Investigation of deep groundwater flow systems in the Main Karoo Basin of South Africa

By
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Declaration of work

I declare that, “The investigation of deep groundwater flow systems of the south western Karoo Basin in South Africa” is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged as complete references.

Thandokazi Maceba  (2938290)

Date: 03 November 2017

Signature:
Dedication of thesis

This thesis is dedicated to my loving parents Maxesha Maxwell and Nogolide Nosandla Maceba.
Acknowledgements

Firstly, I would like to thank the Almighty God for His guidance and continual provision of strength throughout my study period. Furthermore, I would like to express my deepest gratitude to my supervisors, Dr T. Kanyerere, and Dr K. Pietersen, for their continual assistance and guidance throughout the conception and completion of this research. I would like to extend my gratitude to the Water Research Commission (WRC) for their financial support towards my work, without which this research would not have been possible.

I would like to extend my gratitude to Department of Water and Sanitation (Bellville Regional Office), Council for Geosciences (Bellville Regional Office) and the Beaufort West Municipality for collaborating and advising our research team, their contribution is highly appreciated.

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Abstract

The improvement in hydraulic fracturing techniques resulted in the exploitation of natural gas associated with low-permeability of organic-rich shale formations in the United States. South Africa has prospective shale gas reserves associated with the marine black shales of the lower Ecca Group’s Whitehill Formation in the Karoo Basin. The marine shales development in the Karoo Basin is centred on the diversifying the primary energy mix. The Karoo is a semi-arid region whose communities solely dependent on groundwater for their development. Groundwater concerns in the Karoo Basin regarding shale gas development include water resource degradation by stray gas migration and also flowback or produced water from deeper formations.

The main aim of this study was to improve understanding on the risks posed by shale gas extraction on shallow aquifers in order to propose mitigation measures for groundwater protection in the main Karoo Basin. This study employed a conceptual qualitative design to understand aquifer behaviour from the informants’ perspective. The perspectives in the study area were informed by two pre-existing conceptual models used as schools of thought in order to create a site specific conceptual model for the current study. Also, the study also made use of Groundwater Model Multi Criteria Analysis, a risk based assessment to explain potential subsurface risks to groundwater resources.

A site specific conceptual model of local, intermediate and deep groundwater flow systems was developed based on the two models to investigate shallow and deep aquifer systems and their interactions which might lead to potential shallow aquifer contamination. The study found shallow aquifer systems exist at depths <300m, such aquifers were not locally recharged, but recharged by hilltops containing large number of vertical fractures. These aquifer systems are associated with dolerite intrusion. Due to thermal effects, dykes caused fracturing of adjacent rocks such as sandstone/ mudstone significant increase in yields of adjacent boreholes. The intermediate aquifer systems are mostly associated with fractures, with deep burial fracture systems with fault systems. These systems are normally expressed to the surface as springs to an order of 100-1000 meters. These saline aquifer systems are poorly understood and unknown if they are widespread. These systems are believed
to be isolated compartments which are disconnected from both shallow and regional aquifer systems.

Regional aquifer systems are associated with the Cape Fold Belt and express themselves in the Dwyka Formation where there are structural linkages to regional aquifer systems as indicated in the deep Soekor wells. The existence of deep aquifer systems associated with the Cape Fold Belt is explained by water strikes at the Dwyka Group at depths of 2900m-3300m in the Dwyka Group the Soekor wells KL 1/65 and SA 1/66 located below the Great Escarpment. The current study is of the view that regional aquifer systems are present in the east of the Great Escarpment and associated with the Cape Fold Belt. In the eastern side of the Great Escarpment sub-artesian pressures exist, these pressure systems are not free flowing artesian. They quickly dissipate due to the high recharge of the Table Mountain Group and the Karoo aquifers. However, on the western side of the Great Escarpment there were local and intermediate aquifer systems with an absence of regional systems.

Risk assessment methodology described risk as a combination of likelihood and consequence of a harmful event. These harmful events were referred to as hazards which were classified as i) stray gas migration, ii) groundwater contamination with salts or other dissolved constituents, iii) contamination of groundwater from water management practices and iv) over-exploitation of aquifers. Receptors were characterised as i) aquifer capacity, ii) groundwater users and iii) groundwater dependent ecosystems. The migration potential of stray gas, salts and dissolved constituents is limited to shale gas leases and areas of vicinity of shale gas production wells. The dolerite intrusions, geological structures and petroleum wells are potential pathways that may transmit cross formational flows and propagate drawdown effects. The consequence are potential pollution of potable water sources. These hazards were not applicable to aquifer storage, but have low potential of impacting groundwater users and groundwater dependent ecosystems. Contamination of groundwater from water management practices includes factors such as waste water associated with shale gas production has potential risk for groundwater contamination. Over time, metals, salts, and organics may build up in
sediments, scales, and soil near wastewater storage, treatment, and disposal and/or spill sites. This hazard does not affect aquifer capacity, but has medium potential of impacting groundwater users and groundwater dependent ecosystems.

With respect to these findings the following further empirical investigations should be undertaken to mitigate risks relating to shale gas development techniques. Conceptual risk modelling indicated that highest risk in the Karoo Basin related to over-exploitation of groundwater resources due to competing demands, due to water scarcity in the Karoo. It is likely that shale gas development will impose additional stresses on shallow aquifer resources and mitigation measures should implemented pro-actively.

Keywords: source-receptor-pathway, regional flow systems, hydraulic fracturing, aquifer interaction, flowback and produced water
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List of acronyms

m  meter
C & ~  Circa
m²/day  meters squared per day
m³/h  meters cubed per hour
mg/L  milligrams/liter
km  Kilometer
Ro  Vitrinite reflectance
Soekor  Southern Oil Exploration Corporation
GMMCA  Groundwater Model Multi Criteria Analysis
GDEs  Groundwater Dependent Ecosystems
DWS  Department of Water and Sanitation
Chapter 1 Introduction

1.1 Background

The current study investigated risk to groundwater resources from proposed shale gas developments in south western Karoo Basin. The Karoo is a semi-arid region which has communities solely dependent upon groundwater for their development. Groundwater concerns in the Karoo from shale gas development include source of water and water resource degradation by stray gas migration and also flowback or produced water from deeper formations (after Vengosh et al., 2014). Another concern is the limited knowledge about deeper aquifers, their associated occurrences and their possible interconnection to shallow aquifer systems (KGEG, 2013). Extensive research has been conducted on shallow aquifers because they supply local municipalities and farmers (Dondo and Nhleko, 2008; KEGG, 2013; van Tonder et al., 2013).

Deep groundwater development has been subject of research since the nineteenth century (Weithofer as cited in Hebig-Schubert, 2014). Deep groundwater knowledge has progressed from hypothetically deep seated stagnant water as suggested by (Weithofer as cited in Hebig-Schubert, 2014) to the current understanding of a more dynamic system influenced by both surface processes from meteoric cycle and crustal processes from the lithosphere (Einsele as cited in Hebig-Schubert, 2014). Deep seated groundwater originates from slowly-circulating, deep lying, subsurface aquifers although discharge areas can occur at relatively shallow depths (Hebig-Schubert, 2014). Deep aquifers are poorly characterised worldwide and under researched even though they serve as important sources of water (Hebig-Schubert, 2014). Hydrogeological research in the early 1960s has led to an understanding of regional groundwater systems, their driving forces and hydrochemical dynamics (Tóth, 1962; Toth 1963; Freeze and Witherspoon, 1967).

Deep groundwater volumes have been estimated from depth ranges of 305 – 3000 m in California Central Valley (Kang and Jackson 2016). The conceptualization of
The hierarchically distribution of groundwater flow systems was reproduced by (Fourmarier in 1939 as cited by Toth, 2009). The model divided major water with a sub-basin to the left from its crest. From both sides, the sub-basin draws two groundwater flow systems. These systems can be referred to as local, intermediate and regional systems (Toth, 2009). The local systems are superimposed on layer systems that originate on the principal divide and move towards the main valley. These systems are separated by sub-vertical boundaries and different order system and are separated by sub-horizontal boundaries (Toth, 2009).

![Diagram of flow systems](image)

**Figure 1: Theoretical flow pattern and boundaries between different flow systems (from Toth, 1963; Hebig-Schubert 2014).**

The nature of aquifers is usually influenced by the lithology, which plays a role in the transmission and storage of water. Hubbert (1940 as cited in Toth, 2009) suggested an analytical solution for groundwater flow systems that is differentiated into homogenous aquifers. In homogeneous aquifers hydraulic conductivity is independent of where it is measured within the formation. Aquifers in local flow systems have high groundwater flow velocities and relatively large recharge areas. Whereas in regional flow systems the aquifers have lower groundwater flow velocities and relatively small recharge areas.
study concluded with key findings which proposed that regional groundwater flow systems are always dynamic with changing local flow systems, vertical extension of local flow systems depends on the topography and groundwater velocity becomes lower with depth and that mineralization of groundwater of groundwater increases with its depth according to its velocity within the aquifer.

Genesis of deep groundwater on a regional scale was described using linking hydrochemical facies to ion concentrations. Deep groundwater is expected at zones of depth >600m. These zones are distinguished by high mineralisation, high calcium chloride, sodium chloride and are usually devoid of $^3$H values and contains low $^{14}$C (Holting et al., 1969; Glynn and Plummer, 2005; Hebig-Schubert 2014).

1.2 Problem statement

The South African government identified shale gas exploration in the Karoo Basin as a possible source to diversify the energy mix. The main concerns centred on the possible pollution of shallow aquifer systems due to sole dependence for the Karoo population. The problem is the lack of deep seated boreholes and sufficient knowledge of these aquifer systems. Furthermore, the lack of sufficient knowledge on deep groundwater flow systems has potential to lead to shallow aquifer contamination. Contamination would be through migration pathways formed by faulting, fracture networks, and compromised well integrity which could transport gases and dissolved constituents from deeper underlying formations into the shallow aquifer systems. The absence of deep seated boreholes has led to knowledge uncertainty pertaining to shallow and deep aquifer interaction and the pathways that would lead to shallow aquifer contamination.

The current study assumes that the use of hydrogeological conceptual modelling and risk based assessment methodologies are complementary approaches in describing potential risk to aquifer contamination. To characterise groundwater contamination from potential shale gas development, migration pathways such as faults and fractures could transport contamination to shallow aquifer systems. Understanding of the afore-mentioned is
necessary for holistic understanding of water resource management and utilization in groundwater dependent areas such as the Karoo region.

1.3 Research question

The current study provides scientific basis of conditions and recommendations that could be used to support the combination of methodologies such as conceptual modelling and risk assessment methodologies. Three sub-questions that needed to be addressed include: i) How can hydrogeological conceptual modelling and risk assessment methodologies be used to understand possible contamination of shallow aquifer systems? ii) How significant is the role of fault and fracture systems in connecting shallow and deep aquifer systems? iii) What are the possible risk factors for shallow aquifer systems?

1.4 Research objectives

The main aim of the study was to understand the risks posed by shale gas extraction on shallow aquifers in order to propose mitigation measures for groundwater protection in the main Karoo Basin. The specific objectives were:

i) To describe the aquifer systems using a hydrogeological conceptual model

ii) To investigate interaction between shallow and deep aquifer systems.

iii) To establish possible migration pathways that would lead to aquifer contamination.

iv) To explain main risk factors for shallow aquifer systems

1.5 Significance of the study

Groundwater is the only water source for most communities in areas such as the Karoo Basin. Water is mainly used for domestic and agricultural purposes. The major concern in the Karoo is the contamination of readily accessible water supply i.e surface water or groundwater (Steyl and van Tonder, 2013). One distinguishing feature of Karoo Basin’s
varied geology is the presence of the dolerite sills and dykes that influences groundwater occurrence. However, there is sparse information on the structure of deep dolerite sills and associated deep groundwater and water strikes in the Karoo lithostratigraphic formations, with available data coming from the shallow depth of <300m (KGE, 2013). The presence of deep-water strikes in the Karoo formations and associated dolerites, their yield and composition of the water are still debatable (Steyl and van Tonder, 2013).

The current study is important because it will improve water resource management at local and region scales. It will also improve knowledge of geohydrologists, groundwater managers on groundwater flow systems, source-pathway-receptor linkages and risk factors that have potential contamination to shallow aquifer systems. The information in the current study is needed by DWS and other water institutions, municipalities and farmers associations. Additionally, this study informs geohydrologists, DWS officials and other stakeholders such as municipalities, farmers associations and other officials from the oil and gas industry the relevant risk factors that are more likely to lead to contamination of groundwater. Geohydrological consulting firms will benefit a lot as well in their daily endeavours. Furthermore, this study has laid the foundation for researchers and scholars to bridge the knowledge gap as far as deep groundwater flow systems, conceptual modelling and risk methodologies are concerned.
1.6 Research framework

Figure 2: Conceptual study framework
1.7 Thesis outline

This thesis consists of six chapters. Chapter 1 provides an introduction where study background, problem statement, research question and thesis statement, study objectives, significance of the study and framework of the study have been provided. Chapter 2 reviews literature such as the geology, petroleum and groundwater system in the world and how lessons can be learnt and applied to the Karoo Basin. Chapter 3 is the research design and methodology where the research design, data collection and data analysis methods quality assurance and quality control and study limitations are outlined. Chapter 4 consists of the hydrogeological conceptual model, a 3-dimensional representation of hydrogeological process in the Karoo Basin. Chapter 5 outlines key risk factors of the Karoo Basin which are shale gas development hazards, aquifer intrinsic vulnerability pathways, potentially impacted receptors and the application of risk methodology. Chapter 6 outlines the conclusion and recommendations of the study.
Chapter 2: Literature Review and theoretical framework

2.1 Introduction
This chapter provides a summary of key literature reviewed to highlight tectonic events leading to the formation of the Karoo Basin and other sedimentary basins which underwent extensive research. The main aim is to understand geology, petroleum and groundwater systems in sedimentary basins which have proven shale gas resources in order to adopt international best practice and lessons learnt and transposed to the Karoo Basin to establish extensive knowledge prior to shale gas development.

2.2 Geological, petroleum and groundwater systems of the Karoo Basin
2.2.1 Geological setting
The supercontinent Gondwana formed a Precambrian basement to extensive sedimentary basins most notably the Cape and Karoo Supergroup. Southern Gondwanaland experienced four major compression and extension periods along the southern margin. These events contributed to the construction and syn-tectonic history of the Karoo Basin (de Wit and Ransome, 1992, Newton et al., 2006). The Karoo Basin is linked to compressional events in the Cape region recorded between ~ 300 Ma and ~ 215 Ma with a combined eight events in total (Halbich, 1983; Catuneanu et al., 1998). This thick-skinned deformation involving basement and movement along crustal structures is thought to result from subduction of the palaeo-Pacific plate below the Gondwana plate over 1500 km further south (Cole, 1992). Modern explanations for basin formation based on seismic data supports a thin skinned tectonic thrust model for the evolution of the Cape Fold Belt without significant fore deep stratigraphic thickening of the Karoo Basin strata (Lindeque et al., 2011). The lack of basement deformation on seismic data suggested that the Cape Fold Belt and the Karoo Basin developed as a result of wide, thin-skinned folding (Scheiber-Enslin et al., 2014).

During the time of its formation, the main Karoo Basin covered much of the southern Africa and surrounding Gondwana continents (Johnson et al., 2006). Basin remnants covers 700 000 km², is capped by thick basaltic lava succession of the Drakensberg Group.
and is riddled at depth with dolerite sills and dykes (Duncan and Marsh, 2006). Significant exposure of the main Karoo Basin is due to uplift and erosion, with 2 to 7 km of rock eroded during two episodes of uplift in the Early and Mid-Cretaceous (De Wit, 2007). Deposition of the main Karoo Basin over the Cape Basin (~500 to ~300 Ma) separated by a 30 Ma hiatus occurred from the Late Carboniferous (~300 Ma) to Mid-Jurassic (~180 Ma) as the Dwyka, Ecca and Beaufort Groups. The overlying Stormberg Group, consisting of the Molteno, Elliot and Clarens Formations, formed as the basin shrank towards the northeast (Johnson et al., 2006). The geological stratigraphies of the various groups together with the depositional environments are summarised in Table 1.

### Table 1: Lithostratigraphic table for the southern main Karoo Basin, listing Groups, Subgroups, formation and depositional environments (Mccarthy and Rubidge, 2005; Johnson et al., 2006)

<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Depositional environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drakensberg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stormberg</td>
<td>Clarens</td>
<td>Lavas</td>
</tr>
<tr>
<td></td>
<td>Elliot</td>
<td>Aeolian and playa</td>
</tr>
<tr>
<td></td>
<td>Molteno</td>
<td>Meandering rivers and playas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Braided Rivers</td>
</tr>
<tr>
<td>Upper Beaufort</td>
<td>Tarkastad Subgroup</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burgersdorp</td>
<td>Alluvial fan and braided rivers</td>
</tr>
<tr>
<td></td>
<td>Katberg</td>
<td>Meandering rivers</td>
</tr>
<tr>
<td>Lower Beaufort</td>
<td>Adelaide Subgroup:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Teekloof</td>
<td>Meandering Rivers</td>
</tr>
<tr>
<td></td>
<td>Abrahamskraal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Balfour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middelton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Koonap</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Ecca</td>
<td>Waterford</td>
<td>Delta front sands</td>
</tr>
<tr>
<td></td>
<td>Fort Brown</td>
<td>Prodelta slope muds</td>
</tr>
<tr>
<td></td>
<td>Laingsburg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vischkuil</td>
<td>Basin plain turbidites</td>
</tr>
<tr>
<td></td>
<td>Ripon</td>
<td></td>
</tr>
<tr>
<td>Lower Ecca</td>
<td>Collingham</td>
<td>Marine Shales</td>
</tr>
<tr>
<td></td>
<td>Whitehill</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prince Albert</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Glacial diamicrites and muds</td>
</tr>
</tbody>
</table>

The Karoo magmatic activity has been closely linked to the breakup of Gondwanaland (Johnson et al., 2006). The thickest lava of lavas (maximum of 1.65km) covers a portion of the main Karoo Basin within Lesotho and South Africa, with smaller packages throughout southern Africa (Duncan and Marsh, 2006). Sills emplaced at the same time
with dykes in an extensive network covering 390 000 km² of the main Karoo Basin contains carbon rich sediments (Svensen et al., 2007). Dolerite intrusion occurred over a relatively short period, 40Ar/39Ar dating from throughout Gondwanaland estimate emplacement between ~190 and ~178 Ma (Riley and Knight, 2001; Riley et al., 2005; Jourdan et al., 2008), U-Pb dating suggests a rapid emplacement between 183 and 182 Ma over <1 Ma (Svensen et al., 2007; Svensen et al., 2012). Magma source location was inferred using percentage dolerite maps show the highest percentage in the east (Rowsell and De Swardt, 1976; Winter and Venter, 1970). Significant number of swarms concentrates in the northeast Karoo has led to proposal of the source being a triple junction in Southern Zimbabwe (Burke and Dewey, 1973).

