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Environmental and Water Science

Investigating groundwater governance arrangements for unconventional gas exploration and production in main Karoo Basin, South Africa

A thesis submitted in fulfilment of the requirements for the degree of Magister Scientae in the Department of Earth Sciences, University of the Western Cape, Bellville

By

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March 2016

DECLARATION

I declare that "Investigating groundwater governance arrangements for unconventional gas exploration and production in the main Karoo Basin, South Africa" is my work, that it has not been submitted before for any degree or examination in any other university, and that all sources I have used or quoted have been indicated and acknowledged as complete references.

Athenkosi Matshini

March 2016

…………………………………………….

This thesis is dedicated to my late mother Lindiswa Eunice Matshini, my late grandparents Mr. Johnson 'Skhoma' Matshini and Mrs. Nomphumelelo Lydia Matshini

Investigating groundwater governance arrangements for unconventional gas exploration and production in the main Karoo Basin, South Africa

A Matshini

KEY WORDS

Groundwater governance

Shale gas

Hydraulic fracturing

Stray-gas migration

Flowback and produced water

Water management institutions

Analytical framework

South-western Karoo

ABSTRACT

South Africa relies on coal and imported crude oil for most of its energy. The possible production of shale gas in the main Karoo Basin of South Africa provides a potential opportunity to diversify the primary energy mix. However, shale gas exploration and production is associated with environmental impacts that include potential groundwater contamination.

Protecting groundwater resources involves an effective governance regime in place to regulate such risks on groundwater resources. This study made use of a qualitative approach to investigate groundwater governance arrangements in relation to the proposed shale gas development. Further, the study developed and used an analytical framework to assess groundwater governance provisions and capacity at local level for shale gas development.

The following potential risks to groundwater from shale gas developments were identified – contamination of groundwater resources from fugitive gas (methane) originating from shale formation (i.e. stray gas migration), leakage from poorly constructed well casings and abandoned oil and gas wells. Plausible groundwater – gas interaction scenarios from the identified risks include migration through dolerite dykes, sills, natural fracture network and poor construction of well casing, abandoned oil and gas wells. However, the targeted shales for shale gas development in the Karoo is located at depths between ~4000 m southwest and ~5000 m southeast, therefore natural migration of methane from these depths is highly unlikely. Migration of methane gas to shallow aquifers in the south-western Karoo Basin will impact on water use, groundwater dependent aquifers and aquifer sustainability as groundwater is the most vital source of fresh water in the area.

The developed analytical framework for assessing government provisions and capacity shows that local groundwater institutions within the south-western Karoo

Basin lacks the knowledge and understanding of risks associated with shale gas on groundwater resources. Current water use license conditions and requirements are inadequate as they do not address shale gas development directly. This includes discharge policy, water use management, disposal of flow-back and produced water. Also, there are no mitigation measures in place to prevent pollution of groundwater resources from shale gas development.

This study recommends a goal-based regulation approach rather than a prescriptive approach, as the shale gas environment is considered innovative with new technologies being developed daily to minimize its impacts on the environment. A goal-based regulatory regime will enable review of license conditions, adaptation to new technology and promote innovation while protection groundwater resources.

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Perusing my Master degree has taught me that we do not exist in isolation and that *Umntu ngumntu ngabantu* “a person is a person because of people.”

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF BOXES

1. INTRODUCTION

1.1. RATIONALE FOR RESEARCH

South Africa depends on coal and imported crude oil to meet most of its energy demand. The energy system is highly dependent on the coal sector: it currently provides 75% of total primary energy supply, accounts for 85% of installed electricity generating capacity, the production of 92% of electricity, and around 30% of liquid fuels (through Sasol) (Burton and Winkler, 2014). This reliance on coal and other fossil fuels makes South Africa a global emitter of greenhouse gases into the atmosphere (Figure 1). Natural gas plays a small part (roughly 3%) of South Africa's total energy mix (DoE, 2013). The production of shale gas (gas trapped in deep black shales below the earth surface) would give South Africa an opportunity to lower its import dependence and strengthen its energy security. Shale gas offers a bridging fuel towards renewable energy sources and a time-window of opportunity to wean society of coal (De Wit, 2011). In pursuing such an opportunity, one needs to be mindful that shale gas is neither sustainable nor a green energy system (Pietersen et al., 2014). Although, there is a shift towards renewable energy sources, the exploration and production of shale gas seems to present a viable energy option for the future.

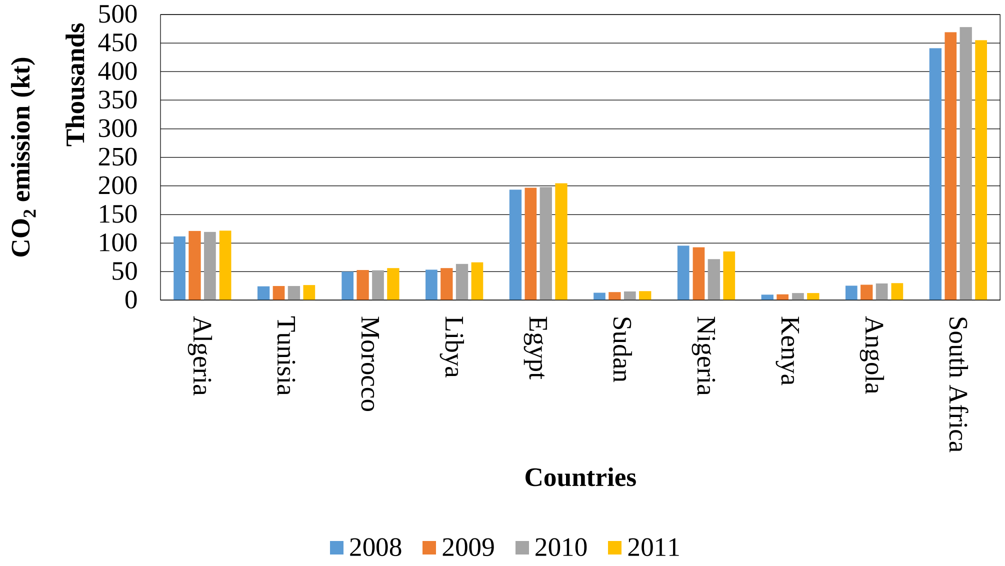

Figure 1: African carbon dioxide (CO_2) emissions

Source: World Bank, 2015.

However, there are major environmental impacts associated with shale gas developments. This includes contamination of water resources (Warner et al., 2013, Vidic et al., 2013, Vengosh et al., 2014), over-abstraction and lowering of water table in water scarce areas (Vengosh et al., 2014), air quality deterioration (Jenner and Lamadrid, 2013, Chang et al., 2012) and soil contamination (Jenner and Lamadrid, 2013). In order to counter-act the risks of shale gas development on water resources an effective regulation regime is required supported by compliance monitoring and enforcement. This study investigates groundwater institutional and governance arrangements required for shale gas exploration and production. This is necessary to support the protection of groundwater resources.

This study contributes to the formulation of robust regulations to protect groundwater resources from shale gas development. This includes understanding the existing policy, technical and regulatory frameworks dealing with shale gas resources and current international best-practices. An outcome of the research knowledge is to ensure coordination between different government departments so as to ensure integrated responses and consistent compliance monitoring and enforcement.

1.2. PROBLEM STATEMENT

Advances in hydraulic fracturing techniques have resulted in production of natural gas from shale formations deep in the subsurface. Regulating shale gas production and the associated environmental and social impacts is complex and dynamic. Therefore, the proposed use of hydraulic fracturing in the Whitehill Formation of the main Karoo Basin to extract the natural gas requires South Africa to develop its technical capacity, institutions and regulatory systems both at national and local levels. However, a study conducted by (Pietersen et al., 2012) found that at local level, governance is either inadequate, weak or non-existing. Further, studies on groundwater governance as it relates to shale gas production, worldwide, is lacking. Thus, a comprehensive gap and barrier analysis of the current groundwater governance arrangements is crucial. The focus of this thesis is on evaluation of groundwater governance provisions and institutional capacity for shale gas development at local level.

1.3. RESEARCH QUESTIONS

This study was guided by the following research questions:

(a) What is the current status of groundwater governance in the south-western Karoo Basin with regard to shale gas exploration and production?

(b) Which gaps and barriers exist within South African groundwater regulatory regime regarding shale gas exploration and production?

1.4. RESEARCH OBJECTIVES

1.4.1. Main Objective

The main objective of this research is to improve knowledge and understanding of groundwater institutions and groundwater governance arrangements in the south-western Karoo Basin that promotes groundwater protection during the proposed shale gas exploration and production.

1.4.2. Specific Objectives

Specifically, this research aims to:

- Investigate the risk factors associated with shale gas exploration and production on groundwater resources in South Africa;
- Develop plausible groundwater-gas interaction scenarios in the main Karoo Basin;
- Determine groundwater institutional and governance best-practice arrangements to promote groundwater protection; and
- Determine gaps and barriers in the South African groundwater institutional and governance system for the exploration and production of shale gas.

1.5. THESIS OUTLINE

The layout of this thesis is as follows.

Chapter 1: This chapter provides the introduction, study rationale, and objective of the study.

Chapter 2: This chapter provides a theoretical framework of the study together with the literature reviewed.

Chapter 3: This chapter presents the research design and the methodology for the study. Further, this chapter describes the study area and highlights the methods used for data collection and analysis and their limitations.

Chapter 4: This chapter displays the results from the analytical framework; provide description of results and discussion of the data collected.

Chapter 5: This section provides conclusions and recommendations of the study.

2. LITERATURE REVIEW

2.1. INTRODUCTION

This chapter provides the theoretical framework for the study by reviewing literature related to shale gas exploration and production and its potential groundwater impacts. Further, this chapter discusses the Karoo shale gas play and also the current groundwater institutional and governance arrangements relating to shale gas exploration and production.

