{hm} (m/day)	0.158
K_{vm} (m/day)	$5.82x10^{-3}$
S_{sm} (m^{-1})	$5.65x10^{-5}$
K_{hf} (m/day)	$3.6x10^{3}$

2.6.3 Groundwater occurrence

The dolerite structures have always been regarded as major targets during groundwater exploration in the Karoo Supergroup. Groundwater is most often associated with the contact zone between the sedimentary rocks and the dolerites (Woodford and Chevallier, 2002). The intruding magmas that produced the dolerite sills and dykes were so hot that, instead of merely baking the Karoo sedimentary rocks, they actually metamorphosed them, which resulted in the formation of *altered* or *baked* zones along the contacts with the dolerites.

The average thickness of Karoo dolerite dykes ranges between 2 and 10 m (Woodford and Chevallier, 2002). Furthermore, dyke thickness appears to be positively correlated to dyke length.

The country rock along the dykes is typically fractured with the fractures forming a set of master joints parallel to the strike of the dyke. The thickness of the zone of fracturing does not vary greatly with the thickness of the dyke (it is usually between 5 and 15 m). The dolerite dykes are also affected by thermal or columnar jointing perpendicular to their margins. These joints also often extend into the host rock over a distance not exceeding 0.3 – 0.5 m from the contact (Woodford and Chevallier, 2002).

Dolerite dykes are usually vertically to sub-vertically orientated. They are associated with thin, linear zones of relatively higher permeability which act as pathways for groundwater in directions parallel to the strikes of the dykes, but they may also act as barriers which are semi- to impermeable to the movement of groundwater in directions perpendicular to the strikes of the dykes (Woodford and Chevallier, 2002). Dykes are often conspicuous as line of vegetation which can be well-observed during dry seasons.

Dolerite dykes are easily detected by the use of simple geophysical techniques (especially the magnetic and resistivity methods), and they are often clearly visible in the field (Woodford and Chevallier, 2002). Their simple geometry makes it easy to conceptualise and site an exploration borehole in the field. Dykes are also cost-efficient groundwater targets due to two properties of the dolerite dykes: (1) they can be highly magnetic and can be easily detected with existing geophysical methods, and (2) they are often associated with the formation of fractures in the contact zones (Botha *et al.,* 1998). Geohydrologists and groundwater-dowsers have sited many successful boreholes on these structures.

2.6.4 Aquifers of the Beaufort Group

The main source area of sediments for the Beaufort rocks is situated along the southern margin of the basin. The coarser grained rocks are found near the Cape Fold Belt, while mudstone, shale and fine-grained sandstones dominate central and northern portion of the basin (Steyl *et al.*, 2011). The geometry of the aquifers in this basin is complicated by lateral migration of meandering rivers over floodplain. Beaufort Group aquifers will therefore be multi-layered and also multi-porous with different thicknesses (Steyl et al, 2011).

The contact plane between two different sedimentary layers will cause a discontinuity in the hydraulic properties of the composite aquifer. The pumping of a multi-layered aquifer will consequently cause the piezometric pressure in the more permeable layers to drop more rapidly than in the less permeable layers (Steyl *et al.*, 2011). It is therefore possible to completely extract the more permeable layers of the multi-layered Beaufort aquifers, without materially affecting the piezometric pressure in the less permeable layers (Steyl *et al.*, 2011). This complex behaviour of aquifers in the Beaufort Group is further complicated by the fact that many of the coarser and thus more permeable sedimentary bodies are lens-shaped. The life-span of a high-yielding borehole in the Beaufort Group may therefore be limited, if the aquifer is not recharged frequently (Steyl *et al*., 2011).

2.6.5 Groundwater potential of aquifers associated with dykes near Bloemfontein

Steyl et al. (2011) conducted a hydrocensus and groundwater potential assessment in the vicinity of Bloemfontein. The authors estimated the potential yield of aquifers associated with dolerite dyke structures by using the geometric mean of the yield of the boreholes drilled along dykes (3 L/s), as determined from pumping tests with 8-hour pump cycles and 14 hour recovery periods. The lengths of the dolerites structures were taken into account during the estimation by assuming that abstraction from boreholes spaced every 250 m along the structure would not influence the available of groundwater at the other boreholes. By multiplying the number of boreholes along a particular dyke with the mean of the yield of the boreholes, the groundwater resource potential of the aquifers associated with the dykes was estimated. The dolerite dykes in the vicinity of Bloemfontein are shown with measured lengths in Figure 9 while their estimated potential yields are listed in Table 2. A total yield of more than 3 800 m^3/day was estimated for the 14 dolerite dykes investigated.

Table 2. Estimation of theoretical potential yield of the dolerite dykes near Bloemfontein (Steyl *et al.*, 2011)

Dyke group name	Number of dykes	Total length of dykes (m)	Number of potential boreholes (250 m spacing)	Estimated yield of dyke groups (m^3/d)
Bloemfontein	14	16650.3	67	3821

2.7 Geophysical Methods Commonly Used for Groundwater Exploration in Karoo Rocks

2.8 Introduction

In this section two geophysical techniques commonly used during groundwater exploration in Karoo rocks are discussed in terms of the principles on which they operate and their application to groundwater exploration. These two geophysical techniques are the magnetic and the resistivity methods. The techniques will be used during the groundwater exploration programme of the current investigations.

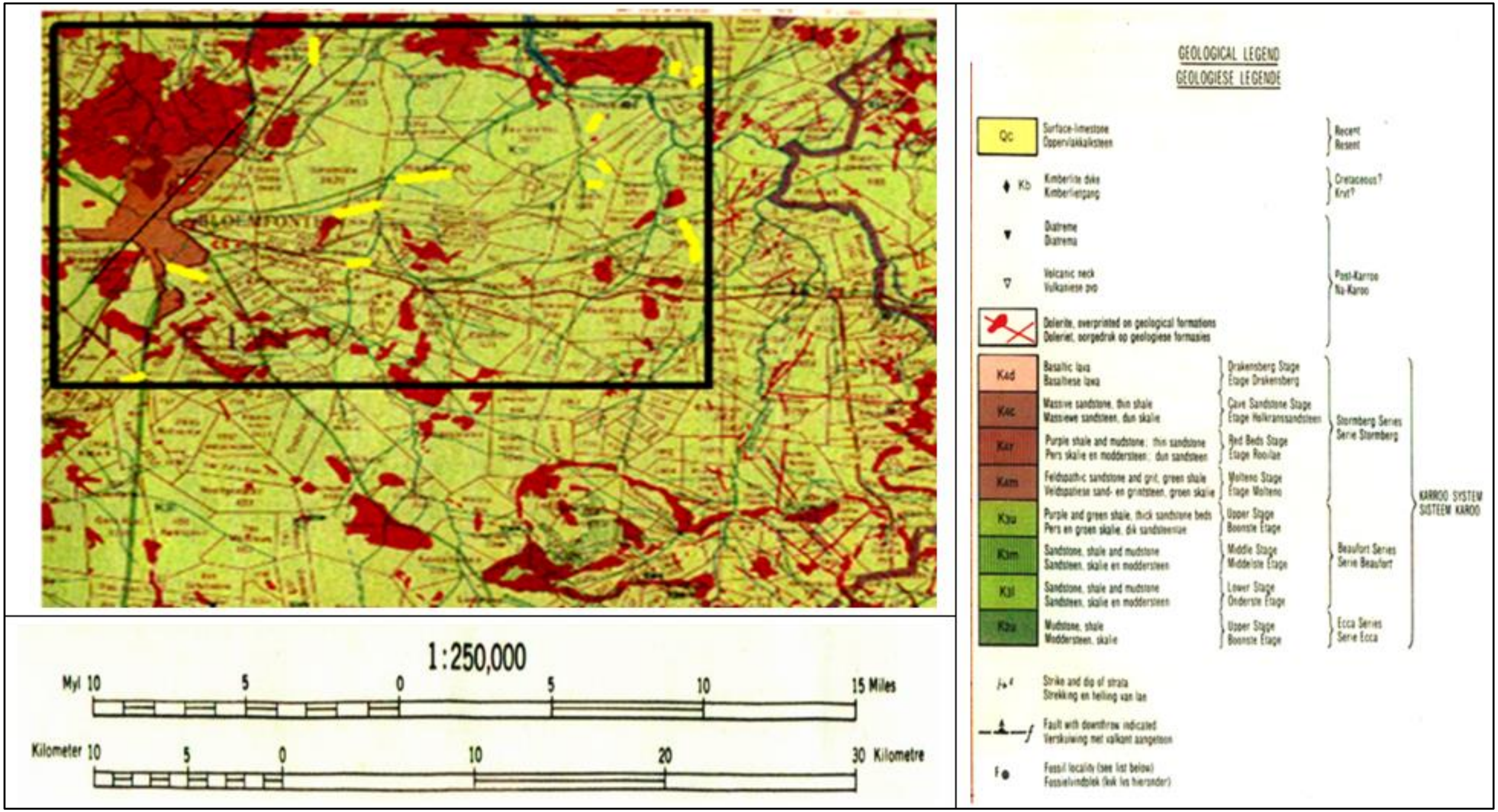

Figure 9. Geology map of Bloemfontein with dykes in yellow (Steyl *et al*, 2011)

2.8.1 The Magnetic Method

2.8.1.1 Introduction

The magnetic method is based on the fact that different earth materials have different magnetic properties. During a magnetic survey, measurements of the Earth's magnetic field are taken to detect changes in the magnetic properties of the subsurface materials. These changes are referred to anomalies and are interpreted in terms of their possible geological origins.

2.8.1.2 The origin of magnetic fields

According to the electromagnetic theory, 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 $\Delta\mathbf{H}$:

$$\Delta\mathbf{H} = (\mathbf{I}\Delta l) \times \frac{\mathbf{r}_1}{4\pi r^2}$$

where $\mathbf{r}_1$ 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 (see Figure 10) (Telford *et al.*, 1990).

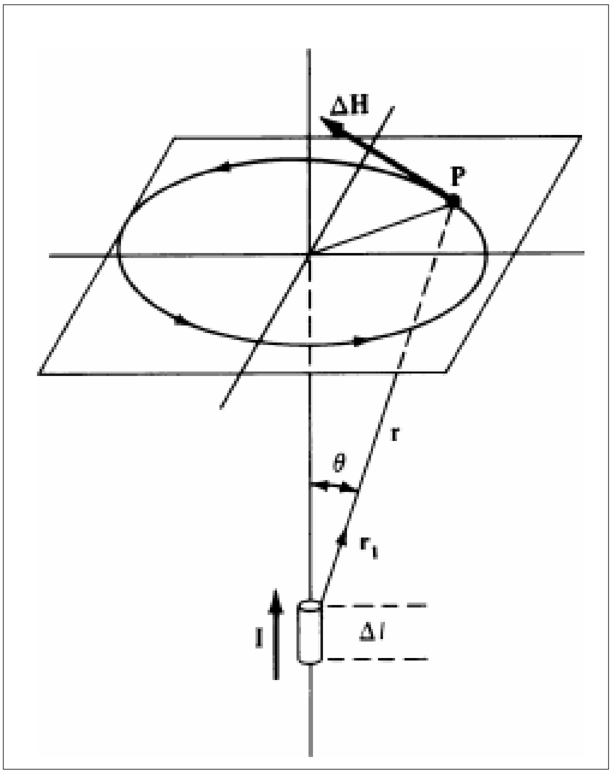

Figure 10. Current flow giving rise to a magnetic field according to Ampère's law (Telford *et al*. 1990).

2.8.1.3 The Earth's magnetic field

The Earth is surrounded by a magnetic field which is generated and maintained by convective motions of molten rock in the fluid outer core (Dormy and Mandea, 2005). The earth's outer core 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 (Gadallah and Fisher, 2009). The magnetic field lines point vertically downwards at the north magnetic pole and point vertically upwards from the south magnetic pole (refer to Figure 11) (a compass needle aligns itself along the magnetic field line at the position of measurement).

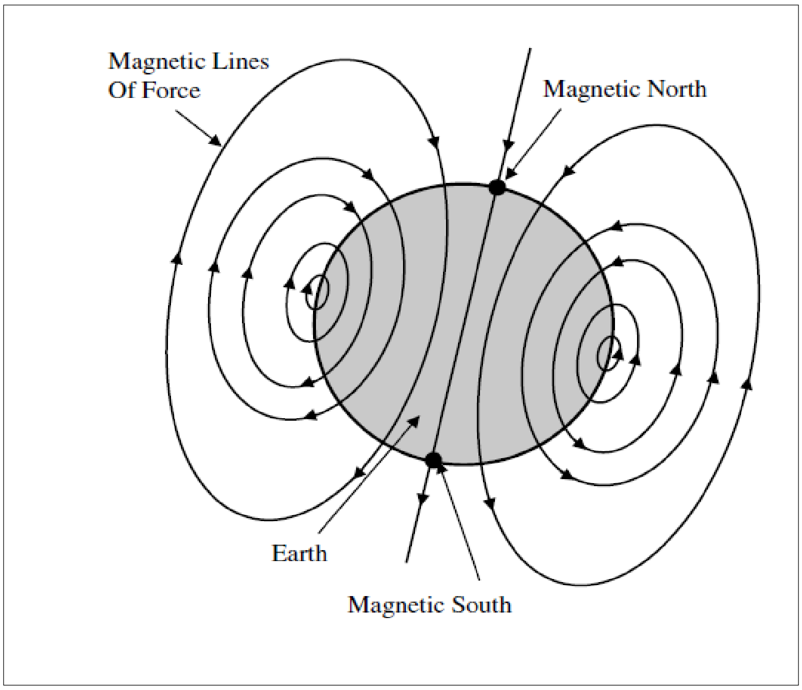

Figure 11. Illustration of the Earth's magnetic field (Gadallah and Fisher, 2009)

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 with a tilt of approximately 11 degrees compared to the axis around which the Earth rotates. The magnetic poles of the Earth are therefore not coincident with its geographic poles. Currently, the north magnetic pole is located in the Canadian Northwest Territories north-west of Hudson Bay and the south magnetic pole is near the edge of the Antarctic continent. Note that the positions of the magnetic poles are not fixed but constantly change.

The Earth's magnetic field is not constant, but displays daily cyclic changes. These changes are called *diurnal variations*. The main change of the magnetic field is due to changes in the electrical currents in the ionosphere, induced by solar radiation (Maus *et al.*, 2008). Apart from these changes, short-period changes may occur due to solar radiation (Goulet, 2001). These changes are particularly severe during large solar activity, which are often referred to as magnetic storms.

The Earth's magnetic field is a vector quantity, which has a directional component at any point of measurement. To describe the direction of the magnetic field, two parameters are usually defined, namely the *magnetic inclination* (*I*) and the *magnetic declination* (*D*). These parameters are defined relative to the Earth's surface and the direction of geographic north at the position of measurement. The magnetic declination is the angle between true (geographic) north and the direction towards which the compass points (horizontal component of the magnetic field). The magnetic inclination is the angle between the horizontal plane (the Earth's surface) and the direction of the magnetic field (refer to Figure 12).

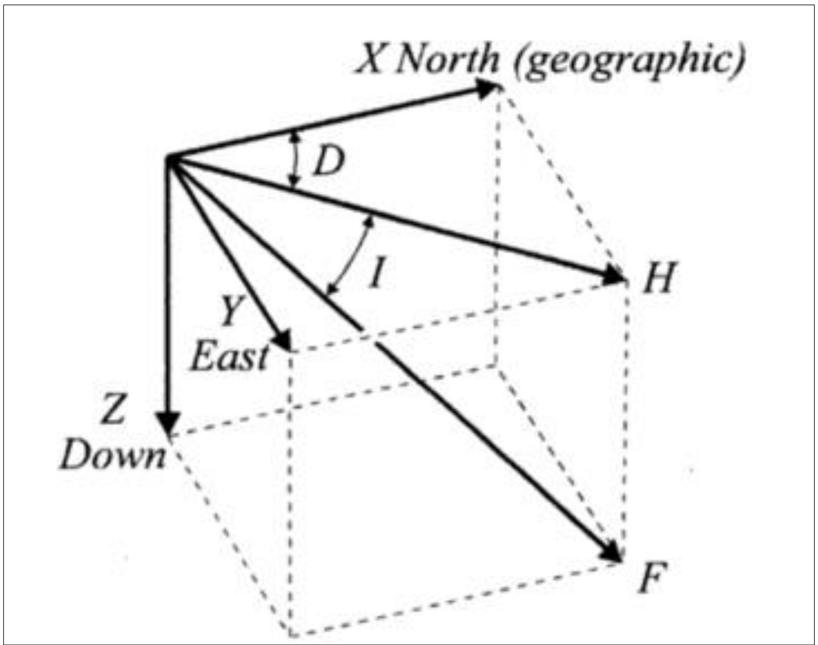

Figure 12. The components of the geomagnetic field (Merrill *et al.,* 1998)

2.8.1.4 Induced magnetism

When a magnetic material, such as iron, is placed in a magnetic field, it may acquire its own magnetism through a process known as induction. The induced magnetisation is directly related to the magnetic susceptibility of the material, as well as the strength of the inducing field (refer to Figure 13).

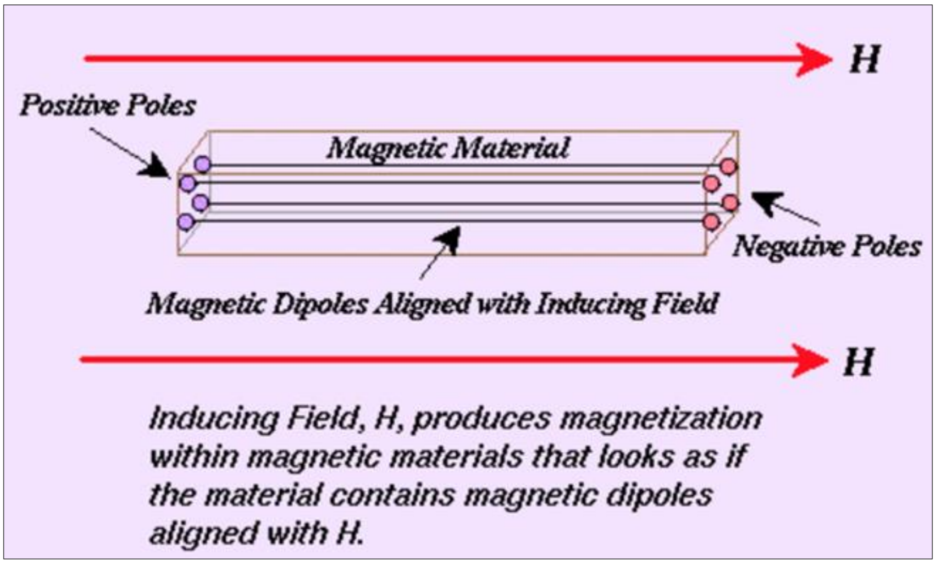

Figure 13. Induced magnetization (Mariita, 2007)

Earth materials in the crust may acquire their own magnetic fields in the presence of the Earth's magnetic field if these materials have large magnetic susceptibilities. The magnetic susceptibilities of sedimentary, metamorphic and igneous rocks, are typically low, high and very high, respectively, although large variations in the magnetic properties occur within the different rock types. The susceptibilities may further be influenced by small traces of certain magnetic minerals, such as magnetite, hematite and pyrrhotite (Cox, 1999).

2.8.1.5 Remanent magnetism

When a magnetic material has a relatively large susceptibility, or when the inducing field is strong, the magnetic material may retain a portion of its induced magnetization even after the induced field disappears. This phenomenon is called remanent magnetism.

Remanent magnetism also affects earth materials. Rocks can acquire a remanent magnetization through a variety of processes (Mariita, 2007). A typical example is when a volcanic rock cools, and its temperature decreases past the Curie Temperature. At the Curie Temperature, the rock, being magnetic, begins to produce an induced magnetic field. In this case, the inducing field is the Earth's magnetic field. As the Earth's magnetic field changes with time, a portion of the induced field in the rock does not change but remains fixed in a direction and strength reflective of the Earth's magnetic field at the time the rock cooled through its Curie Temperature. This is the remanent magnetization of the rock - the recorded magnetic field of the Earth at the time the rock cooled past its Curie Temperature.

Remanent magnetism represents the magnetic field of the Earth as it was at some previous time. The remanent magnetism therefore generally points in a different direction than the current magnetic field of the Earth (Woodford and Chevallier, 2002). Recording magnetic data across earth materials with remanent magnetism therefore leads involves the measurement of the vector sum of the induced and remanent fields. The magnetic anomalies thus recorded are different from the anomalies from induction alone. The presence of remanent magnetism can therefore lead to problems during the interpretation of the data.

Since remanent magnetism represents a recording of the ancient magnetic field of the Earth, geophysicists use the presence of remanent magnetism in rock materials to map the motion of continents and ocean basins resulting from plate tectonics.

2.8.1.6 Magnetic susceptibilities of minerals

Earth materials require the presence of magnetic minerals to be magnetic. The magnetic minerals that can contribute significantly to the remanence in rocks include iron-titanium oxides, iron-manganese oxides and oxyhydroxites, iron sulphides and iron and nickel-cobalt alloys (Merrill and McElhinny, 1983). In Table 3 some of the magnetic minerals found in earth materials are listed. From Table 3 it can be seen that magnetite, ilmenite and pyrrhotite have very large magnetic susceptibilities compared to the other minerals. These are the most common magnetic minerals that contribute to the magnetism of rocks.

Table 3. Magnetic susceptibilities of some common minerals (Telford *et al.*, 1990)

	SUSCEPTIBILITY x 10^3	
TYPE	**RANGE**	**AVERAGE**
Minerals		
Graphite		0.1
Quarts		-0.01
Rock salts		-0.01
Anhydrite, gypsum		-0.01
Calcite	-0.001 - -0.01	
Coal		0.02
Clays		0.2
Chalcopyrite		0.4
Sphalerite		0.7
Cassiterite		0.9
Siderite	1.0 - 4.0	
Pyrite	0.05 - 5	1.5
Limonite		2.5
Arsenopyrite		3
Hematite	0.5 -35	6.5
Chromite	3 - 110	7
Franklinite		430
Pyrrhotite	1 - 6000	1500
Ilmenite	300 - 3500	1800
Magnetite	1200 - 19200	6000

2.8.1.7 Magnetic rocks

The magnetic susceptibility of a rock depends on its content of magnetic minerals. In Table 4, the magnetic susceptibilities of some common rock types are listed. From this table it can be seen that sedimentary rocks generally have much lower magnetic susceptibilities than either metamorphic or igneous rocks. Igneous rocks are also generally more magnetic than metamorphic rocks.

Table 4. Magnetic susceptibilities of various rock types (Telford *et al.*, 1990)

	SUSCEPTIBILITY x 10^3	
TYPE	**RANGE**	**AVERAGE**
Sedimentary		
Dolomite	0 -0.9	0.1
Limestones	0 -3	0.3
Sandstones	0 -20	0.4
Shales	0.01 - 15	0.6
Av. 48 sedimentary	0 - 18	0.9
Metamorphic		
Amphibolite		0.7
Schist	0.3 -3	1.4
Phyllite		1.5
Gneiss	0.1 -25	
Quartzite		4
Serpentine	3.0 - 17	
Slate	0 -35	6
Av.61 metamorphic	0 -70	4.2
Igneous		
Granite	0 -50	2.5
Rhyolite	0.2 -35	
Dolorite	1 - 35	17
Augite-Syenite	30 - 40	
Olivine-diabase		25
Diabase	1 - 160	55
Porphyry	0.3 - 200	60
Gabbro	1 - 90	70
Basalts	0.2 - 175	70
Diorite	0.6 - 120	85
Pyroxenite		125
Peridotite	90 - 200	150
Andesite		160
Av. acidic igneuos	0 - 80	8
Av. basic igneuos	0.5 - 97	25

2.8.1.8 Magnetic surveying

During magnetic surveys, the Earth's magnetic field is measured at various stations along survey lines (traverses) or on survey grids. The aim of the surveys is to detect changes in the magnetic properties of the subsurface and to relate these changes to the local geological conditions (Telford *et al*., 1990).

Recorded magnetic data are processed to remove the influence of the Earth's diurnal variations and other sources of magnetic noise so that only those changes in the magnetic field related to subsurface changes in magnetic properties remain. These changes are called *magnetic anomalies*. The shapes of the anomalies contain information on the size, shape, geometry and magnetic susceptibility of the geological feature causing the anomaly (Telford *et al*., 1990).

2.8.1.9 Instrumentation

Various types of magnetometers are available for magnetic surveys. These magnetometers operate on different physical principles, but all measure the Earth's magnetic field, or different components of the Earth's magnetic field. Modern magnetometers include: the proton precession magnetometer, the caesium vapour magnetometer, the SQUID (superconducting quantum interference device) magnetometer and the Overhauser magnetometer. These magnetometers each have their own advantages and disadvantages, and each operate at different levels of accuracy.

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. For this reason, the system is often referred to as a *Walkmag*. Photographs of the use of the Walkmag are presented in Figure 14.

Figure 14. Magnetic survey using the Walkmag of GEM Systems

2.8.2 The Resistivity Method

2.8.2.1 Introduction

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, and is easy to operate and inexpensive (Rubin & Hubbard, 2005). Resistivity surveys are of use for determining the depths of contacts between formations, because different geological units have different 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 Basic principles

Resistivity is often first encountered in physics when discussing the resistance of an ideal cylinder of length L and cross-sectional area A of uniform composition (Herman, 2001). For such a setup, the familiar Ohm's Law it used to express the relationship between the injected electrical current (I) and the electrical potential (V) across the cylinder:

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

where R is the resistance of the object. The resistivity (ρ) of the material appears as the material-specific constant of proportionality in the expression for the total resistance of the cylinder.

$$R = \rho \frac{L}{A} \tag{2}$$

For a cylinder consisting of homogeneous material, the resistivity ρ (unit: Ohm.meter, Ωm) can thus be calculated from:

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

From Equation (2) it can be seen that the resistance of a cylindrical object is dependent on both the material properties (ρ) and the geometry (L/A) of the object.

During resistivity surveys, the resistivity of the ground is measured by injecting electrical current into the subsurface and by measuring the resulting electrical potential difference at the surface of the Earth. In the standard configuration, two pairs of electrodes are required, namely: two electrodes used for current injections (the *current electrodes*, normally denoted by A and B), and two electrodes for the measurement of the resulting potential difference (the potential electrodes, normally denoted by M and N) (Herman, 2001) (refer to Figure 15).