Figure 3: Schematic of north-south cross section of the Karoo Basin model (Lindeque et al. 2011).

Karoo dolerite network (Figure 3) understanding has been enhanced by geophysical studies including electrical sounding measurement which divided the dolerites into three zones (van Zijl, 2006). The lower zone consists of flat extensive sills (~30 km) in the lowest stratigraphic units of the basin. These units include Dwyka glacial deposits and submarine laminated shales of the lower Ecca Group. Well data recorded instances where these sills have intruded close to the shales of the Whitehill Formation within the lower Ecca Group (Cole et al., 2011).

The second dolerite zone comprises the most significant number of intrusions occurring within the Upper Ecca and Beaufort Groups and in some instances into the higher formation (Scheiber-Enslin et al., 2014). The reason for this abundance is thought to correspond to first thick sandstone unit emphasizing importance of horizontal and vertical
transportation of magma in the system. This group of intrusions is mostly saucer or basin shaped with these structures usually coalescing to form ring complexes (du Toit 1920). The third zone that has intruded the Stormberg Group is the most dolerite-poor and consists predominantly of dykes thought to feed the overlying lavas northern domain (Chevallier et al., 2001). van Zijl (2006b) suggest that the intrusion style is independent of lithology and the feeding is due to low overburden pressure in this zone. Emplacement horizons determined from wells are the Dwyka-Ecca Group contact, the Prince Albert-Whitehill Formation contact in the lower Ecca and the upper Ecca-lower Beaufort Group contact, as well as lithological boundaries within the Beaufort, (du Toit, 1920; Cole and McLachlan, 1994). Burchardt (2008) highlighted that sills are more likely to intrude between layers of varying mechanical properties due to a change in the stress field, for example between rhyolitic intrusion and basaltic lava flows. In the current study, these structures have the potential to serve as migration pathways as they appear continuously throughout the geological profile in some areas. Additionally, these structures have the potential to connect the local, intermediate and the regional aquifer systems in the areas where they occur throughout the stratigraphy.

In some cases, sills have penetrated below the basin into basement, as well as Cape Supergroup rocks underlying the basin in the south. Basement rocks include the Proterozoic Namaqua-Natal mobile belt in the central part of the basin, while in the northeast underlain by the Archean Kaapvaal craton. The areal extent of the dolerites is limited in the southern part of the basin, with the southern boundary defined as the dolerite line; a line crossing from northwest to southeast across the Beaufort Group. This limitation is thought to be due to previous northward tilting of southern Karoo sediments due to tectonic activity in the Cape region (Planke and Svensen, 2012).

From Karoo observations, dykes are usually between ~2 and ~10 m wide and 5 to 30 km long, while some extend for up to 80 km (Duncan and Marsh, 2006). Dykes are in general compositionally homogeneous across their extents and some show in approximately parallel formation at oblique angle segmentation (Marsh and Mindaweni, 1998). Studies have conducted for knowledge expansion on geometries and mechanisms of formation of
these sills, inclined sheets and dykes. Field observations have led to suggestions that dykes develop into inclined sheets, which in turn develop into an inner and outer sill (Chevalier and Woodford, 1999). Malthe-Sørenssen et al., (2004) used discrete element modelling has shown that symmetrical sills can develop from central injection point. These studies showed how a sill develops into a complex network, with the sill emplacement causing doming of the overlying sediment surface. As the edges of the dome reach a critical angle, stress at the tips causes the sills to develop into an inclined sheet, crosscutting layers. These inclined sheets continue until the magma pressure decreases and the intrusion again follows the bedding and forms an outer sill higher up in the stratigraphy (Scheiber-Enslin et al., 2014).

These results suggest that the size of the inner sill is proportional to the overburden thickness, which Polteau et al. (2008b) proposed is a four or five to one relationship using numerical and field data including Karoo sills. Scatter in these data, however, suggested a ratio of anywhere between two and six to one. Galerne et al., (2011) conducted an experiment that showed relationships between overburden depth and intrusion shape show that sub-circular saucer-shaped sills from above pipe feeders. The study suggested that a pipe feeder is similar to a feeder dyke whose extent is small relative to its depth of emplacement. Alternatively, a feeder that is long with respect to its emplacement depth, such as for a shallow dyke, results in the formation of an elliptical saucer-shaped sill. A feeder length-to-depth of emplacement ration of L/D = 4 or larger is needed in such a case.

The current study made use of a conceptual model to explain local, intermediate and regional aquifer systems, geological features in order to devise mitigation and protection measures for aquifer vulnerability prior to shale gas extraction. These features have the potential to connect brackish saline intermediate aquifer systems to shallow aquifer systems. There are potential connections between regional and intermediate aquifer systems and potential for connection from the shale gas formations of the lower Ecca Group where gas could migrate to the shallow aquifer systems.
2.2.2 Petroleum setting

Black shale source rocks generate hydrocarbons due to burial of large volumes of plant and animal matter under reducing conditions in marine, deltaic or lacustrine environments. Organic material (kerogen) usually deposits with fine clastic sediments, such as clay and silts, which protects the organic matter from microorganisms and oxygenation. Kerogen buries deeper with time and subjected to increased pressure and temperature (diagenesis), which breaks complex kerogen molecules are broken down into smaller molecules, releasing the chemical bonds of the molecules alters to oil and gas (Tissot and Welte, 1984; Peters and Cassa, 1994; Hunt 1995). Kerogen conversion amount to natural gas is determined by the duration of post-depositional heating intensity and burial metamorphism due to maximum depth of burial (Martini et al., 2008).

The generated hydrocarbons are held in place and stored in shale source rock reservoirs. Fine-grained, organic-rich, black shales undergo biogenic and thermogenic processes to generate short hydrocarbon chains such as; methane, ethane, propane, butane, and remaining carbon and clay minerals form a storage mechanism through adsorption which greatly increases the storage volume (Martini et al., 2008). Shale gas separates from shale oil at approximately 120°C, due to high temperature because the oil cooks out. Shale gas can be classified as thermogenic when it is generated from in situ cracking of organic matter or secondary cracking of oil associated with mature organic matter, at maturation temperatures over 120°C (Hunt, 1995). Shale gas can classified as biogenic when it is generated by microbes in areas of freshwater recharge and can be associated with mature or immature organic matter, usually occurring in shallower source rocks (Hunt, 1995). Large volumes of gas adsorbed on organic matter are stored as free gas in micro- pores and macro-pores. Shale gas laminations also have the potential to store gas and act as a migration pathway of gas desorbed from organic material (Rokosh et al., 2009). Adsorbed storage capacity is determined by factors such as mineralogy, temperature, pressure, available volume and partial pressure of methane, gas can also be trapped in fractures and pore spaces and fractures provided there is a seal to keep the gas in place (Martini et al., 2008).
In the Karoo basin, the Whitehill Formation is the most prospective shale gas target. It is located near the base of the Lower Ecca Group (Table 1). The Whitehill Formation has a thickness that can be traced throughout the Karoo Basin (Branch, Ritter, Weckmann, & Sachsenhofer, 2007). The black, organic-rich shale is thought to represent suspension-setting of mud under reducing conditions (Visser, 2004). The Whitehill Formation is regarded as a commercial gas shale play because it satisfied the basic conditions including a high total organic content and gas window maturity (Rowsell & De Swardt, 1976). Whitehill Formation mineralogy suggested that the formation will have positive response to hydraulic fracturing due to silica (SiO$_2$) being the dominant major element component (Scoates et al., 1996). The Whitehill Formation has sufficient thickness and extends over large areas for sweet spots to exist.

The Whitehill Formation has high brittleness of shale due to the predominance of quartz that is important for controlled hydraulic fracturing and successful extraction of gas (Chere et al., 2013). The Prince Albert Formation, the base of the Lower Ecca Group marine shales is also of commercial interest, mostly if this formation is exploited as an extension of the Whitehill play (Cole, 2014).

Risk to shale gas occurrence in the Karoo Basin is governed unique factors such as the thermal tectonic effect of the Cape Fold Belt along the southern margin of the basin. This has resulted in maturities of up to 4% Ro which may have adverse effects on the shale gas content (Petroleum Agency South Africa, 2014). A study conducted by Maré, et al., (2014) used magnetic geothermometers to determine the thermal effect of large-scale dolerite intrusions on the sedimentary strata of the Karoo Supergroup. The study found a general evaluation of the palaeo-temperatures of the organic-rich Ecca Group sediments to temperatures where hydrocarbons normally converted to gas. The greatest thermal effects of the sill intrusions on the sedimentary strata are limited to the contact aureoles suggesting that there is unquantified, potential for hydrocarbon resources remaining between these intrusions (Maré, 2015). A study conducted by Brownfield et al. (2016) estimated undiscovered, technically recoverable mean resource of 44.5 Tcf of shale gas
in the Karoo Province of South Africa and Lesotho (Brownfield et al., 2016). The most promising area to source gas from the Whitehill Formation is south of the southern limit of Karoo dolerite outcrop, but north of the Cape Fold Belt, i.e. ≥ 30 km north of the southernmost Whitehill exposures (Mielke & de Wit, 2009).

2.3 **Groundwater occurrence in sedimentary basins**

Groundwater occurrence is controlled entirely by the presence of secondary permeability within the rock mass (Kirchner et al., 1991). Permeability of non-fractured and joint free Karoo sedimentary rocks is generally ≤10⁻⁸ m/s with the exception of a few argillaceous to arenaceous sandstones comprising the Karoo Sequence – diamicite, shale, mudstone, siltstone, arkose, greywacke and sandstone (Kirchner et al., 1991). Groundwater flow is controlled by primary factors such as stratigraphy, topography heterogeneities in hydraulic conductivities and basin geometry (Freeze, 1974; Jencso & McGlynn, 2011). Vertical groundwater flow within and between formations is difficult to determine, due to higher aquifer anisotropy in a vertical direction relatively to the direction of the bedding (Sayed et al., 1992). Groundwater chemistry is a valuable tool to determine inter-aquifer mixing and flow regimes. Aquifer systems had distinct mineralogical differences, major ion chemistry and δ¹³C values to indicate mixing between aquifer units (Dogramaci and Herczeg, 2002; Cartwright et al., 2010).

Hofmann and Cartwright, (2013) conducted a study using hydrogeochemistry to understand inter aquifer mixing in the onshore part of the Gippsland Basin in south eastern Australia. The study focused on developing a conceptual model using a combination hydrological information, major ion geochemistry, ⁸⁷Sr/⁸⁶Sr stable isotopes and radiogenic isotopes to constrain long-term groundwater flow patterns and assess inter aquifer mixing. In order to enable better management of water in the water resource in a region where there is competing demands for water use for resource, rural and domestic use. Key findings of the study included the combination of major ion geochemistry, stable isotopes and radiogenic isotopes allowed a better understanding of groundwater flow paths and inter-aquifer mixing in the Gippsland Basin which could not be determined from the analysis of hydraulic heads alone (Hofmann & Cartwright, 2013). In the current
study hydrogeochemistry and minerology were used to understand groundwater flow paths and inter-aquifer mixing in areas were dolerite throughout the stratigraphic profile. This was used because there are no deep seated (>300m). Groundwater from deep seated rocks would be characterised by different chemical concentration to groundwater in shallow aquifer systems.

In large basins with complex stratigraphy, hydrogeochemistry is used to constrain inter-aquifer-mixing that are used for water resources. While groundwater extraction mostly occurs within the shallow Quaternary and younger Tertiary aquifers, because the aquifers are hydraulically connected, may increase gradients in between aquifers, which can result in depleting old groundwater resources that will not be recharged (Hofmann & Cartwright, 2013). In porous media aquifers, groundwater ages are estimated using environmental tracers such as $^{14}$C, $^3$H, $^{36}$Cl and chlorofluorocarbons to determine groundwater flow velocities (Cook and Solomon, 1995; Cook and Herczeg, 2000).

Solute transport is characterised by rapid advection through fractures, with diffusive exchange between solute in the fractures and that in the relatively immobile water in the matrix in fracture media (Cook et al., 2009). Cook et al (2009) revealed that groundwater flow through vertical can result in rapid movement and very young apparent groundwater ages at considerable depth. Localised recharge in fractured rock aquifers with a network bedrock wells completed to observe conditions in shallow aquifers using snow melt. Gleeson et al, (2009) conducted a study to determining heterogenous fractured network and overlying soil characteristics govern recharge to fractured crystalline aquifers in humid climatic conditions. The study indicated that bedrock transmissivity and soil thickness is heterogeneous at the site scale underlain by silty sand with a thickness of >1m. Bedrock aquifers of depths ≤ 20m recharged locally due to δ2H-depleted snowmelt within two days (Gleeson et al., 2009).

Karoo aquifers have low storativity and small thickness. The most productive aquifers are found where water-bearing alluvial deposits overlie the fractured and weathered strata (Kirchner et al., 1991). Groundwater in Karoo aquifers must therefore be stored mainly
in the sedimentary rocks and not in the fractures. Fractures in Karoo aquifers are therefore not the main storage units for water, but serve only as conduits for the water to move from the sedimentary rock matrix towards the pumping borehole (Woodford and Chevallier, 2002).

Karoo sedimentary rocks have a special case of storage-dependant recharge is that of “dual porosity” (Vegter, 1995). Permeable open fractures in sedimentary formations may fill up rapidly under favourable recharge conditions whilst the uptake of water from the open fractures into adjacent pores and micro-fractures is slow (Vegter, 1995). Complete replenishment of the available storage space may only be realised during a prolonged period of rainfall (Vegter, 1995).

Karoo aquifers in South Africa formed in sedimentary rocks such as mudstone, siltstone, shale and sandstone of the Karoo Supergroup. These lithologies have been fractured, intruded and metamorphosed to varying degrees which cover much of the interior of the country. The shallow aquifer system (c.300 m) is well understood due to decades of detailed research and groundwater exploration relative to the deeper aquifer system (KGEA, 2013). Prominent deformation caused by dolerite dykes and sills in the Karoo Basin. This improves transmissivity of Karoo aquifer systems along dyke contact zones, with depth along strike, host rock, stress regime, mode of intrusion and subsequent weathering (KGEA, 2013).

Transmissivity may not be constant along such zones given the multiple layers of alternating mudstone, siltstone, shale and sandstone that make up the Karoo sedimentary sequence (KGEA, 2013). Karoo strata owe their water-bearing properties to the fracturing, which is generally limited to the top 30 metres or so below the surface. Weathering processes played an essential role in opening incipient fractures/joints and in converting the rocks into more porous media.

Aperture and areal extent of water-yielding fractures in Karoo Formations are limited, and therefore unable to store large quantities of water (Botha et al., 1998). Formations therefore act as the main storage units of water in Karoo aquifers. The conventional view is that these formations are dense and relatively impermeable, relative to formations such
as unconsolidated sands and dolomite (Woodford and Chevallier, 2002). Karoo Formations are indicative of important consequences for the behaviour of Karoo aquifer systems such as flow which is resembled in porous medium that obey Darcy’s Law (Woodford and Chevallier, 2002).

The formations contain large quantities of water, but are not able to release it readily over small areas, such as the circumference of a borehole (Woodford and Chevallier, 2002). The boreholes receive majority of its water from water yielding fractures because the Karoo formations being dense. A drop in the piezometric pressure will be created within the fracture, resulting in a flux imbalance of water across its interface with the rock matrix, although the flux might be small, the flow over a large water-yielding fracture can be considerable (Woodford and Chevallier, 2002).

A study conducted by Woodford and Chevallier (2002), hypothesized that sandstone and shale surrounding the fractures are the only other storage units available; they must be the main suppliers of water to the boreholes. The hypothesis tested by Woodford and Chevallier (2002) assumed that vertical hydraulic conductivity of the sandstone is $10^{-6}$ m/s and that the hydraulic gradient between the sandstone and fracture is unity, (no pressure difference exists between the fracture and sandstone), and that the water flows towards the fracture under gravity. In this case, water can percolate into the fracture at a rate of 56,549 m$^3$/h (Woodford and Chevallier, 2002).

### 2.4 Shale gas and groundwater

Stray gas is methane gas appearing where it is unwanted. Hydraulic fracturing improves permeability of the host rock by creating locally dense network of open and connected hydraulically conductive fractures (Healy, 2012). Well leakage occurs when there is a source of fluid, breakdown of one or more well barriers, a fluid movement driving force, which could be fluid buoyancy or excess pore pressure due to subsurface geology (Davies et al., 2014). Unconventional shale reservoirs have low permeability relative to conventional sandstone or carbonate reservoirs (typically ranging between $3.9 \times 10^6$ and
9.63 x 10⁶ millidarcy). Fluid movement from and through shales is likely to slow. As a result, the potential for deep seated shales to be the source of pollutants in the near surface environment under natural conditions is low (Jackson et al., 2014).

A study conducted by Myers (2012) reviewed potential scenarios of transport from the Marcellus shale, 1500m below ground surface to the using interpretative modelling. The modelling showed that advective transport could require up to ten of thousands of year for contamination to move to the surface. However, hydraulic fracturing of shales and conductive faults or fracture zones could reduce transport time to tens or hundreds of years (Myers, 2012).

Osborn et al. (2014) reviewed evidence of methane contamination to aquifers overlying the Marcellus and Utica Shale Formations of the north-eastern Pennsylvania and upstate New York associated with shale gas extraction. The study detected methane concentrations in 51-60l drinking wells across the region, concentrations were substantially high closer to natural gas wells. The study used δ¹³C-CH₄ and δ²H-CH₄ values and the ratio of methane to higher chain hydrocarbons to differentiate shallower biologically derived methane from deeper physically derived thermogenic methane (Osborn et al., 2011). The key findings of the study was that methane found in drinking water wells in proximity to the gas operations was consistent with deeper thermogenic methane source and therefore associated with gas wells and hydraulic fracturing activities. The study conclusion was that methane found in the drinking water wells in proximity to the gas operations was consistent with a deeper thermogenic methane source and therefore associated with gas well and hydraulic fracturing activities (Osborn et al., 2011).