The global financial crisis in 2008 affected all states and changed all balances causing a collapse of economic and social structures in some countries (Öztürk et al., 2013). Further, Öztürk et al., (2013) predict that the world will be hit by an energy crisis, which is defined as a great strait in energy supply in an economy. This energy crisis will be a result of annual global energy increase of about 1.6% resulting in many developing countries unable to meet its energy demands (Öztürk et al., 2013).

Most countries produce energy from fossil fuels but this has caused serious problems globally (Fyfe et al., 1993: Öztürk, et al., 2013) such as:

(a) The climate change caused by greenhouse gas emissions;
(b) The breakdown of the ozone layer and the increase in level of ultraviolet light
(c) Acid rain
(d) The decrease in biodiversity
(e) Increase in soil erosion
(f) The contamination caused by waste in industry and life styles.

The current global energy crisis has led to investigation of alternative sources of energy which produces less carbon emissions. Shale gas has gained momentum as an alternative source of energy with low carbon emissions compared to coal.

Hydraulic fracturing has advanced the production of unconventional gas in the United States (U.S.) and this has sparked a global interest, with countries such as United Kingdom (U.K) already granting licenses to explore their own natural gas reservoirs (Hays et al., 2015). Meanwhile, concerns about environmental impacts associated with shale gas development still persist (Kharak et al., 2013, Warner et al., 2013, Vengosh et al., 2014, Hays et al., 2015) among others; and therefore, regulation of shale gas production is crucial to minimize such hazards. Vengosh et al (2014) identified four potential risk factors for water resources from unconventional gas exploration and production, namely:

(a) Contamination of shallow groundwater with fugitive hydrocarbon gases,

(b) Contamination of surface water and shallow groundwater from spills, leaks from inadequately treated waste,

(c) Accumulation of metals and radioactive elements in water bodies resulting into deterioration of the quality of water in surface water bodies; and

(d) Water shortages resulting from over-exploitation of water for hydraulic fracturing mostly observed in arid and semi-arid regions that practice unconventional gas developments.

2.2. GLOBAL SHALE GAS STATUS

2.2.1. Shale characteristics

Shale is characterised as a clastic fine-grained sedimentary rock that is formed from compaction of sequential deposition of clay particles and mineral particles (Robb, 2014). The composition of shale rock places shale in a class of sedimentary rocks named as mudstones. However, shale is different from other mudstones as it compromises of multiple thin layers, and fissile, where the rock splits into thin sheets along the lamination (Robb, 2014).

Unconventional gas resource rocks are categorised as low permeable with small pores which restrict migration of oil or gas from host rock (Robb, 2014, Ratner and Tiemann, 2015). However, according to (Ratner and Tiemann, 2015), geology is what makes a resource unconventional. Unconventional formations are fine-grained, organic-rich, sedimentary rocks - usually shales and similar rocks, with the shales being both the source of and the reservoir for oil and natural gas, unlike conventional petroleum reservoirs (Geel et al., 2013; Ratner and Tiemann, 2015). Also, their definition of unconventional resources is "p*etroleum accumulations that are pervasive throughout a large area and are not significantly affected by pressure exerted by water (hydrodynamic influences); they are also called "continuous-type deposits or tight formations" of which contrast with conventional resources such as oil and gas which occur in porous and permeable sandstone and carbonate reservoirs"*. The pressure exerted by water results in migration of hydrocarbons upwards from organic sources until they reach an impermeable cap, which can be a shale formation (trapped in reservoir rock). Unconventional formations have extremely small pore spaces and thus lack of permeability resist the flow of hydrocarbons, unless natural or artificial fractures occur (Ratner and Tiemann, 2015).

One of the processes commonly used to release gas trapped within the shale formation is hydraulic fracturing. Hydraulic fracturing is a well stimulation technique used in the oil and gas industry to increase production. However, Robb (2014) argues that, before the gas can be released, the formation need to have enough gas to cause pressure that will enable it to travel through the pores that are relatively 1000 times more restrictive compared to the ones in conventional sandstone reservoirs.

Even though development of shale gas is challenging compared to conventional resources, the technology for extracting this gas has been practiced in other countries, such as U.S and their production has been increasing (from ± 1% of U.S. domestic gas production in year 2000 to 20% by year 2010) shifting the U.S to a major gas producer (Rahm, 2011). Countries such as U.K and others are currently at various stages in developing their own unconventional gas resources (Atilgan and Azapagic, 2015) with only Canada producing shale gas at commercial levels becoming the second largest producer after the U.S (U.S EIA, 2013). With the exploitation of unconventional resources expected to transform gas markets around the world, the (U.S EIA, 2013) and (McGlade et al., 2013) provided assessed estimates (Figure 2) of global technical recoverable shale gas, shows that most of the gas is concentrated in 10 countries – U.S., China, Argentina, Algeria, Canada, Mexico, Australia, South Africa, Russia and Brazil. However, according to (McGlade et al., 2013), future development of unconventional resources in these countries is subjected to multiple uncertainties.

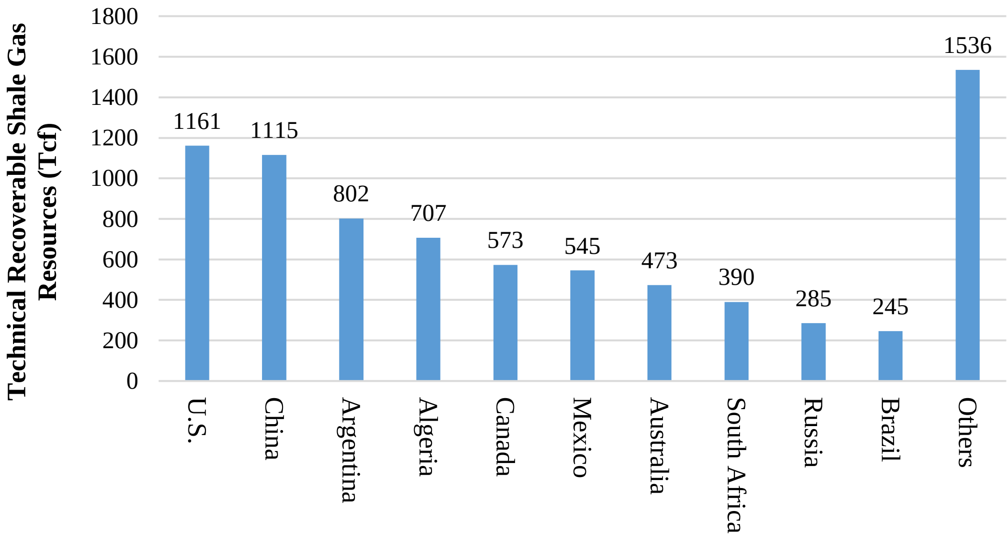

Figure 2: Assessed world shale gas

Source: Advanced Resources International, 2013.

2.2.2. United States of America

The U.S. has a significant history of natural gas production from shale formations, Robb (2014) argues that the first production well of shale gas was completed in 1821 and production has been occurring since. Technological innovation advanced the production of shale gas and the 'Halliburton1 Loophole' (Box 1) which exempted hydraulic fracturing from disclosing the chemicals and additives used in hydraulic fracturing are believed to be the drivers of acceleration in shale gas (Rahm, 2011, Jenner and Lamadrid, 2013).

Box 1 Halliburton Loophole

Since hydraulic fracturing typically introduces a mixture chemicals of which some as classified as toxic into the ground, concerns over contamination of water supplies have arisen and therefore should hydraulic fracturing be regulated by the EPA (Environmental Protection Agency established in the 1970, in part to address at the federal level, public awareness and concern over pollution and contamination of the environment) under the Safe Drinking Water Act.

But due to another federal law that was enacted in 2005, the EPA does not have the authority to regulate the underground injection of chemicals during the hydraulic fracturing process. This prohibition was a result of the provisions within the 2005 National Energy Act, commonly referred to as "Halliburton Loophole".

The Halliburton Loophole refers to legislation introduced in the 2005 Energy Policy Act (Bush/Cheney Energy Bill) that exempts hydraulic fracturing and oil and gas drilling from key federal regulations such as Safe Drinking Water Act of 1974 and the Clean Water Act of 1972. As such, the Halliburton Loophole legislation represents a significant reduction in federal oversight of drilling and fracking operations.

Halliburton Loophole exempted natural gas companies from disclosing all data related chemicals and content used during hydraulic fracturing. Further, exempts hydraulic fracturing from other state regulations when it comes to large volumes of water being abstracted from basins. This, implicated research relating to assessing impacts associated with unconventional gas on water resources, as data linking the type of additives present in the fracturing fluid were not available.

Source: *Cusolito, 2010, Hines, 2012, Schaeffer and Bernhardtand, 2014.*

There are roughly 19 geographic basins in the U.S. that serve as potential commercial sources of shale gas production (Robb, 2014). These include the Barnet Shale (in Fort Worth Basin), the Antrim shale, the Caney shale, the Marcellus shale and others located in the Appalachian Basin. Further, the Marcellus shale according to (Considine et al., 2010) has the potential to be the second largest shale gas play producer in the world, with an energy content of about 87 billion barrels of oil.

2.2.3. Australia

Australia's geology and industrial conditions according to (Advanced Resources International, 2013) resemble those of the U.S and Canada, which makes it a potential shale gas and shale oil producer. Six major sedimentary basins were assessed in Australia, which include Cooper Basin, Maryborough Basin, Perth Basin, Willston Basin, Georgia Basin among others. Further, the six basins consisted of estimated 437 Tcf technically recoverable shale gas resources (Figure 2) and that the Cooper Basin has the potential of becoming the first commercial source of shale hydrocarbons in Australia because of its existing gas processing facilities and logistics infrastructure. In addition, the Maryborough and Perth basins are considered prospective basins for shale gas exploration and production as they both contain marine shales and considered over-pressured and gas saturated (Box 2).