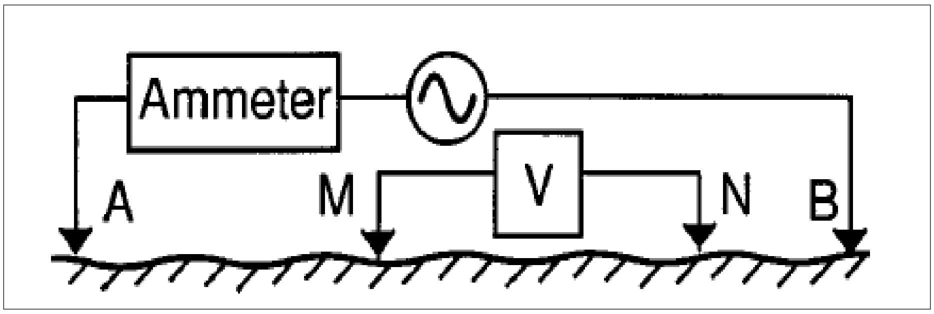

Figure 15. General configuration of surface resistivity surveys (Herman, 2001)

During resistivity surveys on the surface of the Earth, current flow in the subsurface is not restricted to a single pathway. Rather, the electrical current flows in three dimensions through the earth materials in the subsurface. It is therefore not possible to directly measure the resistivities of the subsurface materials. However, it is still possible to obtain information on the subsurface resistivity distribution.

For a standard four-electrode setup, such as shown in Figure 15, it is possible to calculate the *apparent resistivity* of the subsurface. The apparent resistivity is the resistivity that would have been recorded using such a setup on a homogeneous subsurface (Herman, 2001). The apparent resistivity (ρ_a) may be calculated from the following equation:

$$\rho_a = K\frac{V}{I} \tag{4}$$

where *K* is called the *geometric factor*. Comparison of Equations 2 and 3 shows that the equation for the apparent resistivity of the subsurface has the same form as the equation for the resistivity of the cylinder, that is, it depends on the ratio between the electrical potential and the electrical current, as well as on a geometrical factor describing the geometry of the materials through which current flow takes place (Herman, 2001).

For a standard four-electrode setup, the geometric factor may be calculated from:

$$K = \frac{1}{2\pi}\left[\left(\frac{1}{AM} - \frac{1}{BM}\right) - \left(\frac{1}{AN} - \frac{1}{BN}\right)\right]^{-1} \tag{5}$$

where AM represents the distance between the A current electrode and the M potential electrode, and so forth.

2.8.2.3 Depth of investigation

The depth of investigation during a resistivity survey using the standard four-electrode configuration depends on the distance between the current electrodes (the AB distance). Larger current electrode spacings lead 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

2.8.2.4 Sounding and profiling

The resistivity distribution of the subsurface can be investigated in either a lateral sense to investigate lateral changes in the subsurface resistivities, or in a vertical sense to investigate resistivity changes with depth. Measurement of the lateral changes is called *profiling*, while measurement of the vertical changes is called *sounding* (Telford *et al*., 1990).

During profiling, the current electrode separation (AB) is kept constant while the entire array is moved laterally across the surface of the Earth during surveying. This allows constant depths of investigation to obtain a profile of the resistivity changes at a specific depth of investigation (Telford *et al*., 1990).

During sounding, the centre of the electrode array is kept constant, while the AB-separation is increased to allow different depths of investigation. Apparent resistivity data corresponding to different depths of investigation may thus be recorded (Telford *et al*., 1990).

2.8.2.5 Electrode geometries

Different electrode geometries (arrays) are possible using the standard four-electrode configuration. Each electrode geometry is characterised by advantages and disadvantages in terms of their abilities to resolve vertical and lateral changes in resistivities, their depths of exploration, their sensitivities to noise, and their coverage of the subsurface (Loke, 1999).

The most commonly used electrode geometries are the Wenner, Schlumberger and Dipole-Dipole arrays. These, and a few other, arrays are shown in Figure 16.

2.8.2.6 The resistivities of earth materials

The resistivities of some common earth materials are listed in Table 5. From the values listed in this table it seen that igneous and metamorphic rocks typically have high resistivity values. The resistivity of these rocks is greatly dependent on the degree of fracturing, and the percentage of the fractures filled with groundwater (Loke, 1999). Sedimentary rocks, which usually are more porous and have higher water content, normally have lower resistivity values. Wet soils and fresh ground water have even lower resistivity values.

Clayey soil normally has a lower resistivity value than sandy soil. However, note the overlap in the resistivity values of the different classes of rocks and soils. This is because the resistivity of a particular rock or soil sample depends on a number of factors such as the porosity, the degree of water saturation and the concentration of dissolved salts (Loke, 1999). The resistivity of groundwater varies from 10 to 100 Ωm, depending on the concentration of dissolved salts.

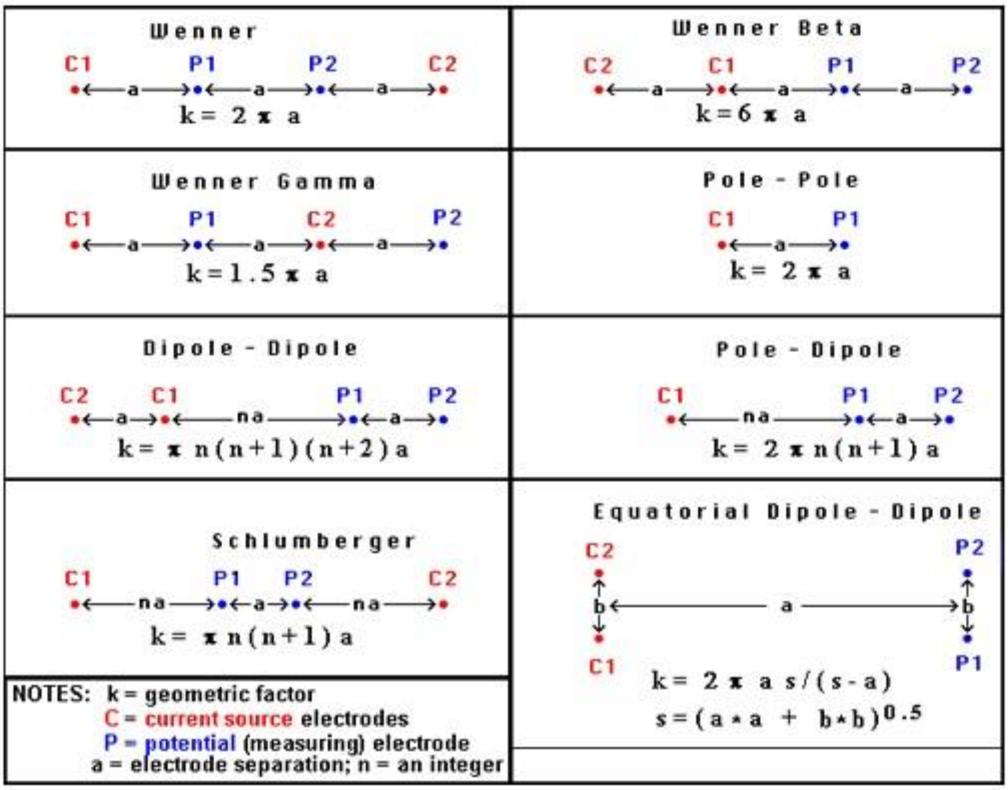

Figure 16. Examples of commonly used electrode arrays (Loke, 1999)

Table 5. Resistivities of some common earth materials (Loke, 1999)

MATERIAL	RESISTIVITY (Ω.m)	CONDUCTIVITY (Siemen/m)
Igneuos and metamorphic rocks		
Granite	$5x10^{3}$ 10^{6}	10^{-6} - $2x10^{-4}$
Basalt	10^{-3} - 10^{-6}	10^{-6} - 10^{-3}
Slate	$6x10^{-2}$ - $4x10^{-7}$	$2.5x10^{-8}$ - $1.7x10^{-3}$
Marble	10^{-2} -2.5x 10^{-8}	$4x10^{-9}$ - 10^{-2}
Quartzite	10^{-2} - $2x10^{-8}$	$5x10^{-9}$- 10^{-2}
Sedimetary		$5x10^{3}$ - 10^11
Sandstone	8 - $4x10^{-3}$	$2.5x10^{-4}$ - 0.125
Shale	20 - $2x10^{-3}$	$5x10^{-4}$ - 0.05
Limestone	50 - $4x10^{-2}$	$2.5x10^{-3}$ - 0.02
Soils and Waters		
Clay	1 - 100	0.01 - 1
Alluvium	10 - 800	$1.25x10^{-3}$ - 0.1
Groundwater (fresh)	10 - 100	0.01 - 0.1
Sea water	0 - 15	6.7

2.8.2.7 2D Electrical Resistivity Tomography

Two-dimensional (2D) electrical resistivity tomography (ERT) can be thought of as resistivity surveys during which both sounding and profiling data are recorded to provide information on the subsurface resistivities in 2D-sections underlying the survey lines. This technique 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 (Loke, 1999). The system selects which electrodes should act as current electrodes and potential electrodes during a particular measurement of the subsurface resistivity.

Figure 17 shows a typical setup for a 2D ERT survey with a number of electrodes along a straight line attached to four multi-core cables (numbered 1 to 4). Normally a constant spacing between adjacent electrodes is used. The multi-core cable is attached to an electronic switching unit which is connected to the resistivity meter (Loke, 1999). The sequence of measurements to take, the type of array to use and other survey parameters (such as the magnitude of the electrical current to be used) can be adjusted according to the aims of the survey.

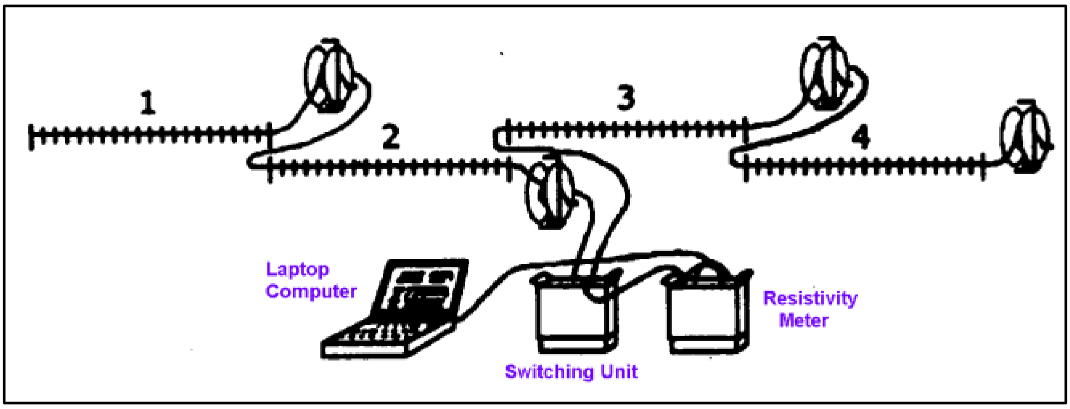

Figure 17. The typical arrangement of electrodes in 2-D ERT survey (Loke, 1999)

2.8.2.8 Application of electrical resistivity tomography (ERT)

Electrical resistivity tomography (ERT) is commonly used to locate near-surface conductive 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.

2.8.2.9 Advantages and disadvantages of ERT

Some of the advantages and disadvantages of ERT, are listed in Table 6.

Table 6. Advantages and disadvantages of electrical resistivity tomography (Kumar, 2012)

Advantage	Disadvantage
To interpret the subsurface geophysical anomaly quantitatively from 2D resistivity models of the	ERT only provides measurement of electrical resistivity. Interpretation needs to be provided.
Extract the range of true resistivity from the inverted resistivity models	Ground-truthing is needed, just like any other geophysical technique
Large density data coverage for beter resolution and less time for data acquisition	

2.8.3 Application of geophysics for groundwater studies

Groundwater applications of near-surface geophysics include mapping the depth and thickness of aquifers, mapping the location, orientation, and thickness of the dolerite dykes, locating preferential fluid migration paths such as fractures and fault zones and mapping contamination to the groundwater. Surface geophysical methods can reduce the risk and unnecessary costs by assisting in the siting of wells in locations with the most potential to produce acceptable quantities of water

(Hasbrouck and Morgan, 2003). Surface geophysical methods have been used for decades to successfully and economically explore for groundwater resources (Hasbrouck and Morgan, 2003).

Electrical and electromagnetic techniques have been extensively used in groundwater geophysical investigations because of the correlation that often exist between electrical properties, geological formations and their fluid content. Most electrical techniques introduce an electrical current in the ground by directly coupling with the ground (Raghunath, 2003). The resulting electrical potential is then used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials, and the fluids within them, will show different abilities to conduct an electric current (Raghunath, 2003). In general, sequences with high clay content show higher conductivity as do saturated sequences and especially sequences where saline (or sometimes other contamination) fluids are present.

The true resistivity of earth material is dependent upon composition, grain size, water content, and other physical characteristics. In general, fine-grained materials have lower resistivities than coarse-grained materials (Hasbrouck and Morgan, 2003). Unweathered and unfractured hard rocks such as lithified sedimentary rocks, volcanic rocks, plutonic rocks, and some metamorphic rocks generally have high resistivities. The presence of fracturing and weathering lowers the resistivity of these rocks. Additionally, the occurrence of groundwater will greatly reduce the resistivity of all rocks and sedimentary materials through electrolytic conduction (Hasbrouck and Morgan, 2003). Because of this effect, groundwater is a good target for electrical and electromagnetic geophysical methods that measure resistivity.

CHAPTER 3:
DESCRIPTION OF THE STUDY AREA

3.1 Introduction

In this chapter the study area of the current investigations is described in terms of its regional setting, geological setting, regional geomagnetic setting, topography and drainage, climate, and surface hydrology.

3.2 Regional Setting

The study was carried in an industrial area, located south of the city of Bloemfontein, in the Free State Province of South Africa. The location of Bloemfontein within the Free State Province is shown in Figure 18.

3.3 Geological Setting

From the 1:250,000 geological map presented in Figure 19 it can be seen that Bloemfontein is mostly underlain by rocks of the Karoo Supergroup. These rocks predominantly consist of sandstones shales and mudstones. Large dolerite intrusions of Jurassic age occur at surface within the city boundaries and particularly to the north of the city. No dolerite outcrops have been mapped within the Study Site of the current investigation (refer to Figure 19). No major faults or dykes are indicated in the geological map covering the city. However, a prominent ring-dyke, known as the Central Ring-Dyke, is known to partially underlie the city. The spring after which Bloemfontein was named, is known to be associated with the Central Ring-Dyke. The approximate position of the Central Ring-Dyke is shown in Figure 20. The position of the dyke was inferred from local dolerite outcrops, as well as observations on changes in the surface topography.

3.4 Regional Magnetic Setting

From the airborne magnetic map covering the city of Bloemfontein (refer to Figure 21), a number of prominent zones of high magnetic field strength (red colours) are seen to the north-east, south and south-west of the city. These zones are in all likelihood due to the presence of large dolerite intrusions in the form of prominent sills. To the south-west of the city boundaries, a prominent linear magnetic feature with an apparent west/east strike is observed. This magnetic feature appears to extend to the Study Site of the current investigation, and is most probable due to the presence of a large dolerite dyke which could potentially be associated with high-yielding aquifers.

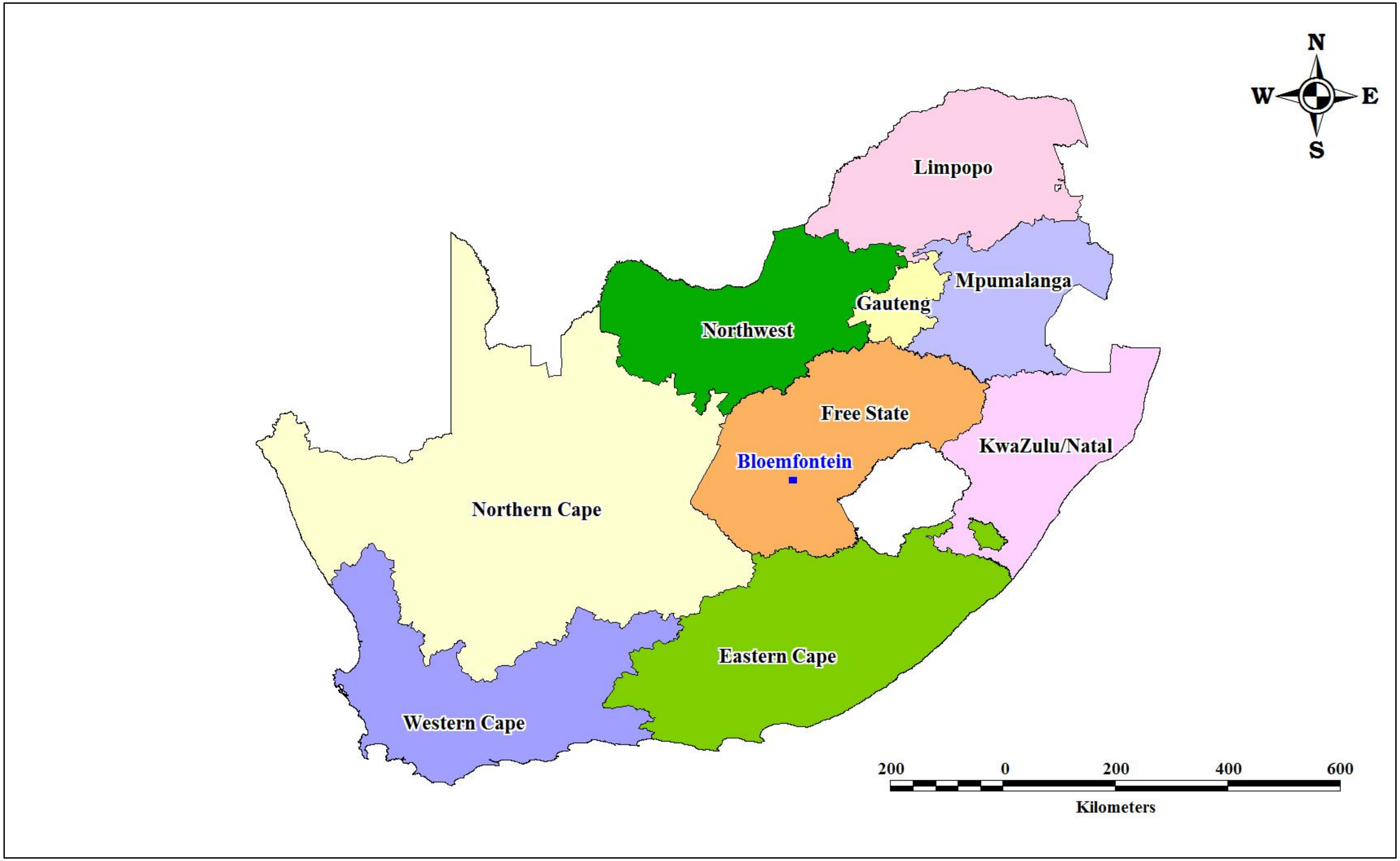

Figure 18. Regional setting of the city of Bloemfontein

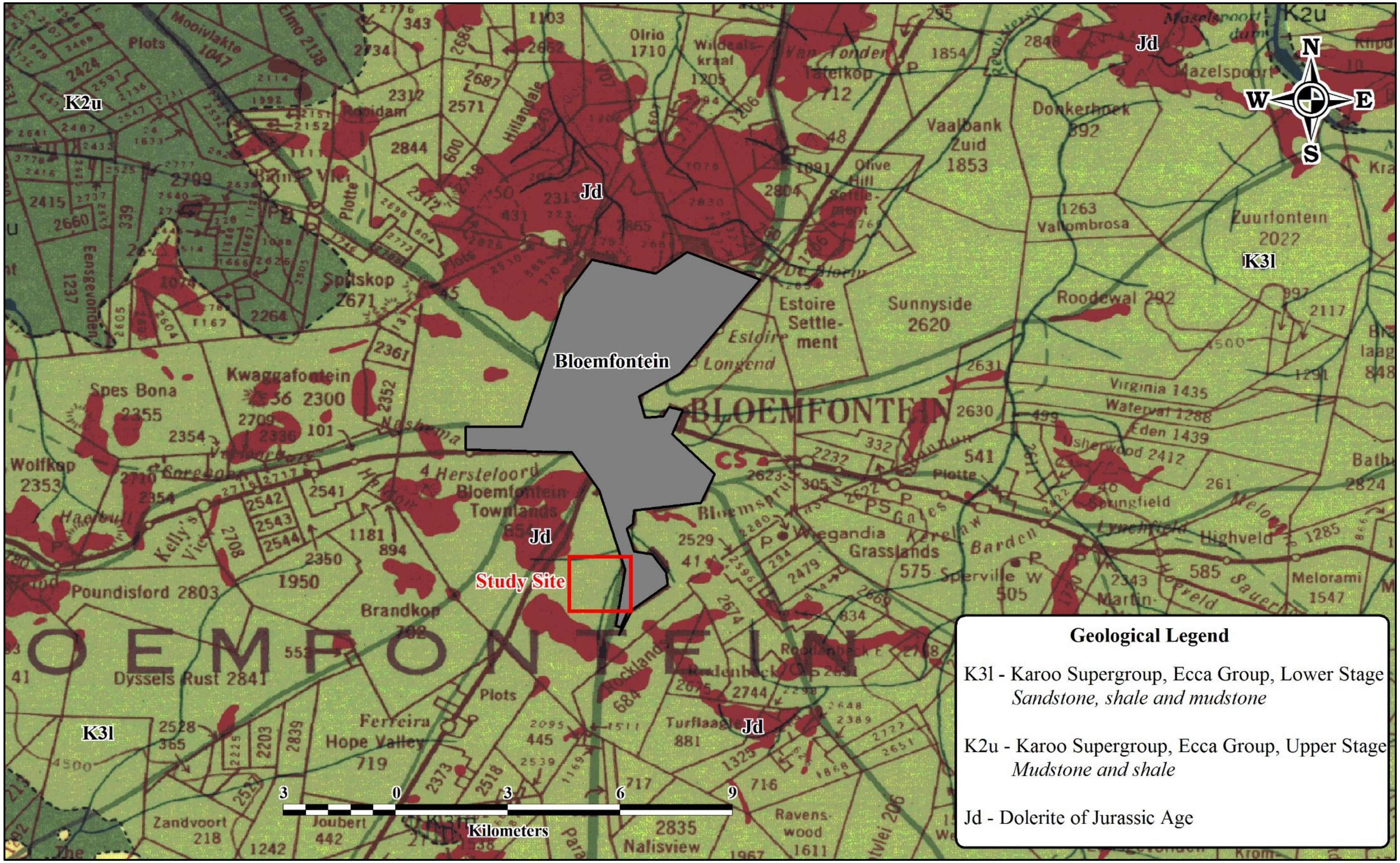

Figure 19. Geological setting of the city of Bloemfontein

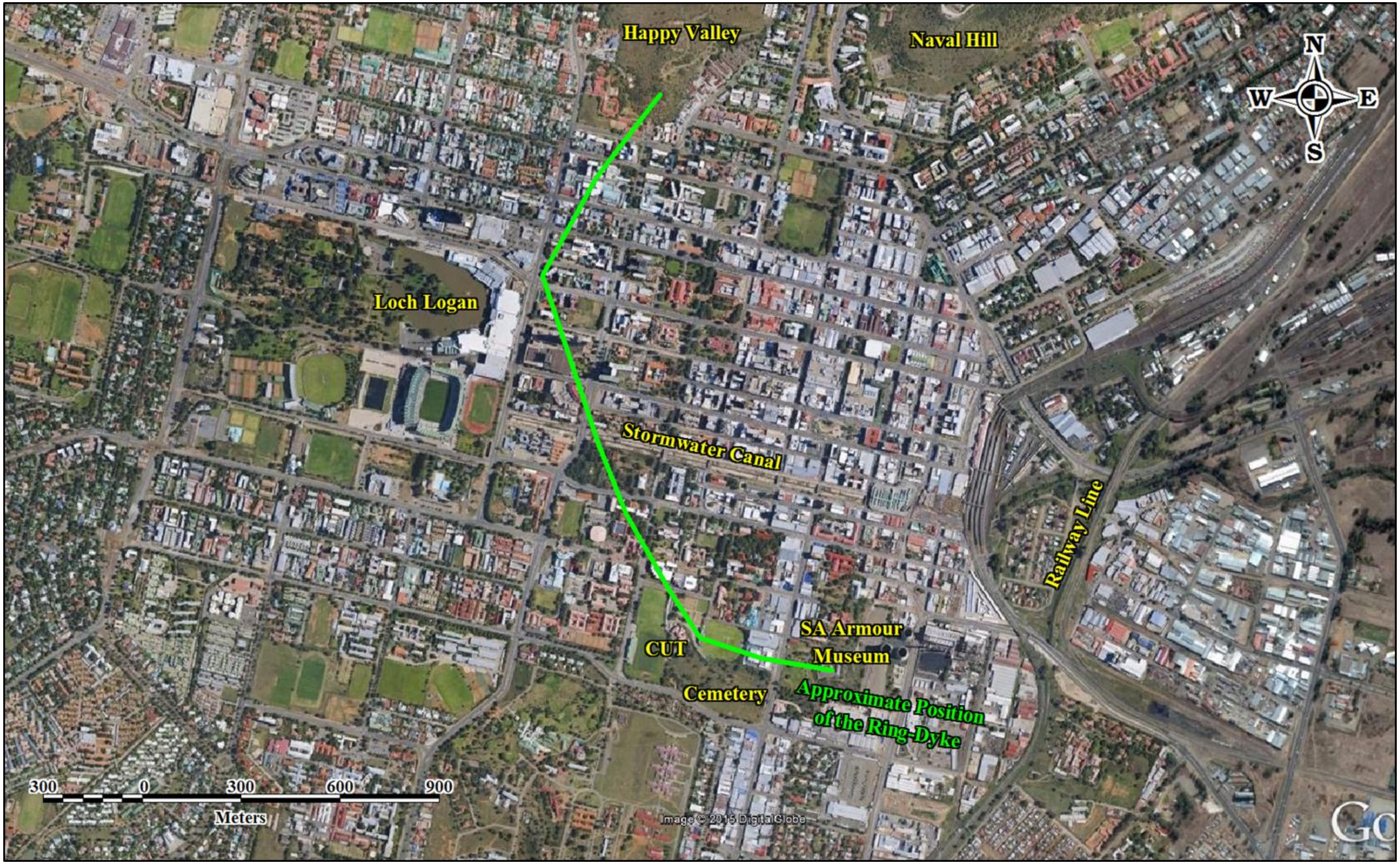

Figure 20. Approximate position of the Central Ring-Dyke partially underlying the city of Bloemfontein (Google Earth, 2015)

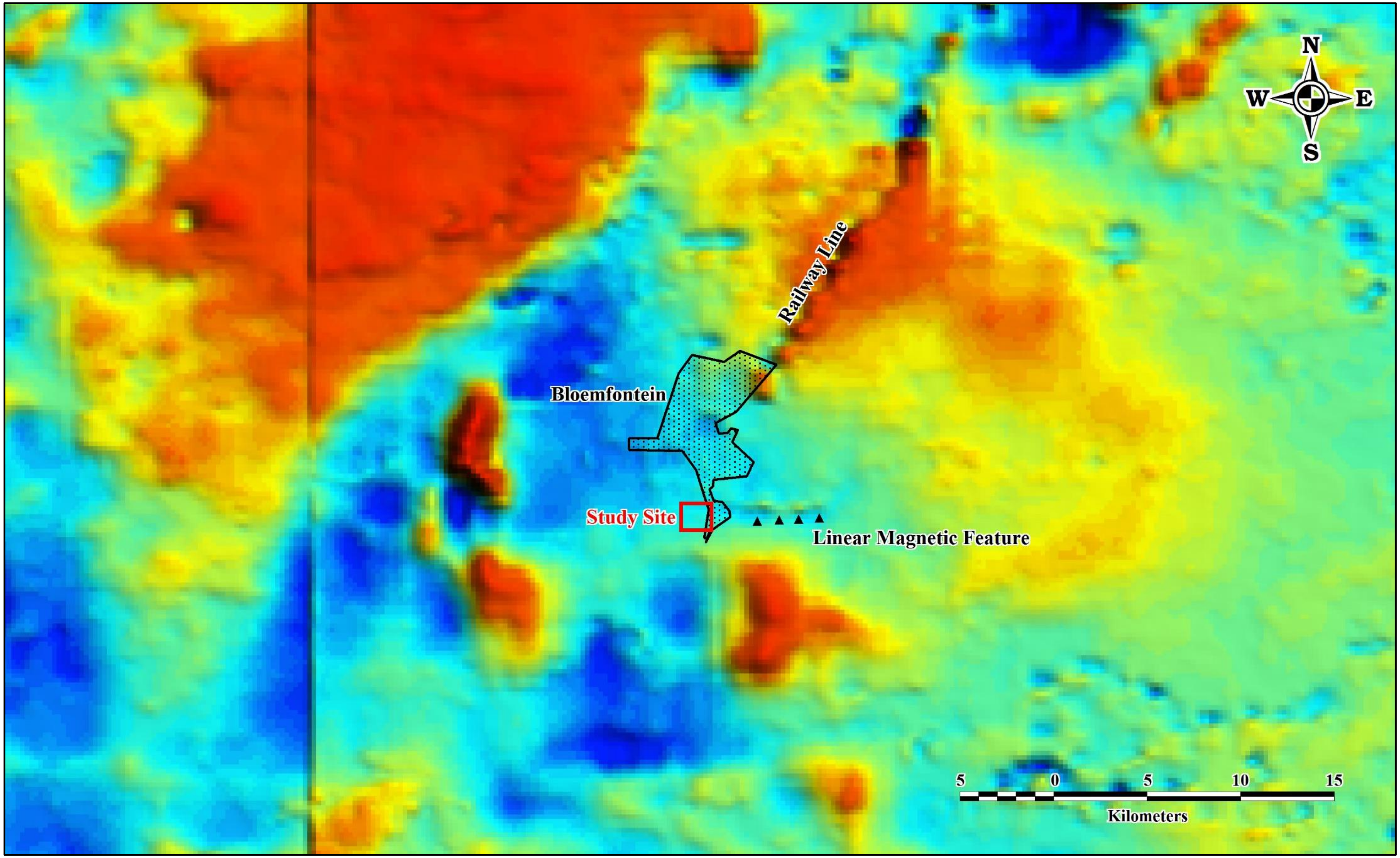

Figure 21. Regional magnetic setting of the city of Bloemfontein

3.5 Climate

3.5.1 Precipitation

Bloemfontein is located at the central regions of Karoo Basin and almost uniformly at approximately 1 300 metres above mean sea level (mamsl). It is regarded as a semi-arid area. The area lies within a summer rainfall region where the mean annual precipitation (MAP) is 550 mm and the highest rainfall is typically in January to March (see Figure 22). Snow is uncommon; however, snowfalls did occur at the airport as recently as 2007.