A study conducted by Davies (2011) opposed findings of the Osborn et al (2011) study. Davies (2011) was of the view that evidence for implicating hydraulic fracturing needs detailed scientific evidence. Davies (2011) noted that the water well dataset was small, non-random and covered a geological diverse area that is up to 200km wide. Furthermore methane contamination could be attributed to inadequate cementing of gas wells rather than hydraulic fracturing processes. A study conducted by Jackson et al. (2011), revealed
that any declaration that hydraulic fracturing is unrelated to the methane contamination in the Marcellus Basin remains equally unproven (Jackson et al., 2011). Further investigation is needed across sedimentary basins to determine the mechanisms controlling the higher methane concentrations observed, moreover geographic and stratigraphic data on the isotopic distribution of methane and ethane with depth (Jackson et al., 2011). Therefore based on these two views, this study adopted both these views because shale gas development has not occurred in the Karoo Basin therefore, these views were considered as lessons learnt that thorough investigation suitable for the particular sedimentary basin is necessary due to differences in geological setting prior to shale gas development.

Flewelling & Sharma (2014) conducted a study that indicated that hydraulic fracturing affects a limited portion of the entire thickness of the overlying bedrock and is unable to create direct hydraulic communication between black shales of the Marcellus, Bakken and Eagle Ford and shallow aquifers via induced fractures (Flewelling & Sharma, 2014). However, each shale gas play is different and the detailed geometry of shale formation in relation to local aquifer systems needs to be defined, risk of hydraulic connectivity between shale gas formations and the local aquifer systems should be evaluated prior to hydraulic fracturing operations. Based on this description the presented aim was to assess potential risks posed by shale gas development on shallow aquifer systems and relevant mitigation measures for groundwater protection in the main Karoo Basin.

There are geological settings that show deviations from their general considerations. Such specific non-general conditions could include, for example, small basins with significant topography, hydraulic systems that are not in long-term equilibrium, special local geological features, or fluid convection that may be thermally induced (Wiese, 2013). The targeted sources in the Karoo are overlain by very thick and tight shale deposits, such as the Tierberg Formation, up to 800m thick that would prevent any natural gas from escaping (Pietersen et al., 2016). However, caution should be exercised especially since other artificial routes can be created for gas to escape (Pietersen et al., 2016).
Stray gas migration in shallow aquifers potentially occurs by the release of gas-phase hydrocarbons through leaking casings or along well annulus from abandoned oil and gas wells. Poor well integrity is a more likely cause of elevated concentrations of thermogenic methane in shallow groundwater and water supplies than pathways induced solely by hydraulic fracturing (Davies, 2011; Jackson et al., 2011). A study conducted by Vengosh et al (2014) identified this risk of contamination of shallow aquifers in areas adjacent to shale gas development through stray gas leaking from improperly constructed or failing gas wells (Vengosh et al., 2014).

2.4.1 Groundwater contamination with salts or other dissolved constituents
Similar to stray-gas contamination, it is unlikely that groundwater contamination will result in migration of salts or other dissolved constituents from deep-seated shale formations to shallow aquifer system due of hydraulic fracturing (Flewelling & Sharma, 2014a). Conditions necessary for upward include an upward head gradient generated by mechanisms such as topography or overpressure (Flewelling & Sharma, 2014). A study conducted by Flewelling & Sharma (2014) in the Marcellus, Bakken and Eagle Ford shale plays, where an upward gradient, permeability is low, low upward flow rates and mean travel times are often >106 years (Flewelling & Sharma, 2014). Saline groundwater flow rate would be substantially slower than natural gas flow rate and would depend on the pressure gradients and hydraulic connectivity between the over pressurized annulus or leaking sites on wells and overlying aquifers (Vengosh et al., 2014).

2.4.2 Implications to the Karoo Aquifers
Sedimentary strata overlying the target formation in the Karoo Basin consists of a shale, mudrock, sandstone and dolerites. The afore-mentioned lithological succession are characterised by low matrix transmissivities ranging 0.5-50m²/day (Steyl et al., 2012). These transmissivity values were carried out on shallow aquifer systems. Matrix transmissivity at greater depth are expected to be less than these values and dolerite matrix has been found to be impermeable (Davies et al., 2014). Under the afore-mentioned conditions, migration of hydraulic fluid would possibly be underdeveloped.
Deep hydrogeological investigations and groundwater modelling will have to be completed during the initial exploration step into shale gas, in order to prevent such problems being encountered (Kotze, 2012). Knowledge and information on deep aquifer systems in the Karoo Basin is limited to the warm water springs in the main Karoo Basin. There are about 16 naturally occurring warm water (thermal) springs (with temperature ranging from 26-41°C) in the main Karoo Basin south of latitude 28 degrees, with a few more occurring further north (Kent, 1949). These springs provide evidence of natural connections between deep groundwater and the surface. These waters originate at a maximum depth of between 450 and 1,150 m, as calculated from the geothermal gradient and the surface temperature of the waters (Kotze, 2012). Taking into account the areal extent of the Karoo Basin, there is limited natural leakage between deep circulating and shallow groundwater. The water is originally meteoric and mainly deviates in composition due to different composition in rock composition (Kent, 1949).

According to Kent (1949) all the waters are of meteoric origin and mainly deviate in composition due to compositional differences of the lithologies associated with the springs indicating the presence of connate old water. In the central and eastern Karoo, water has NaCl as the prominent constituent with total dissolved solids ranging between 4955 mg/l to 754 mg/l. However, some springs in Stinkfontein, south of Beaufort West and the Cradock spring are characterised by high NaHCO₃ and SO₄ contents. Biogenic methane is one of the main gases in some cases the only gas associated with the hot springs in the main Karoo Basin. The other gases present are mainly H₂, N₂, He and Ar (Kent, 1949).

Even though deep seated groundwater flows as springs to surface, there is no negative known contamination of surface water. Therefore this forms a reference point to monitor deep seated groundwater and its pathways for potential risks that could be posed to shallow aquifer systems. There is a rapid deterioration in water quality below 1 000m due to contact time with geological formation, due to extended infiltration time or the rate of water movement in the subsurface (Kent, 1949). In Aliwal North, one site had a flow of 3821 m³ in 24 hours, while other sites varied between tens to hundreds on m³ in 24 hours.
(Kent, 1949). A special feature of the Karoo Basin is the dolerite dykes and sills intrusions, which reduce permeability of the formations due to its unweathered state below depths of 30-40m (Nhleko, 2008). Although contamination could be possible, any negative influence of these spring waters on surface water and/or shallow aquifers is apparently very limited and if it does occur, it is restricted to a small area (Kent, 1949). Based on these facts the present study aimed to investigate mitigation and groundwater measures prior to shale gas development due to the sole groundwater reliance in the Karoo region for domestic and agricultural usage.

Concerns on the mobilisation of radioactive elements such as uranium and heavy metals naturally derived from shales during the hydraulic fracturing process could be brought to the surface with the flow back and produced water (Vengosh et al., 2014). Studies conducted on the Lower Ecca Group marine shales have indicated that the shales are not enriched in possibly hazardous elements (Hofmeyer, 1971; Zadawa, 1988; Cole & McLachlin, 1994; Viljoen, 2004). However, further mineral identification would be recommended during the initial exploration and drilling phase for shale gas so that appropriate measures are taken in terms of minimising mobilisation and disposal if present in the backflow fluid (Butt, 2012).

2.5 Chapter summary

This chapter examined literature that governed principles of geology, petroleum and groundwater systems in sedimentary basin. The main aim of this chapter was to understand the aforementioned systems in sedimentary basin globally, especially basins which are being explored for shale gas development and/or hydraulic fracturing.

The main underlying issue with methods used in sedimentary basin that underwent shale gas development by means of hydraulic fracturing and the Karoo Basin is the geological setting. The Karoo Basin is characteristic of dolerite dykes and sills relative to global sedimentary basins where shale gas development has occurred. These dolerite structures usually extend between 2 and 10 m wide and extend from 5 to 30 km while some extend to 80km in length. The hydraulic fracturing technique is used to stimulate and improve fluid flow includes vertical drilling range from depths of 5 to 10 km. These structural
features have the potential to serve as migration pathways which could facilitate stray gas migration, flowback and/or produced water flow from shale gas formations or regional aquifer systems into shallow aquifer systems were groundwater in the Karoo region is used for domestic and industrial purposes.

Combining methods applied in other sedimentary basin of different geological setting posed concern on the validity and reliability of the methods when applied in the Karoo Basin. However, using these best practice methods could be adopted as lessons learnt which could yield best practices for the Karoo Basin.
Chapter 3: Research design and Methods

3.1 Introduction
This chapter outlines the research design, data collection methods, data analysis methods, data quality assurance, ethical consideration and the limitations to the study. The research design contains sub-topics such as study area, sampling site description, study population, unit of analysis, sampling site design and sample size. The data collection and analysis sub-sections consist of the available methods, the selected methods, data collection tools used and the procedure followed in this study. While, data analysis methods encompass sections such as available methods for data analysis, the chosen data analysis method, data analysis tools used and the procedure followed.

3.2 Research design
The aim of this section is to describe the study area, sampling sites, study parameters, the unit of analysis, sampling design and sample size. Descriptions of the above-mentioned parameters are explained per objective. There are close relations between objective two and three; therefore most explanations will encompass both objectives due to their interlinking nature. The type of research design used in this study is the case study design whereby an experimental technique is used to assess site specific cases of deeper seated groundwater flow in the Karoo Basin.

3.2.1 Study area description
The study area is located in the Breede-Gouritz Catchment in the towns of Beaufort-West, Merweville and Leeu-Gamka. These catchments fall in the quaternary catchments L11G, L11F, J21A, J21B, J21C,J21D, J22F, J22K, J23A, J24A and J24B in the Western Cape South Africa. Figure 3.1 illustrates the catchment outline comprising of the Witteberg-Swartberg mountain ranges north of the catchment. In this catchment water flows from areas of high to low elevation. Furthermore, the presence of hydraulic gradient along the topographical gradient also influences groundwater flow, indicating that groundwater typically discharges at streams and dams.
Groundwater recharge in the Western Cape occurs during the late summer season where precipitation increases the water table elevation, while groundwater discharge is dependent on the presence of hydraulic gradient differences from between the recharge
and the discharge point. The Witteberg-Swartberg mountain range receives more than 1000mm but most of the low lying central valley receives 100-300 mm annually (Le Maitre, 2009). The estimated recharge derived from the Groundwater Resource Assessment is 305Mm$^3$ y$^{-1}$ for the entire Gouritz River System and and 257 Mm$^3$ y$^{-1}$ for the main tributaries (DWA, 2005).

The Karoo Supergroup is characterised by low permeabilities and consequently low borehole yields (often less than 1 l/s) although higher yields are occasionally found to the north of Beaufort West dolerite dykes and sills start outcropping (Woodford and Chevalier, 2002). Unconsolidated alluvium aquifers are associated with the large rivers in the area such as the Sand River, Swart River and Dorps River. These rivers are ephemeral for much of the courses (Murray, 2007). Unconsolidated aquifers are associated with large rivers in the area such as Sand River, Swart River and the Dorps River. These rivers are ephemeral for much of the courses the occasional flow recharging the groundwater.

![Map of the study areas in the quaternary catchments indicated by the red borderer.](http://etd.uwc.ac.za)
3.2.2 Study sampling sites

This section presents selected sites for groundwater chemistry. The selection of the sites was based on sampling sites that the Department of Water and Sanitation (DWS) monitors quarterly. The collaboration included going to the field with DWS for orientation because some boreholes are no longer monitored because they have either collapse inward or have dried up. However, the sampling procedures of the two institutions were done both jointly and independently.

Water samples were collected from thirty-four DWS boreholes, which are evenly distributed throughout the three towns. The boreholes as indicated on Figure 3.1 were used for this investigation of water quality. These sites were selected based on the potential of hydraulic fracturing for the development of shale gas in the Karoo Basin. This was done to obtain better understanding of shallow and deep aquifer systems in the Karoo Basin and risk factors associated with contamination of potable groundwater.

The possible migration pathways that would lead to contamination also need evaluating and building a model that would be case-study specific due to lack of boreholes that extend deeper than 300m and into the deeper aquifer systems. In order to understand interaction between shallow and deep aquifer systems is dependent on factors such as faults, fractures, lithology, permeability and porosity. The faults and fractures have ability to either link (forming migration pathways) or disconnect lithologies based on rock properties. Seismic sections interpretations display how faults sub-surface intersects the lithologies forming possible pathways. To determine vulnerability of groundwater to contamination risks factors whether hazards or receptors that are likely to have an influential role such as migration pathways, fault overlap between deep and shallow aquifers, fault orientation, formation overlaps and borehole age need to be taken into consideration during the risk assessment stage.

3.2.3 Study population and units of analysis

In investigating deep groundwater flow in the Karoo Basin, various parameters were measured. These parameters included analysis of anions, cations and trace elements by collecting water samples from the boreholes. The present study made use of a multi-
methodological approach to investigate interactions between deep and shallow aquifer systems and how this interaction might lead to contamination of potable water by stray gas migration or flowback fluid. The study used conceptual modelling, hydrochemical analyses and structural geometry to infer possible scenarios that have potential to pollute shallow aquifers. However, the hydrochemical analyses were inconclusive and were not used in this study.
Chapter 4: Groundwater conceptualization

4.1 Introduction
This chapter presents two models a review on providing evidence on deep groundwater flow regimes and the potential impacts of hydraulic fracturing on groundwater in the Karoo Basin. There are two main schools of thoughts regarding the conceptualisation of deep groundwater flow in the Karoo Basin. This chapter explored both schools of thoughts on regional scale, investigated the geological and hydrological features of the study area for better understanding of groundwater risks associated with shale gas development on both local and eventually regional scale.

4.2 Methods used
In order to create a conceptual model, the current study reviewed the above-mentioned models in order to understand the geological setting, methodology of conceptual model construction and the application of secondary data from a regional to local scale. A site specific conceptual model of local, intermediate and deep groundwater flow systems was developed based on the two models conducted by van Tonder et al (2013) and van Wyk (2013) with Rosewarne (2013) and Rosewarne et al (2014). The van Tonder et al (2013) model argued that the Karoo Basin was under artesian conditions meaning that contamination will always try to migrate upwards in the Karoo Basin. Arguments put forward included the existence for more than 14 warm water springs in the Karoo and all Soekor wells of surface elevation less than 1 000m above mean sea levels were artesian. In this study such a model was reviewed to provide insight to argument of the current study which states that the Karoo Basin cannot be under artesian pressure because spring water that reached the surface dissipates and does not reach the surface.

A study by van Wyk (2013) contradicted the van Tonder study and argued that regional hydrogeological characteristics of these systems and inadequate recharge zones to sustain artesian flow or semi-artesian conditions do not support the artesian conditions of the system. Furthermore, van Wyk (2013) argued that the existence of isolated pressure compartments as a result of the lithostatic pressurization in deeper sections many of the
sedimentary successions provided a more realistic explanation for the pressurized water strikes observed during deep drilling operations in southern Africa.

4.3 Data collection and analysis method

4.3.1 Potential hydraulic fracturing impacts on Karoo groundwater

This section is explained in two papers by van Tonder (2013) and Atangana and van Tonder (2014) titled potential impacts on groundwater in the Karoo Basin of South Africa and Stochastic risk and uncertainty analysis for shale gas extraction in the Karoo Basin South Africa. These authors described research done on the potential impact that hydraulic fracturing could have on groundwater in the Karoo Basin. Dolerite intrusions are what differentiate South Africa from the rest of the countries which have estimated or proven shale gas reserves. These structures are associated with relatively high yielding boreholes due to the fractured contact with aureole that exist between the Karoo dolerites and adjacent Karoo sediments. The conceptual model for the current study was hand drawn and edited with Corel Draw software. The drawing was informed by the literature in the explained in this section.

These studies highlight compromised cement annuli of gas wells as the major preferential pathways along which methane and hydraulic fracturing fluid could enter into shallow aquifer systems. Furthermore, the studies outlined upward migration of fluids which depends on the apertures of cement cracks and fractures in the rock formations. Atangana & van Tonder et al (2014) aimed to understand possible scenarios of post closure leakages of capped wells and its effect on neighbouring private boreholes. A model was constructed to investigate vertical and horizontal flow and mass transport to understand probable spread of contamination in shallow aquifer systems. The model assumed that Karoo Basin is under artesian pressure.

Organic shales are not overlain by impermeable boundaries therefore Ecca shales are more susceptible to over-pressurization which has potential to lead to gas and water flow due to compromised well integrity. Shallow aquifer systems pollution is inevitable by deep organic water should the pressures rebuild to and the organic shales are not enclosed by impermeable boundaries. However, should the pressure not rebuild and a well is positioned in a closed system with impermeable boundaries then groundwater is unlikely
to result from depth. Furthermore shallow aquifer systems are confined and after borehole closure, there is likely to be an increase in fluid pressure in a rock, the fluid pressure approaches lithostatic pressure and the forces act at sediment grain contact.

In the Karoo Basin deep groundwater information on water strikes, artesian flow and water quality was recorded in wells located below the Great Escarpment which is on the eastern side of the Karoo Basin (KGEG, 2013). Regional artesian conditions in the Karoo Basin are hypothesised to occur between the Cape fold Belt and the Great Escarpment due to local topographic, stratigraphic and structural characteristics (KGEG, 2013). The above-mentioned model assumes that structural geometry and hydraulic status are in a system where there is sustainable artesian flow to drive pollution upward into shallow aquifer systems. The afore-mentioned factors in the Karoo Basin are not in an ideal free flowing artesian system due to factors including diverse climatic conditions, aquifer hydraulics and lithostatic pressurisation.