Box 2: Over-pressured shale

Fluid overpressure is subsurface pressures that significantly exceed the expected hydrostatic pressure (i.e. the product of the unit weight and vertical height of a fluid column) (Teige et al., 1999) Most geological formations of overpressuring relate to the following mechanism:

- Disequilibrium compaction in young and rapidly buried argillaceous sediments;
- Thermal expansion of pore fluid;
- Loss of bound water arising from the smectite - Illite transformation at depth;
- Hydrocarbons generation / maturation in kerogen – rich source rocks; and
- Tectonic compression.

As rocks and soils are vertically compressed during burial, their change in porosity (compaction) depends on the change in effective stress. Further, according to Terzaghis principle, the weight of the overlying sediments in borne partly by solid rock matric framework and partly by pore fluid (Teige et al., 1999). If the pore fluids are free to escape as overburden stresses increases (i.e.

hydrostatic loading) the rocks will compact as function of the increase in effective vertical stress. Alternatively, if pore water fluid fails to escape at a sufficient rate during burial, an increase in pore water fluid pressure will reduce the compaction process because the effectiveness stress remains low.

This is often referred to as disequilibrium compaction. Over-pressured shales develop during the generation of natural gas. Due to low permeability, much of the gas cannot escape; therefore pressure builds in the pore space, increasing the internal pressure of the rock. . Pore pressure estimates in shales are commonly based on wireline logging methods and analysis of drilling parameters, as low permeability prevent fluids from flowing fast enough into a test string to allow direct measurements to be made.

Source: Teige et al., 1999.

The Cooper Basin contains the Nappameri Trough which contains thick, over-pressure organic rich shales at prospective depths (Advanced Resources International, 2013). Further, this basin has existing service industry capacity for hydraulic fracturing and drilling. However, as the area may seem as an ideal basin for shale gas exploration and production, the shales in the basin were deposited in lacustrine environment not marine which poses a risk of clay content that is unknown in terms of behaviour if it could be hydraulic fractured. Also, elevated CO_2 volumes have been observed in deep troughs throughout the basin. However, even though the basin has risks, the three major deep troughs (Nappameri, Patchawarra and Tanappera) are considered potential regions for shale gas and shale oil exploration and production because of their depths (1,524 km southern and 3,962 km centre) and thermal maturity. Also, there are active exploration and evaluation programs studies for shale gas and shale oil in the basin by Beach Energy, Senex and DrillSearch Energy (Advanced Resources International, 2013).

2.2.4. Canada

Canada has series of large hydrocarbons basins consisting of thick, organic-rich shale (U.S EIA, 2013) . These basins where assessed by the U.S EIA, the largest concentration of shale gas resource lies within the Western Canadian Sedimentary Basin, that extends from northeast British Colombia to southwest Manitoba.

Further, other basins were the Horn River Basin, the Cordova Embayment and the Liard Basin (both located in British Colombia and the Northwest Territories), Doig Phosphate Shale in British Colombia and Alberta among others.

The U.S. EIA (2013) study, estimates the risked shale gas (is the intermediate gas volume of which its value takes into account the uncertainty associated with the relative level of geological knowledge and production history for a given country's shale gas projects) in-place for Canada to be around 2413 tcf, with 573 tcf risked, technically recoverable shale gas resource (Figure 2; Table 1). However, it is argued (U.S EIA, 2013) that, as more drilling information occurs, it will improve the accuracy of the estimates.

Table 1: Shale gas reserves of Canada

Region	Basin/Formation	Risked Resource In-place	Risked Technical Recoverable Resource
		Natural Gas (tcf)	Natural Gas (tcf)
British Columbia / Northwest Territories	Horn River (Muskwa / Otter Park)	375.7	93.9
	Horn River (Evie / Klua)	154.2	38.5
	Cordova (Muskwa / Otter Park)	81.0	20.3
	Liard (Lower Besa River	526.3	157.9
	Deep (Doig Phosphate)	100.7	25.2
	Sub-Total	1237.8	335.8
Alberta	Alberta (Banff / Exshaw)	5.1	0.3
	E/W Shale (Duvernay	482.6	113.0
	Deep Basin (Nordegg)	72.0	13.3
	N.W. Alberta (Muskwa)	141.7	31.1
	S. Alberta (Colorado)	285.6	42.8
	Sub-Total	987.1	200.5
Saskatchewan / Manitoba	Williston (Bakken)	16.0	2.2
Quebec	App. Fold Belt (Utica)	155.3	31.1
Nova Scotia	Windsor (Horton Bluff)	17.0	3.4
	Total	2413.0	572.9

Source: *U.S EIA, 2013.*

The Horn River Basin is characterized by series organic-rich shales, with the Middle Devonian age Muskwa/Otter Park and Evie/Klua being the most prominent. The above mentioned two shale formations were mapped in the Horn River Basin by (U.S EIA, 2013) to provide a prospective area with sufficient thickness and resource concentration favorable for shale gas development. However, there are other shales present within the basin, these include the high organic-content, lower thermal maturity, poorly defined Missippian Banff/Exshaw shale and the thick, low organic-content Late Devonian Fort Simpson Shale (U.S EIA, 2013).

The Middle Devonian Muskwa/Otter Park shale is the main targeted shale in the basin, with a drilling depth averaging to 2.4km for the prospective area (U.S EIA, 2013). The targeted shale is over-pressurized in the center, with an organic-rick thickness of about 120m, average total organic content (TOC) of about 3.5%, average thermal maturity (R_0) 3.5% (considered high) which puts the shale in the area under dry-gas window(U.S EIA, 2013). Further, the Muskwa/Otter shale has high quartz and low clay content with CO_2 content of about 11% in the in-place of shale gas.

The Evie/Klua Shale is the second targeted shale in the Horn River Basin because of its shale interval. Further, the Evie/Klua Shale and Muskwa/Otter shale are separated by an organically-lean rock interval. This targeted shale (Evie/Klua) has an average TOC of about 4.5%, thickness of about 49m (gross) and 44m (net), thermal maturity (R_0) of about 3.8% which is considered high and place this shale under the dry gas window (U.S EIA, 2013). While the other shales within the River Horn Basin (Upper Devonian/Lower Mississippian Banff/Exshaw Shale and the Late Devonian Fort Simpson Shale) are considered as less favorable reserves because of their TOC which is relatively 5% (Banff/Exshaw Shale) and less than 1% (Fort Simpson Shale) (U.S EIA, 2013).

2.3. HYDRAULIC FRACTURING PROCESS

Unconventional gas resources have recently been exploited using the latest advanced technologies (Robb, 2014). In recent years, the producers of unconventional gas resources have developed or further improved their technologies to enable them to produce large volumes of natural gas, by being able to hydraulic fracture even thin formations, however at higher costs. The use of horizontal drilling combined with hydraulic fracturing is one of the best technological advances that have enhanced the ability of producers to make a commercial return (Robb, 2014).

Horizontal drilling involves a process of vertical drilling to certain depth, then drilling occurs horizontal at the ‘kick-off point’ to the targeted area to access the larger portion of the gas resource (Figure 3). This process enables a number of directional well that can be drilled from one well pad to minimise environmental footprint of the whole process on the surface (Robb, 2014, API, 2010). During the process of drilling, and to its end, a series of cementing and well casing are installed on the well to prevent well from collapsing, avoid interconnection with shallow groundwater and after production well sealing. When drilling is completed with all casings installed, a perforating gun is then inserted to the targeted zone to perforate the well to prepare for hydraulic fracturing (API, 2010).

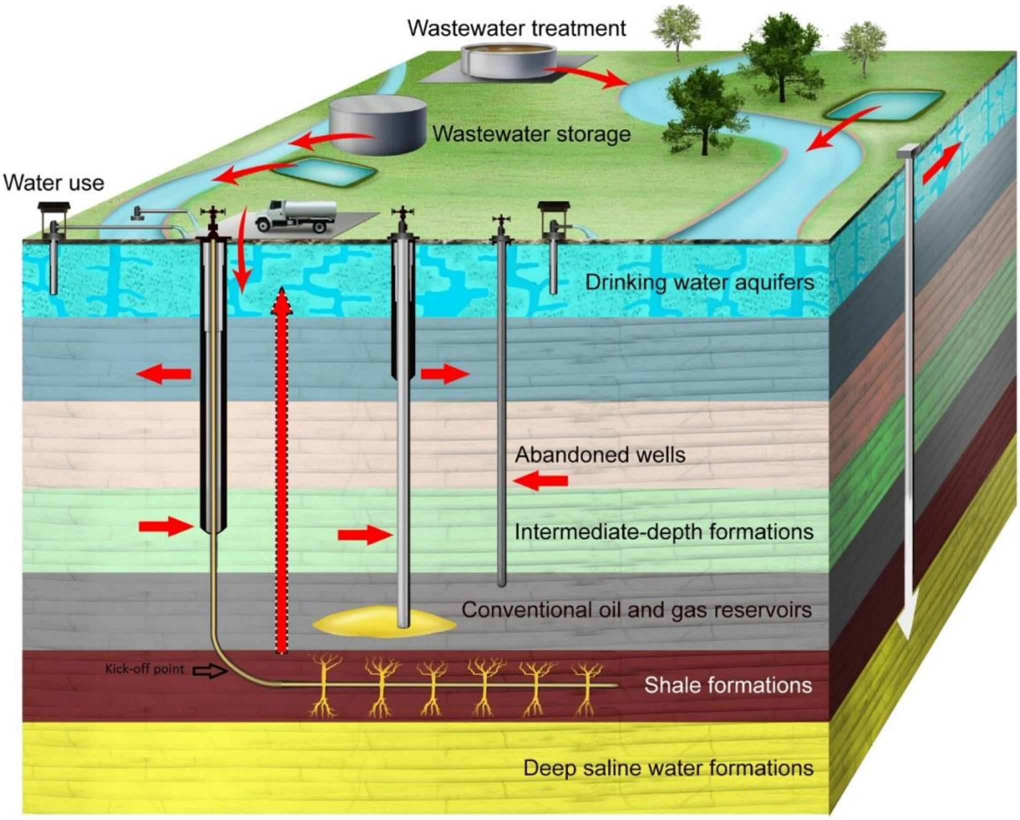

Figure 3: Hydraulic fracturing (Shale Gas well)

Source: Vengosh et al., 2014.