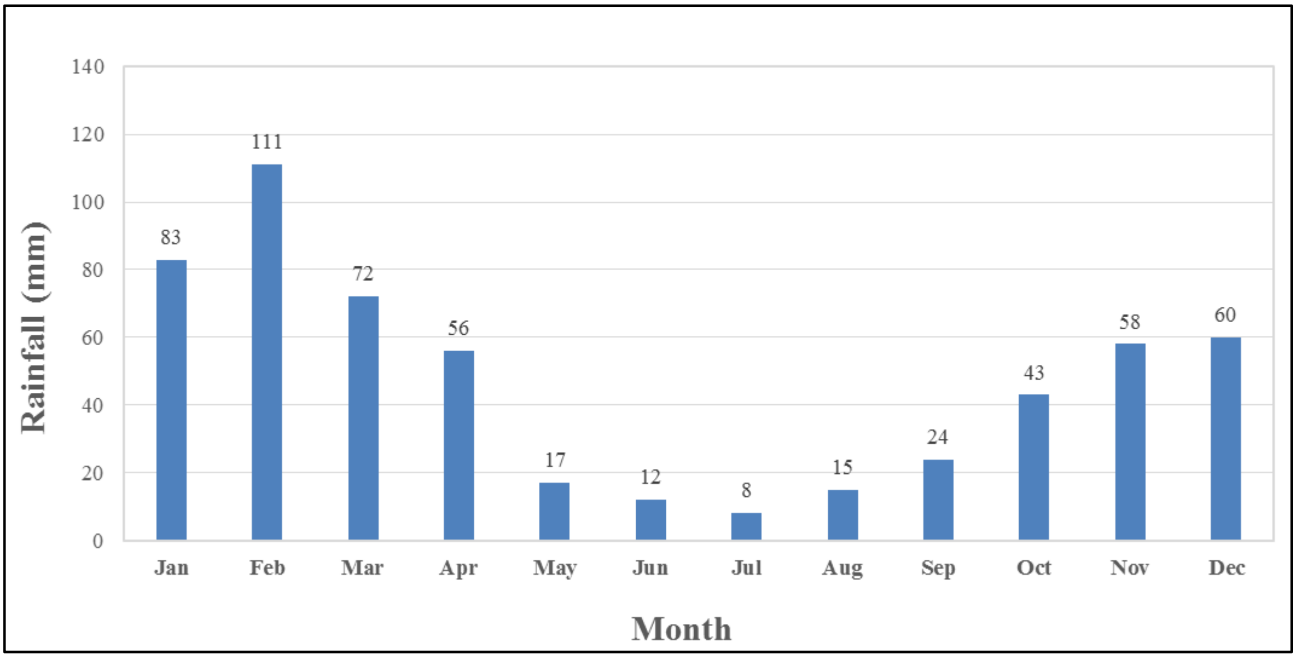

Figure 22. Average monthly rainfall for the city of Bloemfontein

3.5.2 Temperatures

Over the course of a year, the temperature typically varies from -3°C to 30°C and is rarely below -6°C or above 34°C.

The *warm season* lasts from 1 November to 14 March with an average daily high temperature above 27°C. The hottest day of the year is 28 December, with an average high of 30°C and low of 14°C.

The *cold season* lasts from 23 May to 8 August with an average daily high temperature below 19°C. The coldest day of the year is 8 July, with an average low of-3°C and high of 17°C (WeatherSpark, 2017)

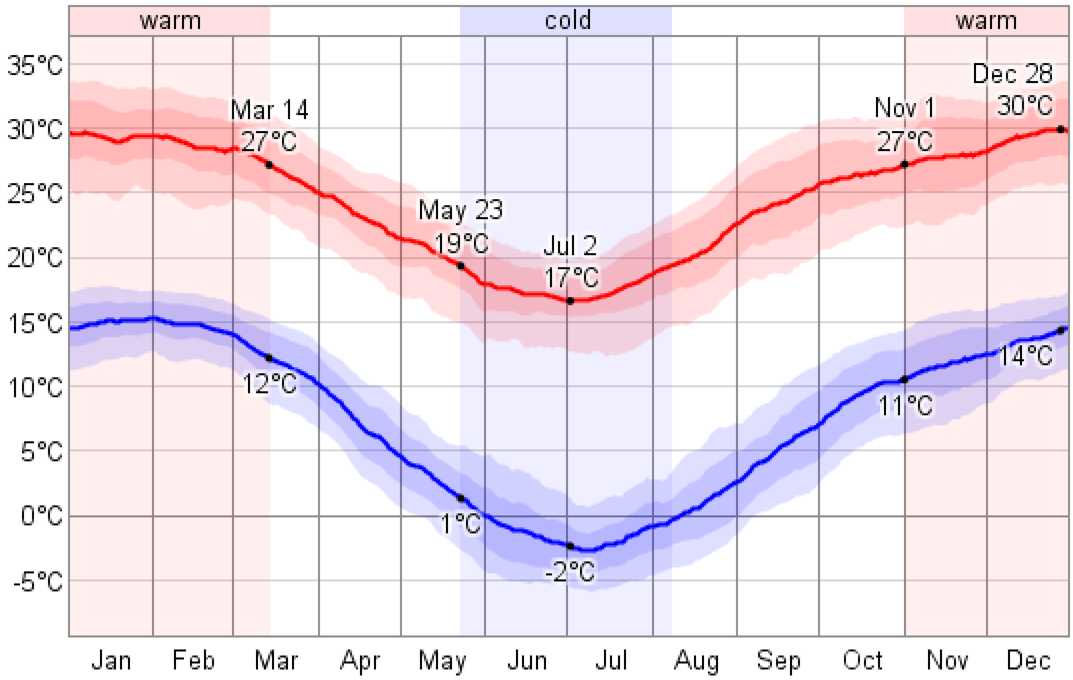

Figure 23. The daily average low (blue) and high (red) temperatures for Bloemfontein with percentile bands (WeatherSpark, 2017)

3.5.3 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) (refer to Figure 24). 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).

3.5.4 Wind

Over the course of the year typical wind speeds vary from 0 to 7 m/s (calm to moderate breeze), rarely exceeding 9 m/s (fresh breeze) (refer to Figure 25). The highest average wind speed of 3 m/s (light breeze) occurs around 22 November, at which time 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, at which time the average daily maximum wind speed is 4 m/s (gentle breeze) (WeatherSpark, 2017).

The wind is most often from the north (14% of the time), north-east (11% of the time), and west (10% of the time). The wind is least often from the south east (4% of the time) (WeatherSpark, 2017).

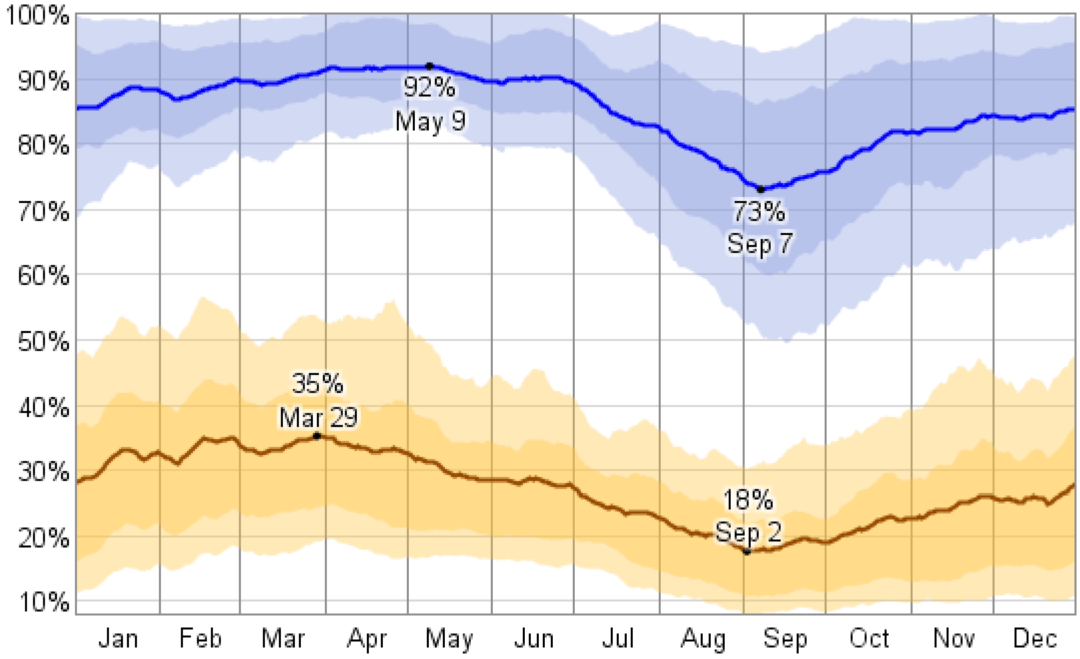

Figure 24. The average daily high (blue) and low (brown) relative humidity for Bloemfontein with percentile bands (inner bands from 25th to 75th percentile, outer bands from 10th to 90th percentile) (WeatherSpark, 2017)

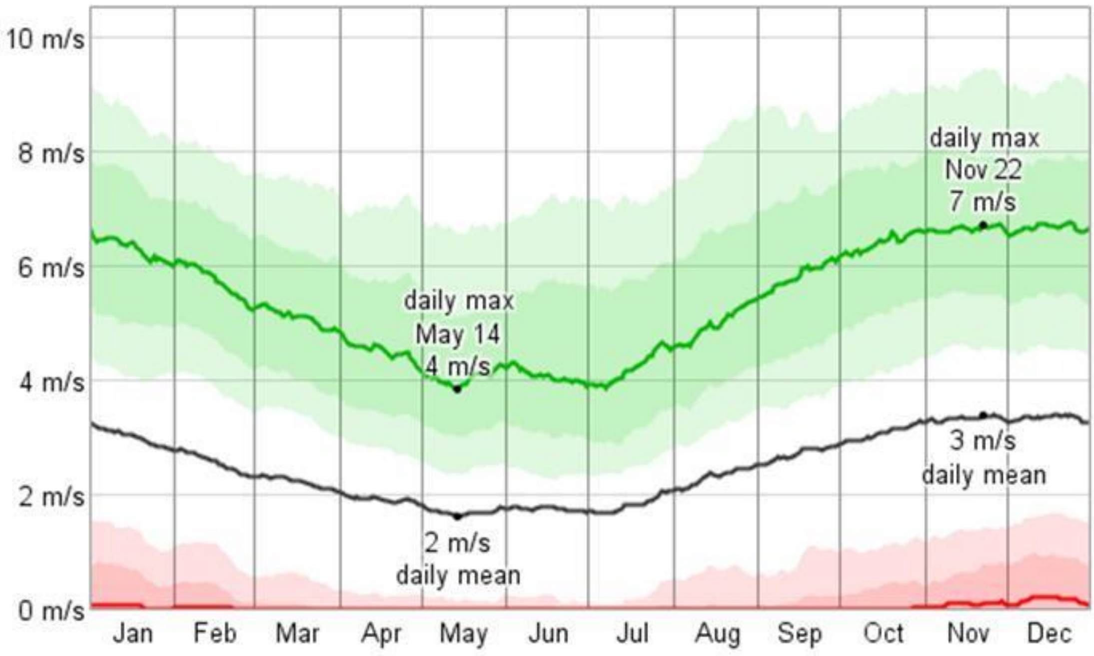

Figure 25. Wind speeds in the city of Bloemfontein (WeatherSpark, 2017)

3.5.5 Dew point

The dew point is often a better measure of how comfortable a person will find the weather than relative humidity because it more directly relates to whether perspiration will evaporate from the skin, thereby cooling the body. Lower dew points feel drier and higher dew points feel more humid.

Over the course of a year, the dew point typically varies from -7°C (dry) to 16°C (comfortable) and is rarely below -14°C (dry) or above 18°C (mildly humid) (refer to Figure 26) (WeatherSpark, 2017).

There are two periods in the year that are most comfortable: the first is between 1 January and 18 April and the second is between 5 November and 31 December. The air feels neither too dry nor too muggy during these periods.

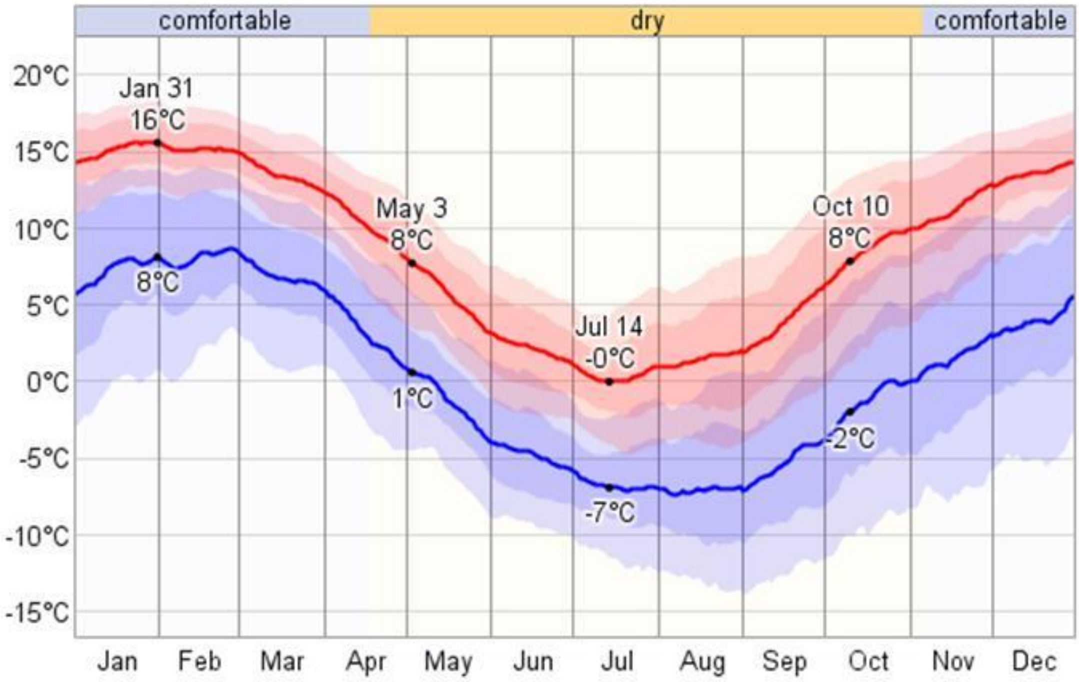

Figure 26. Dew point values in the city of Bloemfontein (WeatherSpark, 2017)

3.5.6 Daylight

The length of the day varies significantly over the course of the year. The shortest day is 20 June with 10:16 hours of daylight; the longest day is 21 December with 14:01 hours of daylight (see Figure 27).

The earliest sunrise is at 5:08 am on 1 December and the latest sunset is at 7:19 pm on 7 January. The latest sunrise is at 7:10 am on 3 July and the earliest sunset is at 5:23 pm on 8 June (WeatherSpark, 2017).

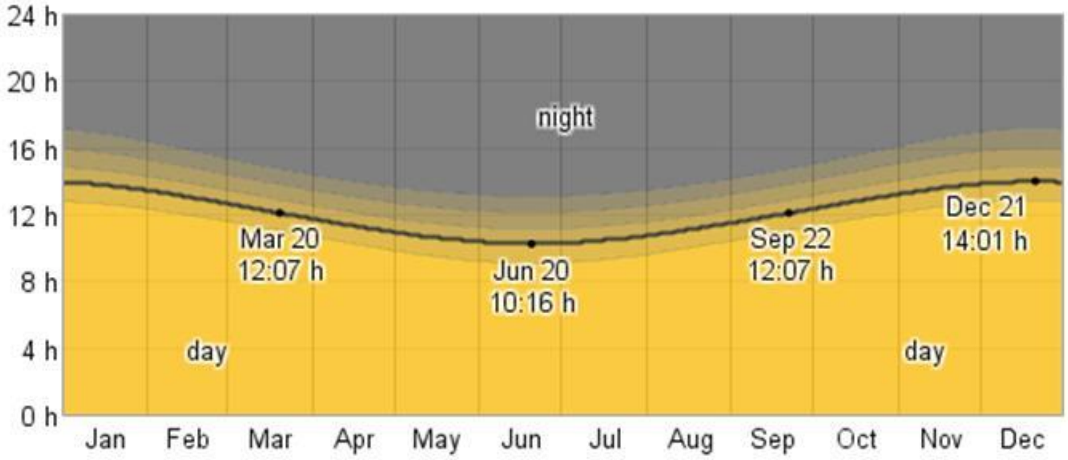

Figure 27. Sunshine experienced in the city of Bloemfontein (WeatherSpark, 2017)

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 28). The Modder River basin is a large basin with a total area of 1.73 million hectares (see Figure 29). 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 30).

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 30). This dam is operated by Bloemwater and was completely dry at the end of 2016.

3.7 Topography and Drainage

The surface topography in the vicinity of Bloemfontein is shown in Figure 31. It is seen that the topography is mostly relatively flat, apart from a number of sharp hills and ridges to the north, west and south-west of Bloemfontein. These hills and ridges are all dolerite structures that are less prone to weathering than the surrounding sedimentary rocks of the Karoo.

The study site is located in an area with a slight topographic gradient to the north-east. Ridges occur to the west, south and south-east of the study site. It therefore appears that the local catchment in which the site occurs has a limited area. A meandering non-perennial streams runs through the study site in a north-westerly direction, following the topographic gradient. This stream is confluent with the Bloemspruit at a position approximately 5 km north-east of the site.

3.8 Geohydrology

As discussed in Section 3.3, 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 (also refer to Section 2.6).

The type of aquifer present in the study are 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.

Deep core holes (up 5 550 m deep) drilled by Soekor in the late 1960s confirmed that the hydraulic conductivities of the sandstone/siltstone of the Beaufort Group are very low, ranging from 0.00 to 2 m/d (Golder Associates, 2011)

In the study area, the depth of the groundwater table ranges from 20-30 m below the surface. The blow-yields of boreholes in the Mangaung Metropolitan Municipality range from 0.4 to 3.0 L/s (Steyl *et al.*, 2011).