4.3.2 Evidence and drivers of deep groundwater flow regimes

The following section consists of work conducted by van Wyk (2013) titled southern African Pre-Cretaceous deep groundwater flow regimes evidence and drivers in order to understand evidence and drivers of flow in the Karoo Basin. The above-mentioned study provided an overview of deep drilling results and hydrogeological observations made from three sites in southern Africa to assess their potential to drive deep flow artesian and semi-artesian aquifer systems. These systems are the Aranos Basin, Taabboschgroet Karoo Graben and the western Karoo Basin. In the current study reviews and references will only entail work of the western Karoo Basin due to the study location relevance that is in the southwestern Karoo Basin.

Large sedimentary units in southern Africa have the structural geometry to drive regional artesian systems. However, conditions such as diverse climate and aquifer hydraulic limitations counteract these conditions to such a level that sustainable basin-like deep flow mechanisms are probably non-existing with the exception of areas where deep mining activities occurred. Several drilling projects in South Africa, Botswana and
Namibia have undoubtedly proven the existence of pressurized groundwater strikes below 300m in the Northern Kalahari to depths of 3000m in the western Karoo Basin. The regional hydrogeological characteristics of these systems indicate challenges regarding the availability of sufficient recharge zones required to drive sustainable artesian flow or semi-artesian conditions. Isolated pressure compartments exist due to lithostatic pressurisation in deeper sections of many sedimentary successions was suggested as a more realistic for water strikes observed during deep drilling operations.

In the southern section of the Main Karoo Basin where Soekor conducted hydrocarbon exploration, there were cases of deep (>1500m) high pressure saline water bearing zones which yielded temporary artesian discharges. Evidence of deep flow circulation (~1000m) is provided by hot springs located throughout the Karoo Basin. A number of these hot springs are situated in the Karoo Formations and rise alongside dykes/faults (Kent, 1949).

4.3.3 Hydrodynamics of confined aquifer systems

Deep groundwater flow regimes in sedimentary graben/basin context is explained by flow characteristics of a basin-like model with artesian and semi artesian conditions changing to isolated compressed compartments in the deeper parts of the structure. The study made use of a basic model of a confined aquifer system that is of water bearing formation sealed at the top and bottom by formations of minimal to no permeability and is characteristic of tilted/folded terrains. However, to have a confined system, the requirement is to have a phreatic section of the same confined water bearing strata exposed to be part of the natural recharge at higher elevation. In shallow aquifer systems, a degree of leakage through confining formations may contribute to the confined system. However, when the confining layer becomes thicker, this leakage contribution significantly decreases. The permeability, porosity and source recharge at the intake area drives the deep flow systems and subsequently the status of the artesian/semi-artesian system (Fig. 6)
Figure 4: Conceptual configurations of artesian /semi-artesian systems and stagnant/compressed compartments with phreatic intake area (modified after Van Wyk, 2013).

The conceptual configurations account for water in the saturated part of the phreatic section exerts hydrostatic pressure transferred to the deeper confined part of the water bearing formation and cause the water level to ascend in boreholes (semi-artesian) and or secondary pathways to the surface (artesian/ thermal springs). Flow resistance is caused by lithostatic pressurisation from the overlying rock load in deeper confined sections of an artesian basin model. This may cause entrapment of water representing zones of groundwater stagnation that is mostly significantly pressurized. Globally deep exploration for hydrocarbons and fresh water aquifers at depths >300m has encountered water bearing zones exerting abnormal hydrostatic pressure compartments with hydraulic features. One of these hydraulic features is internal fluid pressures which are not related to any regional topographically controlled phreatic recharge zones.

These pressure compartments are conventionally bounded by low permeability bed such as mudstones and shales on top and below. However, no lateral boundaries were observed except low permeability zones in the water bearing strata. The possibilities of burial of once effective artesian system may be altered to stagnant but significantly pressurized compartments due to pressure and heat generation. Additional pressurisation may follow during/ after large epeirogenic movement. Under these hydraulic characteristics, pressurized compartments are effectively isolated from surrounding compartments to
such an extent that these compartments could retain large potentiometric pressure head throughout geological time (Mazor, 1997). Furthermore (Ortoleva and Wescott (1994), cited in Mazor, 1997) suggested that pressurized compartments range from 10-20km$^2$ to 50 000km$^2$ and occur from depths.

The study concluded with key findings that incorporate elements of the conceptual model and hydraulic characteristics of the western Karoo Basin. The study proposed basinal components necessary for the effective deep flow, confined formations with high permeability characteristics and sustainable direct rainfall recharge. Firstly, the Karoo Basin does not comply in terms of regional sustainability due to the absence of sustainable confined aquifer conditions supporting effective deep flow component between specified recharge area and an artesian/semi-artesian aquifer system. These systems would probably lose artesian/semi-artesian characteristics within a relatively short distance from the recharge area. Furthermore the evidence of a distant discharge area ±50km and the existence of travertine or similar deposits exists where a balance between long-term recharge and deep flow discharge. In this regard the western Karoo Basin partially complies, several springs although indications are that they rise from <1000m with the dolerite dyke contact zones as their preferential pathway.

Secondly, the basin needs confined formation with high permeability characteristics open to unconfined recharge area in part of the geological structure. The western Karoo Basin partially complies even though there are no regional high permeable stratum such as primary sandstone in the formations of the Ecca and Dwyka Group that can serve as pressurised aquifer system. A portion of the basin is overlies the Table Mountain Group strata, the possibility of those orthoquartzites may be linked with a phreatic system that is ±100km to the south is unlikely. However, possibilities of secondary permeability caused by the Cape Fold Belt orogeny and recent tectonic events can provide a deep flow system from a recharge area such as the Swartberg Mountain range. Although core drilling in the Karoo Basin indicated that secondary pressurised water bearing zones and a large percentage of the fractures were cemented. In addition, incompetent, massive mudrock strata (2000m Bokkeveld and 500m Dwyka) isolate the Ecca and Beaufort
Groups of the western Karoo Basin from Table Mountain Group deep flow sources (van Wyk, 2013).

The final factor is the ability to receive sustainable direct recharge from rainfall and/or indirect recharge from contributing drainage system. The potential recharge area for the western Karoo falls on the dry side of the Swartberg Mountain Range. Rainfall events are intermittent and depths are low. Drainage patterns of the Gamka River does not show any preferential drainage or copy the primary west-east fold-axis directions, thus contribution of surface water to a phreatic aquifer system which could sustain pressures in a deeper permeable aquifer.

4.4 Conceptualization of the groundwater flow in the south-western Karoo Basin

The significant development of the east to west conceptual model can be attributed to factors such as aquifer parameters, topography, recharge, groundwater flow direction, and stratigraphy and dolerite intrusions of the Karoo Basin. The shallow aquifer systems are linked to meteoric water while the deep is linked to saline brackish water.

The conceptual model created in this study is derived from pre-existing literature. Groundwater flow systems are classified as shallow, intermediate and regional flow systems. In the study area recharge used was secondary from literature studies that were conducted on the J21A and L11F catchment in the Beaufort West area. The groundwater recharge was estimated to be 1.8% (~ 3.5 Mm3/a) and 2.3% (3.8 Mm3/a) respectively (DWAF, 2005).

4.4.1 Shallow aquifer systems in the south western Karoo Basin

Shallow aquifer systems are found at depths that are <300m (KGE/3, 2013). These aquifers systems are not locally recharged, but only recharged by hilltops containing large number of vertical fractures (Kirchner et al., 1991). Sandstones and mudstones of the Beaufort Group are characteristic of significantly low primary porosity and permeability due to diagenesis. These sandstones and mudstones have secondary hydrogeological rock properties due to diagenesis effects. These rock properties include degree density,
continuity and interconnection of fracturing, storage and groundwater flow (Kotze and Rosewarne, 1997).

Shallow aquifer systems in the Karoo Basin are highly associated with dolerite intrusion within the Karoo Basin. Due to the thermal effects, dykes caused fracturing of adjacent rocks such as sandstone/mudstone, significantly increasing the yields of boreholes adjacent to the dykes (van Wyk & Witthueser, 2011). These structures are classified into three zones such as the lower, middle and upper zones.

The lower zone consists of flat extensive sills at approximately 30km in the lowest stratigraphic units of the basin. The stratigraphy includes the glacial deposits of the Dwyka Group and submarine laminated shales of the lower Ecca Group closer to the Whitehill Formation (Cole et al., 2011; Scheiber-Enslin et al., 2014). The middle dolerite zone consists of the most significant number of saucer or basin shaped intrusions. These intrusions usually coalescing to form rings and complexes and occur in the Upper Ecca and Beaufort Groups with extension into higher formations (du Toit 1920; Scheiber-Enslin et al., 2014). The upper zone intruded the Stormberg Group is the most dolerite poor and consists of dykes that are thought to feed overlying lavas (Chevallier et al., 2001). van Zijl (2006b) suggested that dyke intrusion style is independent of lithology, because of the overburden pressure in the upper zone (van Zijl 2006b; Scheiber-Enslin et al., 2014).

4.4.2 **Intermediate aquifer systems in the south western Karoo Basin**

The intermediate aquifer systems are mostly associated with fractures, with deep burial fracture systems with fault systems. These systems are normally expressed to the surface as springs to an order of 100-1000 meters (KGE, 2013). These are saline aquifer systems poorly understood and unknown if they are widespread. These systems are believed to be isolated compartments which are disconnected from both shallow and regional aquifer systems (van Wyk, 2013). This has proven to be the case where water strikes were encountered in the VR1/66 at depth ranging from 700-800m along a dolerite intrusion (van Wyk, 2013). This water system is far away from both the shallow and deep aquifers. Gravity-driven regional flow is induced by elevation differences in the water table and its pattern is organised into hierarchal sets of flow systems (Toth, 2009). Groundwater flow
direction follows topographic gradient, but is impacted by local abstractions and the presences of dykes and sills (van Wyk & Witthueser, 2011). Geological structures have strong bearing on groundwater flow directions; dolerite dykes are most substantial due to being semi permeable to impermeable (van Wyk & Witthueser, 2011). In the study area dolerites were encountered in the northern sections of the study area.

4.4.3 Regional aquifer systems in the south western Karoo Basin

Regional aquifer systems are associated with the Cape Fold Belt and express themselves in the Dwyka Formation where there are structural linkages to regional aquifer systems as indicated in the deep Soekor wells. The existence of deep aquifer systems associated with the Cape Fold Belt is explained by water strikes at the Dwyka Group at depths of 2900m- 3300m in the Dwyka Group the Soekor wells KL 1/65 and SA 1/66 located below the Great Escarpment (KGEG, 2013).

Dolerite dykes are distributed along the western, central and eastern Karoo Basin. This study focuses on the western Karoo dolerite intrusions of the Soekor wells in the study area denoted by the red font. The western Karoo Basin has dolerite ring structures and curvilinear ring feeder dykes. The deep Soekor well QU1/66 (Fig 4.4) is situated on the edge of a ring-structure and may lie within a second one. The scale in which these structures were mapped in indicated that they are prominent in the area and can be assumed to be ≥3m thick (KGEG, 2013).
The presence or absence of dolerite dykes in certain areas of the Karoo Basin was determined in the 1960s and 1970s when Soekor was exploring for hydrocarbons. Seismic lines assisted in downhole exploration of the wells. The current study entails five Soekor wells which are SA1/66, QU1/66, KA1/66, AB1/65 and KW 1/67 (written in red). Dolerite dykes thickness are represented by red triangles (QU1/66 and AB 1/65) have a thickness $\geq 150m$, green triangles represent thickness $\leq 150m$ (KA1/66 and SA1/66) and the blue triangle represents no dolerite further south of the dolerite line which is KW 1/67.

Figure 5: Map of the Karoo Basin indicating dolerite thickness (modified after Scheiber-Enslin et al., 2014).
Dolerites in well QU 1/66 start at the Beaufort Group and extend down to the Granite Gneiss while dolerites in AB1/65 start at the Beaufort Group and end at the Lower Ecca Group. Dolerite intrusions in the Karoo Basin are also found in depth ranges similar to those of shallow aquifer systems. These intrusions are associated with potential high yielding boreholes when they intrude sandstone formation and are associated with relatively lower yielding boreholes when they intrude mudstone formations. In the absence of dolerite structures groundwater is associated with structural features and in some cases combined with alluvial systems. In the absence of dolerite of structural features groundwater has low potential. Water quality is influenced by topography, lower lying areas are Na-Cl rich and the higher lying areas are Ca-HCO₃ rich (Adams et al., 2001). These geological structures are classified as a risk attribute due to them being potential conduits that may facilitate cross-formational flow or gas migration and transmit drawdown effects.

Water strikes at depths of 3000, 3200 and 3300m in KL 1/65 and at depths of 2900 and 3150m in SA 1/66 encountered on Dwyka rocks and anywhere shallow was presumably of sub-artesian origin (KGEG, 2013). These strikes are indicative of fracture zones produce free flowing water at the surface which may contain minerals such calcite and
quartz due to faults and fractures running c. 3500m (KGEG, 2013). These faults and fracture produce flow rate that range between 1-4 l/s, porosity of the sandstones varying from c. 0.5-0.20% and temperatures ranging from 46-77°C at the surface (KGEG, 2013). Groundwater at depth is more saline to the west of the Great Escarpment due to more stagnant conditions. Total Dissolved Solid values recorded from strikes were 1390 mg/L at depths of 1016m and 10010mg/L at depths of 3184m (KGEG, 2013). Rose (2008) suggested that the Beaufort West Spring situated on the contact of the Teekloof Formation and the Town dyke is linked to the deeper groundwater system. The Town dyke has structural influence on the deeper groundwater flow system due to it facilitating migration of deeper groundwater towards the surface (Rose, 2008).

The current study believed that regional aquifer systems were present in the east of the Great Escarpment and associated with the Cape Fold Belt. The eastern side of the Great Escarpment sub-artesian pressures exist. These pressure systems are not free flowing artesian and quickly dissipate due to the high recharge of the Table Mountain Group and the Karoo aquifers. However, on the western side of the Great Escarpment there exist local and intermediate aquifer systems and there is an absence of regional systems.
Figure 7: Site specific hydrogeological conceptual model of the study area (modified after Chevalier et al., 2016; KGEG, 2013).

Figure 7 shows the hydrogeological conceptual model of the south western Karoo Basin. This diagram indicates shallow, intermediate and regional aquifer flow systems, this diagram is not drawn to scale and it incorporates formations of the Karoo Supergroup, Cape Supergroup and the Namaqua- Natal Granite Gneiss and does not extend further than that. Mean sea level was obtained by subtracting the depth to water from the height above sea level in order to get a representative mean sea level in relation to the conceptual model. The Nuweland and Swartberg Mountain ranges serve as recharge areas with flow...
driven by topography towards lower lying areas. Kirchner et al (1991) reported that aquifers are not locally recharged, but only in hilltops which contain large number of vertical fractures. Recharge from higher lying areas could generate free flowing groundwater out of a well head. This could arise if the Dwyka Group or the Cape Supergroup is penetrated as free flowing groundwater was encountered in some Soekor wells (KGEG, 2013).

Sedimentary basins have natural conditions favourable for upward head gradients by either topography or overpressure (Flewelling and Sharma, 2014). Upward migration of produced water, dissolved constituents and stray gas is dependent on dolerite dykes and associated fracturing, sandstone layers containing secondary permeability and evidence of upward flow. These structural features are steeply dipping at angles usually exceeding 70° smaller dykes can extend for tens of kilometres in length and the larger dykes extend for hundreds of kilometres (Woodford and Chevalier, 2002). Fractures on host rock occur during and after dyke intrusion. These fractures induce flow through Karoo Formations due to their secondary permeability and is characterised as faster through fractured zones relative to unfractured zones (Woodford and Chevalier, 2002).

In order for upward flow to occur, the head gradient must be large enough to overcome density gradients associated with increasing salinity with depth. Flewelling and Sharma (2014) reported that there are certain instances of upward head gradients in black shale vicinity, however, high upward head gradients would need to be sustained over thick sequences (>1000m) of highly permeable bedrock to drive a significant amount of brine into shallow fresh groundwater. For migration pathways to allow for potentially migration of stray gas and fluids that might lead to aquifer contamination, factors such as constraints on permeability, causes of low permeability at depth and conditions for upward flow need to be realised. Permeability in sedimentary basins is fundamentally anisotropic across a spatial scale where horizontal permeability is often a magnitude or more greater than vertical permeability (Desbaratas, 1987; Clennell et al., 1999; Flewelling and Sharma, 2014). Permeability lowers with depth due to finer sediments settling down first. Permeability is partially dependent on effective stress, which controls compaction amount and fracture apertures in a given rock layer. The void and connectivity decrease with
increasing effective stress thereby restricting flow and lowering permeability (Flewelling and Sharma, 2014).

The current study conceptual model subscribes to the van Wyk (2013) school of thought regarding the potential to drive flow, artesian / semi artesian aquifer systems because it is cognisant of pressure as resulting in lithostatic compartment due to different strata, rather than assuming it to be uniform throughout the basin as argued by van Tonder et al (2013). Sedimentary basins have natural conditions favourable for upward head gradients by either topography or overpressure (Flewelling and Sharma, 2014). Upward migration of produced water, dissolved constituents and stray gas is dependent on dolerite dykes and associated fracturing, sandstone layers containing secondary permeability and evidence of upward flow. These structural features are steeply dipping at angles usually exceeding 70° smaller dykes can extend for tens of kilometres in length and the larger dykes extend for hundreds of kilometres (Woodford and Chevalier, 2002). Fractures on host rock occur during and after dyke intrusion. These fractures induce flow through Karoo Formations due to their secondary permeability and is characterised as faster through fractured zones relative to unfractured zones (Woodford and Chevalier, 2002).

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and fracture apertures in a given rock layer. The void and connectivity decrease with increasing effective stress thereby restricting flow and lowering permeability (Flewelling and Sharma, 2014).

4.5 Summary of Chapter

The conceptual model presented and supported by literature in this chapter provides an indication of local, intermediate and regional groundwater flow systems in the southwestern Karoo Basin. Dolerites have potential to serve as migration pathways in areas where they occur from surface passing through the target formations of the Lower Ecca Group and onto the Dwyka Group. Wellbores have potential to serve as migration pathways as they would be extending from target formations to the surface. Wellbore deterioration is inevitable with time (over decades). However, hydraulic fracturing of areas with no dolerite intrusion would protect shallow aquifers systems because migration pathways would only be wellbores and deteriorating mechanical integrity which is likely to occur over decades.