Hydraulic fracturing as defined in API (2010) involves injection of large pressurized volumes of water containing sand and additives below the surface to the targeted low permeability formations, to create cracks/fissures for gas migration (Steyl et al., 2012, Vermeulen, 2012). The fissures developed by the high pressured water allow the natural gas to flow from the formation, to the well and to the surface (API, 2010, Clark et al., 2013).

When the production of gas is no longer economically viable, the well head is removed and head filled with cement to prevent leakages of gas and fluids to the surface (Clark et al., 2013) and the land is rehabilitated.

Hydraulic fracturing is associated with environmental risks, which include risk to groundwater resources as highlighted in the results and discussion section (4.2). This study investigated and identified the major risks to groundwater resources from hydraulic fracturing processes as mentioned by other scholars (Vengosh et al, 2014; Pietersen et al, 2014; and Pietersen et al., 2016). The major risks to groundwater have been summarized by Pietersen et al., (2016) as:

(a) Stray gas migration;
(b) Flowback and produced water;
(c) Waste residue associated with shale gas exploration and production; and
(d) Shale gas development as a competing water demand

2.4. THE KAROO SHALE GAS PLAY

South Africa is characterised as having one of the major sedimentary basins that contains thick, organic- rich shales – the Main Karoo Basin (U.S EIA, 2013). The Main Karoo Basin covers two thirds of South Africa as it stretches 600 000 km^2 with a maximum thickness of about 5600 m^2. The lithology of the Main Karoo Basin resemble changing environment from glacial to deep marine, deltaic, fluvial and aeolian which accumulated under different climatic conditions (Johnson et al., 2006, Steyl et al., 2012). However, the Karoo basin is dominated by dolerite intrusions (Figure 4) that are thought to impact the available shale gas resources and limit the seismic imaging [making exploration difficult]. (U.S EIA, 2013). The Whitehill Formation and to a lesser extent the Prince Albert Formation of the Lower Ecca Group is the main target of shale gas exploitation.

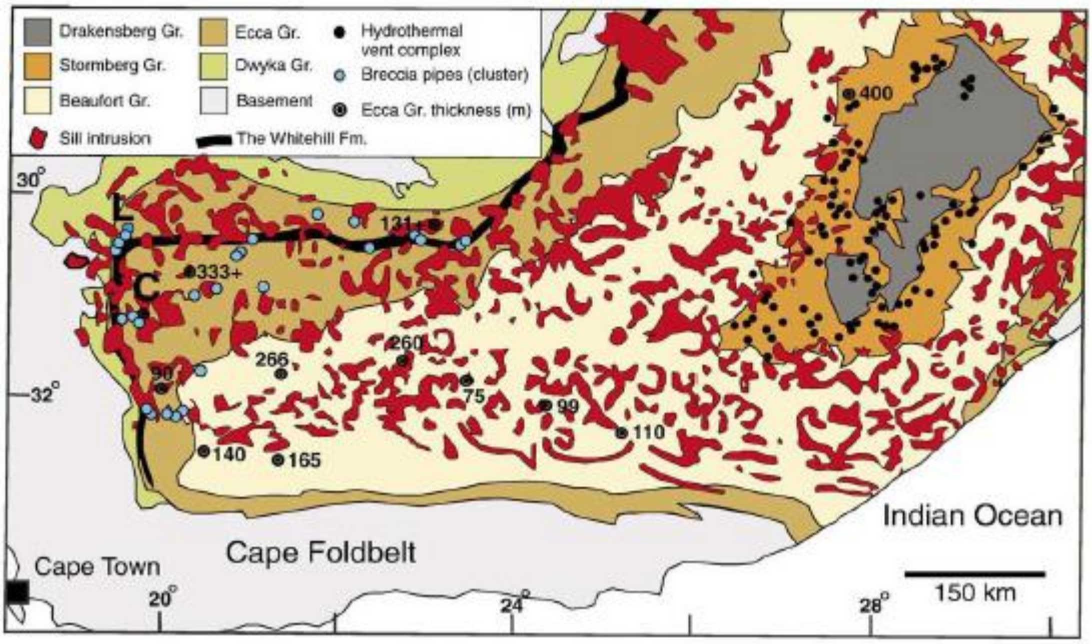

Figure 4: Igneous Intrusions in the Karoo Basin, South Africa

Source: Svensen et al., 2007.

The U.S. EIA (2013) estimated the Lower Permian –age Ecca Group to contain 1559 Tcf of risked shale gas-in-place, with 370 Tcf as the technically recoverable shale gas resource (PASA, 2013). Further, of the larger Ecca Group combined with the prospective area is estimated to contain a thickness of about 3048 m with boundaries on the east, south and west/northwest indicated by outcrops of Upper Ecca Group (U.S EIA, 2013). Also, the thermal maturity and depositional limits of the prospective area puts the Lower Ecca Group (Figure 5) under the dry-gas window (U.S EIA, 2013).

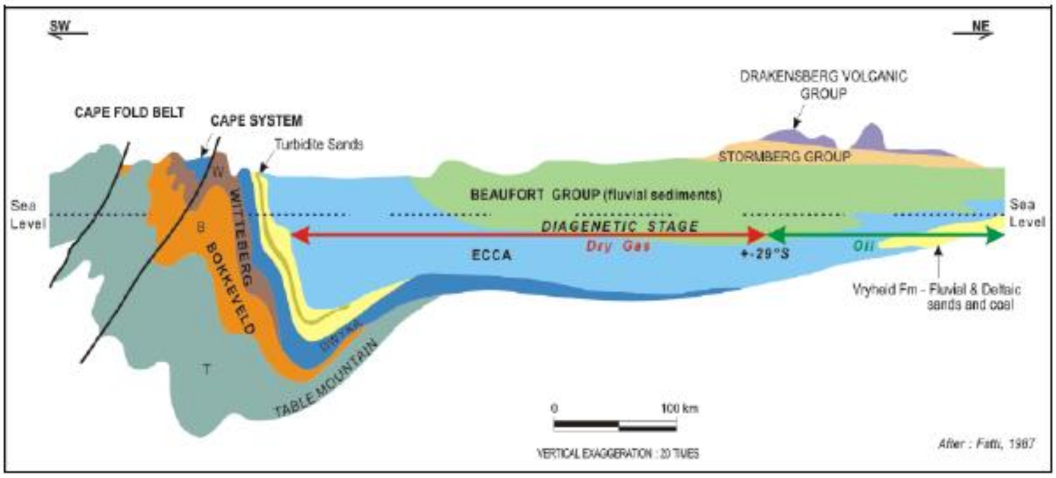

Figure 5: Schematic Cross-Section of Southern Karoo Basin and Ecca Group Shales

Source: McLachlan and Davis, 2006.

The Prince Albert Shale has a thick, thermal mature area that is favourable for shale gas exploitation. The thickness of this shale ranges from 61 m to 242 m, with averages of about 120 m, with a net organic-rich thickness of about 37 m (U.S EIA, 2013). Further, the TOC of this shale ranges between 1.5% and 5.5% (with averages of 2.5%), thermal maturity (R_0) is considered high (between 2% and 4%) because of the presence of ingenious intrusions, however this puts the shale under dry-gas window.

The Whitehill Shale is one of the main shale gas targets in the Main Karoo Basin, with an average depth to prospective target of about 2.4 km from surface (U.S EIA, 2013). The average TOC of this shale is 6%, thermal maturity (R_0) between

2% and 4% (dry gas window). Further, the main minerals within the Whitehill Formation are quartz, pyrite, calcite and chlorite, which make this shale favourable too hydraulic fracturing and a primary target of shale gas exploitation (U.S EIA, 2013).

The thickness of the overlying formations of the Ecca Group which include Tierberg formation plays a pivotal role in the upward movement of fluid hydrocarbons to shallow aquifers. The thickness of the Tierberg Formation has been argued by other scholars as having the potential to restrict any upward fluid or gas movement (Steyl et al., 2012), however other preferential pathways such as dolerite dykes, sills and faults require intensive investigation to determine their influence in upward fluid movement.

2.5. GROUNDWATER GOVERNANCE

Groundwater is regarded as a common pool resource which means effective groundwater institutional and governance arrangements are necessary to promote sustainability, equity and efficiency. However, (Seward, 2013) pointed out that in order to assess groundwater governance, a proper definition is required. Further, definition of governance is vital before defining groundwater governance. The UNDP (1997) defines governance as “The exercise of political, economic and administrative authority in the management of a nation's affairs at all levels — and thus comprises the mechanisms, processes and institutions through which the citizens of the nation articulate their interests, mediate their differences and fulfil their legal rights and obligations.” Furthermore, (Varady et al., 2012) defines groundwater governance as “*The process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom, and rule of law”*. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global (Varady et al., 2012). Understanding the issues surrounding groundwater governance is precondition for developing relevant policies and effective regulations to protect groundwater from shale gas development.

Groundwater governance is considered more complicated than surface water management because of the following characteristics (Wijnen et al., 2012):

(a) Groundwater is easily appropriated simply by capturing it ("law of capture");
(b) The fact that groundwater is not readily visible combines with well technology to allow individuals to establish de facto rights to the water under their land;
(c) There is no built-in need to cooperate within governance framework. The individual character of groundwater frees the user from constraining governance or cooperation within neighbours; and
(d) It is hard to measure the unseen resource, and it is difficult to manage what you cannot measure."

These characteristics have implications in developing effective governance structures. In some countries and state, groundwater rights belong to the land owner, which makes it difficult to assess and manage as the resource is subjected to poor management including over-abstraction.

There are several frameworks used to assess/analyse groundwater governance. The analytic framework documented in (Wijnen et al., 2012) distinguishes three parts of groundwater governance system: policy level, strategic level and the local government level (Figure 6):

(a) Setting policies: the nation sets its objectives for groundwater;
(b) Strategic level governance functions: setting up the institutions and instruments to align stakeholder behaviour and actual outcomes with policy objectives; and
(c) Local level governance: organizations and institutions that control the

actual outcomes on the ground and which respond in varying degrees to rules and incentives from a strategic governance level.