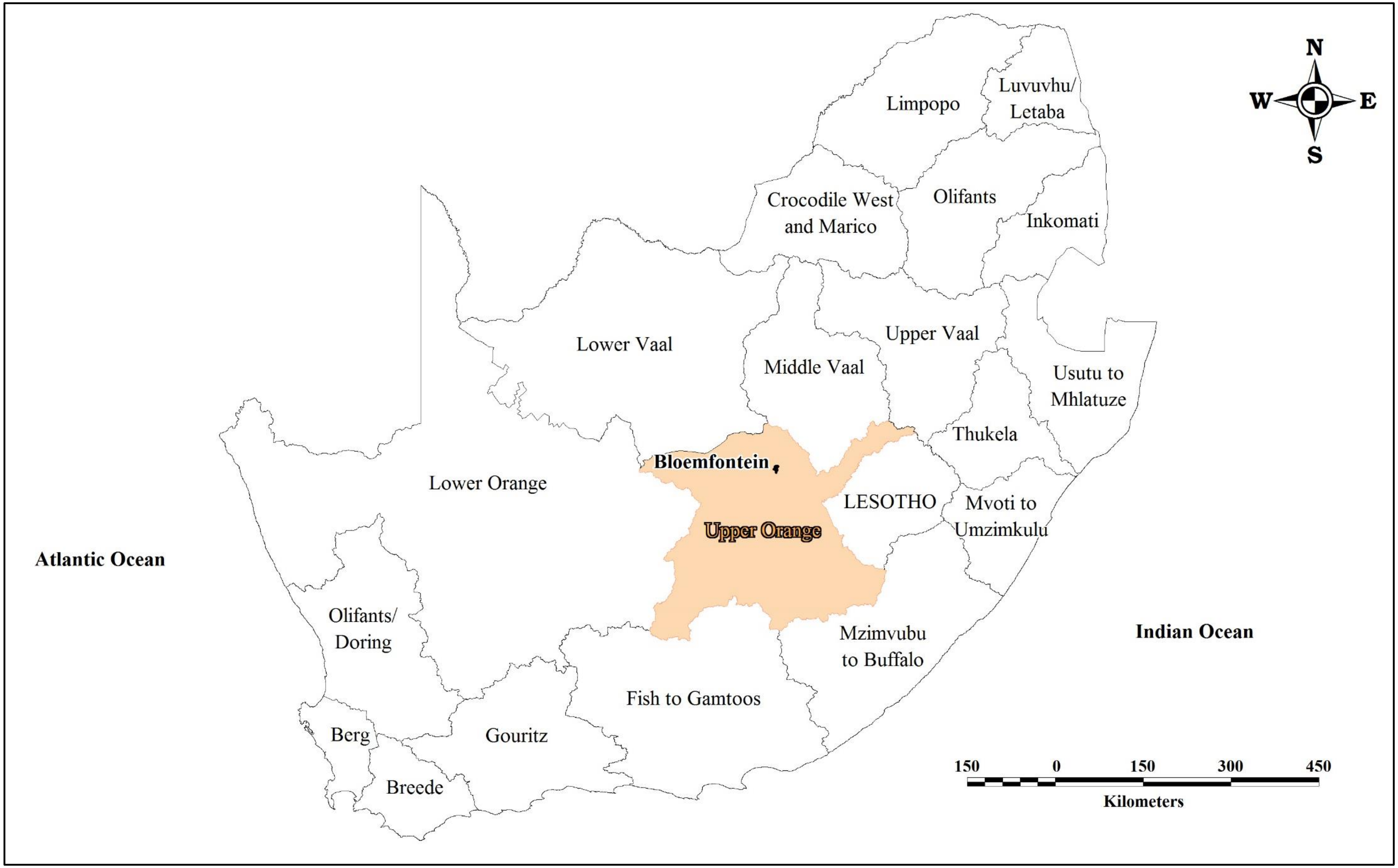

Figure 28. Water Management Areas of South Africa

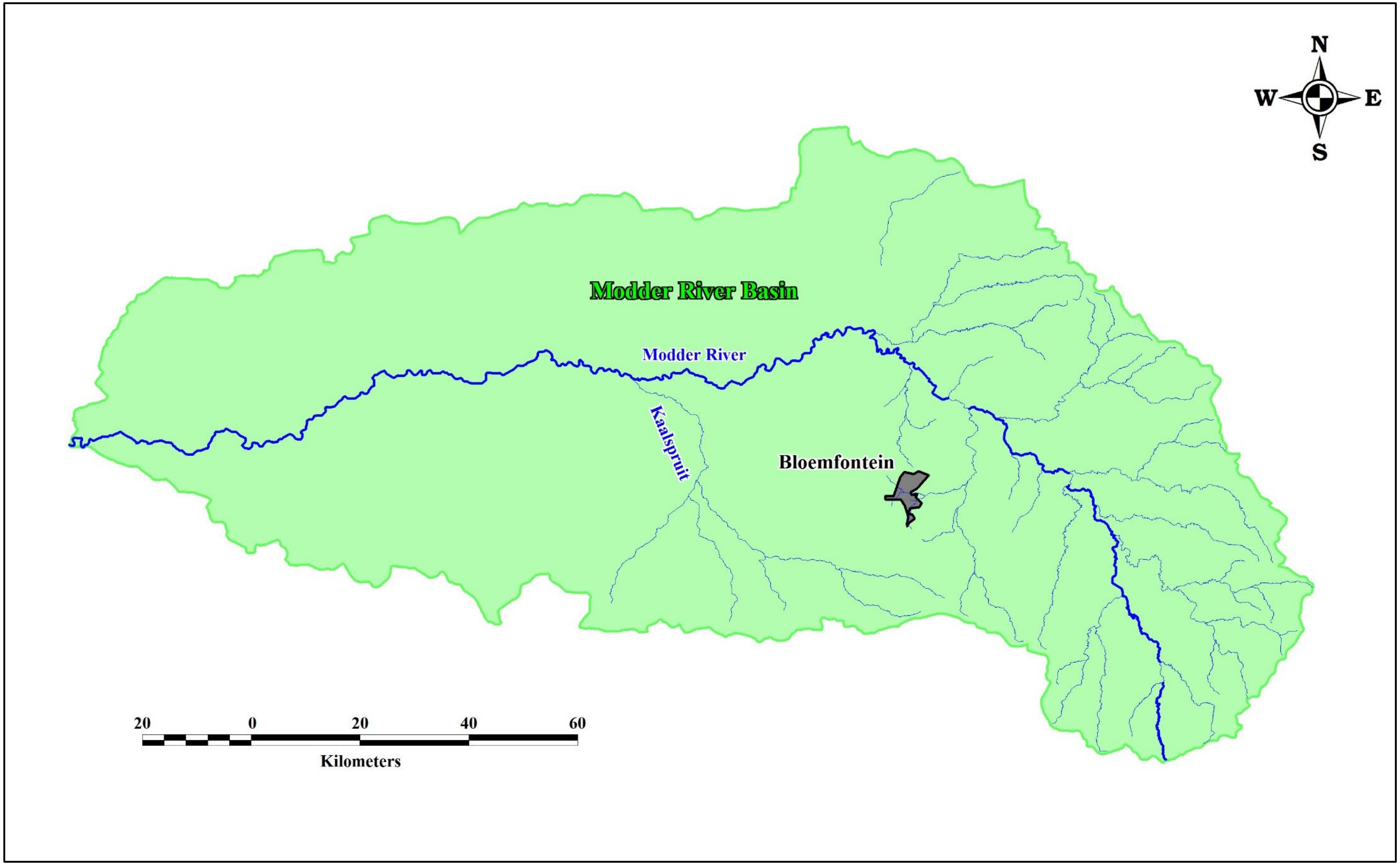

Figure 29. Location of Bloemfontein within the Modder River Basin

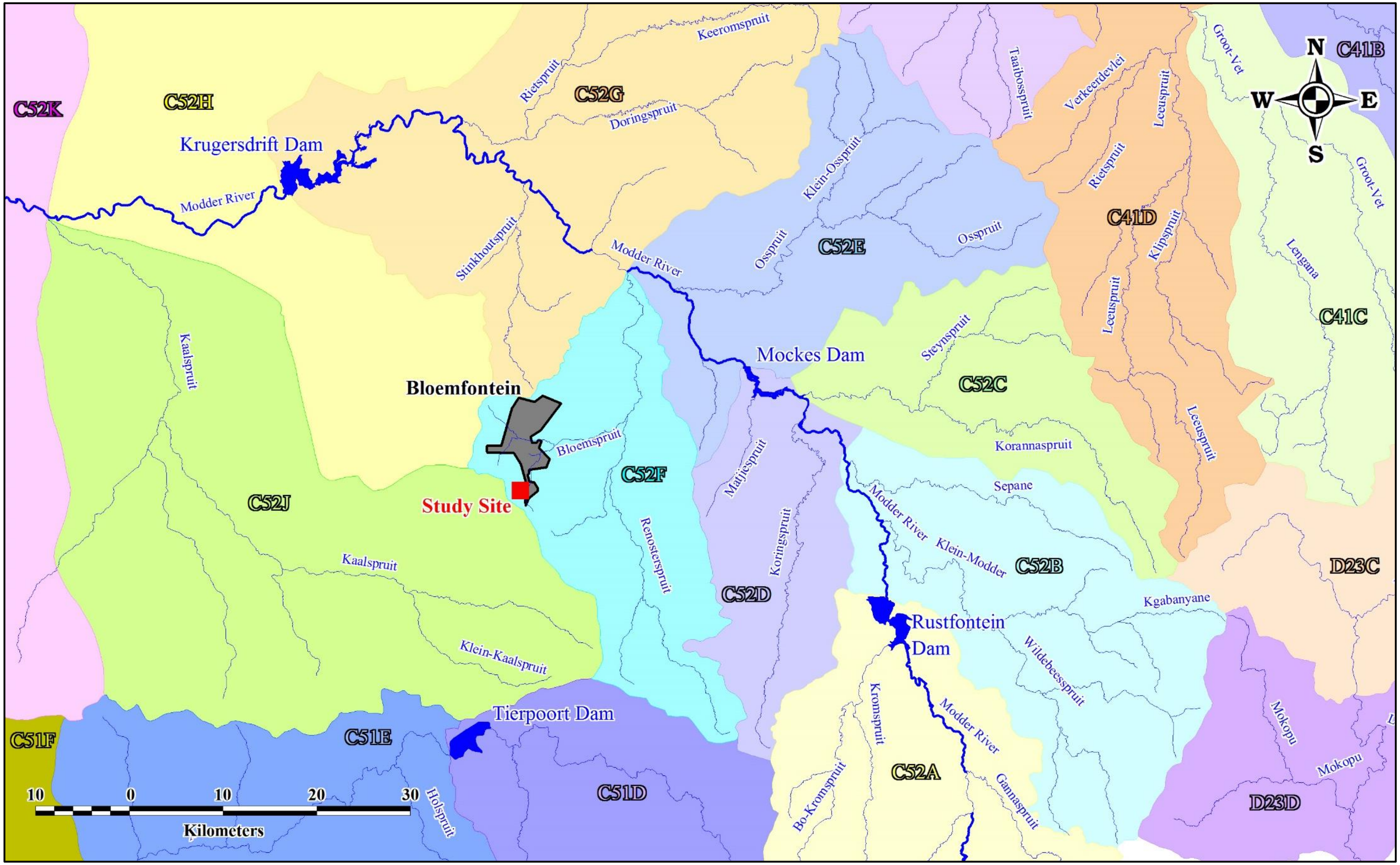

Figure 30. Quaternary subcatchments and major surface water bodies in the area surrounding Bloemfontein

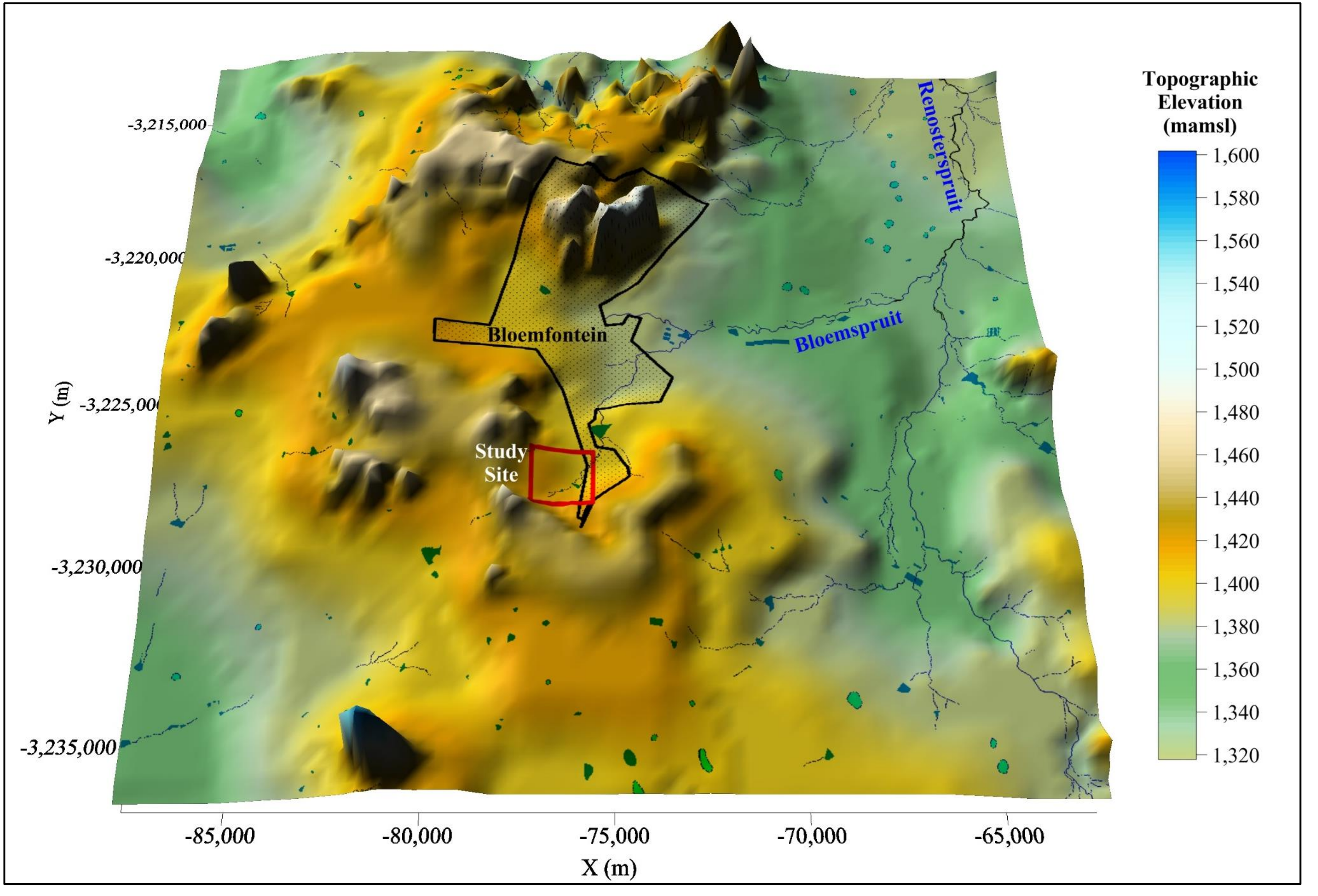

Figure 31. Surface topography and drainage in the vicinity of Bloemfontein

Baseflow, which is the groundwater component of river flow, is negligible in Bloemfontein (Steyl *et al.*, 2011). The Groundwater Harvest Potential (maximum volume of groundwater that can be abstracted annually per surface area of an aquifer system) ranges from 10 000 to 15 000 m^3/km^2/annum. To prevent over-exploitation of the groundwater resources, abstraction of groundwater should not exceed these volumes (Steyl *et al.*, 2011).

3.9 Structures and Transition Zones

Geological features such as bedding planes, fractures, joints, and contact zones are observed throughout the study area. Although the fractures, joints and contact zones typically have small to moderate extents, these features are all likely to affect groundwater flow in the study area. Examples of some of these geological features within the study area are shown in the photographs presented in Figure 32 (bedding), Figure 33 (contact zones), Figure 34 (joints) and Figure 35 (fractures).

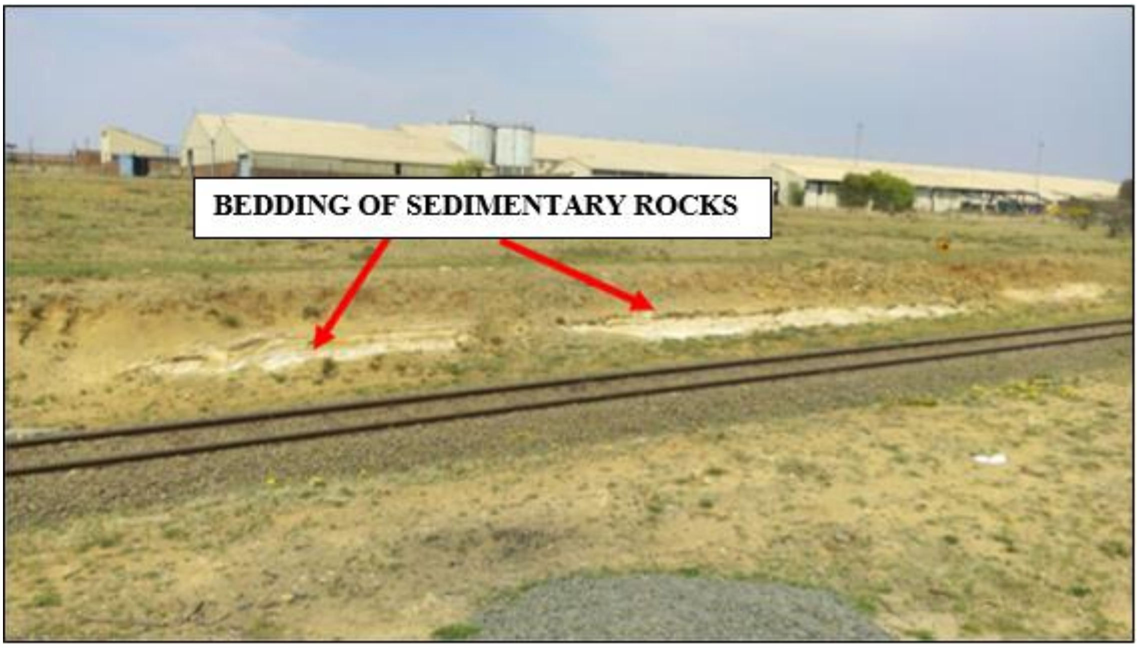

Figure 32. Railway cross-cutting revealing the bedding of the sedimentary rocks in the study area

The contact zones in the study area were formed during the intrusion of dolerite dyke through sedimentary rocks. The sandstone was altered during the intrusion, which resulted in extensive fracturing in the vicinities of the intrusives. These contact zones between dolerite and Karoo sediments are often targeted during groundwater exploration programmes because they form preferential pathways for groundwater flow.

Joints in the intrusive dolerites were formed as a result of contraction and expansion due to cooling and decompression. These structures have been recognised for their important role in groundwater flow (Rey, 2016).

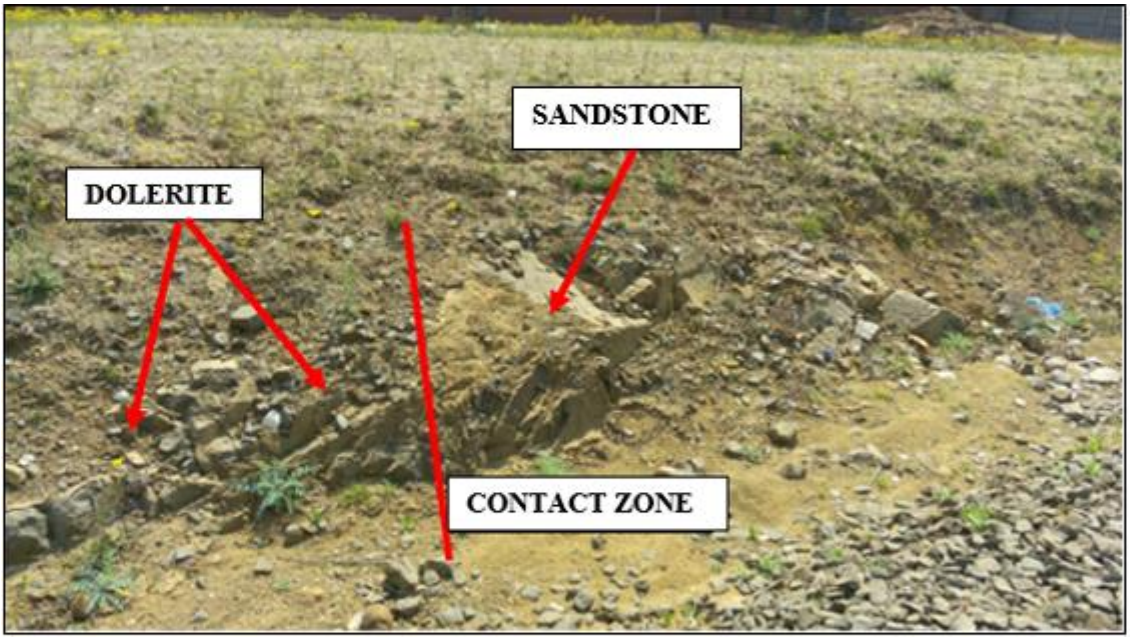

Figure 33. Contact zone between dolerite and sandstone in the study area

Figure 34. Joints in the dolerite in the study area

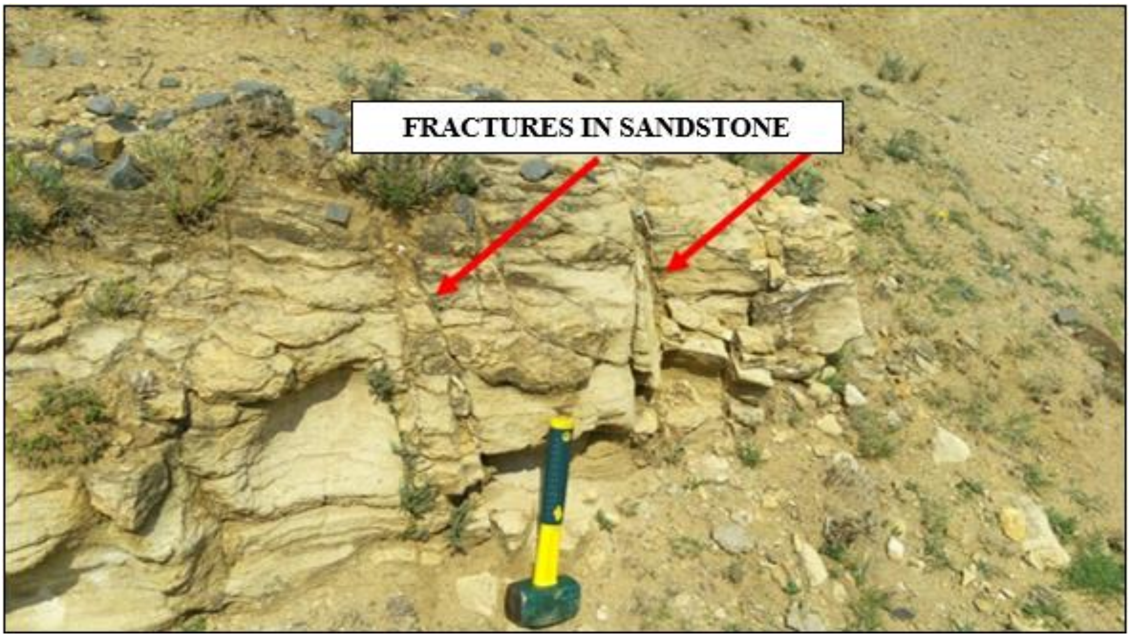

Figure 35. Fractures in the sandstones in the study area

The fractures in the study area may have been formed by several process, including tectonic movements, pressure relief due to erosion of overburden rock, and fracturing during the intrusion and cooling of the dolerite magmas. Fractures often form preferential pathways for groundwater flow, and are hence often targeted during groundwater exploration programmes to obtain high-yielding boreholes. The fractures in the study area open with no secondary mineralisation in the apertures. These fractures therefore form permeable zones for groundwater migration.

3.10 Soil and Vegetation

The southern and western parts of Bloemfontein are mainly dominated entirely by grass, called *Eragrostic abtuse*. Due to the aridity and occurrences of frost in winter, tree species are rare in this landscape and are restricted to river banks and protected slopes and valleys of the many doleritic hills (Steyl *et al.*, 2011).

Dolerite dykes and sills have provided the parent material for the swelling and contracting clay soils that are commonly found in the study area. These clays are called *montmorillonite*. These soils are adequately fertile for agricultural purposes. The clay component of the soils retains water, thereby acting as a water source for plant growth.

3.11 Recharge

Estimation of recharge in the Karoo is not different from other geological formations, except that the aquifer is normally only covered by a thin layer of soil, which limits the application of methods relating to the unsaturated zone (Woodford and Chevallier, 2002). Dolerite outcrops are regarded as preferential areas of recharge. Karoo aquifers can only be optimally exploited and managed if a reliable method can be obtained to estimate their long-term sustainable yield. The sustainable yield of these aquifers is dependent upon the rate of recharge from the rainfall, storativity and subsurface inflow and outflow to and from the aquifer system (Woodford and Chevallier, 2002).

Rainfall recharge into porous matrix can occur in two ways, namely: (a) direct, vertical infiltration through the layers of soil, and (b) through vertical fractures which are exposed at the surface and regarded are preferential pathways. The latter method results in the water initially entering the fracture system, after which it flows from the fracture system into the matrix due to the induced pressure gradient between the two systems (Woodford and Chevallier, 2002).

According the recharge map of South Africa (Vegter, 1995) (Figure 36), recharge in the Bloemfontein area is approximately 20 mm/annum, which translates into a recharge percentage of approximately 3.6% of the MAP.

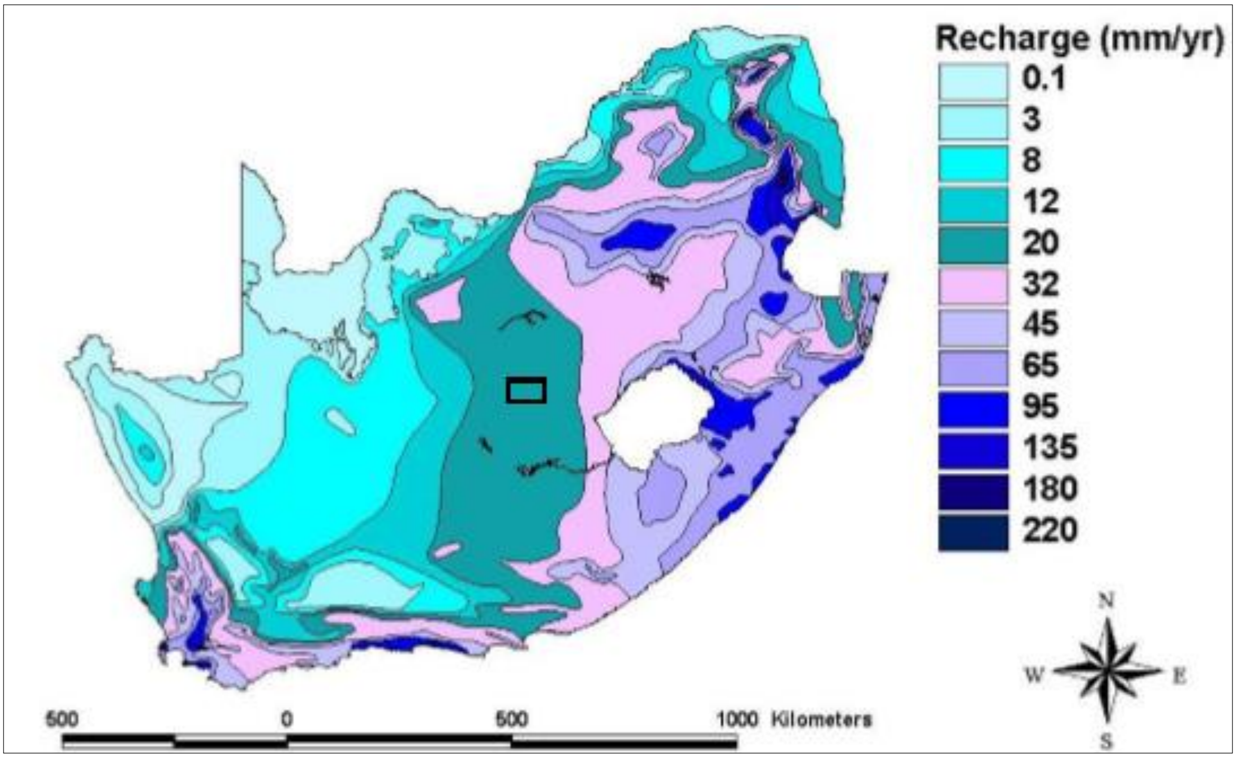

Figure 36. Mean annual groundwater recharge from precipitation (Vegter, 1995)

CHAPTER 4:
GROUND GEOPHYSICAL INVESTIGATIONS

4.1 Introduction

Ground geophysical surveys were carried out at an open space south of the manufacturing site of Coca Cola Fortune (Pty) Ltd situated in Church Street within the Mangaung municipal area, industrial area and the suburb of Fauna. The site was selected for the investigations, since dolerite outcrops had been noted in a road cutting in the industrial area to the east of the Study Site. This dolerite outcrop appeared to be a thick dyke, possibly running through the Study Site, although no outcrop of the dyke was visible within the Study Site. The presence of a wetland within and to the south of the Study Site appeared to be associated with the possible dolerite structure.

The aims of the ground geophysical investigations were to detect and delineate any dolerite structures within the Study Site. If detected, the geometries (thicknesses, dips, strikes) of such structures were to be determined from an analysis and interpretation of the geophysical recorded data.

In order to achieve the aims, geophysical surveys were carried out along the selected traverses. Two techniques were used during the survey, namely the magnetic method (Walkmag) and the 2D resistivity method (known as 2D electrical resistivity tomography, ERT). These techniques were selected because dolerite are known to be generally highly magnetic, while the resistivities of dolerites are generally much higher than those of Karoo sedimentary rocks. Large contrasts in the physical properties of the dolerite structure(s) and the host rock were therefore expected (Woodford and Chevallier, 2002).

4.2 Magnetic Survey

4.2.1 Survey geometry

From satellite images covering the Study Site, a change in the soil colour and the vegetation density could be observed in the area south of the Coca Cola factory. This change occurred along a line with an approximate north-east/south-west strike (refer to Figure 37). It was thought that the changing surface conditions could be a manifestation of changes in the subsurface conditions due to the presence of a linear dolerite structure. The ground geophysical survey focussed on this area, although surveys were also conducted in areas to the south and west. The survey consisted of 1) a reconnaissance magnetic survey, 2) two detailed magnetic surveys on grids, and 3) an ERT survey on four profiles across a magnetic lineament identified from the magnetic surveys.

Several surface and subsurface constraints had to be taken into consideration during the planning phase of the surveys. Infrastructure in the form of buildings, roads, metal structures, overhead powerlines, and buried pipes and cables is present within the Study Site (see Figure 37). This infrastructure not only acted as obstacles to the survey, but also as sources of noise, affecting the quality of the recorded magnetic data.

The survey geometries of the three magnetic surveys are shown in Figure 38 (reconnaissance survey), Figure 39 (survey on Grid 1 south of the Coca Cola Factory), and Figure 40 (survey on Grid 2 immediately south of the Coca Cola Factory). The two surveys on the grids both investigated the presence of possible linear structures identified from the satellite images and reconnaissance survey.

4.2.2 Results

The results of the magnetic surveys on all the different traverses are presented as profiles of the total magnetic field in **Appendix A**.