Of great concern in this study area is the lack of sufficient knowledge pertaining to deep groundwater systems (>300m) and its potential to interact with intermediate and shallow aquifer systems. In order to understand risks posed mitigation measures for groundwater protection in the southwestern Karoo Basin. Therefore, conceptual modelling approach provided a foundational understanding of local intermediate and regional flow systems in the study area.
Chapter 5: Assessment of key risk factors for groundwater from shale gas development

5.1. Introduction
Risk is the alignment of potential sources of hazards, exposure pathways through which a harmful event could lead to adverse impact outcomes for receptor and the affected resources (WorleyParsons, 2013). Proper framing of potential hazards to groundwater systems in the Karoo Basin from shale gas development and identification of migration pathways that have a potential to propagate associated stray gas methane and deep saline brines into shallow aquifer systems are important in developing a strong approach to assess associated risks. This chapter identifies various natural and anthropogenic attributes contributing to intrinsic vulnerability of the south western Karoo Basin. Various factors are involved in risk assessment from the hazard identification to potential hazard contaminating the receptor. However, this section explores proximity of aquifers to shale formations, aquifer hydraulic properties, aquifer interconnectivity, geological structures and potential pathways and induced aquifer connectivity and baseline groundwater quality.

5.2 Methods used
Risk is typically defined as the combination of likelihood and consequence of a harmful event occurring. Risk assessment involves identifying sources of potential harm, assessing the likelihood that harm (an impact) will occur and the consequences if harm does occur (WorleyParsons, 2013). The first step in risk assessment involved establishing the risk context. The primary risks included assessment of vulnerability of shallow aquifers to shale gas related developments in the Karoo Basin. The main steps involved in risk assessment included hazard identification involving analysis of what, how, where and when a harmful event could occur, exposure pathway identification to assess the causal pathways through which a harmful event could lead to an adverse outcome (impact) for a receptor. Moreover, consideration of the likelihood of an impact for the receptor and the severity of that outcome (consequences) and risk estimation to determine the chance that potential harm would be realised.
Estimating risk involves using scientific evidence that takes into account the abovementioned factors of source (hazard), pathway (vulnerability) and receptor (consequence), to determine the combination of the likelihood and consequences of an adverse outcome. The risk estimate should also incorporate uncertainty in the inputs used for the risk assessment. The risk estimate is typically not quantitative, but instead estimates relative risk. Relative risk can be expressed as either low, moderate or high. In an environmental risk assessment context, the source-pathway-receptor approach is widely used as a scientific tool to estimate relative risk, including but not limited to contaminated sites.

The method used in this study is the Groundwater Model Multi Criteria Analysis. This

The equation Risk = Source × Pathway × Receptor was used to express that risk is the alignment of source, pathway and receptor resulting in an impact (WorleyParsons, 2013). The risk profile of a given area is not static; it can vary in space and time. Risk will vary spatially in response to the sources of hazards and receptors, as well as the subsurface pathways related to the geology and hydrogeology of an area. Although intrinsic vulnerability may or may not be a static entity (subsurface pathway changes due to hydraulic fracturing), the sensitivity of a receptor and the level of development intensity (or hazard) may change with time. As such, the risk profile of a given area can also change with time (WorleyParsons, 2013).

5.3. Aquifer intrinsic vulnerability

To assess risks that potential hazards may pose to receptors, pathways by which an impact may propagate to a receptor must be understood. This section identifies various natural and anthropogenic attributes that contribute to intrinsic vulnerability of Karoo aquifers.

5.3.1 Aquifer hydraulic properties

Hydraulic properties of aquifer have the potential to facilitate fluid migration that has a potential to contaminate shallow aquifer systems. Sedimentary strata above targeted shale formations in the Karoo Basin consist of shale, mudrock, sandstone and dolerite succession, these rock types are characteristic of low matrix transmissivities ranging between 0.5 and 50 m²/day (Dondo et al., 2010a). These values were obtained from
pumping tests carried out on Karoo aquifers <200m deep, matrix transmissivities at greater depths are expected to have less than these values and dolerite matrix has been found to be quite impermeable (Rowsell and Connan, 1979). With the aquifer properties conditions, migration of hydraulic fluid is likely to be slow.

Carbonaceous shale units characterised by white weathering outcrop in the lower Ecca Group are targeted for hydraulic fracturing. The distribution of Whitehill Formation led to further investigation into dynamics of the main Karoo Basin and other stratigraphic formations equivalent to the Whitehill Formation to extend the potential target area (Steyl et al., 2013). The targeted shale gas horizons are located between c. 1700 to 1900m in the western Karoo and 1290 in the eastern Karoo Basin (KGE, 2013). It is unlikely that highly saline groundwater or brine will be encountered during gas well drilling, because Soekor well KL1/65 located below the Great Escarpment produced groundwater with Total Dissolved Solids of 1390mg/L from depth of 1 000m (KGE, 2013).

The main properties of flow in Karoo aquifers were derived by Botha et al (1996) on the University of the Free State Campus Site from field observations and the three dimensional model which showed that:

- The fracture dimensions are too limited to store significant quantities of water. The water is thus stored in the Karoo formations.
- There exists a vertical pressure gradient in both the upper and lower aquifers, directed towards the fracture in the main aquifer.
- The high-yielding boreholes derive their water from the fracture in the main aquifer.
- When one of the high-yielding boreholes is pumped, the vertical pressure gradient across the site increases dramatically towards the pumped borehole.
- Water in the three aquifers flows mainly in the vertical direction. It is only in the fracture where the flow is predominantly horizontal (Botha et al., 1996).

The geology of the Karoo Basin is characterised by folding and faulting as well as enigmatic dolerite intrusions. These factors interfere with groundwater flow and are a contributing factor to why groundwater flow dynamics is still a work in progress (Dondo and Nhleko, 2008). Dondo and Nhleko (2008) investigated the usage of 3-D modelling in verification of geological borehole data in the Karoo region for a better pictorial
representation that assists in providing a response to the question of storativity at a local scale in the Karoo Basin where aquifers systems are layered extensive and there is interconnectivity. The study delineated three aquifer systems. Aquifer 1 is a secondary aquifer that is restricted to a depth not more than 20m (Botha et al., 1996). These aquifers are classified as intergranular and fractured and contain primary porosity. These occur as a result of alluvium with deeply weathered Beaufort sediments, with borehole yield of 0.1 to 0.5 l/s. The alluvia can also act as storage reservoirs which recharge the underlying aquifers (DWAF, 2002).

Aquifer 2 is a secondary fractured rock aquifer associated with dolerite intrusions and is found at depths greater than 50m (Botha et al., 1996). These aquifers are classified as fractured rock aquifers, they have secondary porosity which can yield 5 l/s. Fracturing occurs as result of weathering, folding, fracturing, faulting and jointing. High groundwater potential exists at the dolerite sediment contact zones from fractures within the sandstone layers (DWAF, 2002). In the absence of barriers like dykes and sheets of dolerite, groundwater is mainly dammed by sandstone beds. Sandstone has generally low porosity and is secondarily silicified, so that it forms an excellent aquifer (Rossouw and de Villiers 1953).

Aquifer 3 is a secondary deeper aquifer that occurs at depth of 80-90m. There seem to be interconnectivity in the aquifer systems found <300m (Botha et al., 1996). However, interconnectivity between the shallow and deeper aquifer systems remain a mystery due to the lack of information and research of deeper groundwater flow dynamics (Botha et al., 1996).

5.3.2 Geological Structures and Potential pathways

The presence of geological structures and primary faults may influence aquifer vulnerability by providing pathways that could facilitate vertical propagation of stray gas from shale formations to shallow aquifer systems. Whether or not faults have potential to facilitate vertical propagation of stray gas migration, increasing aquifer vulnerability depends on a number of factors, but this study reviewed preferential groundwater flow zones and dolerite sills and rings aquifer systems as found throughout the Karoo Basin.
Preferential groundwater flow zones are associated with the highly fractured zones along faults as well as within contact zones associated with intrusive igneous bodies. The zones adjacent to the dykes and sills are generically highly fractured due to their intrusive nature and are thus often associated with fault zones (Younger et al., 2002). These highly fractured contact zones have higher transmissivity values and represent zones through which the groundwater can move more freely as opposed to the adjacent host rock, and could thus also affect the natural groundwater flow characteristics of the shallow weathered zone aquifer (Younger et al., 2002).

In the majority of the areas where shale formations have potential to represent a good prospective target for exploration are also characterised by multiple dolerite intrusions. Drilling in a dolerite sill environment will face challenges that can be overcome if sufficient investigation is carried out on these intrusive structures at depth. There is sparse information on the structure of deep dolerite sills and associated deep groundwater and water strikes in the Karoo lithostratigraphic formations (Steyl et al., 2012).

Research has shown flat structures associated with lithological contacts or dolerite sills are regarding targets for groundwater exploration in term of strikes and yields (Botha et al., 1998, Chevallier and Woodford, 1999, Chevallier et al., 2001, Woodford and Chevallier, 2002). Chevalier et al., (2001) conducted a study in the Qoqodala dolerite ring systems in the dolerite ring system which intruded the Beaufort Group investigated water flow associated with a sill or ring complex (Chevallier et al., 2004a). The study reported that the back of the inclined sheet between the two upper sills are structurally complex with several dolerite offshoots and water strikes. Major sandstone bar with interbedded shale has been displaced by the inclined intrusion. Water strikes and fractures mainly occur at lithological contacts such as dolerite contacts or sandstone contacts. Boreholes drilled into upper aquifer unit generally strike a relatively large number of low-yielding water interception, while discrete higher yielding water interceptions are of the deeper aquifer units. The Qoqodala site shows that Karoo aquifers in dolerite sill or ring environments are compartmentalised and multi-fractured aquifers to depths of 250 m.
Several water strikes can be intercepted during drilling and artificial connection between aquifers can be created (Chevalier et al., 2001).

5.3.3 Wellbore pathways

Induced aquifer connection can include natural pathways that may exist between aquifers; various artificial connections may exist through formations or potentially formed in the future. The main cause for increased aquifer connectivity as outlined by Worley Parsons (2013) included:

- Poorly sealed groundwater observation or water supply bore allowing groundwater or gas migrate along the bore annulus
- Poorly constructed or seal petroleum or gas exploration wells, providing a migration pathways for fluid between discrete aquifer intervals.
- Old and abandoned bores such as oil and gas exploration, production wells, irrigation bores and stock and domestic bores which have not been appropriately decommissioned or rusted and decayed have the potential to allow for free movement of water or gas between formations

There are a number of boreholes located on the study area which belong to the property owners, municipality or the Department of Water and Sanitation (DWS), these boreholes can be grouped into unmonitored and monitored by the municipality or DWS. Unmonitored boreholes have a potential to serve as preferential pathways for stray gas migration by connecting to formations that have induced permeability. Hydraulic seal on the outside of the outside of bore casing may degrade due to physical and chemical reactions and produce pathways for fluid or gas movement. However, in the Karoo Basin vertical separation from target marine shale formations to shallow is of thousands of meters apart. The marine shales and shallow aquifer systems are separated by consolidated rock material with low permeability and porosity. Therefore wellbores have the potential to serve as migration pathways.

5.4 Potentially impacted resources

The resources that have the potential to be impacted are the shallower aquifer systems (receptors) used for domestic and agricultural purposes. This section reviews aspects such
as aquifer storage and groundwater users that are likely to be impacted by shale gas development. For example, possible migration of stray gas methane via preferential flow paths could contaminate the aquifer systems. These groundwater management aspects should be taken into consideration when devising means of mitigation and/or protection strategies. The value of aquifer storage is dependent on its uniqueness in terms of ecosystem habitat. The sensitivity and value of receptors are key criteria in determining the level of risk posed by the hazard.

5.4.1 Aquifer capacity
Groundwater sustainability is a phenomenon that encompasses groundwater depletion and groundwater sensitivity. In groundwater resource management both these concepts are identified as key indicators of groundwater sustainability (UNESCO, 2007). Groundwater depletion and the lack of groundwater sensitivity lead to decline in water levels and impacts groundwater storage. Groundwater level decline evaluation needs to take into account its dependence on natural and seasonal fluctuations due to natural and climatic conditions and aquifer characteristics (Worley Parsons, 2013). The critical issues arising is the amount of water to be extracted from the aquifer without producing non-reversible impacts on groundwater quantity and quality or surface geotechnical stability (UNESCO, 2007).

Potential groundwater depletion is always benchmarked using drawdown. In a confined aquifer water is supplied from compression of the pore space and expansion of water molecules, while unconfined aquifers water is supplied by gravity drainage at the water table. Specific yield values are much greater than aquifer storativity values. The given amount of drawdown on an unconfined aquifer will yield greater volumes of water relative to the confined aquifer. Drawdown is a key indicator of sensitivity of the resource. An aquifer with a large amount of drawdown will be more resilient to groundwater level fluctuations than aquifer with low drawdown (Worley Parsons, 2013). Therefore changes in age and origin of groundwater at specific locations in the aquifer can be an indication of groundwater depletion (UNESCO, 2007). The Beaufort West Municipality experienced drought conditions during 2009-2011 impacting on the security
of water supply. This drought period was characterized by decline in water levels in the major surface water source of Beaufort West and the Gamka Dam, reduced to such levels that caused uncertainty regarding uninterrupted drinking water supply (Worley Parsons, 2013). The lack of water in the Gamka Dam over the years, due to drought conditions has exerted pressure on the groundwater sources which are inadequate to supply the Beaufort West municipal water requirements without surface water supply from the Gamka Dam (Worley Parsons, 2013). For many communities in the Karoo region groundwater is the only source of water supply. However, aquifer capacity would decrease due to competing demands.

5.4.2 Groundwater users

Groundwater use is a concept based on measurable and observable data to provide information on social (groundwater accessibility, exploitability and use), economic (groundwater abstraction, protection and treatment requirements) and environmental (groundwater vulnerability, depletion and pollution) aspects of groundwater resource policy and management (UNESCO, 2007). In this section these aspects were applied to the Karoo basin in light to possible shale gas development in the area.

The social aspect of water in Beaufort Municipality is supplied via independent distribution systems to Beaufort West, Merweville, Nelspoort and Murraysburg. Beaufort West and Nelspoort are reliant on both groundwater and surface water sources, while Merweville and Murraysburg utilise groundwater services only (Worley Parsons, 2013). The mean annual rainfall varies from 200-300mm per year (KV3, 2009). This in itself places a burden on sustainability of bulk water supply. The economic activities in the rural areas include extensive sheep farming and angoras, while urban areas activities include transport and communication, wholesale and trade, catering and accommodation, general government services and manufacturing (KV3, 2009).

The allocated bulk water supply is 2 064672 m³, with further known development of 15 000 m³/year. The demand in 2007 was approximated to 2595188 m³ exceeding the allocated bulk water supply (KV3, 2009). The Beaufort West Water Treatment Works (WTW) is adequate with regard to treatment of water from the Gamka Dam (KV3, 2009). However, groundwater from the boreholes within the Beaufort West and Merweville
areas are disinfected by means of chlorination before being distributed into the water supply system. A study conducted by (Kv3, 2009), recommended that proper management of groundwater sources are managed well and the quality of water does not deteriorate, then the current level of treatment holds as acceptable.

5.4.3 Groundwater dependent ecosystems
The state of groundwater-dependent ecosystems (GDEs) depends on variables such as the groundwater quantity and quality, physical characteristics and chemical characteristics. These groundwater variables include quantity, location, timing, frequency, duration of groundwater delivery, water quality and temperature (WorleyParsons, 2013). Groundwater supports aquatic biodiversity by providing access to habitat and regulation of water chemistry and temperature. However, changes in the above-mentioned variables have the potential to alter the structure and function of a GDE (WorleyParsons, 2013).

In the Great Artesian Basin (GAB) springs have a separate and unique ecology that is totally reliant on water within the basin. The examples include mound springs of the GAB which are classified as ‘Endangered Ecological Community’ (GABCC, 2010; Rolfe, 2008). A study conducted in Queensland of individual fish and plant species prevalent to spring communities are listed as endangered or vulnerable under the Nature Conservation Act 1992.

Groundwater Dependent Ecosystems in South Africa described according to the aquifer system and the habitat type. GDE classifications range from in-aquifer and cave ecosystems, springs and seep related GDE, wetlands, riverine aquatic ecosystems, riparian ecosystems, terrestrial ecosystems and estuarine and coastal ecosystems (CSIRO, 2004). In this study the GDE focused on the spring and seep related GDEs due to the study nature. This GDE type occurs in most aquifer types in South Africa excluding the unconsolidated Kalahari sands where the water table is below the surface in its extensive primary aquifer (CSIRO, 2004). The springs and seep related GDE can be subdivided into three types. Type 1 account for the shallow seasonal springs and seeps emanating at perched water tables, which can be interpreted as interflow or rejected recharge.
These springs are vulnerable to drought and climate change, but not abstraction from the deeper aquifer. Type 2 is the lithological controlled springs, due to the presence of interbedded aquitards, located mainly at the Peninsula - Cedarberg, Goudini – Skurweberg and Nardouw – Bokkeveld contacts. These springs are vulnerable to climate change and abstraction. Type 3 accounts for fault controlled springs (FCS). These may include hot water springs and are vulnerable to climate change and excessive abstraction (CSIRO, 2004). A study conducted by Kok (1992) revealed that springs in the Karoo Basin often occur at the contact between dolerite dykes or sills and Karoo shales and the contact can be highly fractured and cater for groundwater flow up to 50l/s (Kok, 1992). However, shale gas development and extraction has the potential to flow and migrate into these springs, thereby contaminating groundwater source of ecosystems. There is concern for continuous survival of GDEs, and the need to manage the impacts from potential and expected changes to groundwater quality and quantity needs to be integrated in local and national water management strategies.

5.5 Risk Assessment in the study area

This section describes shale gas development hazards, associated receptors as well as their linkage from the hazards to the receptors through subsurface pathways.

5.5.1 Selected hazards and receptors

The hazards in this study area were identified as stray gas migration, groundwater contamination with salts or other constituents, surface water contamination, contamination of groundwater from waste residue deposits and over exploitation. The potential receptors were identified as aquifer storage, groundwater users and groundwater dependent ecosystems based on the likelihood hazards might have on receptors due to shale gas development.
Table 2: Linkage Estimation of magnitude of risk (modified from Vengosh et al., 2014; Worley Parsons, 2013).