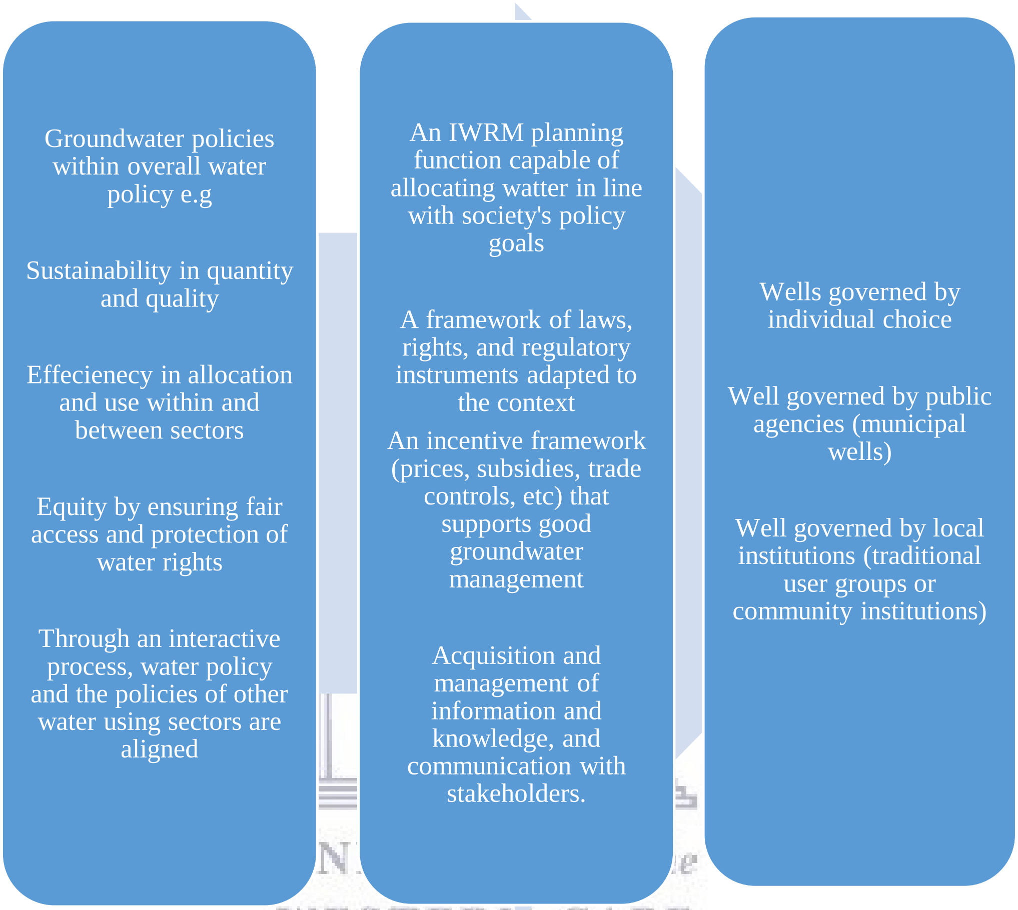

Figure 6: A framework for analyzing and assessing groundwater governance

Source: Wijnen et al., 2012.

Wijnen et al. (2012) analytical framework for analysing groundwater governance was synthesised from literature as basis of analysing and for identification of governance gaps. The analysis drew examples from both literature and detailed review of governance arrangements from five countries case studies: South Africa, Morocco, India, Kenya, and Tanzania to understand the main issues and bottlenecks for groundwater improvement. Literature underpinning the above framework involve studies and frameworks by Huntjens (2010, 2011, 2011a, 2012), Pahl-Wostl and Lebel (2010) and OECD report on Water Governance (2011).

Strengths of the framework include its flexibility to be adapted to specific country situations and its ability to highlight issues at the various levels (policy, strategic, and local) and across those levels. The framework has been developed in recognition of the variation in concepts (incentives, enforcement, etc) and tools (financial subsidies, regulation, etc) that may be applied at each level.

Wijnen et al. (2012) argue that in countries such as South Africa, India, Kenya, Morocco and Tanzania, groundwater developments and abstraction took place ahead of governance arrangements, and that resulted in exploitation and deterioration of the groundwater resource. Studies conducted by Mumma et al., (2011), Pietersen et al., (2012) showed that some of the above countries did have policy frameworks before groundwater developments commenced, but the policies were poorly enforced with those of water-use sectors, particularly agriculture. Further, formal governance arrangements were top down, some cases showed decentralization at basin level as well as some moves towards creating partnership with local collective management organization (Wijnen et al., 2012). However, the water rights and regulations of the above countries were not adapted to fast changing realities of groundwater, and information and knowledge was insufficient to support good governance with public agencies underfinanced and lacking the capacity to effectively implement.

In South Africa currently, regulations such as "Technical Regulations for Petroleum Exploration and Exploitation" (Act No.28 of 2002) have been developed and gazetted to effectively regulate shale gas developments (RSA, 2015). However, Esterhuyse et al. (2014) argue that South Africa does not have the capacity to manage shale gas exploration and production because of the various gaps that exist in the South African legislation regarding shale gas. Further, to enable effective management of unconventional gas exploration and production, it is necessary to consider issues such as (Esterhuyse, 2013):

(a) Risk factors associated with all phases of shale gas exploration not only hydraulic fracturing;

(b) The increasing impacts of shale gas development and their management;

(c) Non localisation of unconventional gas, that is, the fact that unconventional gas is not localised to specific areas necessitates the monitoring of land-use activities in conjunction with groundwater regulation (Esterhuyse et al., 2014).

Therefore, management of groundwater resources should account for the following: integrated management of the process by all departments, amendments in regulations and legislation to improve management of groundwater resources, integrated water resource management (IWRM) should be implemented among others. In addition, political will is vital to ensure management and protection of groundwater resources, also adherence with South African constitution is vital for ensuring safety and protection of groundwater resources (Esterhuyse et al., 2014).

2.5.1. International perspective on groundwater related regulations on shale gas

This section describes some of the crucial aspects that require attention for regulation of groundwater during shale gas developments, based on international practice. Water is vital during different stages (Figure 7) of shale gas developments; from drilling, exploration to production and so forth (Esterhuyse et al., 2014). Further, during exploration baseline monitoring according to Esterhuyse et al., (2014), Pietersen et al., (2014) is crucial compared to other stages; regulations on other stages include water abstraction, emergency event control, drilling and disposal of wastewater are vital. Regulations and mitigation measures for disposal of flowback is vital for prevention of water resource contamination.

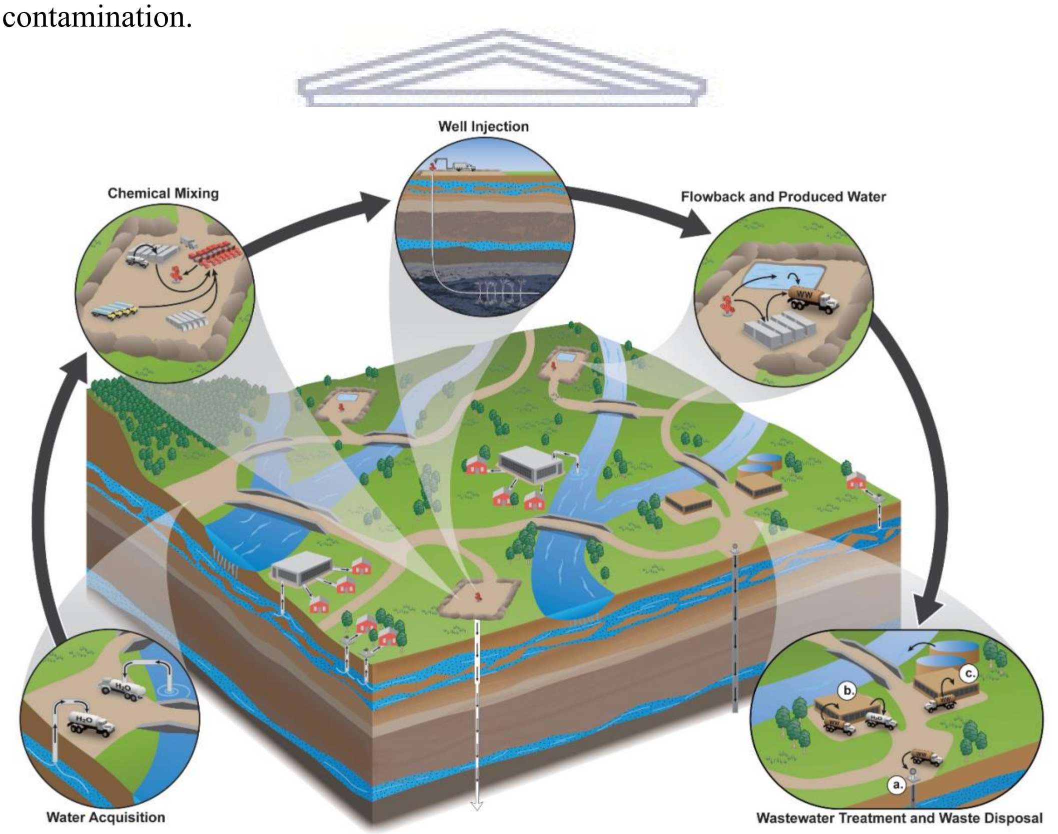

Figure 7: The stages of the hydraulic fracturing water cycle

Source: U.S EPA, 2015.