The magnetic data recorded on Traverses 01, 02 and 03 of the reconaissance survey revealed the presence of a prominent magnetic feature within the Study Site, running through the area immediately south of the Coca Cola factory. As examples, the magnetic anomalies recorded on Traverses 01, 02 and 03 are shown in Figure 41, Figure 42 and Figure 43, respectively. A prominent magnetic anomaly is observed in the northern parts of Traverses 01 and 02, while a large anomaly is also seen in the eastern parts of Traverse 03. From the positions of these anomalies, the geological structure causing the anomalies appears to be linear with a north-west/south-east strike.

A contour map of the magnetic data recorded on Grid 1 is presented in Figure 44. From the contour map it is clear that the linear feature identified from the satellite image (refer to Figure 39) has a strong magnetic response. However, the shapes of the magnetic anomalies recorded on this grid show that the anomalies are due to shallow metallic infrastructure, such as a buried pipe. The anomalies are very sharp, with small wavelengths, indicating a near-surface origin to the anomaly. As an example of the magnetic profiles recorded on Grid 1, the magnetic data recorded along Traverse 11 of the grid are shown in Figure 45. The sharp magnetic anomaly can be clearly seen in the magnetic profile of this traverse.

Figure 37. The presence of a possible subsurface structure indicated by the change in soil colour and vegetation across the Study Site

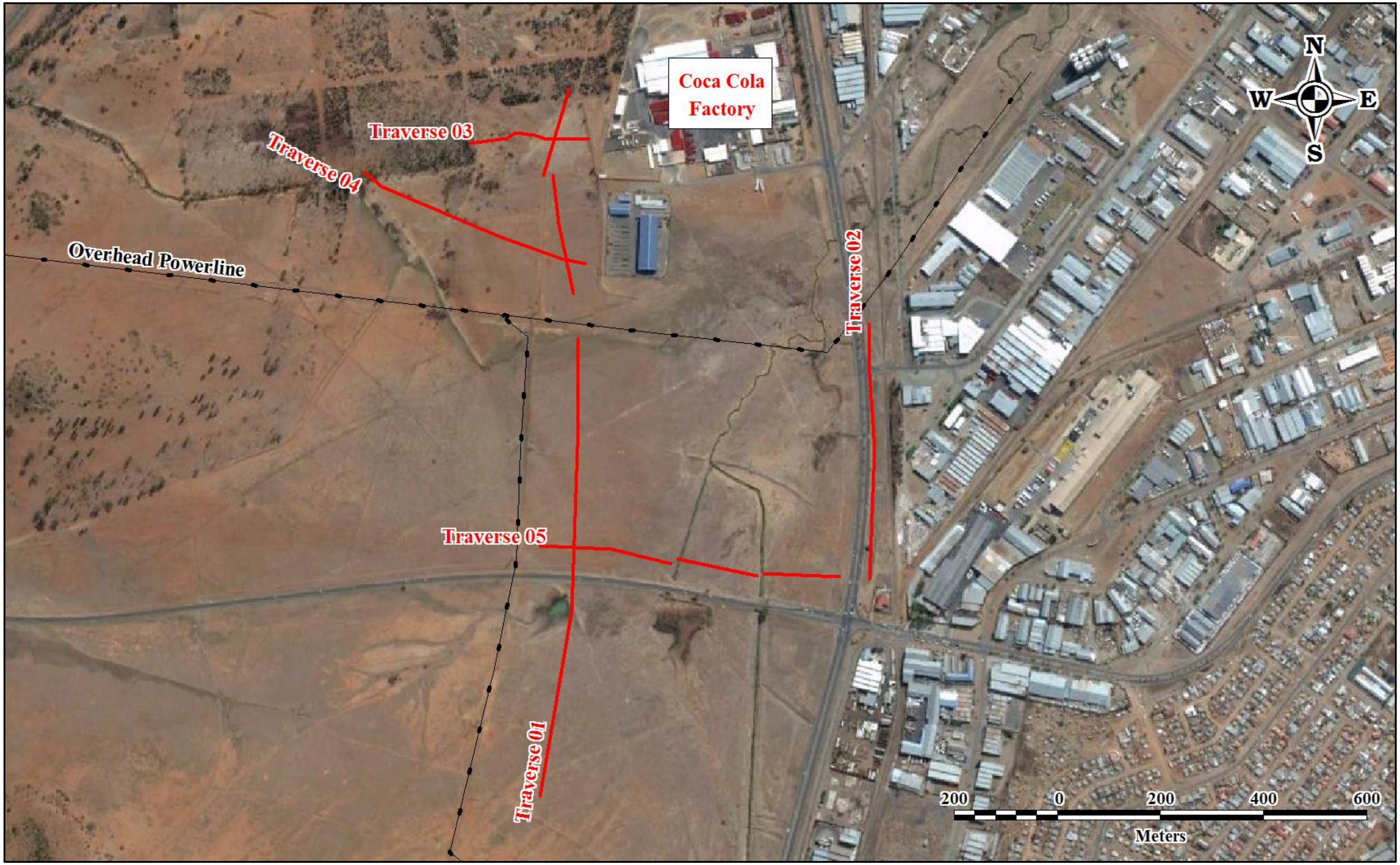

Figure 38. Positions and orientations of traverses on which magnetic data were recorded during the reconnaissance survey near the Coca Cola factory

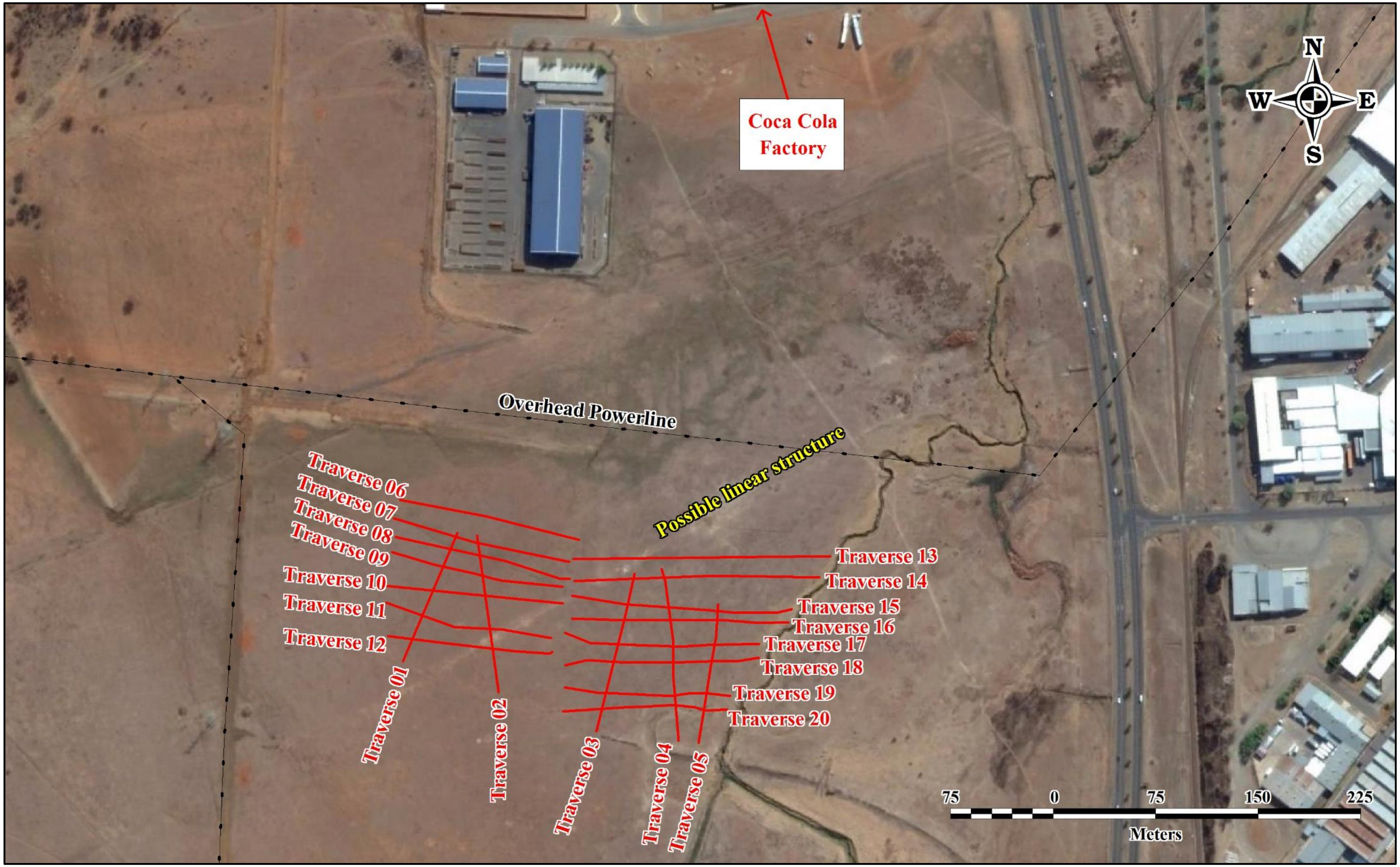

Figure 39. Positions and orientations of traverses on which magnetic data were recorded on Grid 1 south of the Coca Cola factory

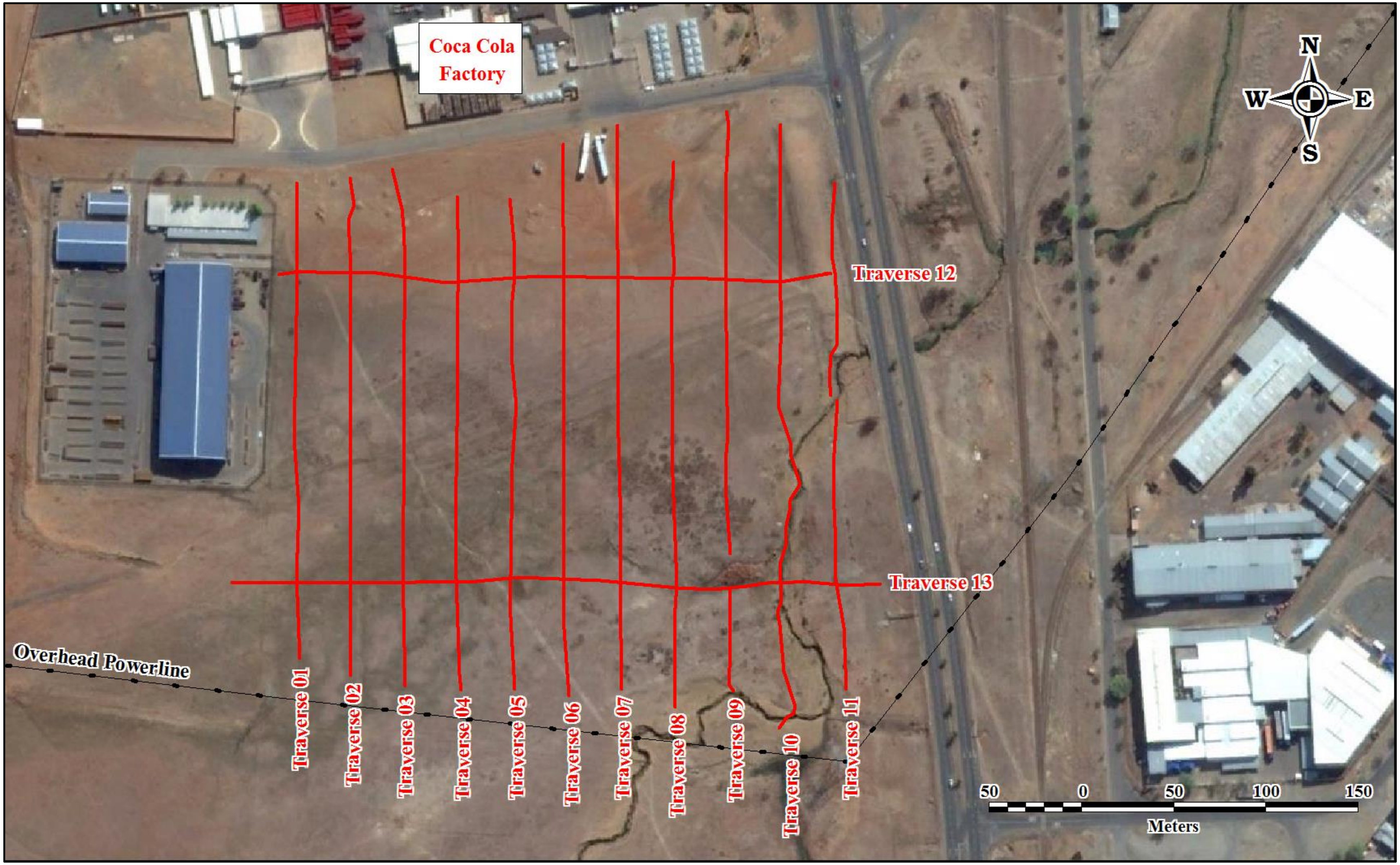

Figure 40. Positions and orientations of traverses on which magnetic data were recorded on Grid 2 immediately south of the Coca Cola factory

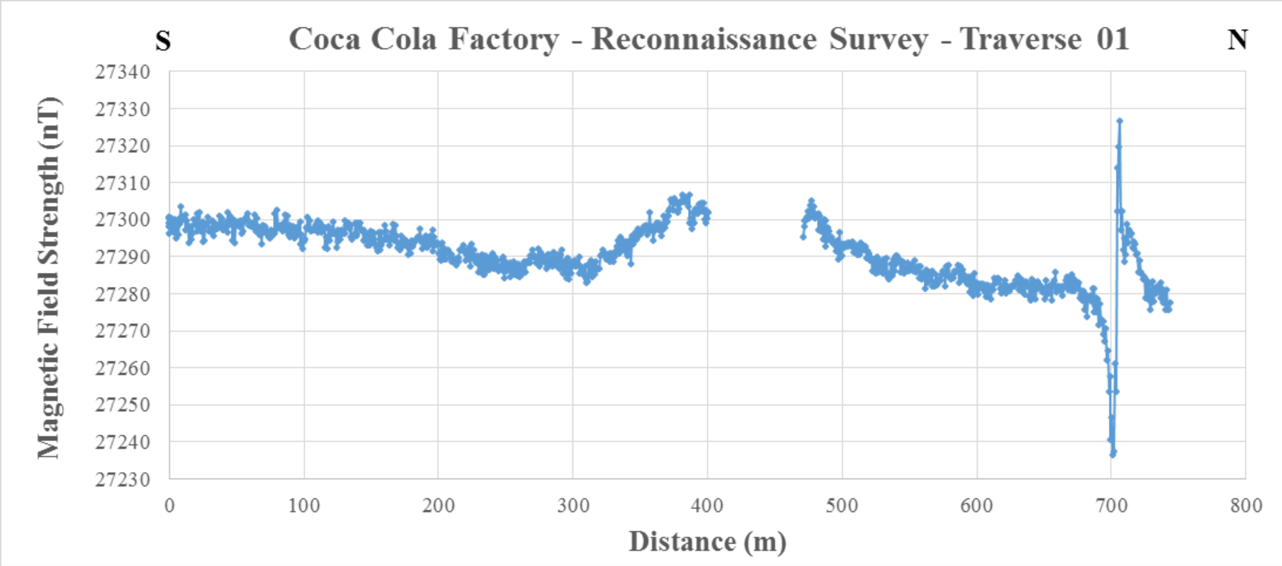

Figure 41. The total magnetic field recorded along Traverse 01 of the reconnaissance survey

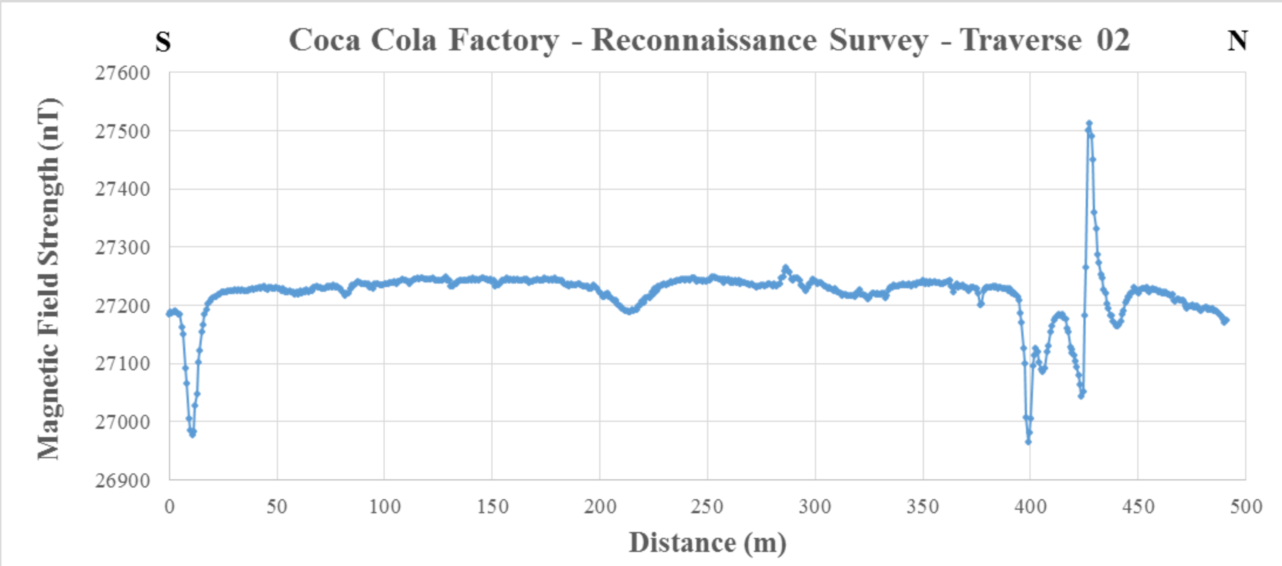

Figure 42. The total magnetic field recorded along Traverse 02 of the reconnaissance survey

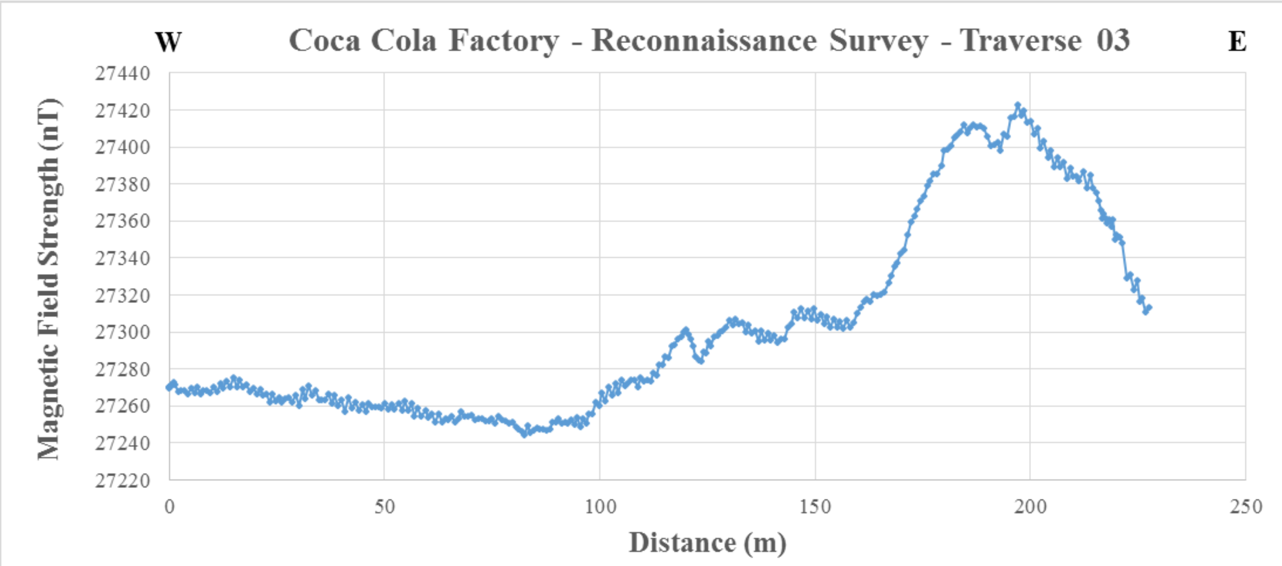

Figure 43. The total magnetic field recorded along Traverse 03 of the reconnaissance survey

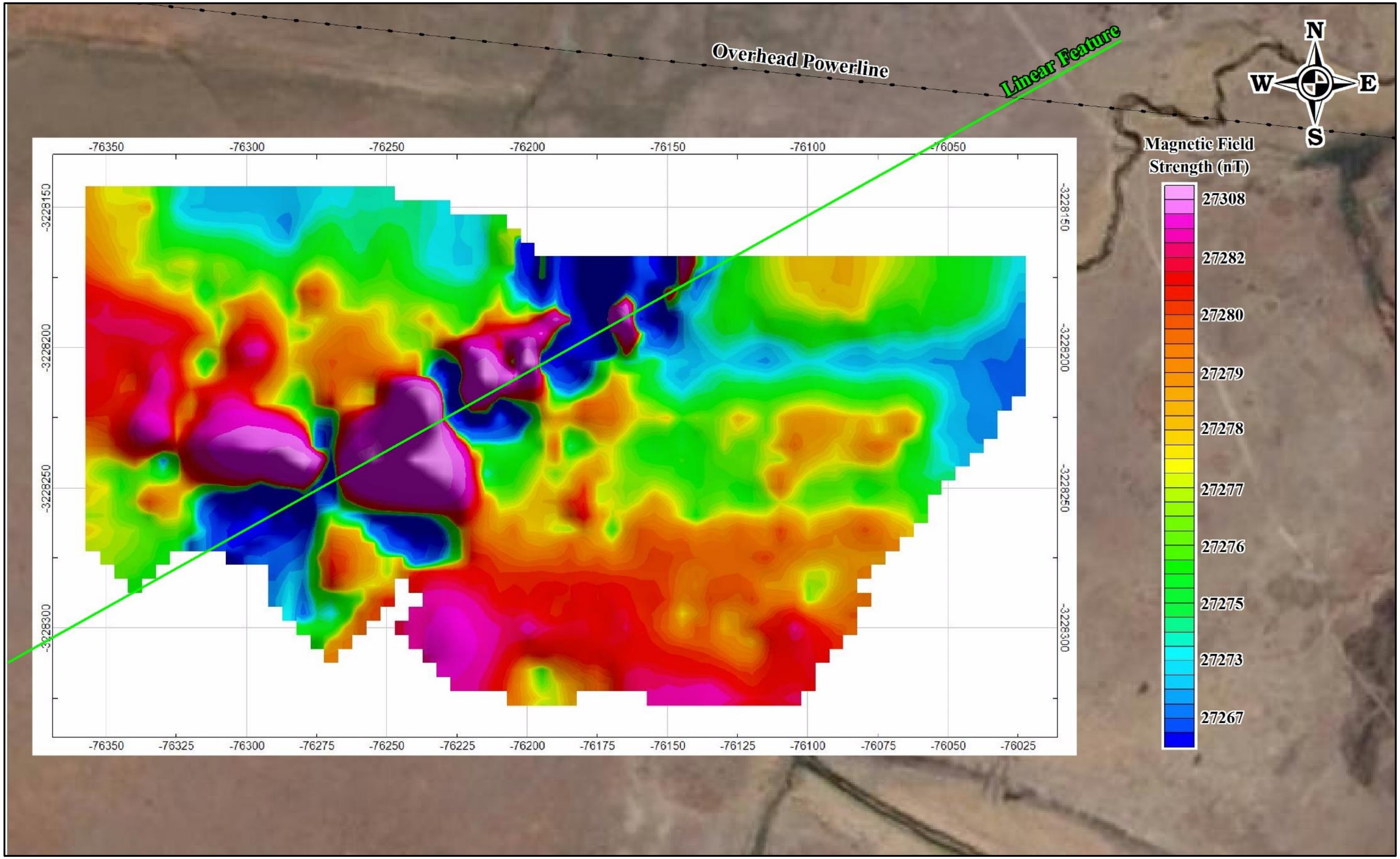

Figure 44. Contour map of the total magnetic field recorded on Grid 1 south of the Coca Cola factory

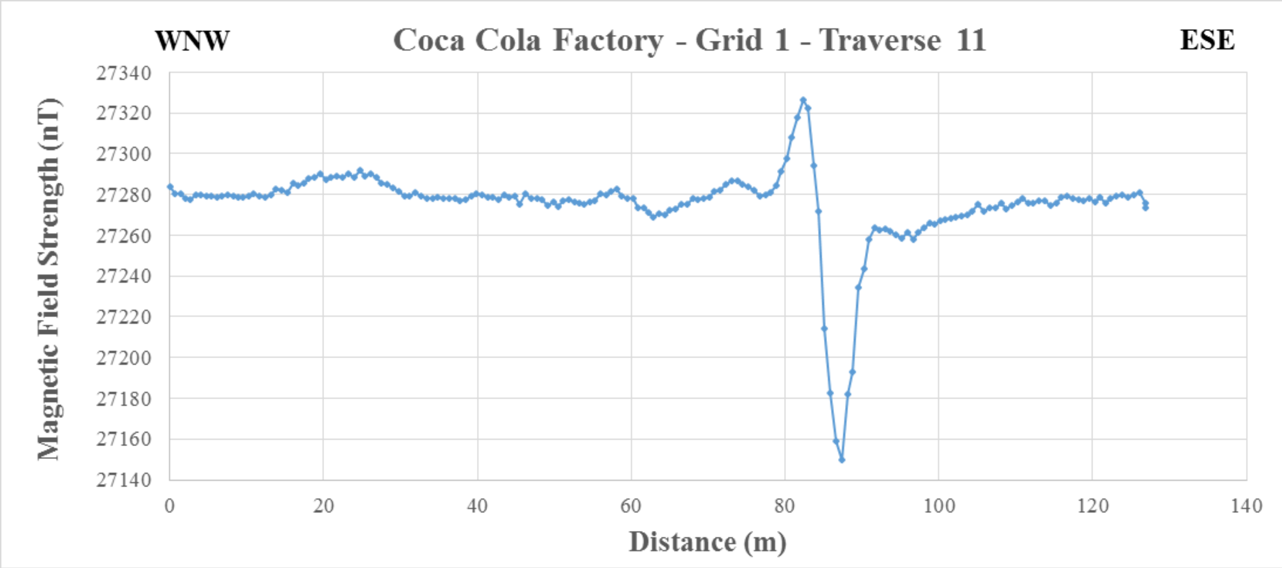

Figure 45. Profile of the total magnetic field recorded along Traverse 11 of Grid 1

A contour map of the total magnetic field recorded on Grid 2 is presented in Figure 46. A very prominent, broad magnetic anomaly with a north-west/south-east strike is observed south of the Coca Cola factory. This anomaly is most probably due to a large dolerite dyke and corresponds well with the position of the change in soil colour and vegetation identified in Figure 37. The anomaly is probably the same one observed in the airborne magnetic map covering the site (refer to Figure 21). As an example of the magnetic response recorded on this grid, the total magnetic field recorded on Traverse 07 of Grid 2 is shown as a profile in Figure 47. A very prominent, broad magnetic anomaly can be seen near the centre of this traverse. The anomaly has an amplitude of approximately 150 nT and a spatial wavelength of at least 100 m (although the traverse did not intersect the structure perpendicularly).