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Aquifer Capacity</th>
<th>Groundwater Users</th>
<th>Groundwater Dependent Ecosystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stray gas contamination</td>
<td>N/A</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Groundwater contamination with salts or other dissolved constituents</td>
<td>N/A</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Contamination of groundwater from waste water residue deposits</td>
<td>N/A</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Over-exploitation of aquifers</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

N/A = not applicable

Quantifying potential risks to groundwater requires analysis of hazard, pathway, and receptor interrelationships to assess the relative likelihood and severity of potential adverse outcomes (Somaratne et al., 2013; Liu and Ramirez, 2017). Results are summarized in a risk matrix format (Table 2). The colours denote the overall severity of the risk (green is low, yellow is moderate, and red is high).

Table 2 indicates that aquifer capacity is not likely to be impacted by stray gas contamination, groundwater contamination with salts or other dissolved constituents and contamination of groundwater from waste water residue deposits. However, this receptor has high likelihood of being impacted by over-exploitation of aquifers. Groundwater users and groundwater dependent ecosystems have low likelihood of being impacted by stray gas migration and groundwater contamination with salts and other dissolved constituents. Furthermore, these receptors have medium likelihood of being impacted by
groundwater contamination from waste residue deposits and a high likelihood of being impacted by over-exploitation of aquifers.

These hazards are best dealt with through Best Management Practices and appropriate groundwater monitoring programs in order to mitigate and protect these receptors. The development of incident-specific response in protecting the receptors is of utmost importance. In the event of adverse effects on groundwater levels and quality be detected through groundwater monitoring, such response plans would need to be implemented.

The migration potential of stray gas, salts and dissolved constituents is limited to shale gas leased areas and areas in the vicinity of shale gas production wells. Dolerite intrusions, geological structures and petroleum wells are potential pathways that could potential transmit cross stratigraphic flows and propagate drawdown effects. Possible consequence is pollution of potable water sources (Maceba et al., 2017). Pollution of groundwater resources by upward migration of fractures and any fluids they contain requires (Younger, 2016a): sufficient hydraulic interconnection a permeable pathway and sustained driving head oriented upwards. The Whitehill Formation is known to be regionally persistent in composition and thickness and can be traced throughout the entire Karoo Basin (Branch et al., 2007). In borehole SA 1/66 the Whitehill Formation was intercepted at 2,790 m (Branch et al., 2007; Lindeque et al., 2011) and 4,404 m in KW 1/67 (Lindeque et al., 2011).

A study conducted by Scheiber-Enslin et al. (2015) showed that in the south-eastern Karoo, limited borehole data showed a broad deepening of the basin compared relative to the southwestern Karoo Basin. This trend is reflected in the overlying Whitehill Formation, with depths of between ~3,000 to 4,000 m in the southwest and southeast respectively, deepening to over 5,000 m in the southeast due to faulting (Scheiber-Enslin et al., 2015). With the shallow aquifers typically occurring at depths of <300 metres, there is a vertical separation of 1000s of metres. Vertical movement of groundwater is dependent on aquitard properties. These properties are key characteristics include aquitard thickness, vertical hydraulic conductivity and storativity (Worley Parsons, 2013).
Larger aquitard thicknesses that provide vertical separation of aquifers from the impacts of shale gas extraction will tend to lower the vulnerability of the aquifers; and lower vertical hydraulic conductivity values of the aquitards will lead to lower aquifer vulnerability (Maceba et al., 2017). The targeted Whitehill Formation is separated from shallow aquifers in the upper parts of the Abrahamskraal Formation by most likely the Waterford and the Tierberg Formations. The sedimentary rocks of the Mesozoic Karoo Basin are gently folded and become near horizontal towards the Escarpment (Lindeque et al., 2007). The integrated crustal model presented by Lindeque et al. (2011) constrains a shallow Karoo Basin, with deformation of the Karoo Supergroup, at least locally, detached from the Cape Supergroup below. Low angle thrusts appear rooted in the Whitehill- and Prince Albert Formations of the Ecca Group, which acted as local décollement surfaces (Lindeque et al., 2011).

Therefore, in the current study vertical separation between target formations and shallow aquifer systems has proven to be low risk to groundwater contamination with salt and other dissolved constituents and to stray gas migration, because of compact sedimentary material and low permeable and porosity.

5.5.2 Subsurface pathways and attributes considered

Shale gas has potential to migrate upwards into the receptor, causing an adverse risk outcome provided that migration pathways are in place. The potential pathways identified in this study include the proximity of aquifers to the prospective Whitehill Formation, deep and shallow aquifer interconnectivity, dolerite intrusions, geological structures as well as well induced pathways.
Table 3: Shale Gas Development Hazards and Associated Pathway Attributes.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Proximity of aquifers to the prospective Whitehill Formation</th>
<th>Aquifer inter-connectivity</th>
<th>Dolerite intrusions</th>
<th>Geological structures</th>
<th>Wellbore pathways</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stray gas contamination</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Groundwater contamination with salts or other dissolved constituents</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Contamination of groundwater from waste water residue deposits</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Over-exploitation of aquifers</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

X= identified attributes, empty box = no pathway; Modified from (Vengosh et al., 2014; Worley Parsons, 2013).

Proximity of aquifers to perspective Whitehill Formation is only associated with hazards such as surface water contamination, contamination of groundwater from waste water residue deposits and over-exploitation of aquifer, while other pathway attributes are associated with all other hazards. Shallow aquifer systems (receptors) in the Karoo Basin are found at depth c. <300m and shale gas extraction is estimated to occur at c2000m depth (KGEG, 2013). The operation would take place at a more regional scale that is overlain by intermediate systems. These systems are mostly associated with deep burial fault and fractures systems and are normally expressed through springs. This system is disconnected from both the local and the regional aquifer systems.
Aquifer interconnectivity can be attributed to the existence of dolerite intrusions and geological structures that might serve as potential pathways for connectivity between shallow and deep aquifer systems. Rock water interaction and hydrochemistry would give an indication of the origin of the water, where deeper seated water would be more saline relative to shallower aquifer systems. The understanding of the Karoo dolerite network has led to the classification of dolerite zones into three zones such as the upper, middle and the lower dolerite zone (van Zijl, 2006). The first dolerite zone is the most dolerite-poor zone and predominantly consists of dykes that are thought to feed the overlying lavas (Chevallier et al., 2001).

A study conducted by van Zijl (2006) suggested that due to low overburden pressure in this zone, the intrusion style is independent of lithology. Burchardt (2008) highlighted that sills are more likely to intrude between layers of varying mechanical properties due to a change in the stress field. The preferred emplacement horizons are the Dwyka-Ecca Group contact, the Prince Albert-Whitehill Formation contact in the lower Ecca and the upper Ecca-lower Beaufort Group contact, as well as lithological boundaries within the Beaufort (Scheiber-Enslin et al., 2014; Cole and McLachlan, 1994; du Toit, 1920). The second dolerite zone is thought to consist of the most significant number of intrusions. This second group of intrusions is mostly saucer- or basin-shaped, with these structures usually coalescing to form ring complexes (du Toit, 1920). These intrusions occur within the Upper Ecca and Beaufort Groups and in some instances into the higher formations. The abundance is thought to correspond to the first thick sandstone unit, emphasizing the importance of horizontal, as well as vertical transport of magma in the system. The third and lower zone consists of flat extensive sills (~30 km) in the lowest stratigraphic units of the basin (Scheiber-Enslin et al., 2014).

These units include the glacial deposits of the Dwyka Group and submarine laminated shales of the lower Ecca. Inclined sheets that formed at the tips of these sills outcrop in the lower Beaufort in the south-eastern basin. Therefore these structures have the potential to serve as potential pathways from the hazard to the receptors. Geological pathways within the Karoo Basin are thought to have formed during basinal formation and
deformation. A geological and geophysical study conducted by Tankard et al. (2009) attributed both Cape and Karoo Basin formations to periods of crustal uplift, followed by subsidence along crustal faults and long periods of regional subsidence resulting from subduction driven mantle flow (Tankard et al., 2009).

A study conducted by Lindeque et al (2011) suggested that the Cape Fold Belt and Karoo Basin developed due to wide, thin skinned folding. This folding resulted from far-field southward subduction leading to continent-continent collision, arc collision or suturing south of the Cape Fold Belt. Furthermore, the study interpreted series of low-angle listric faults in the Karoo sediments linked to local décollement surfaces in the lower Ecca Group. If groundwater naturally migrates from deep (>1500 m) to shallow (500 m) Karoo groundwater systems, or if hydraulic fracturing activities induced such flow, then the routes would be through specific geologic structures that form preferential flow paths (Murray et al., 2015).

The possibility of shale gas exploration and development in the Karoo has led to environmental concerns including wellbore induced pathways. One concern is that deep borehole drilling and hydraulic fracturing process may create conduits through which deep-seated groundwater could migrate to shallow aquifers.

Murray et al. (2015) suggested if deep groundwater is of poor quality and if shale gas development facilitates upward migration of deep seated groundwater. There is a possibility for poor quality groundwater to blend with shallow aquifer that could be used for water supplies. In some areas, deep groundwater may even issue to the surface through leaking shale gas boreholes, should lose their integrity. However, this upward flow will take place for an extended period of time, if the deep-seated Karoo shales are sufficiently permeable to allow groundwater flow under sufficient pressure for the flow to rise to the surface and hydraulically linked to an extensive area so that flow continues over time (Murray et al., 2015). However, this is a long term concern, due to the integrity of deep boreholes may be compromised decades or centuries after abandonment through slow deterioration of the sealing cements used in borehole grouting and plugging (Murray et al., 2015). High-pressure process may marginally open existing
fractures that were previously impermeable and thus allow for slow migration and deep-seated groundwater. Crustal instability may only occur in years to come with the required intensity to cause upward movement of water through old or new faults and fractures (Murray et al., 2015). The current study was informed by the Murray et al. (2015) and identified potential pathway which are the induced well bore because they come from the depth of the target formation to the surface.

5.5.3 Attribute ranking and weighting factors

Key attributes and their data source were selected and used in the applying of GMMCA methodology to assess risks related to shale gas development and extraction for selected receptors and associated pathways outlined in Table 5.5. These 9 attributes were categorized as source (hazard, H), pathways (vulnerability, V) and receptor (consequence, C) with subscripts used to identify their use in the risk calculations.

Table 4: Selected risk calculation attributes modified after (Vengosh et al., 2014; WorleyParsons, 2013).

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Type</th>
<th>Source of information</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawdown</td>
<td>HV1</td>
<td>DWS monitoring data</td>
<td>Most significant effect that can result in depressurisation of shallow aquifer due excess abstraction from deep aquifers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Municipal wellfields</td>
<td></td>
</tr>
<tr>
<td>Gas migration potential</td>
<td>H2</td>
<td>Shale gas leases</td>
<td>Gas migration potential is limited to shale gas leases &amp; areas in vicinity of eventual production wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissolved constituents migration</td>
<td>H3</td>
<td>Shale gas leases</td>
<td>The dissolved potential is limited to shale gas leases &amp; areas in vicinity of eventual production wells</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dolerite intrusions</td>
<td>V2</td>
<td>Geological maps</td>
<td>Potential conduits may facilitate cross-formational flow / gas migration and transmit drawdown effects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Well logs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lindeque et al., 2011; KGEG, 2013; Scheiber-Enslin et al., 2014</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 indicated that simulated drawdown is used to define both the hazard and pathway component associated with shale gas development and extraction. The hazard, drawdown can result in depressurisation of shallow aquifer due excess abstraction from deep aquifers. The pathway (vulnerability) component of being the propagation of drawdown towards the adjacent aquifers, as it is affected by proximity of those aquifers to the shale gas formations, aquifer hydraulic properties and aquifer interconnectivity.
Table 5: Risk calculations as applied to hazards modified after (Vengosh et al., 2014; WorleyParsons, 2013).

<table>
<thead>
<tr>
<th>Hazards</th>
<th>Aquifer storage</th>
<th>Groundwater users</th>
<th>Groundwater dependent ecosystems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stray gas contamination</td>
<td>$H_2 \times (V_2+V_3+V_4) \times (C_2+C_3+C_4)$</td>
<td>$H_2 \times (V_2+V_3+V_4) \times C_5$</td>
<td></td>
</tr>
<tr>
<td>Groundwater contamination with salts or other dissolved constituents</td>
<td>$H_3 \times (V_2+V_3+V_4) \times (C_2+C_3+C_4)$</td>
<td>$H_3 \times (V_2+V_3+V_4) \times C_5$</td>
<td></td>
</tr>
<tr>
<td>Contamination of groundwater from waste water residue deposits</td>
<td>$H_3 \times (V_2+V_3) \times C_2$</td>
<td>$H_3 \times (V_2+V_3) \times C_2$</td>
<td></td>
</tr>
<tr>
<td>Over exploitation of aquifers</td>
<td>$HV_1 \times (V_2+V_3+V_4) \times C_1$</td>
<td>$HV_1 \times (V_2+V_3) \times (C_1+C_2+C_3)$</td>
<td>$HV_1 \times (V_2+V_3) \times C_5$</td>
</tr>
</tbody>
</table>

For aquifer storage, the receptor is vulnerable to over-exploitation of aquifers. Attributes that are likely to cause vulnerability include drawdown, dolerite intrusions, geological pathways and aquifer storage available head. For groundwater user receptors vulnerability is likely to be caused by all the hazards represented tabulated above. The attributes of association include drawdown, dolerite intrusion geological pathways, petroleum pathways, gas migration potential, dissolved constituents migration, aquifer storage available head, groundwater users, borehole density and allocation of volume and
The groundwater dependent ecosystems receptor is also vulnerable to all hazards tabulated in Table 2. The attributes are more likely to be associated with this vulnerability include drawdown, gas migration potential, dissolved constituent migration, dolerite intrusion, geological pathways, petroleum well pathways and groundwater users.

5.5.4 Drawdown attributes considered
Groundwater-level drawdown is the main hazard related to shale gas development and exploration, as well as reflecting vulnerability aspects of drawdown propagation to adjacent aquifers. Ranking factors anticipating ranges in drawdown associated with shale gas development and extraction is dependent on consolidated or unconsolidated aquifers. The most significant effect resulting in depressurization of shallow aquifers was due to excess abstraction from deep aquifers. The ranking on Karoo aquifer systems is consolidated aquifer due to high magnitudes of drawdown experience in the Karoo region and the weighting value is $W_t = 5$, the highest value attributed to the Surat and Bowen Basins (Worley Parson, 2013). The ranking scores for consolidated and consolidated aquifers are associated with an individual scale of drawdown magnitude that reflects the different range of potential effects for each aquifer type (Worley Parson, 2013).
Shallow aquifer systems are expected experience variation in drawdown due to sole dependence of local residence to groundwater supply and minimal rainfall in the area. The above tabular representation categories drawdown values ranging $<1$ to 5 as basement assessment trigger, the 5 to 15 range is referred to as the good regulatory threshold trigger and the drawdown values $>20$ are referred to as the relatively certain to cause detrimental impacts to affected resources.
Table 6: Groundwater Drawdown Magnitude Ranking Values for Unconsolidated Aquifers

<table>
<thead>
<tr>
<th>Groundwater drawdown ranking value (Rnk1)</th>
<th>Unconsolidated aquifers</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt;1</td>
<td>Baseline assessment trigger</td>
</tr>
<tr>
<td>2</td>
<td>1 to 2</td>
<td>Make good regulatory threshold</td>
</tr>
<tr>
<td>3</td>
<td>2 to 3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>3 to 5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5 to 10</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10 to 15</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15 to 20</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>&gt;20</td>
<td></td>
</tr>
</tbody>
</table>

5.5.5 Gas migration potential attributes considered

The potential for gas migration associated with shale gas development and extraction exists. Gas may migrate upward along other natural or induced pathways such as old wells with compromised well integrity, along conduits such as dolerite intrusions as well as geological structures (Murray et al., 2015). The potential for gas migration is more likely to be a potential hazard for groundwater users and groundwater dependent ecosystems.
Table 7: Gas Migration Potential Ranking Values

<table>
<thead>
<tr>
<th>Gas migration potential</th>
<th>Ranking value (Rnk&lt;sub&gt;2&lt;/sub&gt;)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>0</td>
<td>No risk of gas migration due to shale gas development</td>
</tr>
<tr>
<td>Yes</td>
<td>10</td>
<td>Potential risk due to active geological and old wells with compromised integrity as well as dolerites</td>
</tr>
</tbody>
</table>

The gas migration potential is ranked 0 if the potential does not exist and 10 if the potential for the hazard reaching the receptor through migration pathways does exist.

5.5.6 Geological pathways attributes considered

Geological pathways in the lower Karoo Supergroup formed during basinal formation. The lack of basement deformation on seismic data instead suggests that the Cape Fold Belt (CFB) and Karoo basin developed as a result of wide, thin-skinned folding. This folding is said to have resulted from far field southward subduction leading to continent-continent collision, arc collision or suturing south of the CFB (Lindeque et al., 2011). Faults were not identified in the upper Karoo Supergroup formations. However, low angle listric faults in Karoo sediments linked to local decollement surface in the lower Ecca Group (Lindeque et al., 2011). Faults can potentially serve as feasible pathways for the upward propagation of stray gas migration and other contaminations to shallow aquifer systems (Myers, 2012; Smythe, 2016). However, several authors dismissed this concept, because faults to serve as possible pathways factors such as vertical extent of faulting across formations, tectonic stresses which may either open or close fault pathways and fault mineralisation prevail (Saiers and Barth, 2012; Birdsell, 2016; Engelder, 2016; Verdon, 2016; Westaway, 2016; Younger, 2016a; Younger, 2016b). Numerical modelling in a North German Basin of hydraulic fluid injection and its potential migration through the layered geological underground at basin scale revealed no actual contamination hazard for shallow aquifers,
despite the implementation of highly permeable preferential pathways (fault zones, fractures) and parameters that are highly favourable for solute transport (no sorption, no degradation) (Pfunt et al., 2016).

Table 8: Fault Overlapping Between Aquifer and Shale Gas Zones Ranking Values.