Several countries have developed regulations and legislations for governing shale gas developments. The U.S. for example has a mixture of laws, statues and regulations (federal, state, regional and local level) that often apply in petroleum and gas exploration (Rahm, 2011). The implementation of such regulations covers different phases of unconventional gas exploitation, from exploration to site rehabilitation and environmental protection. Regulations such as the Clean Water Act, Clean Air Act and Safe Drinking Act are responsible for water resource protection and National Environmental Policy Act, Resource Conservation and Recovery Act regulate environmental impacts and hazardous waste (Rahm, 2011). However, implementation of these regulations depends on the level of governance at either Federal or State Level and States regulations differ from one State to another. The major groundwater governance priorities are water quality, conflict between users and declining groundwater levels (Gerlak et al., 2013). A complicating factor is that in some states, groundwater and other minerals are privately owned

The lack of baseline monitoring prior unconventional gas developments in the U.S. has resulted into the country not being able to trace the occurrence of incidents related to shale gas on groundwater quality (GOA, 2012).

The other aspects of importance are the disposal of flowback and produced water. In the U.S and Canada, the operator is required to make use of deep injection wells. In the absence of deep injection wells operators are required to treat the produced water before disposal. The operators require permits which sets conditions such as adequate well cementing, well integrity testing and retesting of well integrity every 5 years (Rosewarne et al., 2013). Further, during the life span of the well, the operator is required to comply with monitoring requirements, which include tracking of well pressure and groundwater quality measurements.

2.5.2. Groundwater Governance in South Africa)

In South Africa prior to 1994, management of water resources was governed by 1956 Water Act which focused mostly on surface water resources (Pietersen et al., 2011a). However, the review of the 1956 Water Act and the institutional arrangements for water management guided the development of the current water legislation (Pietersen et al., 2011a). The current legislation considers water as a public resource which is subjected to national control, making the national government a custodian for the protection, management and allocation of South African water resources. South African water resources are not privately owned, instead licences are issued for water use, and the Department of Water and Sanitation (DWS) oversee that the implementation of National Water Act (RSA, 1998). The National Water Act serves as foundation of water governance in South Africa (Pietersen et al., 2012).

2.5.2.1. Regulations

The South African government has set out legislations and policies to enable protection and management of its water resources. The National Water Act (NWA) now only makes provision for one "right" to water, the Reserve, which is the water that is required for basic human needs and to maintain water ecosystem functioning. Except for the water required for this Reserve and basic human needs use, all other water uses must be authorised by the Department of Water and Sanitation or a Catchment Management Agency (CMA) (RSA, 1996, RSA, 1997, RSA, 1998). The NWA, (1998), through its regulatory instruments such as schedule 1 use, general authorisation, existing lawful use and licensed water use regulate water use of South Africa water resources.

(a) Schedule 1 water users are authorised for small volumes of water for household use only and no application for a license is required;

(b) General authorisation may be granted when large volumes of water are required for a specific type of water use or category of water use, however the users are required to register but do not need license;

(c) Existing lawful use - this allows water use that was lawfully used before the NWA came into effect to continue until it can be converted into a licence using compulsory licensing.

(d) Licensed Water Use – Licences are issued under the NWA, and require approval of an application by the Department of Water and Sanitation

The minister of water and sanitation declared "*The exploitation and or producing of onshore naturally occurring hydrocarbons that requires stimulation, including but not limited to hydraulic fracturing and or underground gasification, to extract, and any activity incidental thereto that may impact detrimentally on the water resource*" as controlled activity. Therefore, this enables the minister to regulate all activities that have a detrimental impact on water resource. Further, the operators of hydraulic fracturing will have to obtain a water use license in terms of section 21.

2.5.2.2. Institutions

The management of water resources in South Africa involves cooperation of different institutions such as the DWS and Departments of Environmental Affairs (DEA) who have the role of protection, conservation and maintenance of the ecosystems in surface water bodies. Other departments such as Department of Mineral Resources (DMR), Tourism, Energy, Health, Human Settlement have a role regulating and managing the use of both surface and groundwater resources as they are some of the major water users. As highlighted above that roles and responsibilities with management of both surface and groundwater in South Africa occurs at three different levels of governance, namely: policy level, strategic level and local governance. The DWS sets out policies and regulatory framework and the regional and local level institutions role is to implement policies and regulations (Pietersen et al., 2011b). Further, the national government developed Catchment Management Areas (CMAs) for efficient management of water resources and implementation of policies and regulations at regional/catchment level.

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2.5.2.3. Local Level

Local level groundwater governance involves management or governance of wells by individuals (well for farm irrigation, domestic water supply), wells governed by public agencies or local level state agencies such as municipalities or wells governed by local institutions (traditional user groups or community institutions (Wijnen et al., 2012). A study conducted by (Pietersen et al., 2011a) found that groundwater governance at local level is weak, pointing out that lack of funding, poor cross-sector policy, inadequate capacity within the local institutions over groundwater protection and management are among the causes for governance of the groundwater resources.

2.6. CONCLUSION

Recent global interest in shale gas has a number of reasons why shale gas is becoming increasingly favoured as an alternative source of energy in many countries with large prospective reserves. These reasons include its contribution towards a wide spectrum of the economy. However, shale gas can be considered a bridging fuel, which plays a crucial role in the energy supply. But, its capacity to reduce greenhouse emission is still uncertain. Further, when exploiting shale gas, one need to cautions that there are environmental concerns which are associated with such practice and that effective regulatory frameworks are vital in managing the operation and protecting the environment and for some countries which are still at early stages of developing shale gas resource have a chance of learning from countries such as U.S which will later improve their regulatory frameworks.

South Africa's potential to explore shale gas resource in the main Karoo Basin will improve the country's energy mix. However, the presence of some geological formations such as dolerite and sill intrusions increases the risk associated with shale gas exploration and production on groundwater resources. Therefore, extensive geological and hydrogeological studies of the Karoo Basin are crucial to mitigate such risks on groundwater resources.

In, South Africa, effective groundwater governance is still a challenge, especially at local level due to in-adequate capacity to implement necessary policy frameworks for groundwater management.

3. RESEARCH DESIGN AND METHODOLOGY

3.1. INTRODUCTION

This chapter presents the study design, sampling methods and the methods used for collecting and analysing data. A description of the study area is also provided with its hydrogeological characteristics. Further, this section provides quality assurance of the collected data, ethical clearance and presents the study limitations.

3.2. RESEARCH DESIGN

There are two primary approaches for conducting research, namely qualitative and quantitative. This study adopted the use of a qualitative approach to address the research questions and the research objectives. Qualitative research is considered as an exploratory research, which takes into account of complexity by incorporating the real-world context and often collect data that cannot be adequately expressed numerically. Further, uses reports and people's account as data. On the other hand, quantitative research relies on numerical data, variables and use of statistical analysis to explain a particular phenomenon (Tewksbury, 2009).

Qualitative research uses a naturalistic approach that seeks to understand phenomena in context – specific settings (Golafshani, 2003). This type of research approach provided better understanding of groundwater governance institutional arrangements for the proposed shale gas exploration and production in the Main Karoo Basin.

The research questions for this study cantered on the perspective and insights of groundwater governance professionals, national government departments and local groundwater management institutions regarding the proposed shale gas development, thus, a predominantly qualitative approach was the most appropriate method to provide an in-depth understanding of groundwater institutional and governance arrangements.

3.3. SAMPLING

Purposive and convenience sampling methods were chosen for this study. In adopting a purposive sampling strategy, the researcher selected the most productive sample to answer the research question (Marshall, 1996). This involved developing a framework of the variables that might influence an individual's contribution and will be based on the researcher's practical knowledge of the research area, the available literature and evidence from the study itself (Marshall, 1996). Convenience sampling is a technique used to select a sample on the bases of accessibility to the researcher, these includes attending conferences, workshops and interviews with international experts not planned.

The workshop whereby this study benefited from, consisted of a number of guest speakers, these include Department of Water and Sanitation, Duke University, Ohio State University, Water Research Commission, Petroleum Agency of South Africa, the host SLR and UWC. However, purposive sampling was used to select the "sample" to be interviewed which included: groundwater governance experts, DWS officials, the Breede-Gouritz Catchment Management Agency representatives, the Western Cape Department of Environmental and Development Planning officials, the Beaufort Local Municipality, and representatives from Beaufort West farmers union. Further, review of local and international groundwater resource regulations concerning shale gas exploration and production was considered to enable development of international best practice, gaps and barriers within the local governance regulatory regime. Convenience sampling in this study provided the researcher with an opportunity to interact with international experts in the field of groundwater and shale gas. Further, attendance of workshops and conferences meant that South African experts in the field of geohydrology and also representatives and officials from water management institutions were easily accessible for interviews in terms of time for data collection and logistics.

3.4. STUDY AREA

The study area consists of the following towns: Beaufort West, Merwewille and Leeu Gamka (Figure 8). Study site characteristics such as geology, institutions, water resources and climate are discussed in the sections that follow.

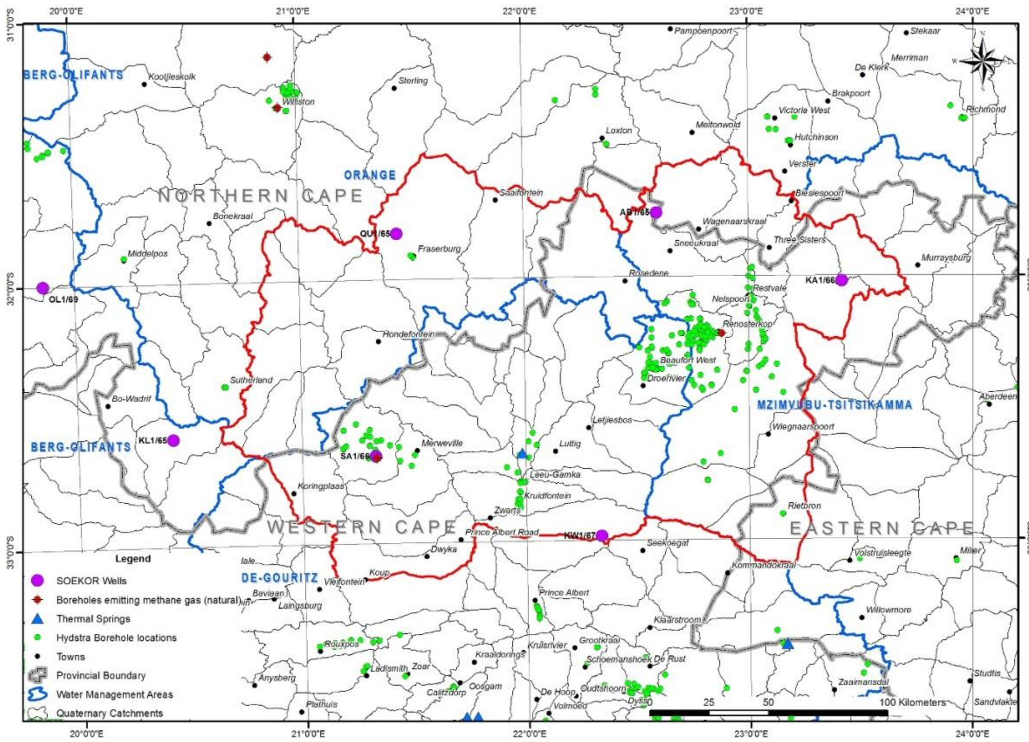

Figure 8: Study site.