4.3 ERT Survey

4.3.1 Survey geometry

The ERT survey was conducted at positions as determined from the results of the magnetic survey. The major linear magnetic anomaly was targeted during the ERT survey to measure the resistivity changes across this structure in an attempt to gain further information on the geometry of the structure. ERT data were recorded on two profiles (ERT Profiles 1 and 2) across the prominent magnetic anomaly identified immediately south of the Coca Cola Factory. The positions and orientations of these ERT profiles are shown in Figure 48. Apart from these two ERT profiles, ERT data were also recorded on two additional profiles in an attempt to investigate the lateral extent of the geological feature responsible for the prominent magnetic anomaly. The positions and orientations of these profiles (ERT Profiles 3 and 4) are shown in Figure 49.

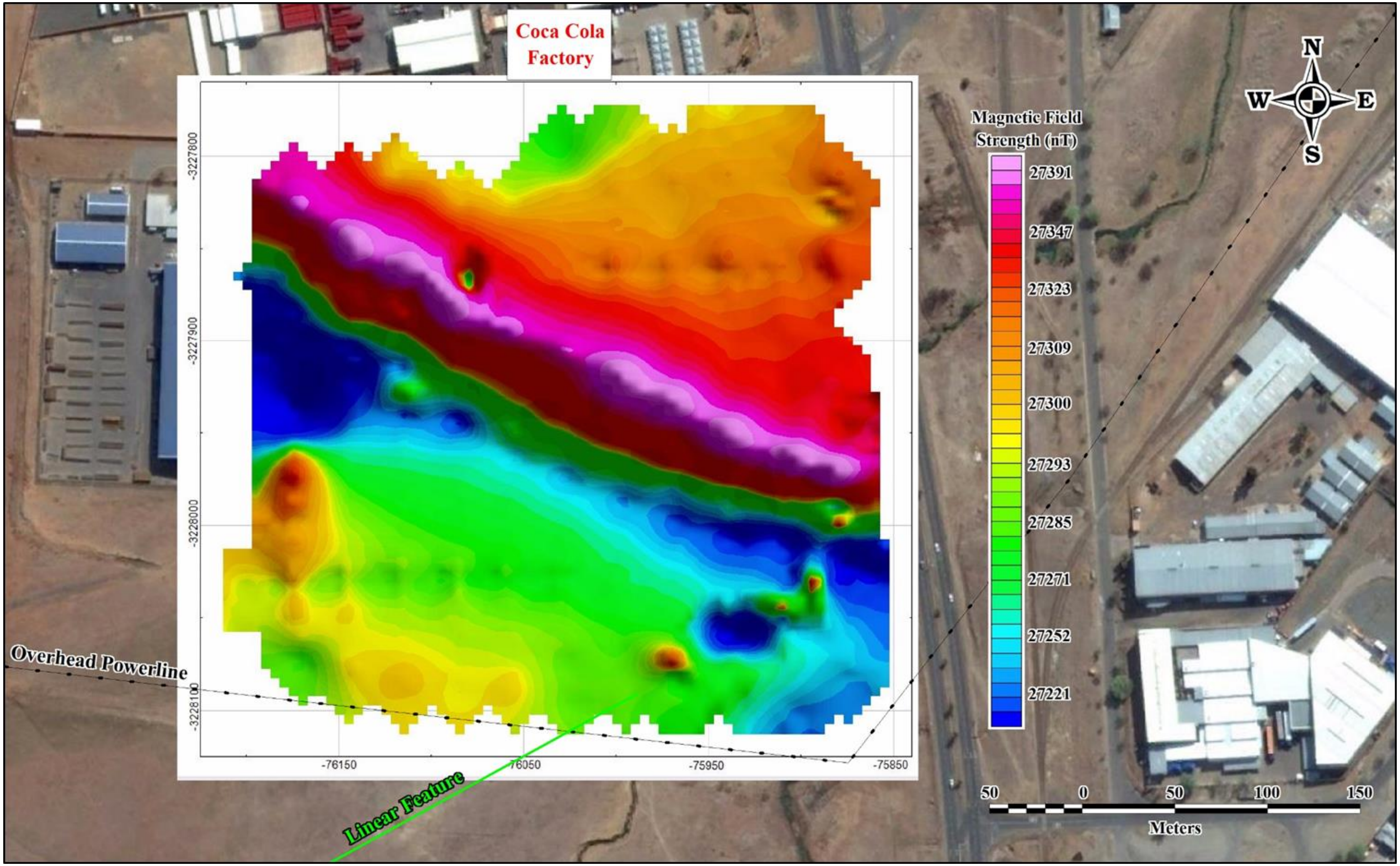

Figure 46. Contour map of the total magnetic field recorded on Grid 2 immediately south of the Coca Cola factory

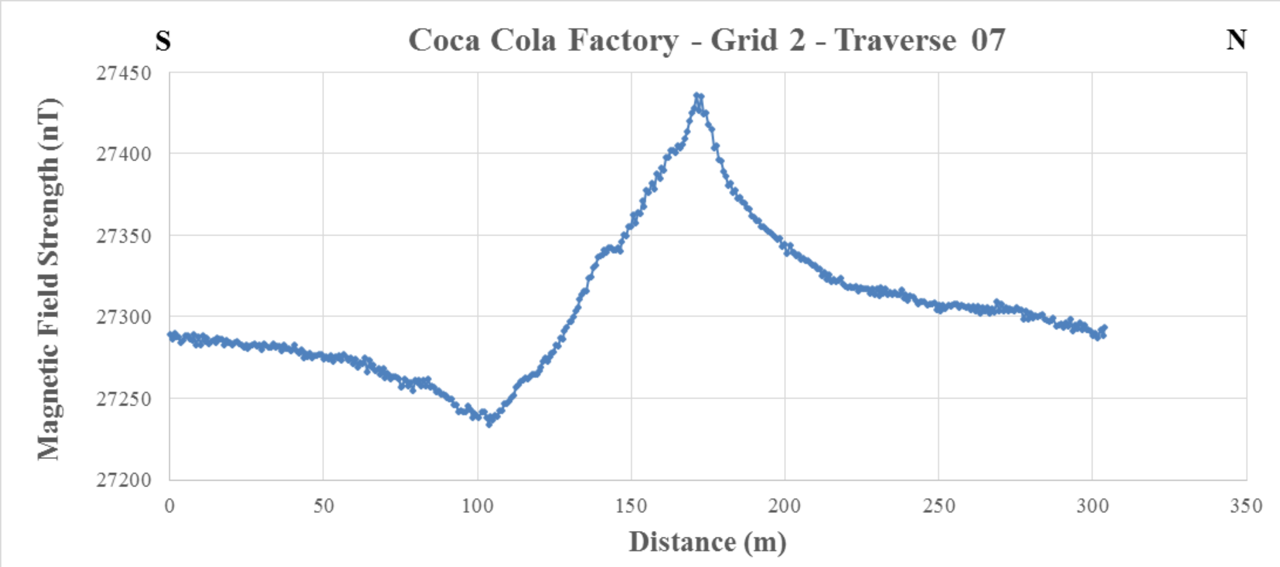

Figure 47. Profile of the total magnetic field recorded along Traverse 07 of Grid 2

The ERT surveys employed the Wenner geometry, using standard electrode spacing of 5 m to allow maximum depths of investigation of approximately 65 m.

4.3.2 Results

The results of the ERT surveys are presented as modelled resistivity sections of the subsurface underlying the profiles. The four modelled resistivity sections are shown in Figure 50 to Figure 53. The modelled resistivity sections of ERT Profiles 1 and 2 reveal the presence of a prominent resistive structure near the centre of the profiles. This structure is in all likelihood a thick dolerite dyke, or possibly a ring-dyke. The contacts between the host rock and the structure are sharper on the south-western side than on the north-eastern side, suggesting that the structure dips to the north-east. Low resistivities on the south-western side of the structure could possibly indicate higher degrees of water saturation at these positions.

The data recorded on ERT Profiles 3 and 4 were very noisy, resulting in artefacts in the inverted resistivity models, such as the near-vertical zone of low resistivity in Profile 03 (refer to Figure 52). These profiles were located in the industrial area east of the Study Site and along a road west of the Study Site. These areas are characterised by the presence of surface and subsurface infrastructure. Although the purpose of Profiles 3 and 4 was to investigate whether the dolerite structure could be detected at positions remote from the Study Site, the positions of the profiles were constrained by the surface infrastructure, and it is possible that these profiles were displaced from the structure. The data recorded on these two profiles will therefore not be further considered during the interpretation of the results of the geophysical investigations.

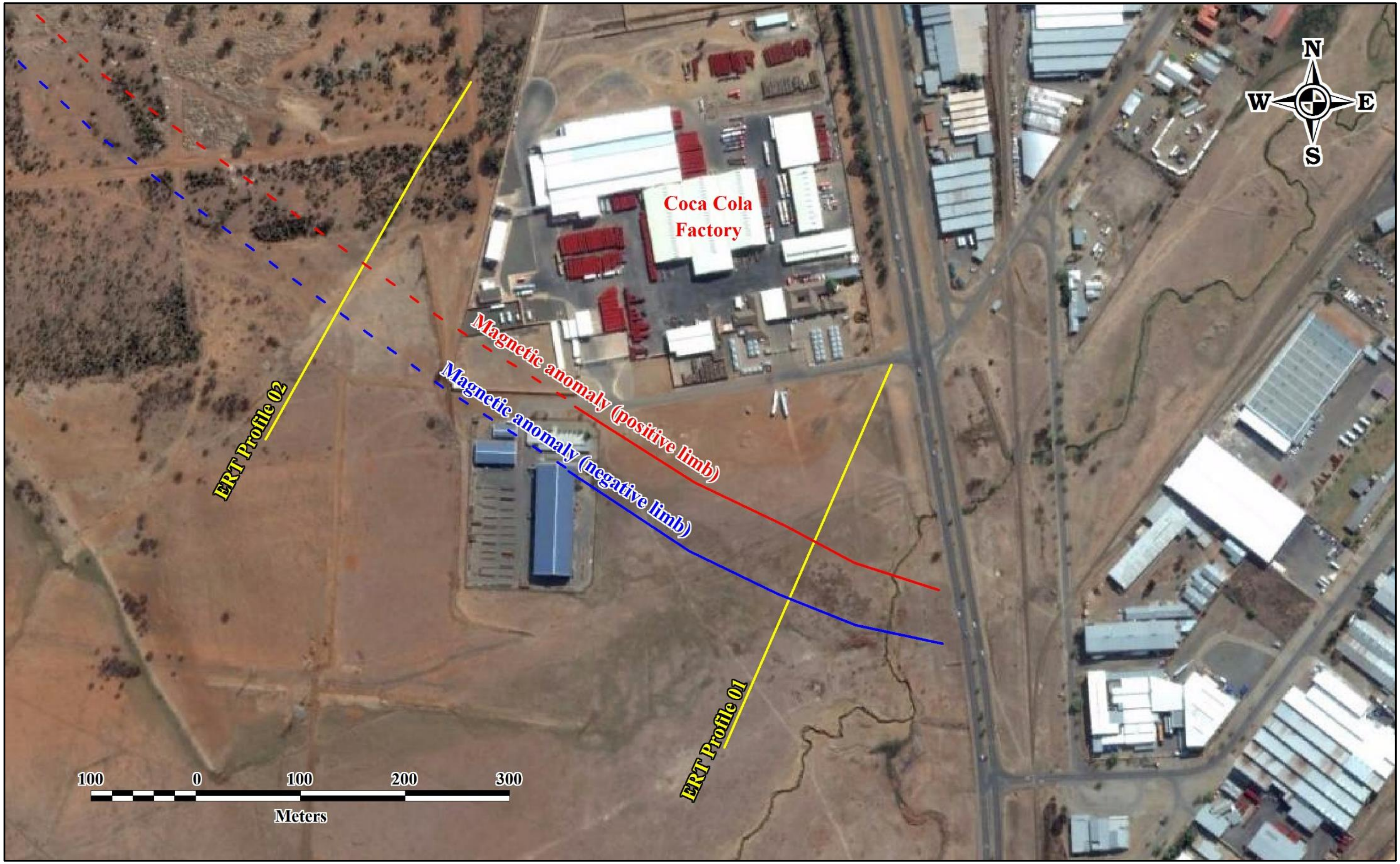

Figure 48. Positions and orientations of the profiles on which ERT data were recorded near the Coca Cola factory

Figure 49. Positions and orientations of ERT Profiles 3 and 4

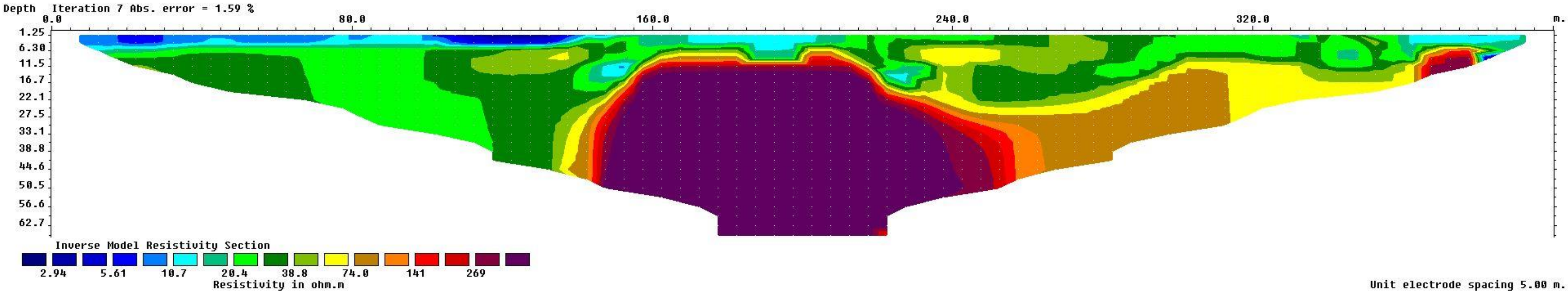

Figure 50. Modelled resistivity section along ERT Profile 01 (SW to NE)

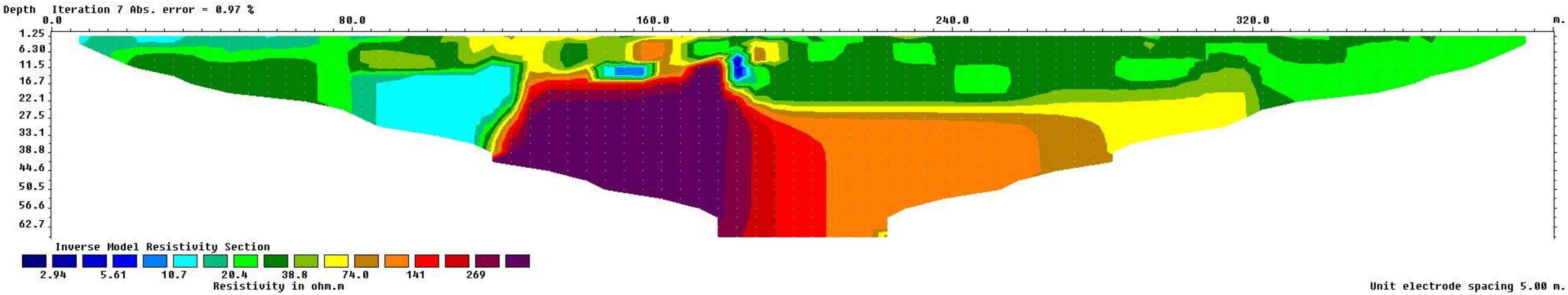

Figure 51. Modelled resistivity section along ERT Profile 02 (SW to NE)

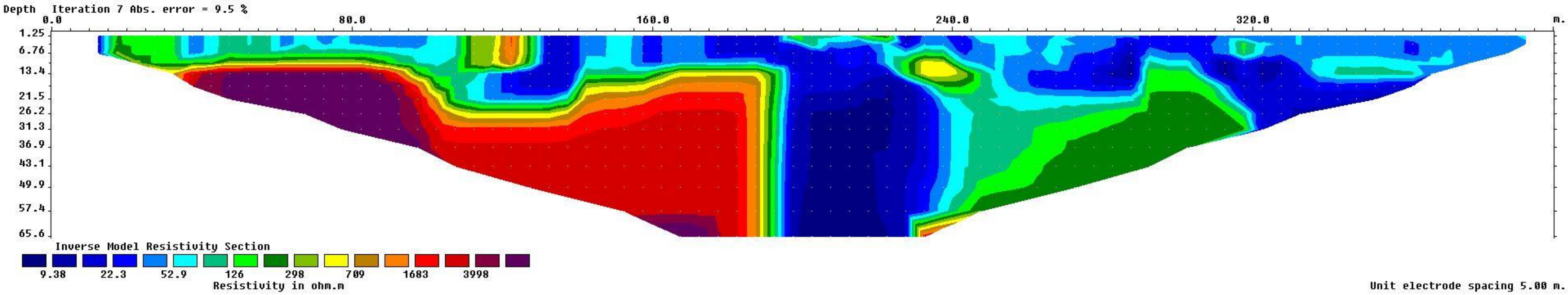

Figure 52. Modelled resistivity section along ERT Profile 03 (SW to NE)

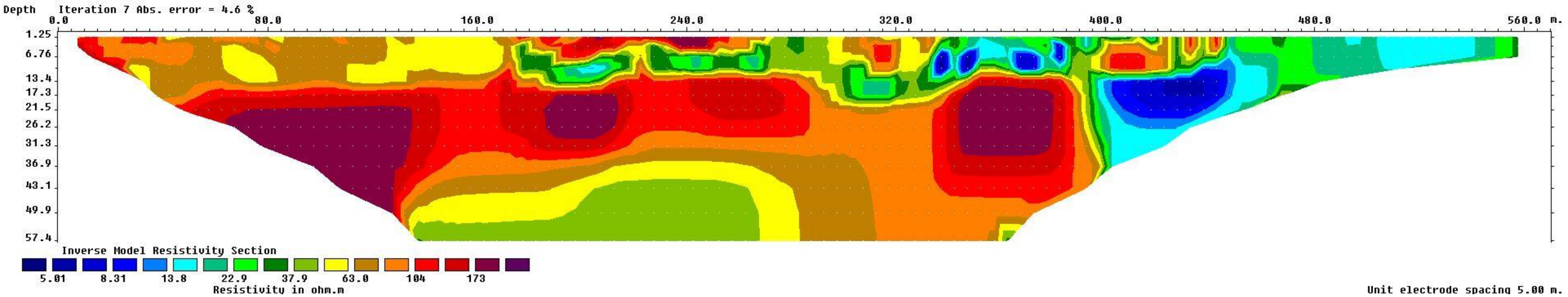

Figure 53. Modelled resistivity section along ERT Profile 04 (SW to NE)

4.4 Interpretation

The purpose of the interpretation of the geophysical data was to gain information on the geometry of the dolerite structure and its possible association with potential aquifers. For the purpose of interpretation, the ERT data recorded on Profile 01 will be considered. This profile was selected for interpretation since detailed ERT and magnetic data were recorded along this profile. In addition, a gravity survey was conducted along the profile by EEGS (Pty) Ltd. The gravity data recorded were included to allow the data from multiple geophysical methods to improve the final interpretation.

The results of the magnetic (Walkmag) and gravity surveys along ERT Profile 01 are presented in Figure 54 and Figure 55, respectively.

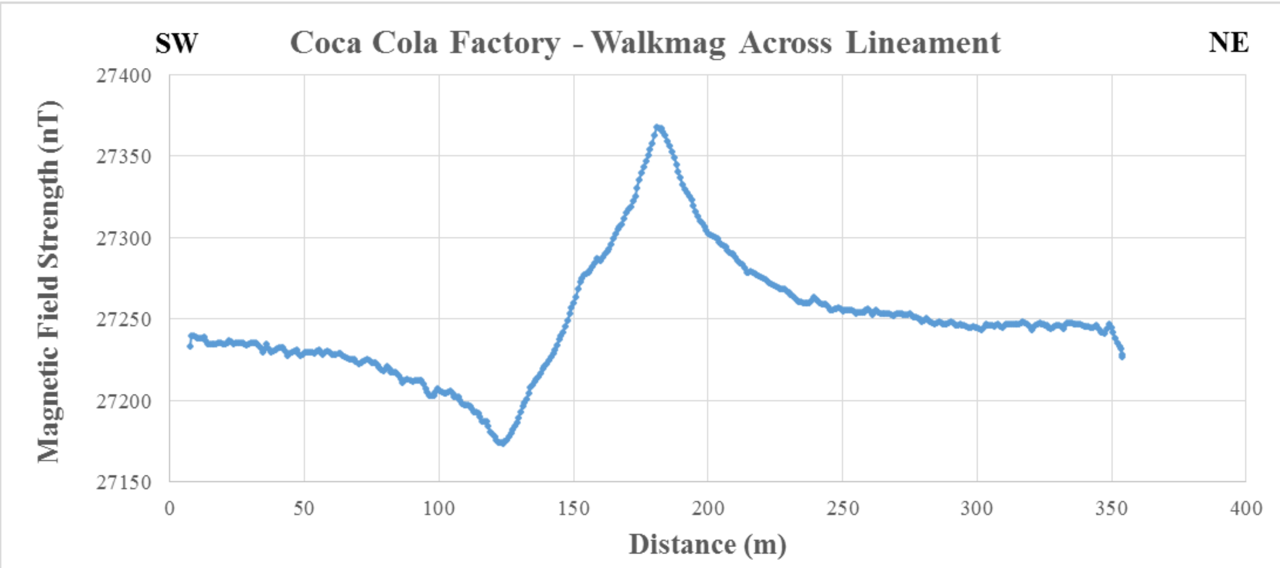

Figure 54. Profile of the total magnetic field recorded along ERT Profile 01

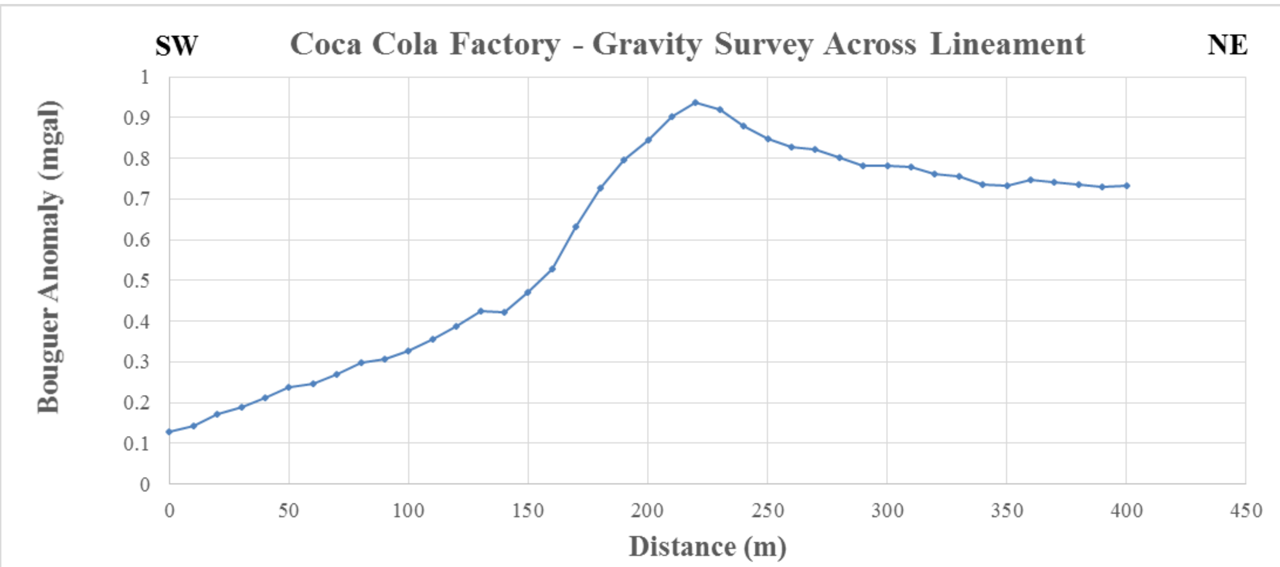

Figure 55. Bouguer anomaly recorded along ERT Profile 01 using the gravity method

The recorded magnetic and gravity data were interpreted in terms of the geometry of the structure causing the observed anomalies by using the software package *pdyke*. This software package allows the forward modelling of the magnetic and gravity responses that can be expected for subsurface structures of different geometries. The aim of the interpretation was to find a model for the subsurface structure that yields similar magnetic and gravity responses that were recorded in the field.

The results of the forward modelling with pdyke are shown in Figure 56 and Figure 57 for the modelled magnetic and gravity responses, respectively. Comparison of these figure with the field data (Figure 54 and Figure 55) shows that a very good agreement is obtained for both the magnetic and gravity data. The density contrast of 0.6 g/cm^3 is typical for the contrast between dolerite and Karoo sedimentary rocks.

The modelled dolerite has the following properties:

- It has a dyke-like geometry,
- It is 40 m thick,
- It dips towards the north-east at an angle of 45^o, and,
- It is buried to a depth of approximately 10 m.

From the above geometry, it appears that the dolerite structure is either a thick dyke with a shallow dip, or possible a ring-dyke with a local dip to the north-east. The modelled geometry is also in agreement with the results of the ERT survey conducted on Profile 01 which suggested that the structure dips towards the north-east. The larger thickness suggested by the ERT profile is in all likelihood the result of the inferior resolving power of resistivity data, especially for the deeper measurements.

From the results of the ERT survey on Profile 01 (refer to Figure 50), it can be seen that lower resistivities occur on the south-western side of the dolerite structure. These lower resistivities may indicate that the south-eastern contact zone between the dolerite structure and the sedimentary host rock has a higher water content than the north-eastern contact zone. Furthermore, from the topographic gradient at the Study Site, surface water and groundwater flow is also expected to be to the north-east. The dolerite structure may therefore act as a barrier to groundwater flow resulting in the accumulation of groundwater against its south-western contact. This would also explain the presence of the wetland that occur south of the dolerite structure (refer to Figure 37).