<table>
<thead>
<tr>
<th>Faults overlapping the Lower Ecca Group</th>
<th>Ranking value (Rnk₃ₐ)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>0</td>
<td>A fault pathway does not exist</td>
</tr>
<tr>
<td>Yes</td>
<td>1</td>
<td>A fault pathway does exist</td>
</tr>
</tbody>
</table>

Fault orientation was used as aquifer vulnerability attribute because tectonic stress regimes may influence fault pathways. The potential for fault-related pathways were considered based on the possible reactivation of pre-existing faults under modern subsurface stress regime which is oriented roughly in NE to SW directions (Worley Parsons, 2013). Based on the tectonic stress regime, faults oriented in a NW to SE manner would be suspected to be forced closed due to compressional forces. While faults oriented in a general N to S or NE to SW direction may have undergone strike-slip motion leading to possible reactivation and creation of potential pathways for flowback fluid and gas migration as reflected on Table 5.10. The overall fault pathway, fault overlap and fault orientation ranking are combined in the equation: Rnk₃ = Rnk₃ₐ x Rnk₃ₐ. This equation reflects that only those faults are considered in the risk calculations that are interpreted to transect the Karoo Supergroup with emphasis on the Dwyka and the Ecca formations (Rnk₃ₐ). The assigned ranking values range from 0-10 is determined by fault orientation (Rnk₃ₐ) and the weighting value is Wt= 3, the highest value attributed to the Surat and Bowen Basins, this is applied in the Karoo Basin due to these being sedimentary basins (Worley Parson, 2013).

5.5.7 Wellbore pathways
Wellbore pathways represent potential pathways although localised, for drawdown propagation, flowback and produced water as well as gas migration from shale gas formations to adjacent formations. Wellbores that transect multiple aquifers have the
potential to drawdown as well as facilitating gas migration between aquifers if they possess some form of pathway such as screens extending across multiple aquifer layers, poorly sealed wellbore annuli or failure of the casing (Worley Parsons, 2013). The potential for wellbore to be compromised is a function of its construction and its condition which are a function of wellbore age. The aforementioned functions are aquifer vulnerability attributes used in the assessment of wellbore pathways including the depth of bores, age of bores and the existence of formation overlaps with the Lower Ecca formations and the overlying Karoo Formations.

The potential for a compromised well to act as a conduit between Whitehill Formation and other formations is directly related to the formations it transects. Conditions for compromised wells to serve as possible vulnerability include bores extending into the Whitehill formation and deeper, thereby creating the risk of being a conduit. To address this aspect, total depth was compared with each assigned geologic layer from the Karoo conceptual model and each units used in the risk mapping of wellbores (Table 5.11).

Table 9: Fault Orientation Ranking Values

<table>
<thead>
<tr>
<th>Fault Orientation</th>
<th>Ranking value (Rnk3b)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northwest</td>
<td>1</td>
<td>Perpendicular to direction of maximum compressive stress, faults likely closed due to compressive force</td>
</tr>
<tr>
<td>West-northwest</td>
<td>2</td>
<td>Roughly perpendicular to direction of maximum compressive stress, faults likely closed due to compressive force</td>
</tr>
<tr>
<td>North-northwest</td>
<td>3</td>
<td>Trending in direction of maximum compressive stress; minor strike slip potential</td>
</tr>
<tr>
<td>West</td>
<td>4</td>
<td>Roughly 45° aspect to compressive stress, some strike slip potential</td>
</tr>
<tr>
<td>North</td>
<td>6</td>
<td>Trending in direction of maximum compressive stress; moderate strike slip potential</td>
</tr>
</tbody>
</table>
North-northeast 8 Trending in direction of maximum compressive stress; higher strike slip potential

East-northeast 9 Trending in direction of maximum compressive stress; higher strike slip potential

Northeast 10 Aligned with direction of maximum compressive stress, high strike slip potential

Table 10: Well bore formation overlaps

<table>
<thead>
<tr>
<th>Borehole extends into or below Whitehill and Prince Albert Formations</th>
<th>Ranking Value (Rnk 4a)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>0</td>
<td>Borehole does not transect Whitehill or Prince Albert Formations</td>
</tr>
<tr>
<td>Yes</td>
<td>1</td>
<td>Borehole does transect Whitehill or Prince Albert Formations</td>
</tr>
</tbody>
</table>

The second aspect of vulnerability of wellbore pathways is the age of the bore. Well construction in the Karoo Basin dates back to late 1960-1970s during the drilling of the Soekor wells. Well construction materials and techniques have improved with time and the older bores and are generally assumed to be at higher risk of failure and are consequently more likely to provide a pathway for flowback and produced water as well as gas migration (Worley Parsons, 2013). The age of a bore constitutes the second input to the vulnerability mapping associated with wellbore pathways as summarised in Table 11.
Table 11: Bore Age Range Ranking Values

<table>
<thead>
<tr>
<th>Age range of wells per 1.5 kilometre square (Years)</th>
<th>Ranking Value (Rnk 4b)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>3</td>
<td>Lower risk of connected pathways due to evolved well construction and sealing practices and likely integrity of well completion materials</td>
</tr>
<tr>
<td>30-75</td>
<td>6</td>
<td>Moderate risk of connected pathway due to diminished standards for well installation and sealing and possible compromise of well completion materials</td>
</tr>
<tr>
<td>&gt;75</td>
<td>10</td>
<td>Highest risk of connected pathway due to diminished standards for well installation and sealing and higher likelihood of compromised well completion materials</td>
</tr>
</tbody>
</table>

Rnk4 = Rnk4a × Rnk4b

The equation above reflects only those bores that are completed both in the shallow aquifers as well as the Whitehill Formation. The ranking value for those bores ranging from 3-10 are based on the bore age and the weighting value is Wt4 = 3, the value attributed to the Surat and Bowen Basins. The lower weight compared with the groundwater drawdown attribute is a reflection of the localised effects of such pathways and the uncertainty associated with bore construction and integrity (Worley Parson, 2013).

5.5.8 Aquifer storage reduction attributes considered

Aquifer sensitivity to drawdown impacts is expressed through available head. Assessing impact from drawdown induced by groundwater extraction is a magnitude of groundwater drawdown against available head.
Aquifer storage relative impact (x,y) = \frac{\text{Simulated Drawdown}}{\text{Available Head}}

Table 12: Information For Calculating Aquifer Storage Relative Impact.

<table>
<thead>
<tr>
<th>Borehole ID</th>
<th>Drawdown (m)</th>
<th>Borehole depth</th>
<th>Available Head</th>
<th>Drawdown Head</th>
<th>Aquifer storage relative impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWAF_BH1</td>
<td>21.75</td>
<td>59.72</td>
<td>39.97</td>
<td>21.75/39.97</td>
<td>0.54</td>
</tr>
<tr>
<td>BWAF_BH2</td>
<td>23.21</td>
<td>93.34</td>
<td>70.13</td>
<td>23.21/70.13</td>
<td>0.33</td>
</tr>
<tr>
<td>BWAF_BH3</td>
<td>30.02</td>
<td>70.54</td>
<td>40.52</td>
<td>30.02/40.52</td>
<td>0.74</td>
</tr>
<tr>
<td>SL_BH1</td>
<td>23.59</td>
<td>92.3</td>
<td>68.71</td>
<td>23.59/68.71</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Available head was calculated as the difference between the borehole depth and drawdown. Both drawdown and available head vary spatially within an aquifer and as such aquifer storage will also vary spatially. A study conducted by Worsley Parsons (2013) showed that in some consolidated aquifers the available head is very high because of the large depth of the aquifer within the Surat or Bowen basins leading to large available drawdown, while the projected drawdown is comparatively low (Worsley Parsons, 2013). In the Karoo Basin the available head is very high because of the large depth of the aquifer leading to large available drawdown and high aquifer storage relative impact.

Table 13: Aquifer Storage Reduction Ranking Values

<table>
<thead>
<tr>
<th>Aquifer storage relative impact</th>
<th>Ranking value (Rnk5)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 (i.e. &lt;1%)</td>
<td>1</td>
<td>Very minor impact to water availability in a bore</td>
</tr>
<tr>
<td>0.01-0.05 (i.e. 1%-5%)</td>
<td>3</td>
<td>Minor impact to water availability but not likely to influence well productivity</td>
</tr>
<tr>
<td>Range</td>
<td>Rank</td>
<td>Description</td>
</tr>
<tr>
<td>---------------</td>
<td>------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0.05-10</td>
<td>5</td>
<td>Decline in available head will likely start to affect well productivity</td>
</tr>
<tr>
<td>0.10-0.15</td>
<td>7</td>
<td>Decline in available head will likely start to affect coast and productivity</td>
</tr>
<tr>
<td>0.15-0.20</td>
<td>9</td>
<td>Notable decline in available head, cost and productivity implications anticipated</td>
</tr>
<tr>
<td>0.20</td>
<td>10</td>
<td>Significant decline in available head; implications for lifting costs and productivity likely to occur</td>
</tr>
</tbody>
</table>

Taking into account the aquifer storage reduction values in Table 15, the aquifer storage values in the Karoo Basin are >0.20 thereby obtaining a ranking value of 10 which would imply significant decline in the available head. A weighting value of \( W_{t3} = 5 \) was attributed given the importance of describing potential consequences to aquifer receptor (Worley Parsons, 2013). Major aquifers in the Bowen and Surat Basin have depths to the formation tops that increase towards the basin centres, resulting aquifer storage will increase in the same direction while relative aquifer storage impacts would decline towards basin centres or conversely increase towards recharge areas (Worley Parsons, 2013). It is suspected that the same would apply in the Karoo Basin due to its sedimentary nature that is similar to both the Surat and Bowen Basin.

### 5.6 Groundwater users attributes considered

The majority of the people in the Karoo region are reliant on groundwater to sustain high municipal, agricultural and industrial activities. The existing bulk water supply and water resources for the Beaufort West have shown that the demand in the region exceeded the allocated bulk water supply (K^V_3, 2009). Groundwater use is dependent on population. The total population in the Beaufort West water management area was approximated to 37 600 in 2006, of which 82% lived in urban areas and 18% in the rural areas (K^V_3, 2009).

In order to assess potential associated risk implications to the municipality water supplies bulk water supply and treated water supply were considered. In 2006, the Beaufort West Municipality experienced water an annual loss of 465532m\(^3\) bulk water supply which was...
estimated to 16.7%. The treated water supply annual losses were 524,466 m$^3$ the percentage of the loss was 22.6% and the total amount loss of the treated water supply is 989,996 m$^3$ which is 35.6% (K$^3$, 2009). In 2007, the Beaufort West municipality had an bulk water supply annual loss of 133,327 m$^3$ which represent 4.9%, treated water supply of 837,495 m$^3$. The total annual losses were 970,822 m$^3$ which were 35.6% (K$^3$, 2009) as indicated in Table 14 below.
Table 14: Bulk water supply and treated water supply for the Beaufort West Municipality

<table>
<thead>
<tr>
<th>Year</th>
<th>Bulk Water Supply</th>
<th>Treated Water</th>
<th>Monthly Losses (m$^3$)</th>
<th>Monthly Losses (%)</th>
<th>Annual Losses (m$^3$)</th>
<th>Annual Losses (%)</th>
<th>Treated Water Consumption</th>
<th>Monthly Losses (m$^3$)</th>
<th>Monthly Losses (%)</th>
<th>Annual Losses (m$^3$)</th>
<th>Annual Losses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-06</td>
<td>269867</td>
<td>211180</td>
<td>58687</td>
<td>21.7</td>
<td>211180</td>
<td>198480</td>
<td>12700</td>
<td>6</td>
<td>71387</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Feb-06</td>
<td>301132</td>
<td>203690</td>
<td>97442</td>
<td>32.4</td>
<td>203690</td>
<td>165446</td>
<td>38244</td>
<td>18.8</td>
<td>135686</td>
<td>45.1</td>
<td></td>
</tr>
<tr>
<td>Mar-06</td>
<td>260875</td>
<td>213750</td>
<td>47125</td>
<td>18.1</td>
<td>213750</td>
<td>166615</td>
<td>47135</td>
<td>22.1</td>
<td>94260</td>
<td>36.1</td>
<td></td>
</tr>
<tr>
<td>Apr-06</td>
<td>243620</td>
<td>186120</td>
<td>57500</td>
<td>23.6</td>
<td>186120</td>
<td>142578</td>
<td>43542</td>
<td>23.4</td>
<td>101042</td>
<td>41.5</td>
<td></td>
</tr>
<tr>
<td>May-06</td>
<td>126873</td>
<td>158040</td>
<td>-31167</td>
<td>-24.6</td>
<td>158040</td>
<td>149248</td>
<td>8792</td>
<td>5.6</td>
<td>-22375</td>
<td>-17.6</td>
<td></td>
</tr>
<tr>
<td>Jun-06</td>
<td>158498</td>
<td>158290</td>
<td>208</td>
<td>0.1</td>
<td>158290</td>
<td>117997</td>
<td>40293</td>
<td>25.5</td>
<td>40501</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>Jul-06</td>
<td>200299</td>
<td>163850</td>
<td>36449</td>
<td>18.2</td>
<td>163850</td>
<td>161235</td>
<td>2615</td>
<td>1.6</td>
<td>39064</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Aug-06</td>
<td>161078</td>
<td>161230</td>
<td>-152</td>
<td>-0.1</td>
<td>161230</td>
<td>115118</td>
<td>46112</td>
<td>28.6</td>
<td>45960</td>
<td>28.5</td>
<td></td>
</tr>
<tr>
<td>Sep-06</td>
<td>215259</td>
<td>178490</td>
<td>36769</td>
<td>17.1</td>
<td>178490</td>
<td>128343</td>
<td>50147</td>
<td>28.1</td>
<td>86916</td>
<td>40.4</td>
<td></td>
</tr>
<tr>
<td>Oct-06</td>
<td>220189</td>
<td>205660</td>
<td>14529</td>
<td>6.6</td>
<td>205660</td>
<td>112143</td>
<td>93517</td>
<td>45.5</td>
<td>108046</td>
<td>49.1</td>
<td></td>
</tr>
<tr>
<td>Nov-06</td>
<td>296193</td>
<td>229830</td>
<td>66363</td>
<td>22.4</td>
<td>229830</td>
<td>142733</td>
<td>87097</td>
<td>37.9</td>
<td>153460</td>
<td>51.8</td>
<td></td>
</tr>
<tr>
<td>Dec-06</td>
<td>327899</td>
<td>246120</td>
<td>81779</td>
<td>24.9</td>
<td>246120</td>
<td>191850</td>
<td>54270</td>
<td>22.1</td>
<td>136049</td>
<td>41.5</td>
<td></td>
</tr>
<tr>
<td>Jan-07</td>
<td>225132</td>
<td>252231</td>
<td>-27099</td>
<td>-12.0</td>
<td>252231</td>
<td>194,704</td>
<td>57527</td>
<td>22.8</td>
<td>30428</td>
<td>13.5</td>
<td></td>
</tr>
<tr>
<td>Feb-07</td>
<td>262392</td>
<td>264193</td>
<td>-1801</td>
<td>-0.7</td>
<td>264193</td>
<td>178,892</td>
<td>85301</td>
<td>32.3</td>
<td>83500</td>
<td>31.8</td>
<td></td>
</tr>
<tr>
<td>Mar-07</td>
<td>260631</td>
<td>214050</td>
<td>46581</td>
<td>17.9</td>
<td>214050</td>
<td>179,776</td>
<td>34274</td>
<td>16</td>
<td>80855</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>Apr-07</td>
<td>184098</td>
<td>192152</td>
<td>-8054</td>
<td>-4.4</td>
<td>192152</td>
<td>153,522</td>
<td>38630</td>
<td>20.1</td>
<td>30576</td>
<td>16.6</td>
<td></td>
</tr>
<tr>
<td>May-07</td>
<td>222954</td>
<td>205785</td>
<td>17169</td>
<td>7.7</td>
<td>205785</td>
<td>135,747</td>
<td>70038</td>
<td>34</td>
<td>87207</td>
<td>39.1</td>
<td></td>
</tr>
<tr>
<td>Jun-07</td>
<td>204516</td>
<td>193970</td>
<td>10546</td>
<td>5.2</td>
<td>193970</td>
<td>144,782</td>
<td>49188</td>
<td>25.4</td>
<td>59734</td>
<td>29.2</td>
<td></td>
</tr>
<tr>
<td>Jul-07</td>
<td>196722</td>
<td>198000</td>
<td>-1278</td>
<td>-0.6</td>
<td>198000</td>
<td>134,901</td>
<td>63099</td>
<td>31.9</td>
<td>61821</td>
<td>31.4</td>
<td></td>
</tr>
<tr>
<td>Aug-07</td>
<td>221696</td>
<td>214050</td>
<td>7658</td>
<td>3.5</td>
<td>214050</td>
<td>125,962</td>
<td>88076</td>
<td>41.1</td>
<td>95734</td>
<td>43.2</td>
<td></td>
</tr>
<tr>
<td>Sep-07</td>
<td>200408</td>
<td>210170</td>
<td>-9762</td>
<td>-4.9</td>
<td>210170</td>
<td>128,739</td>
<td>81431</td>
<td>38.7</td>
<td>71696</td>
<td>35.8</td>
<td></td>
</tr>
<tr>
<td>Oct-07</td>
<td>236587</td>
<td>212741</td>
<td>23846</td>
<td>10.1</td>
<td>212741</td>
<td>121,943</td>
<td>90798</td>
<td>42.7</td>
<td>114644</td>
<td>48.5</td>
<td></td>
</tr>
<tr>
<td>Nov-07</td>
<td>302996</td>
<td>213108</td>
<td>89888</td>
<td>29.7</td>
<td>213108</td>
<td>130,260</td>
<td>82848</td>
<td>38.9</td>
<td>172736</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>Dec-07</td>
<td>210383</td>
<td>224750</td>
<td>-14367</td>
<td>-6.8</td>
<td>224750</td>
<td>128,456</td>
<td>96285</td>
<td>42.8</td>
<td>81918</td>
<td>38.9</td>
<td></td>
</tr>
</tbody>
</table>
The groundwater use intensity in the Karoo region is high due to sole dependence on groundwater supplies. Boreholes within the study area are more spread out with distance exceeding the 1.5km radius. Ranking with respect to magnitude of estimated water use is interpreted based on Table 16. The ranking scheme is dependent of water use intensity and spatial weighting with higher scores indicating greater water usage. The weight of 1 (W_{t6}=W_{t7}=W_{t8}=1) was attributed for wellbore density, water use and predominant water use ranking values (Worley Parsons, 2013). The same weighting values were applied to
the Karoo Basin ranking due to similar nature to the Surat and Bowen Basin. High water usage is expected in sandstone regions which encountered dolerite intrusions.