3.4.1. Geology of the Karoo Basin

Source: Johnson et al., 2006.

The geology of the main Karoo basin is classified under the Karoo Supergroup, which consist of sedimentary rocks and igneous rocks. The Karoo Supergroup consist of the following geological groups; Drakensberg and Lebombo, Molteno, Elliot and Clarens, Beaufort, Ecca and Dwyka (Table 2). The Beaufort Group has two subgroups namely Tarkastad and Adelaide (Johnson et al., 2006). However, the chosen study area located on the south western Karoo is dominated by Dwyka, Ecca and Beaufort Groups (Figure 9) and the thickness of Karoo formation varies between 2 035 and 5 288 m (Woodford and Chevallier, 2002) . Furthermore, the sedimentary rocks of the Beaufort Group include shales, sandstones, siltstones and mudstones (Adams et al., 2001).

Table 2: Stratigraphy of the Karoo Supergroup

Supergroup	**Group**	**Formation**
Karoo Supergroup	Beaufort Group	Teekloof formation
		Abrahamskraal formation
	Ecca Group	Waterford formation
		Fort Brown formation
		Laingsburg formation
		Vischkuil formation
		Collingham formation
		Whitehill formation
		Prince Albert formation
	Dwyka Group	Dwyka Group

Source: Johnson et al., 2006.

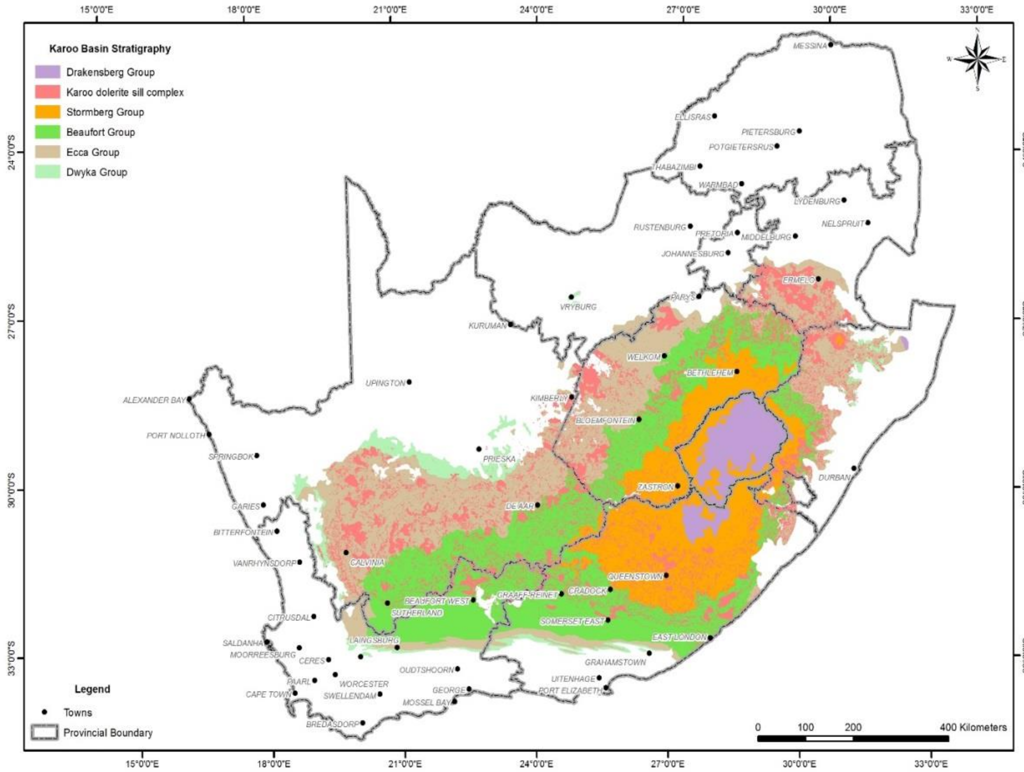

Figure 9: Karoo Supergroup dominating the study area

3.4.1.1. Dwyka Group

The Dwyka Group was formed in the Late Carboniferous to Early Permian, which rest on glaciated Precambrian bedrock on the northern basin margin, but lies on top of the Cape Supergroup (in the south) and Natal Group (in the east) (Johnson et al., 2006). A variety of lithofacies have been observed in the Dwyka Group, namely massive diamictite, stratified diamictite, massive carbonate-rich diamictite, conglomerate, sandstone, mudrock and mudrock with stones. The massive diamictite facies consist of clast-rich but also clast-poor in the north from the bedrock. While, the stratified diamictite facies contains fast changing diamictite, mudrock, sandstone and conglomerate beds (Johnson et al., 2006). Furthermore, the massive carbonate-rich diamictite facies is considered clast-poor contains small angular stones irregular carbonate rock which indicate that they've been formed by rain-out of debris, and the conglomerate facies contains layers boulder beds (single or double). The sandstone facies consist of fine-grained to coarse grained, immature sandstones. However, mudrock with stones facies varies from well-laminated mudrocks to massive boulder mudstones, of which indicates rain-out deposits in the distal iceberg zone. The mudrock facies contains dark-coloured, carbonaceous mudstone and shale.

Thickness of the rock and total organic content are considered for exploration and production, however, due to recent innovation on the unconventional gas industry it is now possible to extract gas from rocks which are 10m thick. Furthermore, for gas producing wells the average total organic carbon ranges between 3 and 12 percent. The Dwyka according to (Steyl and van Tonder, 2013) has an average of 1.9 percent organic carbon which is below the standard of producing wells and the shales in this group are thin and unevenly distributed according to the data collected on 45 sampled wells.

3.4.1.2. Ecca Group

The Ecca Group compromises of 16 formations. This study discusses the Prince Albert and Whitehill formations as these are the formations most likely contain shale gas. These formations have been classified by the (Advanced Resources International, 2013) as having the potential of being gas reserves. The total organic content found in these two formations matches the those found in unconventional gas producing formations (Steyl et al., 2012). However, according to (Steyl et al., 2012) studies which were conducted in the Ecca Group discovered limited gas present in tight shales at the depth of 2000 m to 4000 m below the surface. Furthermore, the lower Ecca Group consist of dark shales of the Prince Albert Formation which overlays the black, organic-rich shale of the Whitehill Formation.

3.4.1.3. Prince Albert Formation

The Prince Albert Formation is found on the south-western half of the Karoo Basin. The northern facies of these formations is easily distinguishable from the southern facies as it is characterised by the majority of greyish to olive-green micaceous shale and grey silty shale. Also, it contains the dark-grey to black carbonaceous shale. The southern facies is characterised by dark-grey, pyrite-bearing, splintery shale (Johnson et al., 2006).

The Prince Albert Formation is considered to be confined on the south-western part of the Karoo Basin. This formation is thin in the north-east and combines with Pietermaritzburg Formation (Dennis et al., 2013). In addition, the formation thickens on the south-western varying between 40 and 150m. Northern facies of this formation are characterised by micaceous shales and grey and silt shale, also dark grey to black carbonaceous shales are observed. In addition, south facies are characterised by pyrite-bearing, dark grey, splintery shale, siltstone and dark coloured chert is also observed (Dennis et al., 2013).

3.4.1.4. Whitehill Formation

The Whitehill formation according to (Dennis et al., 2013) compromises of white, weathered mudrocks, while the black, carbonaceous, pyrite-bearing shale are the predominant facies observed in fresh outcrops and subsurface, contains up to 17% total organic carbon (Steyl et al., 2012, Steyl and van Tonder, 2013). The shales in this formation indicate deposition from suspension settling. However, the lithological character of this formation is lost towards the north together with lower part which contains the siltstone and very fine-grained sandstones (Dennis et al., 2013). The thickness of this formation ranges between 10 to 80 m. According to (Branch et al., 2007), the C_{org} content is generally 3% higher in the south compared to the north due to gasification effect of dolerite dykes in the north.

3.4.1.5. Beaufort Group

The Beaufort Group contains the lower Adelaide Subgroup and upper Tarkastad Subgroup. However, this study will only discuss the lower Adelaide Subgroup because of its presence in the study area (Figure 3). Further, Johnson et al (2006) argue that the Adelaide Subgroup in the southeastern consists of the Koonap, Middleton and Balfour Formations while the west there's Abrahamskraal and Teekloof Formations. The Abrahamskraal Formation in Sutherland according to Adams et al. (2011) is estimated to be 1000 m in terms of thickness with ridges of the Teekloof Formation observed in the north. Further, basaltic dolerites intrusion is observed from east to west and Jurassic sills resulting into fractures in the sedimentary rocks.