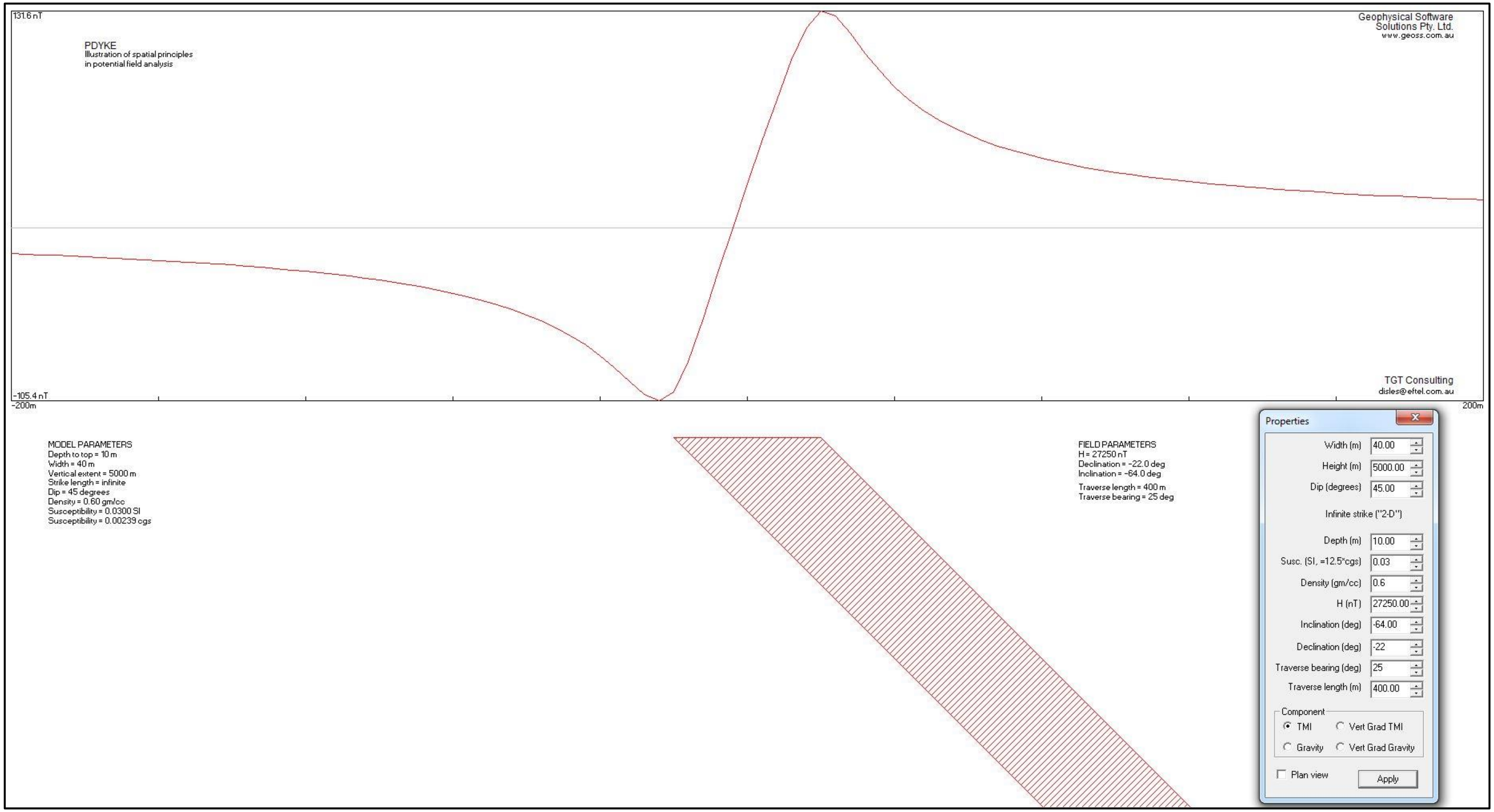

Figure 56. Results of forward modelling of the geometry of the dolerite structure – magnetic response

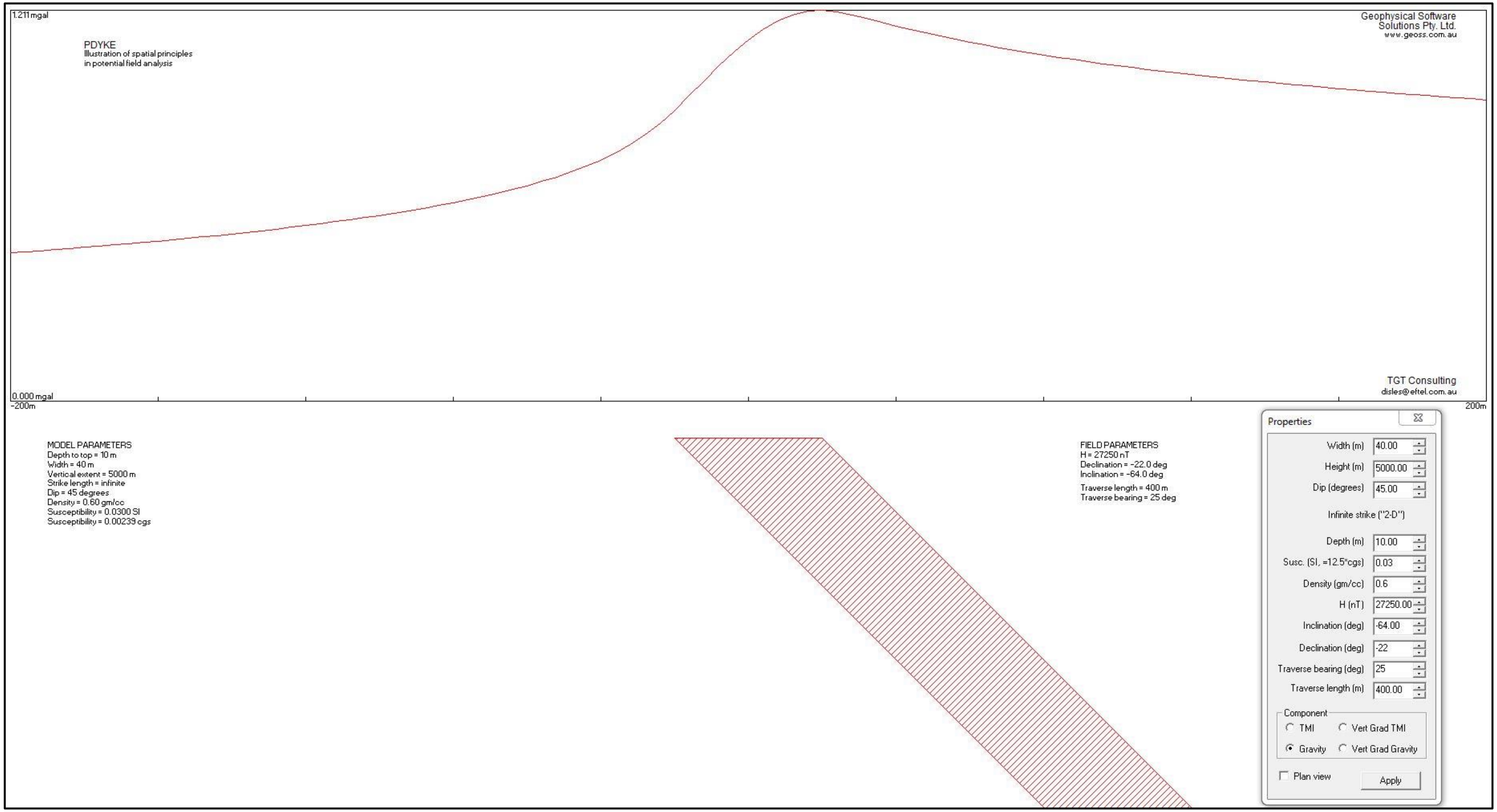

Figure 57. Results of forward modelling of the geometry of the dolerite structure – gravity response

4.5 Discussion

The ground geophysical investigations were successful in detecting and delineating a prominent dolerite structure running through the Study Site. From the magnetic, ERT and gravity data recorded across the structure, estimates of its geometry could be obtained. The structure appears to be either a thick dolerite dyke with a shallow dip, or a ring-dyke. The ERT data suggest that higher levels of groundwater saturation occur on the south-western flank of the structure. This flank should therefore be considered as the primary target for the installation of production boreholes to possibly augment the water supply to the Mangaung Metropolitan Municipality.

It was originally envisaged that the current investigations would incorporate a) the drilling of production boreholes at positions determined from the geophysical investigations, b) the hydraulic testing of the aquifers intersected, and c) groundwater sampling and analyses. These actions were planned to investigate the potential of using the groundwater resource to augment the municipal water supply. However, funding was not received in time to proceed with these actions. The current investigation was therefore severely limited due to circumstances beyond the control of the researcher.

CHAPTER 5:
HYDROCENSUS

5.1 Introduction

One of the original objectives of the current investigation was to drill boreholes at selected sites as determined from the results of the geophysical investigations. These boreholes could potentially serve as production boreholes to augment the municipal water supply with groundwater, but could also be used to investigate the hydraulic properties of the aquifers and the quality of the groundwater. Unfortunately, due to funding problems, no boreholes could be drilled. It was therefore decided that a limited hydrocensus should be conducted to locate borehole that could potentially yield information on the aquifer properties and groundwater chemistry.

The hydrocensus focussed specifically on locating boreholes that occur in the vicinity of known dolerite intrusions within Bloemfontein, similar to the dolerite structure investigated in the current study. Information obtained from these boreholes could potentially allow a better understanding of the geohydrological conditions to be expected at the dolerite structure.

Since a prominent ring-dyke is known to underlie the city of Bloemfontein, and since this dyke is known to be associated with strong aquifers, the hydrocensus focussed on locating boreholes in the vicinity of this dyke. Although boreholes are known to be located on several properties in the vicinity of the dyke, many of the owners would not allow access to their boreholes. For example, many boreholes occur on the property of the Central University of Technology (CUT), but the researcher was refused access to the boreholes. Similar situations occurred at Loch Logan and the Bloemfontein Zoo.

Access to only two boreholes near the dyke could be obtained. These boreholes are located on the properties of two Sasol garages, one near the athletics track adjacent to Loch Logan, and one near the entrance of CUT.

To compare the geohydrological conditions at these boreholes with those at boreholes that have not been drilled near know dolerite structures, two additional boreholes were included in the hydrocensus. These boreholes are both located in the suburb of Willows, approximately 1.5 km from the ring-dyke. The positions of the hydrocensus boreholes are shown in Figure 58 relative to the approximate positions of the ring-dyke known to occur within the city limits.

Figure 58. Positions of the hydrocensus boreholes

5.2 Results of the Limited Hydrocensus

The information gathered during the hydrocensus is summarised in Table 7, while photographs of the identified boreholes are shown in Figure 59 to Figure 62. The photographs show the type and condition of the infrastructure at the boreholes. The hydrocensus sheets used during the field investigations are presented in **Appendix B**.

Table 7. Summary of the results of the hydrocensus

Name	Coordinates		Water level (m)	Borehole depth (m)	Pump type	Casing type	Current water use	Colour	Odour
	S	E							
BH1	29.12215	26.21216	N/A	N/A	Sub	N/A	Irrigation and car wash	Clear	No
BH2	29.11811	26.21128	N/A	N/A	Sub	N/A	Irrigation and car wash	Clear	No
BH3	29.12139	26.19693	10.16	40.5	Sub	Steel	Irrigation	Clear	No
BH4	29.12071	26.19730	8.65	33	Sub	Steel	Irrigation	Clear	No

From Table 7 it is seen that only limited data could be recorded at the identified boreholes. All the identified boreholes are privately owned by GHT Consulting Scientists, two Sasol filling stations and Mr Pieter Coetzer. The boreholes are used for irrigation and car washes at the filing stations. All boreholes are equipped with submersible pumps. Water levels could be recorded at the two boreholes located in Willows, but unfortunately not at the two boreholes located closer to the prominent ring-dyke. These water levels were 8.65 and 10.16 metres below ground level (mbgl).

Due to the presence of infrastructure, access to the boreholes could not be obtained to perform hydraulic tests. However, electrical conductivity (EC) and temperature profiles could be recorded at boreholes BH3 and BH4. The results of the EC and temperature profiling of these boreholes are shown in Figure 63 to Figure 66.

From the EC profile of borehole BH3 (refer to Figure 63) it can be seen that a gradual increase in the EC with depth occurs from approximately 126 mS/m at a depth of 10.16 mbgl to approximately 130 mS/m at a depth of 25 mbgl. The EC then undergoes a sharp increase to approximately 135 mS/m. From this depth until the end of hole (EOH) at 40.5 mbgl, small fluctuations around the value of 135 mS/m are observed. The profile shows that the deeper groundwater has a higher salinity than the shallow groundwater. This may be due to the effects of dilution from recharge and rainwater entering the borehole affecting the salinity of the shallower aquifer.

Figure 59. Borehole at the Sasol filling station next to CUT (BH1)

Figure 60. Borehole at the Sasol filling station next to Loch Logan (BH2)

Figure 61. Mr Pieter Coetzer's borehole in Willows (BH3)

Figure 62. Borehole owned by GHT Consulting Scientists in Willows (BH4)

The EC profile of borehole BH4 (see Figure 64) also displays an increasing trend with depth, but a more gradual trend than at BH3 is observed. Between 20 and 30 mbgl the EC fluctuates around 108 mS/m. At depths greater than 30 mbgl the EC shows further increases to reach a value of 114 mS/m. The less saline water at shallower depths is again likely to be due to the effects of dilution from rainwater and recharge, while the high salinity at the bottom of the borehole may be due to heavier salts accumulating under the influence of gravity.

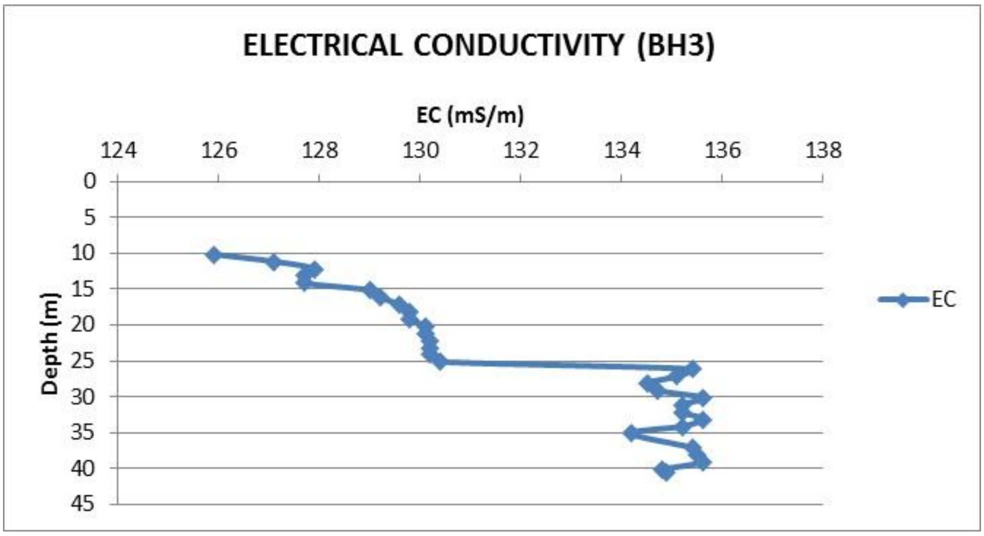

Figure 63. Electrical conductivity profile of borehole BH3

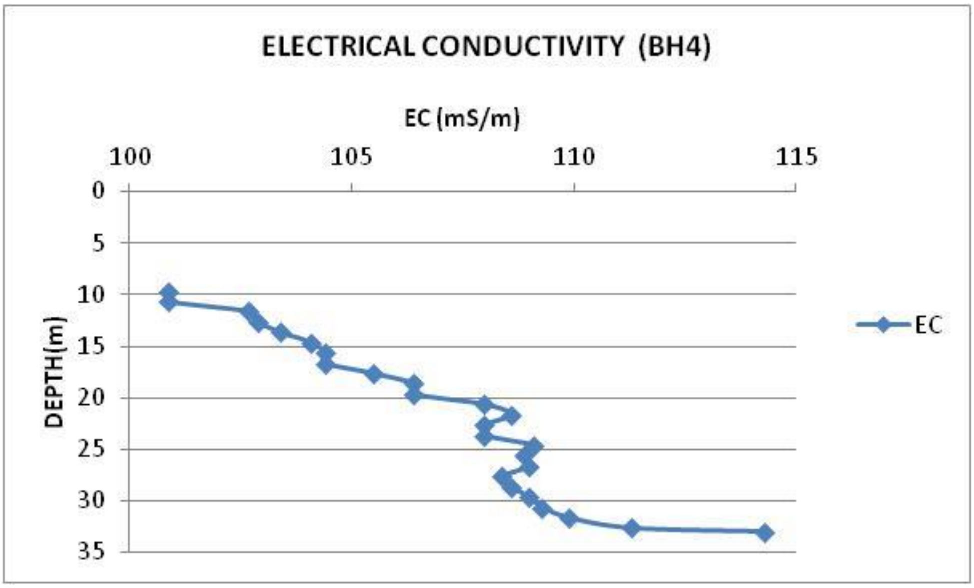

Figure 64. Electrical conductivity profile of borehole BH4

The temperature profile of borehole BH3 displays higher temperatures at shallow depths and at the bottom of the borehole than in its central parts (refer to Figure 65). The higher temperatures near the water table are likely to be due to solar heating. The origin of the higher temperatures at the bottom of the borehole is currently unknown.

The temperature profile of borehole BH4 (refer to Figure 66) shows very consistent values along the entire length of the borehole, ranging from 19.6 to 19.7 mS/m. The slightly higher temperatures are observed at shallower depths and are again likely to be due to heating from the sun.

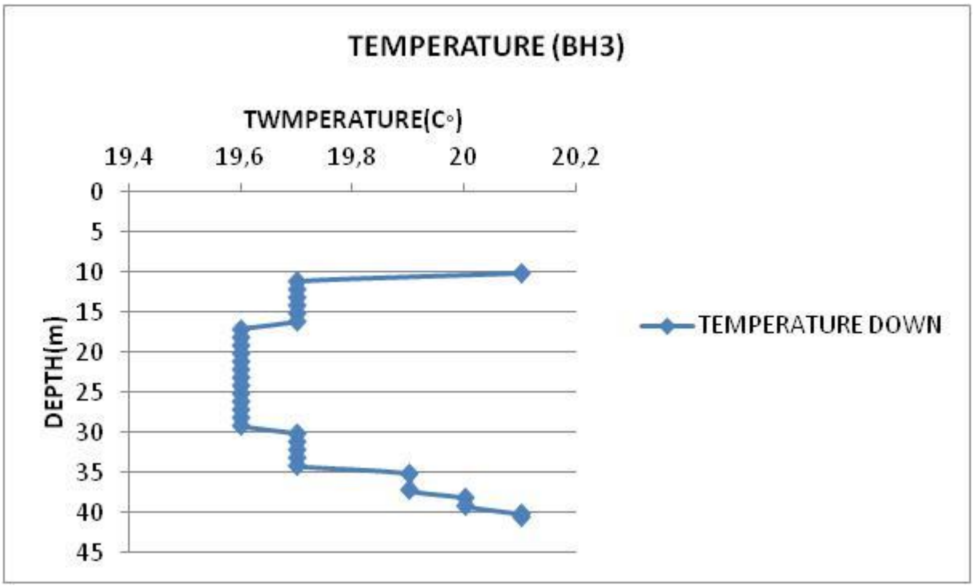

Figure 65. Temperature profile of borehole BH3

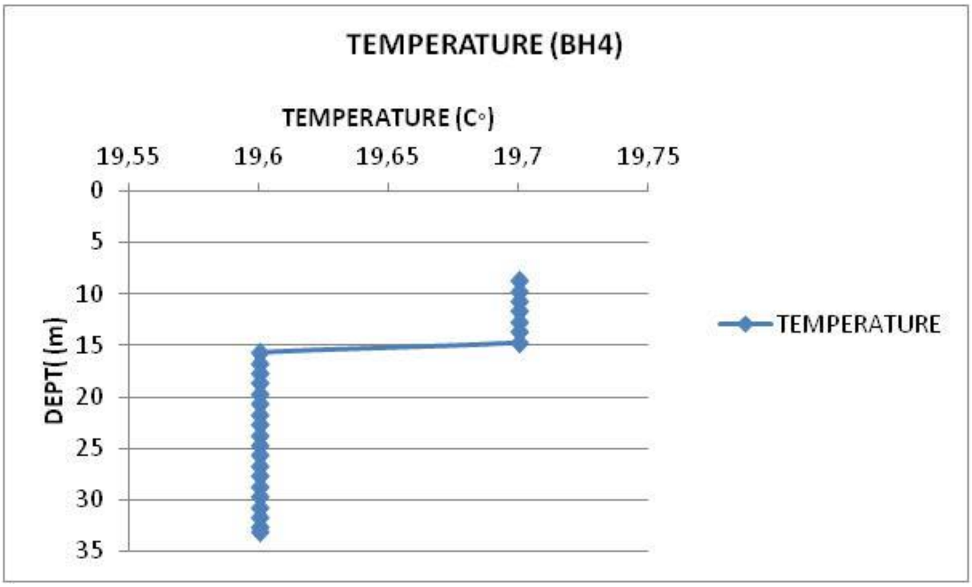

Figure 66. Temperature profile of borehole BH4

5.3 Discussion

The hydrocensus was very limited in terms of the number of boreholes included. This was due to the unwillingness of some of the owners of boreholes to allow access to these boreholes. Especially in the vicinity of the prominent ring-dyke the owners of boreholes were very uncooperative. This is a significant limitation of the hydrocensus, since its purpose was to focus specifically on the boreholes near large dolerite structures to obtain information that could be representative of the geohydrological conditions in the vicinity of the dolerite structure investigated in the current study.

Furthermore, since no hydraulic tests could be performed on the boreholes located during the hydrocensus, no information on the hydraulic properties of the aquifer systems could be obtained. This is another significant limitation of the current study, since no estimation of the potential yield of the aquifer systems can be made without such data.

CHAPTER 6:
GROUNDWATER QUALITY

6.1 Introduction

One of the most significant aspects of groundwater studies is water quality analysis. The determination of physico-chemical feature of water is necessary for evaluating the suitability of the water for different application, such as drinking, domestic, industrial and agricultural use. The groundwater quality may also differ with seasonal changes and is mostly governed by the concentration and composition of dissolved solids (Vikas, *et al* 2012). The natural and anthropogenic effects, such as local climate, geology, and irrigation practices, also have a significant influence on groundwater quality.

The relative abundances of various elements in groundwater mainly depend upon their chemical mobility. The mobility of an element in the hydrosphere is determined by the solubility of its various compounds, the tendency of the ion towards adsorption and base-exchange, and the degree to which it is bound in the biosphere.

In this chapter, the results of the chemical analyses conducted on groundwater samples from the four boreholes located during the hydrocensus are discussed. The purpose of this is to gain insight into the groundwater characteristics, and to evaluate its suitability for its intended use, i.e. augmentation of the municipal water supply to the city of Bloemfontein.

6.2 Chemical Analyses of Groundwater Samples

Four groundwater samples collected during the hydrocensus (refer to Chapter 5) were submitted for chemical analyses to the laboratory of the Institute for Groundwater Studies (IGS). All water samples were pumped from the boreholes using the existing equipment at these boreholes. Water samples were analysed for all the major cation and anion species.

The results of the chemical analyses are presented in Table 8. In this table, the cells are colour-coded according to the standards set by the Department of Water Affairs (DWA) for the quality of domestic water supplies (DWA, 1998). Uncoloured cells indicate that no standards have been set for the particular parameter by the DWA.

Table 8. Results of the chemical analyses performed on groundwater samples

Parameter	Boreholes near ring-dyke		Boreholes remote from ring-dyke	
	BH1	BH2	BH3	BH4
TDS	611	1259	797	602
EC	81.7	169	110	84.7
pH	6.99	6.93	7.13	6.94
Ca	85.72	124.66	104.52	74.31
Mg	28.50	59.54	45.36	34.73
Na	44.84	154.04	57.75	46.61
P.Alk	0	0	0	0
M.Alk	280	461	359	288
K	2.30	3.69	5.16	4.21
F	0.321	0.347	0.296	0.234
Cl	60.47	152.32	110.15	60.50
NO_2 (N)	<0.01	<0.1	<0.1	<0.01
Br	0.302	0.698	<0.400	0.226
NO_3 (N)	7.18	5.35	5.66	4.13
PO_4	<0.1	<1	<1	<0.1
SO_4	76.70	280.72	91.83	75.30
Al	<0.010	<0.010	<0.010	<0.010
As	0.008	0.014	0.006	0.006
B	0.077	0.473	0.083	0.069
Ba	0.063	0.057	0.126	0.069
Cr	<0.010	<0.010	<0.010	<0.010
Cu	0.011	0.013	0.013	0.012
Fe	0.02	0.019	0.018	0.046
Mn	<0.010	<0.010	<0.010	<0.010
Mo	<0.010	<0.010	<0.010	<0.010
Ni	<0.010	<0.010	<0.010	<0.010
Pb	<0.010	<0.010	<0.010	<0.010
Zn	0.060	0.027	0.045	0.071

All values express in mg/L

(blue) Ideal water quality	(orange) Poor water quality
(green) Good water quality	(red) Dangerous water quality
(yellow) Fair water quality	

From the data listed in Table 8, a number of observations may be made regarding the groundwater quality at the four sampled boreholes:

- Near-neutral pH values are observed at all the groundwater sites.
- The groundwater quality at the boreholes is generally good to ideal, although elevated salt concentrations at borehole BH3 render the water quality at this borehole fair.
- The calcium concentrations at all four boreholes are slightly elevated above the ideal concentrations.

- The nitrate concentration at borehole BH1 is elevated above the ideal concentration. The observed elevated nitrate concentration may be due to different sources, including leaking sewerage infrastructure.
- The sodium, chloride and sulphate concentrations at borehole BH2 are higher than at the other boreholes and are elevated above the ideal concentrations.
- The groundwater from borehole BH3 also displays an elevated chloride concentration.
- The trace element concentrations at all the boreholes are very low, often lower than the detection limits of the equipment used by the laboratory for analyses.

When comparing the results of the chemical analyses obtained for the boreholes close to the ring-dyke (BH1 and BH2) with the results obtained for the boreholes at remote locations (BH3 and BH4), it can be seen that groundwater from the two sets of boreholes have very similar qualities, although borehole BH2 has higher salt concentrations than the other boreholes. It can therefore be concluded that no significant difference exists between the qualities of the two sets of boreholes. The presence or absence of the known dolerite structure does not seem to have a significant effect on the groundwater quality.

6.3 Hydrochemical Characteristics

Hydrochemical diagrams may be used to show the absolute or relative abundances of different anions and cations in water samples. In these diagrams, the concentrations are usually expressed in milli-equivalents per litre (meq/L) to prevent the heavier parameters from dominating over the lighter parameters. These diagrams include the Piper, Durov, Extended Durov, SAR and Stiff diagrams.

6.3.1 Piper diagram

A Piper diagram is a graphical representation of the chemistry of water samples. The diagram consists of three areas, namely: a ternary diagram in the lower left describing the major cation concentrations, a ternary diagram in the lower right representing the anion concentrations and a diamond plot in the centre representing a combination of the two ternary diagrams. Depending on the relative concentrations of the major cations and anions, a water sample will plot at a specific position within the central diamond. 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.