Table 15: Wellbore density ranking values.

<table>
<thead>
<tr>
<th>Number of bores per 1.5 kilometre square</th>
<th>Ranking value (Rnk)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Low density of existing bores reflecting economic value of water</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Low to moderate number of bores and economic value of water</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>Moderate density of bores reflecting economic value of water</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>Moderate to high density of existing bores reflecting economic value of water</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>High density of bores reflecting economic value of water</td>
</tr>
<tr>
<td>&gt;5</td>
<td>10</td>
<td>Highest density of bores in the study area reflecting economic value of water</td>
</tr>
</tbody>
</table>

Table 16: Water use intensity ranking values.

<table>
<thead>
<tr>
<th>Water Use per 1.5 kilometre square (ML/d)</th>
<th>Ranking value (Rnk)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.01</td>
<td>1</td>
<td>Low level of water use and dependence on water supplies</td>
</tr>
<tr>
<td>0.01 to 0.05</td>
<td>5</td>
<td>Moderate level of water use; increased reliance on supplies</td>
</tr>
<tr>
<td>0.05 to 1.0</td>
<td>8</td>
<td>Moderate to high water use and dependence on supplies</td>
</tr>
<tr>
<td>&gt;1.0</td>
<td>10</td>
<td>High water use, significant dependence on supplies</td>
</tr>
</tbody>
</table>

The main purpose was selected to outline possible consequences of impacts associated with shale gas development hazards such as stray gas migration, flowback and produced water.
Table 17: Predominant water use ranking values.

<table>
<thead>
<tr>
<th>Predominant purpose</th>
<th>Ranking value (Rnks)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial</td>
<td>3</td>
<td>Lower priority use compares with other activities in the areas due to existing low allocation of water for this purpose</td>
</tr>
<tr>
<td>Irrigation</td>
<td>5</td>
<td>Moderate priority activity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Moderate to high priority activity given high reliance of this activity on groundwater supplies</td>
</tr>
<tr>
<td>Stock and domestic</td>
<td>8</td>
<td>Moderate to high priority activity given high reliance of this activity on groundwater supplies</td>
</tr>
<tr>
<td>Municipal</td>
<td>10</td>
<td>Highest priority given the reliance of communities on water for continued viability</td>
</tr>
</tbody>
</table>

Economic activities in the rural Karoo region include extensive farming of sheep angoras and some hunting farms. The economic activities in the urban areas are trade and communication (25%), wholesale and trade, catering and accommodation (16.68%), general government services (14%) and manufacturing (11%) (KvV3, 2009). Of the above-mentioned activities, there are two activities that require extensive water use relative to the others these are general government services and manufacturing.
Table 18: Hypothetical calculations for south western Karoo Basin groundwater usage

<table>
<thead>
<tr>
<th>Risk Factor</th>
<th>Attribute</th>
<th>Assessment approach</th>
<th>Measured value</th>
<th>Weighting</th>
<th>Ranking</th>
<th>Calculation (Raw)</th>
<th>Score (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawdown</td>
<td>HV&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Magnitude Faults intersecting lower Ecca Group</td>
<td>24.6</td>
<td>5</td>
<td>10</td>
<td>5×10</td>
<td>50</td>
</tr>
<tr>
<td>Geological</td>
<td>V&lt;sub&gt;3&lt;/sub&gt;</td>
<td>Fault orientation, strike slip potential</td>
<td>Yes</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pathways</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well bore</td>
<td>V&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Wellbore intersecting Ecca Group</td>
<td>NE</td>
<td>3</td>
<td>10</td>
<td>3×1×10</td>
<td>30</td>
</tr>
<tr>
<td>pathways</td>
<td>V&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Age range of bore (years)</td>
<td>Yes</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vulnerability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aquifer</td>
<td>C&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Maximum Drawdown Available head</td>
<td>24.6m</td>
<td>5</td>
<td>10</td>
<td>5×10</td>
<td>50</td>
</tr>
<tr>
<td>Capacity</td>
<td></td>
<td></td>
<td>28.97m</td>
<td>5</td>
<td>10</td>
<td>5×10</td>
<td>50</td>
</tr>
<tr>
<td>Water Users</td>
<td></td>
<td></td>
<td>0.31m</td>
<td>5</td>
<td>10</td>
<td>5×10</td>
<td>50</td>
</tr>
<tr>
<td>Consequence Score</td>
<td>C&lt;sub&gt;6&lt;/sub&gt;</td>
<td>Wellbore density</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1×3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;7&lt;/sub&gt;</td>
<td>Water use</td>
<td>0.05</td>
<td>1</td>
<td>5</td>
<td>1×5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>C&lt;sub&gt;8&lt;/sub&gt;</td>
<td>Predominant Use</td>
<td>Municipal</td>
<td>1</td>
<td>10</td>
<td>1×10</td>
<td>10</td>
</tr>
<tr>
<td>Receptor Risk Score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>50+3+5+10</td>
<td>68</td>
<td></td>
<td></td>
<td>68%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>98×68</td>
<td></td>
<td></td>
<td></td>
<td>6664</td>
</tr>
</tbody>
</table>
Hypothetical calculations as seen in Table 18 were used to estimate the risk in the Karoo Basin. These calculations accounted for risk factors which contributed to vulnerability scores and consequence scores. Risk factors that contributed to vulnerability score included drawdown, geological pathways and well bore pathways, while aquifer capacity and water users contributed consequence score. The receptor risk score is indicated by the product of vulnerability score and consequence score.

To determine vulnerability score the current study adopted weighting and ranking values from a study conducted by WorleyParsons (2013) conducted in the Surat and Bowen Basins in Australia. Drawdown assessment was determined from magnitude of secondary pumping test data. A ranking of 10 was attributed and weighting of 5 was adapted and the product of the weighting and ranking values gave a score (raw) of 50 and score in percentage of 50%.

Geological pathways intersecting the lower Ecca Group are present and are attributed a ranking of 1. The fault orientation and strike slip potential was identified as in the NE direction, a ranking of 10 was given and a weighting of 3 was attributed. The weighting and ranking product led to a score (raw) of 30 and score in percentage of 30%.

Wellbore pathways that intersected the lower Ecca group are the old Soekor wells drilled in the 1960s-1970s. The standard weighting is 3 and a ranking of 1 was attributed to the presence of wellbore pathways, a ranking of 6 was attributed due to the wellbore age range. The product of the weighting and the rankings yielded a score (raw) of 18 and a percentage score of 18%. A vulnerability score (raw) of 98 and percentage score of 98% was determined by the summation of the scores for the previously mentioned risk factors the method has an error of 2% that is unaccounted for.

To determine consequence score the current study also used weighting and ranking values from a study conducted by WorleyParsons (2013) conducted in the Surat and Bowen Basins in Australia.

Aquifer storage assessment was the quotient of maximum drawdown and available head. A standard weighting of 5 was used and ranking of 10 was attributed and their product yielded a score (raw) of 50 and a percentage score of 50%.
Water use has three assessment approaches used which include well bore density, water use and predominant use. Borehole density in the Karoo region is sparsely populated and is drilled in clusters whose distance within the cluster is less than 1.5km and greater than 1.5 km away from the next cluster. The measured value is 2, a standard weighting of 1 was attributed, a ranking value of 3 was given and their score (raw) was the product of weighting and ranking which is 3 and the percentage score was also 3%. Water use was attributed a value 0.05 a ranking value of 5 and weighting value of 1 and a score (raw) produced was 5 and a percentage score of 5%. The predominant water use in the area is municipal water use, a weighting of 1 was attributed, a ranking value of 10 was attributed and their score (raw) is 10 and percentage score of 10%. The consequence score was determined by the summation of scores of aquifer storage and water users’ assessment approaches which had a total of 68% and an error of 32% which was unaccounted for. The reception risk score is the product of vulnerability and consequence score which is 664. The risk reception score is 1.766 times more than that of the Lower Springbok Sandstone groundwater user which is 3773 (Worley Parsons, 2013). From this value it can be deduced that risk in the Karoo region is not high relative to the Lower Springbok Sandstone. A larger multiple would have been expected due to variation in depth between these two as the Lower Springbok Sandstone is investigated for coal bed methane relative to the Karoo Basin being investigated for shale gas developments.

5.7 Summary of chapter
In summary, the present chapter provided an indication of risk based analysis by calculating direct relationship between hazards and receptors and the estimation of risk. These receptors are including aquifer capacity, groundwater users and groundwater dependent ecosystems. The hazards include stray gas contamination, groundwater contamination with salts or other dissolved constituents contamination of groundwater from water management practices and the over-exploitation of aquifers. Aquifer capacity has potential to be impacted by over-exploitation of aquifer on high magnitude; other hazards are not applicable to this receptor. However, groundwater users and groundwater dependent ecosystem have low potential to be impacted by stray gas migration and
groundwater contamination with salts and other dissolved constituents. These receptors have medium potential to be impacted by contamination of groundwater from water management practices and high potential to be impacted by over-exploitation of aquifers. Conceptual risk assessment showed that the highest risk in the Karoo Basin is related to aquifer of over-exploited due to competing demands mainly due to the Karoo region primary reliance on shallow aquifer systems for both livelihood and agricultural purposes. It is likely that shale gas development will add stresses on shallow aquifer resources unless mitigation measures are pro-actively implemented. Therefore, there is a high risk to groundwater users and groundwater dependent ecosystems.
Chapter 6 Conclusion and recommendations

6.1 Introduction

In response to the current study’s topic which is the investigation of deep groundwater flow system in the south western Karoo Basin, four objectives were researched and adhered to as outlined in the sub-sections below. The main objective of this study was to understand risks posed by possible shale gas extraction on shallow aquifers. This was done in order to suggest mitigation and protective measures in the Karoo Basin. This study made use of two methods such as hydrochemical and water resource protection analyses. These methods were used to classify, investigate and describe interaction between shallow and deep aquifer systems in order to understand their possible interaction and vulnerability.

The previous two chapters responded to the objectives in order to provide a holistic hydrogeological understanding on a local scale first then on a regional scale. In addition, these chapters provided information that could help prevention and protection of water resources from possible contamination, inform DWS officials and municipal officials to manage the resource in a sustainable manner and for further research developments.

6.2 Hydrogeological conceptual modelling of Karoo aquifer systems

This section of the study addresses the first objective, which was to describe shallow and deep aquifer systems using a hydrogeological conceptual model to explain main risk factors for groundwater contamination. This objective addressed conceptually understanding of local, intermediate and regional groundwater systems and how flow occurs in each system and how these systems interact with one another. Potential hazards identified in the study included potential hazards such as stray gas contamination, groundwater contamination with dissolved salts and other constituents, surface water contamination and contamination of groundwater from waste residue deposits. The main concern regarding hydraulic fracturing was the flowback up of stray gas contamination and produced water possibly contaminating shallow aquifer systems used for agricultural and domestic livelihoods.
Shallow aquifer systems occur at depths <300m. Sandstones and mudstones in the Beaufort Group have low primary porosity and permeability and contain secondary hydrogeological rock properties. When associated with dolerite intrusions, the sandstones and mudstones have high potential water yield. In the absence of these dolerite intrusions these aquifer systems have low potential for water yield and groundwater in these aquifer systems is associated with alluvial aquifer systems.

Water quality in these aquifer systems is influenced mainly by topography with the lower lying areas being Na-Cl rich and higher lying areas being Ca-HCO₃ rich. Intermediate aquifer systems are mostly associated with deep burial fault and fracture systems verified by the daylighting of deep seated springs to the surface. These aquifer systems are saline, poorly understood and have uncertainty regarding being widespread or isolated pressure compartments disconnected from both shallow and deep aquifer systems. Regional aquifer systems are associated with the Cape Fold Belt expressing them in the Dwyka Formation, where there are structural linkages to regional aquifer systems evident from the Soekor wells.

The target formations for hydraulic fracturing for the extraction of shale gas are the Whitehill Formation with the possibility of the Prince Albert Formation if explored as an extension of the latter formation. With the shallow aquifer systems situated at <300m and the target formations situated at <2000m the vertical separation is between the shallow aquifer systems and target formation is vast considering the low porosity and permeability of the Karoo Basin. The risk of contamination of shallow aquifers would exist where there hazards would travel to the receptors through pathways. The receptors for this objective would be the shallow aquifer systems, which could potentially be contaminated by hazards such as stray gas contamination, groundwater contamination with salts and dissolved constituents and contamination of groundwater from waste residue deposits. The pathways have the potential to link the hazards to the receptors include the proximity of aquifer systems from the prospective Whitehill Formations, aquifer interconnectivity, dolerite intrusions as potential pathways, geological structures as potential pathways and wellbore induced pathways. It was shown that, indeed the proper systems for risk to occur in the Karoo Basin need to be aligned. However there is no telling that during the hydraulic fracturing pressure exerted would not induce pathway connectivity between the
shallow aquifer systems and the targeted formation and if connectivity is induced how long it will take for the hazards to reach the receptors. This phenomenon could be further studied in order to develop more knowledge on the flow in the Karoo Basin, and how shallow, intermediate and deep aquifer systems would behave in induced pressure conditions.

6.3 Investigation between shallow and deep aquifer systems

The second objective addressed in this section investigates interaction between shallow aquifers and deep aquifers. Shallow aquifers systems were classified as aquifers that are < 300m and the deep aquifers systems were classified as >300m. This investigation was undertaken using shallow aquifer systems and principles of rock water interaction due to the absence of boreholes drilled at the deep-seated aquifer systems. This objective centred around rock water interaction ideology on the change in groundwater composition as water moves through the aquifer, minerals dissolving and releasing salts, oxidation of sulphides and the cations exchange.

Water samples from shallow aquifers chemical types were identified as Ca-HCO$_3^-$, Ca-Na-Cl, Ca-Na-SO$_4$-Cl, and Na-Cl-SO$_4$. The Ca-HCO$_3^-$ water type is indicated recent recharge groundwater due to high Ca content. The remaining water types were identified as static and discordant groundwater which can be referred to as stagnant and actively being mixing due to high Na content. Findings have shown no interaction between the shallow and deep aquifer systems due to no chemical traces of chemical compositions of deeper lying lithological formations in the water samples. Furthermore conceptual modelling indicated that the Karoo Basin is under semi-artesian pressure systems as a result in lithostatic compartment due to different strata. Prior to shale gas development in the Karoo Basin, there is no interaction between deep and shallow aquifer systems due to no pressure exerted on the subsurface and low porosity and permeability of the rock formation with increased depth. This study recommends 3D geophysical data acquisition and interpretation in order to understand geological parameters such as sub-surface micro and macro faults and fracture networks in order to understand how they could serve as media of connectivity between deep and shallow aquifer systems.
6.4 Potential aquifer contamination through potential migration systems

The third objective addressed possible migration that would lead to shallow aquifer contamination. This objective took into consideration the depth of the targeted shale gas formations, depth of the deeper aquifer systems and the depth of both shallow and deep aquifer systems from the targeted shale gas formations. There exist relations between objective 2 and 3, because interactions between these aquifer systems would facilitated by migration pathways that would enable mixing of deep seated brackish water into the shallow aquifer systems. The conceptual model in Chapter 4 has showed uncertainties regarding microscale faulting and fracture networks occurring at depth that would be activated and extended by drilling and pressure exerted during shale gas extraction processes. Best practices in the shale gas hydraulic fracturing has shown that casing and cement are unlikely to leak as the process is all about capturing the shale gas from the target formations without compromising shallow groundwater aquifer systems. The possibilities of stray gas migration occurring are limited due to low permeability and porosity and vertical separation between the shallow aquifer systems and the targeted shale gas formations in the lower Ecca Group. Migration pathways that could lead to shallow aquifer contamination were identified as wellbores (decades after closure and abandonment), fracture networks, micro-faults and micro-faults need further researching. With time as an independent factor wellbores are bound to be compromised therefore serving as migration pathways for stray gas migration into shallow aquifers when cement is compromised. Micro faults and fractures and fracture networks have the potential to be activated and extended due to increased seismicity that would occur as pressure is exerted during shale gas extraction operations. These factors also require further investigation in order to understand the formations they occur in and their possible contributions as migration pathways.

6.5 Key risk factors for aquifer systems

The fourth objective addressed in this section seeks to determine vulnerability of the Karoo aquifers in order to develop risk factors that would lead to potential mitigate and
protect aquifer systems. In order to achieve this objective, method supporting groundwater risks associated with shale gas developments such as GMMCA Method was used in order to understand possible vulnerability that could affect shallow aquifer systems. This method took into account hydrogeological features with possible groundwater risks associated with shale gas developments.

The GMMCA Method accounts for contamination to occur hazards should migrate via pathways into the shallow aquifer systems. The hazards were identified as stray gas contamination, groundwater with salt or other dissolved constituents and contamination of groundwater from waste residue deposits and over exploitation of aquifers. Receptors were identified as aquifer storage, groundwater users and groundwater dependent ecosystems. The pathways were identified as proximity of aquifers to the prospective Whitehill Formation, aquifer connectivity, dolerite intrusions, geological pathways and wellbore induced pathways.

The study through the GMMCA method estimated hypothetical risk calculations for the receptor risk score which equalled 6664 for groundwater users in the Karoo Basin. This value was compared to the hypothetical calculation of the groundwater use in the Lower Springbok Sandstone which equalled 3773. The value of the Karoo Basin is higher than that of the Lower Springbok Sandstone due to differences in the unconventional gas of interest where the Karoo Basin potential explorations are for shale gas development, whereas the Surat and Southern Bowen Basin exploration is for coal bed methane which occurs at relatively shallower depths than shale gas that is deep seated. Findings from the risk assessment indicated that the hazard that is more likely to pose threats to the Karoo Basin is the over-exploitation of aquifers and is likely to affect all the receptors such as aquifer storage, groundwater users and groundwater dependent ecosystems. This hazard is mostly affected by minimal rainfall experienced in the Karoo region and the sole dependence of groundwater sources for their livelihoods. Minimal rainfall leading to minimal recharge in the Karoo Basin is another concern because of sole dependence on groundwater supplies for sustaining industrial and domestic water needs in the Karoo Basin. Vulnerability in the Karoo has a potential to result due to over-exploitation of aquifers.
Chapter 7 References


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