The Piper diagram for the groundwater samples from the four boreholes is shown in Figure 67. The water samples from BH1, BH3 and BH4 plot within the area of the diagram that indicates that the groundwater is of the calcium-bicarbonate type. However, BH2 plots at a position slightly removed from the other three boreholes, causing this water to be classified as belonging to the calcium-sulphate type. This reflect the fact that the water chemistry at BH2 is slightly different to the water chemistries at the other sites.

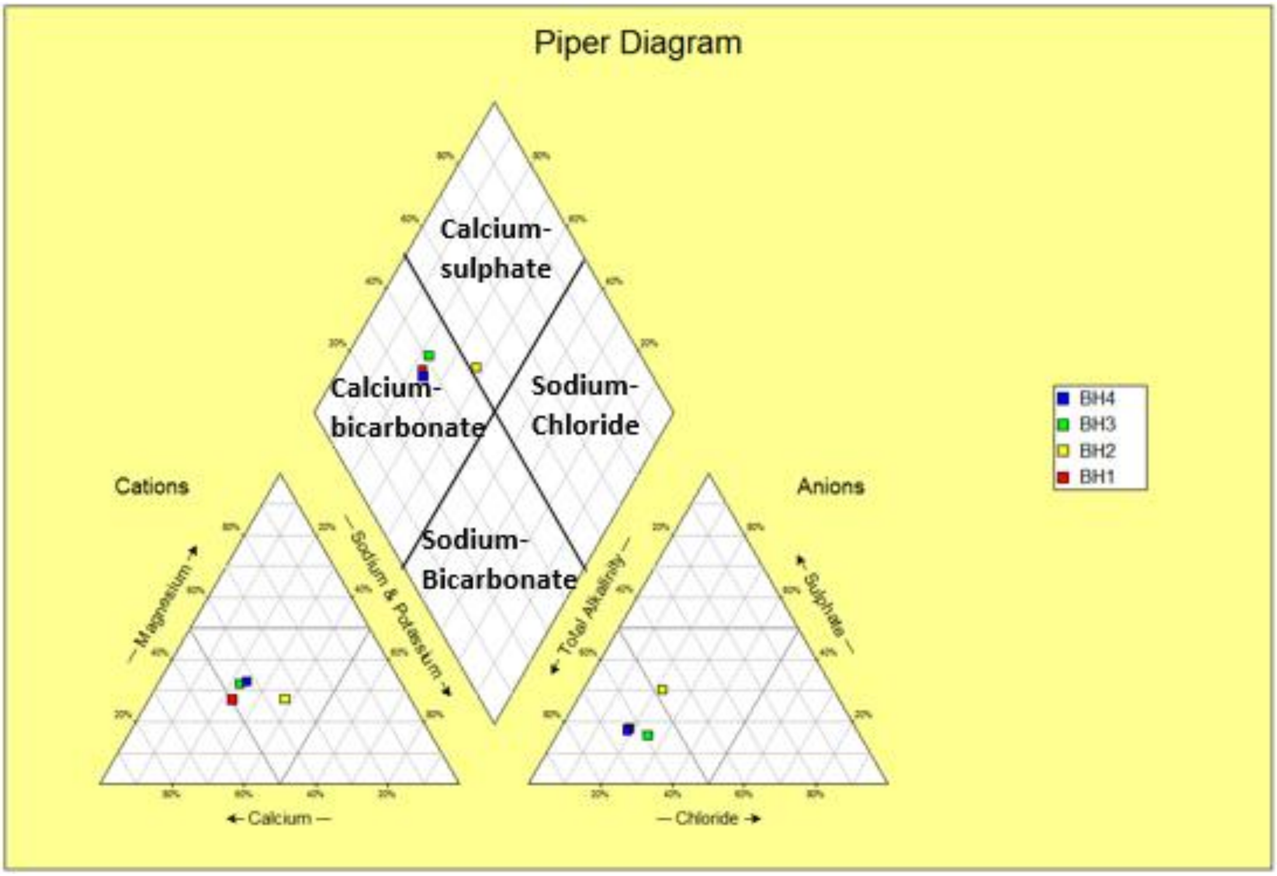

Figure 67. Piper diagram of the groundwater samples

6.3.2 Durov diagram

The Durov Diagram is another way the visually compare the relative concentrations of anions and cations in a water sample. The main advantage of the Durov Diagram is that it allows a graphical visualisation of the concentrations of the eight major ions. The diagram consists of two ternary diagrams where the cations of interest are plotted against the anions. The diagram is used to visualise the cation and anion concentrations relative to the pH and the TDS concentration.

The Durov diagram of the four groundwater samples is shown in Figure 68. Again it is seen that the groundwater from boreholes BH1, BH3 and BH4 have very similar characteristics, plotting close to one another in the diagram, while the groundwater from BH2 plots in a position slightly displaced from the others. The higher sulphate and sodium concentrations observed at BH2 are responsible for this shift in the plotting position.

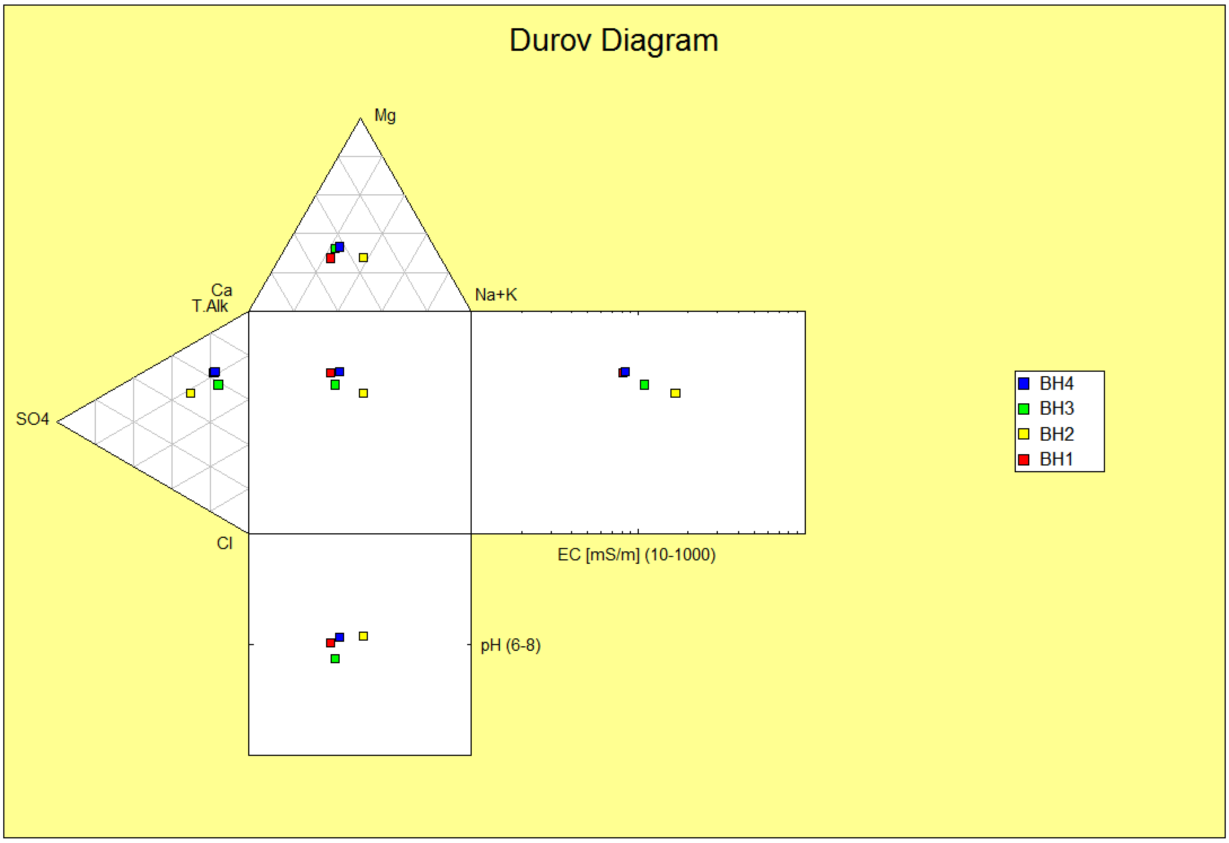

Figure 68. Durov diagram of the groundwater samples

6.3.3 Expanded Durov diagram

The Expanded Durov diagram is a graphical representation similar to the Piper diagram. The central plotting area is a square rather than a diamond but the principal difference is that in the Expanded Durov diagram the percentages of the individual ions are calculated as total ions (Cation + Anions). In the Piper diagram the percentages of cations and anions are plotted separately. The nine blocks in the main square of the diagram represent the hydrochemical facies. These hydrochemical facies are used to distinguish one water type from another

The Expanded Durov diagram of the four groundwater samples is shown in Figure 69. Boreholes BH1, BH3 and BH4 plot in the top central square of the diagram, showing that the water from these boreholes is unpolluted. Borehole BH2, on the other hand, plot in the middle central square, showing that this borehole has been impacted on by contaminants.

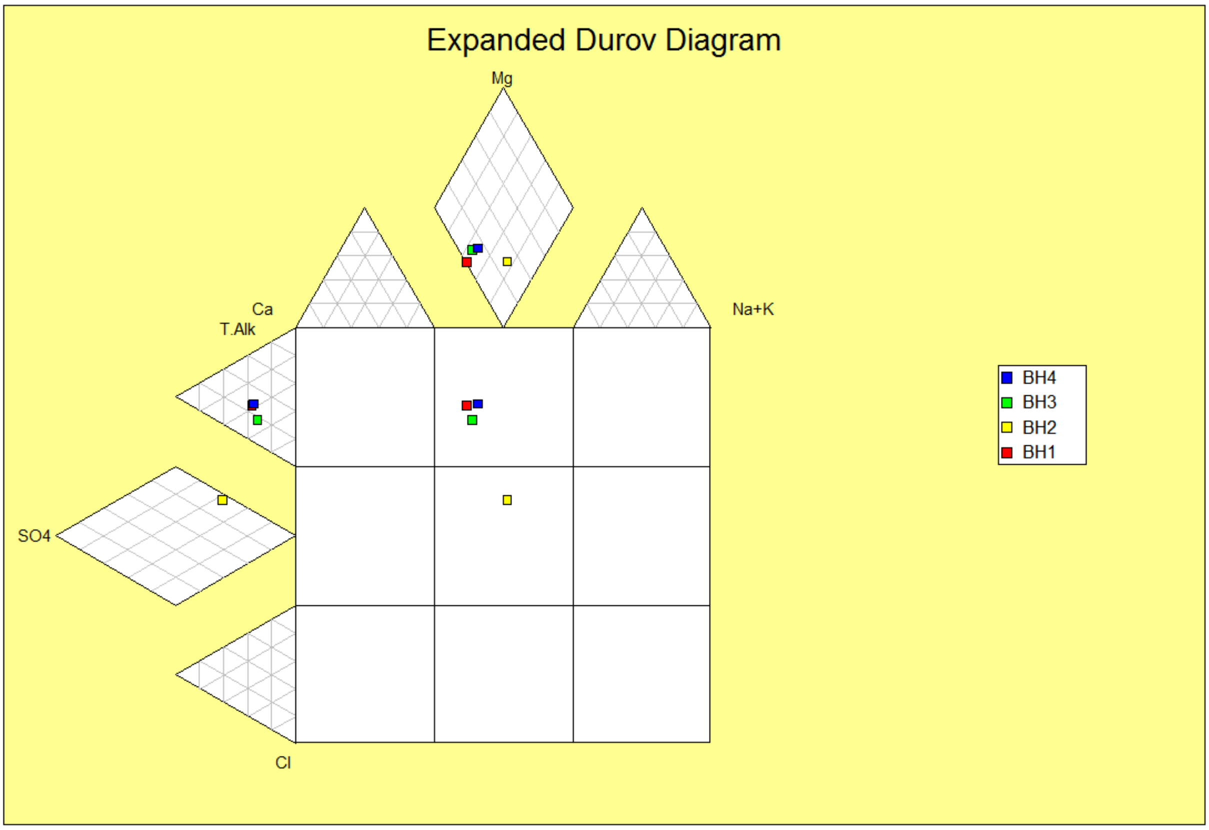

Figure 69. Expanded Durov diagram of the groundwater samples

6.3.4 Stiff diagram

The Stiff diagram is particularly useful to visually distinguish between waters 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 diagrams for the four groundwater samples are shown in Figure 70. From the shapes of these diagrams it is clear that very similar water chemistries exist at boreholes BH1, BH3 and BH4. However, the Stiff diagram of borehole BH2 has a very different shape to the other diagrams showing that water at this site has a different character to the water at the other sites.

6.3.5 SAR diagram

The Sodium Absorption Rate (SAR) diagram is used to evaluate if water is suitable for irrigation purposes. From the SAR diagram of the four groundwater samples (refer to Figure 71), it is seen that the groundwater in all four boreholes is characterised by high salinity of 75-225 mS/m (C3 – high salinity hazard). If this water were to be used for irrigation, it would require soil with a very good drainage to allow leaching of the salts. Accumulation of salts in the groundwater could lead to salinity problems which may affect the uptake of nutrients by plants. Salinity effects are often more severe during crop emergence and early development stages (Tanji and Kielen 2002).

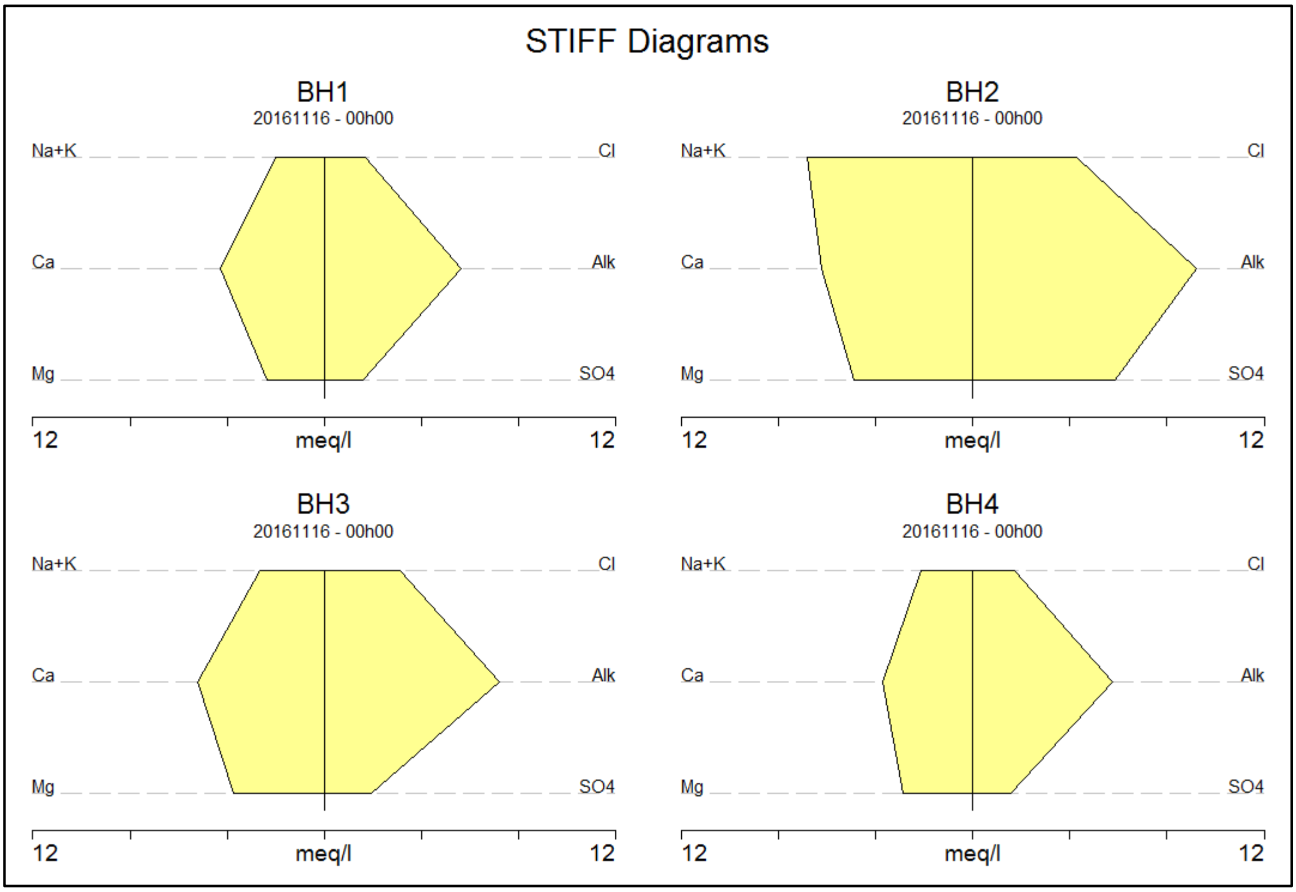

Figure 70. Stiff diagram of the groundwater samples

6.4 Discussion

The results of the groundwater quality analyses and hydrochemical characterisation show that the groundwater from the sampled boreholes is generally of ideal to good quality, although elevated salt concentrations were observed, particularly at borehole BH2. After some treatment, the groundwater should be suitable for human consumption.

Groundwater samples were collected from boreholes BH1 and BH2 near the known ring-dyke to investigate the groundwater quality in the vicinity of a prominent dolerite intrusion. This was done to get an indication of the groundwater qualities that can be expected near the dolerite structure targeted during the current investigations (south of the CBD). The water quality at these boreholes suggests that the groundwater associated with such dolerite structures could potentially be used to augment the municipal water supply. Some treatment may, however, be required. It is also possible that the mixing of purified water from the different water treatment works supplying the city with the groundwater would be sufficient to reduce the salt concentrations to level suitable for human ingestion.

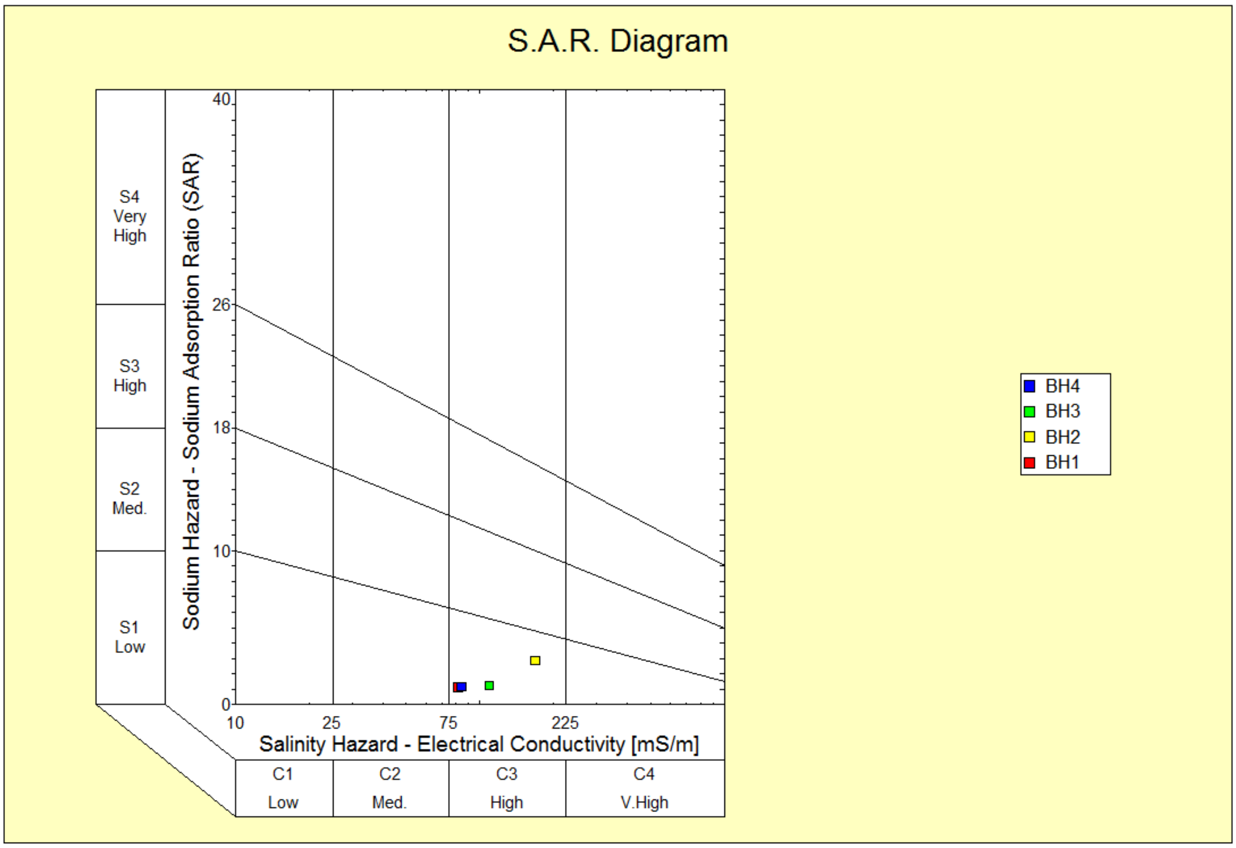

Figure 71. SAR diagram of the groundwater samples

CHAPTER 7:
CONCLUSION AND RECOMMENDATIONS

This aim of this study was to investigate the potential of using groundwater resources associated with a prominent dolerite intrusive which occurs south of the Bloemfontein CBD to supplement the water supply to the Mangaung Metropolitan Municipality (MMM). To achieve this aim, different objectives were identified. These objectives were:

- To locate and delineate the prominent dolerite structure within the municipal boundaries using geophysical methods.
- To investigate the geometry of the dolerite structure.
- To propose drilling positions for the installation of production borehole.
- To assess the suitability of the groundwater resource for municipal use.
- To estimate the abstraction rate from the aquifer that would allow sustainable groundwater use.
- To make recommendation for future utilisation of groundwater resources in the MMM.

Although the dolerite structure was successfully detected and delineated, and the geometry of the structure could be determined from the results of the geophysical survey, funding for the drilling of the boreholes was never received due to delays resulting from disagreements between the MMM and BloemWater. This meant that no boreholes could be drilled as part of the current investigations, which implied that no groundwater sampling could be done and that no hydraulic tests could be performed on the aquifer system to determine a sustainable groundwater abstraction rate. The fact that no boreholes could be drilled should therefore be seen as a major limitation of the current study.

Since boreholes could not be drilled as part of the current investigations, it was decided to investigate the groundwater conditions in the vicinity of another prominent dolerite intrusion within the city boundary. A major ring-dyke, known to be associated with high-yielding aquifers, was therefore targeted during a limited hydrocensus. The purpose of the hydrocensus was to obtain information on the geohydrological condition near the ring-dyke. It was thought that these conditions could be representative of the geohydrological conditions in the vicinity of the dolerite structure targeted during the current investigations.

Although several high-yielding boreholes are known to occur at positions along the perimeter of the ring-dyke, access to only two such boreholes could be obtained. Chemical analyses performed on the groundwater samples collected from these boreholes showed that the water quality ranged from ideal to fair. It should be taken into account that these boreholes both occur in an urban area with several possible sources of contamination that could have impacted on the groundwater quality. It can therefore be concluded that the quality of the groundwater associated with the dolerite structure south of the CBD is likely to be of a similar or better quality. This groundwater is less likely to have been impacted on by contaminants from surface activities, despite the fact that industrial activities do take place to the east and north of the structure.

No information on the hydraulic properties of the aquifer system near the targeted dolerite structure is currently available. However, a high-yielding borehole approximately (8 L/s) was recently drilled by Thaba Nchu Drilling at the Coca Cola factory to the north of dolerite structure. It therefore appears that the dolerite structure is associated with high-yielding aquifers.

Although there are indications that the dolerite structure targeted in the current study may be associated with strong aquifers yielding groundwater of good quality, it is not possible at this stage to draw any definite conclusions on the possibility of using these aquifers to augment the municipal water supply. It is therefore recommended that the following actions be taken during future investigations:

- As suggested by the results of the geophysical investigations, boreholes should be drilled at positions on the south-western flank of the structure.
- Groundwater samples should be collected from these boreholes and submitted to an accredited laboratory for chemical and bacteriological analyses.
- The results of the chemical and bacteriological analyses should be used to assess the groundwater quality in terms of its suitability for human consumption.
- Hydraulic tests should be performed on the boreholes to investigate the hydraulic properties of the aquifer systems.
- The results of the hydraulic tests should be used to estimate a sustainable abstraction rate from the aquifer system.
- A monitoring programme should be developed to monitor the groundwater levels in the boreholes, as well as the groundwater quality. This purpose of this programme will be to ensure that the aquifer system is not over-exploited and to detect changes in the groundwater quality that may indicate impacts from contaminants.

- Depending on the salt concentration of groundwater, a mixing ratio of groundwater to treated municipal water should be calculated that would ensure that the salt concentrations of the water supplied to the city of Bloemfontein all fall within acceptable limits.
- If it is found that the groundwater requires treatment prior to inclusion in the bulk water supply, further recommendations regarding possible treatment actions should be made.

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ABSTRACT

The city of Bloemfontein is currently relying on surface water sources for its potable water supply. However, Bloemfontein is located in a semi-arid area, which means that the surface water resources are unreliable and susceptible to droughts. In addition, the water demand in the city has increased significantly during recent years due to population increases, agricultural growth and industrial development. It is expected that the surface water resources will soon not be adequate to meet the increasing water demand.

This study investigated the possibility of using groundwater resources associated with a major dolerite intrusive to supplement the water supply to the Mangaung Metropolitan Municipality in which the city of Bloemfontein is located. As part of the investigations, geophysical surveys were conducted to detect and delineate a prominent dolerite structure in an area south of the Bloemfontein CBD. The results of the geophysical investigations were used to determine the geometry of the structure and to suggest positions for the installation of boreholes.

Due to funding problems, no boreholes could be drilled as part of the current investigations. The groundwater quality and aquifer parameters could therefore not be investigated directly. A limited hydrocensus was therefore conducted to investigate the geohydrological conditions in the vicinity of another prominent dolerite intrusion known to occur with the city limits. The groundwater conditions at boreholes occurring near this intrusion were investigated and considered to be representative of the conditions at the dolerite structure targeted during the current investigations.

Although no final conclusions can at present be drawn on the possibility of using the groundwater associated with the dolerite structure to augment the municipal water supply, indications are that the aquifer system is high-yielding and the groundwater is expected to be of a good quality.

Since the current investigation was severely limited due to the fact that no boreholes could be drilled on the targeted structure, recommendations for future actions were made. These recommendations include a) the installation of boreholes at the positions suggested by the results of the geophysical survey, b) groundwater sampling and chemical analyses to determine the groundwater quality, c) hydraulic testing of the aquifer system to determine a sustainable yield, and d) the development of a monitoring programme to detect changes in the groundwater conditions that may indicate either over-exploitation or contaminant impacts.