The targeted shale formation for natural exploration and production belongs to the Ecca Group – Whitehill Formation and located at depth of about 4000 m in the southwest Karoo and ~5000 m in the southeast (Scheiber-Enslin et al., 2015). Plausible groundwater – gas interaction within the area are likely to be influenced by dolerite intrusions, dykes and sills as they have the potential to act as conduits for groundwater (Van Tonder, 2013). However, several scholars Davies et al. (2012) and Jackson et al. (2013) have linked migration of stray gas from deep buried to shallow groundwater by leaking well casings or migration along the well annuls.

3.4.2. Climate (rainfall, temperature)

Rainfall in South Africa is unevenly distributed; the country contains areas that receive high rainfall which include KwaZulu Natal, areas receiving winter rainfall with Mediterranean climate (Western Cape), and the arid region which the main Karoo Basin belongs. The Karoo basin is considered as arid to semi-arid region of South Africa; typically the western Karoo region receives about 300-400 mm of rainfall per annum (Adams et al., 2001). Low amounts of rainfall combined with high temperatures results in high evapotranspiration in the area of which in the south western Karoo the evaporation rates are estimated to be between 1800 and 2000 mm per annum. The average annual rainfall according to (Adams et al., 2001) decreases from westwards, approximately from 500mm in the east to <100mm over the north-western areas. In addition, the major parts as described by (Adams et al., 2001) in the south-western Karoo receive summer rainfall, between October and March. Most towns in the Karoo Basin experiences drought conditions due to variability in rainfall and high evapotranspiration.

The south-western Karoo Basin is considered as an arid region with low rainfall and high evapotranspiration resulting in limited surface water resources.

3.4.3. Surface water

The Main Karoo basin consists of limited surface water resources of which resulted into the utilization of groundwater, especially in rural areas in the Karoo. Most of the rivers that drain the south western Karoo are non-perennial rivers which only drains during rainfall periods (Adams et al., 2001) , but in the upper part of the Karoo the major drainage features are the Orange River and its perennial tributaries, the Vaal and Caledon Rivers (Dennis et al., 2013, Adams et al., 2001). The river flow is highest in the east due to increased rainfall in these areas. Other drainage is mostly peripheral, with the high-gradient Rivers flowing from the escarpment to the coast. In the central and western Karoo Basin the rivers are mainly ephemeral, flowing only for short periods of time following heavy rainfall. A number of perennial easterly draining rivers occur along the eastern edge of the basin (Dennis et al., 2013). Furthermore, farmers in the main Karoo basin mostly dam these non-perennial rivers for irrigation and for stock.

The study area is dominated by the Gamka river which consist of three main tributaries, namely the Dwyka, Koekemoers and Leeuw which rise from the Great Karoo, converge and flow south through Swartberg Mountain (RHP, 2007). The Gamka River later joins the Olifants River south of Calitzdorp, and together they form the Gouritz River. The area has limited supply of water and the water is characterized by high salinity, therefore, the area has strong reliance of groundwater for domestic and agricultural supply.

Shallow groundwater is the most vital source of potable water in the main Karoo Basin, however, the Central Karoo utilizes both groundwater and surface water to meet its annual water demands. According to (Western Cape Provincial Treasury, 2007) the area is supported by four dams (Floriskraal, Leeu Gamka, Oukloof and Gamkapoort dam) of which from the data collected by Department of Water Affairs, there has been a major decline in volume of water stored in these dams between October 2007 and October 2015 (Table 3). The Floriskraal Dam supports the Little Karoo's needs, Leeu Gamka and Oukloof Dams supports local farming in Laingsburg and Prince Albert, and Gamkapoort supports the remaining areas in the District Municipality.

Table 3: State of dams in the Central Karoo District in 2007 vs. 2015

Dam Name	**Full storage capacity (million cubic metres)**	**(%) 1 October 2007**	**Full Supply Capacity**	**Water in Dam 10^6 m^3**	**2015-10-12 % Full**
Floriskraal dam	50.3	58.5	48.266	19.282	39.9
Gamkapoort dam	32.7	23.8	36.234	10.900	30.1
Leeugamka dam	14.0	0.9	13.584	0.225	1.7
Oukloof dam	4.2	58.2	4.190	3.061	73.0

Source: DWAF in Western Cape Provincial Treasury, 2007; DWS in Weekly state of reservoirs on 2015-10-12

3.4.4. Land use

The Main Karoo basin ranges from arid to semi-arid. The Karoo is divided into the Little Karoo and Great Karoo, the Great Karoo is classified as semi-desert with generally poor grassland for cattle farming, but generally good for sheep farming. Vegetation in the Karoo basin has been deteriorating for the past 200 years according to (Dean et al., 1995), and according to (Kraaij and Milton, 2006) rainfall variation, changes in land use and wild herbivores are responsible for the cause. The Karoo according to (Dean et al., 1995) is characterised by dwarf shrubs spread across the gently slope plateau of the Karoo Basin. However, it is divided into winter-rainfall Succulent-Karoo biome and summer-rainfall Nama-Karoo biome. The southern, south-western and western parts of the Karoo are dominated by succulent shrubs (Aizoaceae), other parts are dominated by short deciduous shrubs.

3.4.5. Groundwater

In general, the Permian sandstones and mudstones serve as major reservoirs of groundwater in the area, also the Jurassic dolerite dykes and sills (Adams et al., 2001). Fractures and joints govern the occurrence and movement of groundwater in the area. The main Karoo Basin is associated with dolerites intrusions, sills system and other major joints such as the Cape Orogeny, these systems are classified as groundwater target zones due to secondary permeability (Adams et al., 2001).

The Karoo fractured-rock aquifer are characterised by their unpredicted behaviour in terms of groundwater properties, Usher et al. (2006) states that most wells drilled in the Karoo basin have low borehole-yields, some within even <1 *l/s*. However, aquifers in the south and north-east of Beaufort West indicate high yielding boreholes (Western Cape Government, 2011). The aquifer system of Beaufort West according to (Solomon, 2013) has been documented by other authors, including Kotze et al., 1997; Rose and Conrad, 2007; Nhleko and Ndodo, 2008). Beaufort West aquifer system according to Nhleko and Ndodo (2008) is divided into relatively few systems: the top aquifer which stretches to depth of 10m, and is characterised by weather intergranular material that consist of sandstone, mudstone, siltstone and dolerite; the middle fractured-rock aquifer which occurs at depth of about 50m and below and is characterised by thick mudstones and sandstones that are linked to dolerite intrusions. Further, the middle fractured-rock aquifer system is considered having high transmissivity values due to large fractures present in the geology that are associated with dolerite intrusions. Also, the top aquifer system is recharged directly from precipitation and surface water bodies such rivers and pans, while recharge in the middle fracture-rock aquifer is along bedding planes and infiltration of surface run-off which occurs at slower rates.

Rose (2008) in (Solomon, 2013) describes the relationship between high values transmissivity and borehole yield, pointing out that borehole production yield is highly correlated with transmissivity. The table below provides a summary of transmissivity and storativity values of farms located within Beaufort West (Table 4). In addition, Kotze et al., (1997) in (Solomon, 2013) argues that boreholes drilled in a close proximity of dolerite dykes tends to produce high yields as these geological formations have the potential to have high storativity.

Table 4: Summary of transmissivity and storativity values in farms within Beaufort West

Sub-area	Transmissivity (T in m2/day)	Storativity (S dimensionless)
Brandwag east	>200	0.01 - 0.001
Brandwag west	<200	0.0001 - 0.00001
De Hoop	30 – 300	0.001 - 0.00001
Platdoorns Form	<10 to >200	0.00001
Lemoenfontein	100 – 250	0.0001-0.00001
Town well	From 40 to >400	0.001 - 0.0001
Droerivier	<10	0.001 - 0.0001
Hansrivier	>300	0.001 - 0.0001
Sunnyside	100 – 360	0.00001 - 0.000001

Source: Solomon, 2013.

Groundwater interaction between deep and shallow aquifers in the main Karoo Basin has been observed from the geothermal gradient in the thermal hot spring of the Karoo basin. However, in the selected study area there are limited studies regarding deep aquifer flow dynamics. Furthermore, exploration conducted by Soekor in the upper Karoo basin, attempted to fill the gap on knowledge of deep aquifers (>300 m), the study concluded that dolerite dykes can extend few kilometres down, and that hydraulic conductivity (K) along the dyke contact zones vary with depth (Rowsell and De Swardt, 1976).

3.4.6. General Water quality of the main Karoo Basin

Study conducted by the Karoo Groundwater Expert Group (KGEG) shows the water quality improving from west to east, and also from south to north in the eastern Karoo (KGEG, 2012). Groundwater salinity and age increases with depth, generally due to low hydraulic conductivity, longer residence time, gravity (which allows increased dissolution of constituent minerals in the host rocks, stagnation and possible incorporation of connate water) (KGEG, 2013). However, in contrast, the two thermal springs in the Karoo are found to be originating from deeper depths (more than 1000m) from the earth surface show no salinity as the spring in Aliwal North contains total dissolve solids of 1200 mg/*l* (KGEG, 2013).

3.4.7. Water management institutions

There are several institutions which are responsible for implementing integrated water resource management (IWRM) and enforcing effective groundwater governance. , The national Department of Water Affairs and Sanitation are at the forefront of protecting and management all water resources in the country.

3.4.7.1. The Department of Water and Sanitation

The DWS through the NWA (Act of 2008) act the custodian of all waters of South Africa with a responsibility to manage, protect and conserve South African Water resources. The DWS is primarily responsible for developing and implementation of regulations, policies and strategies governing the water sector. Further, DWS has an overriding responsibility for water services provided by local government.

3.4.7.2. The Breede - Gouritz CMA

The Breede - Gouritz Water Management Area (WMA) is situated along the southern coast of South Africa and extends inland across the Little Karoo and into the Great Karoo (Figure 10). The WMA is the resulting of merging of the Breede WMA and the Gouritz WMA. The new WMA is bounded by the Indian Ocean to the south, what will be the Berg-Olifants WMA to west, the Orange WMA to the north and the Mzimvubu-Tsitsikama WMA to the East. (Figure 10).

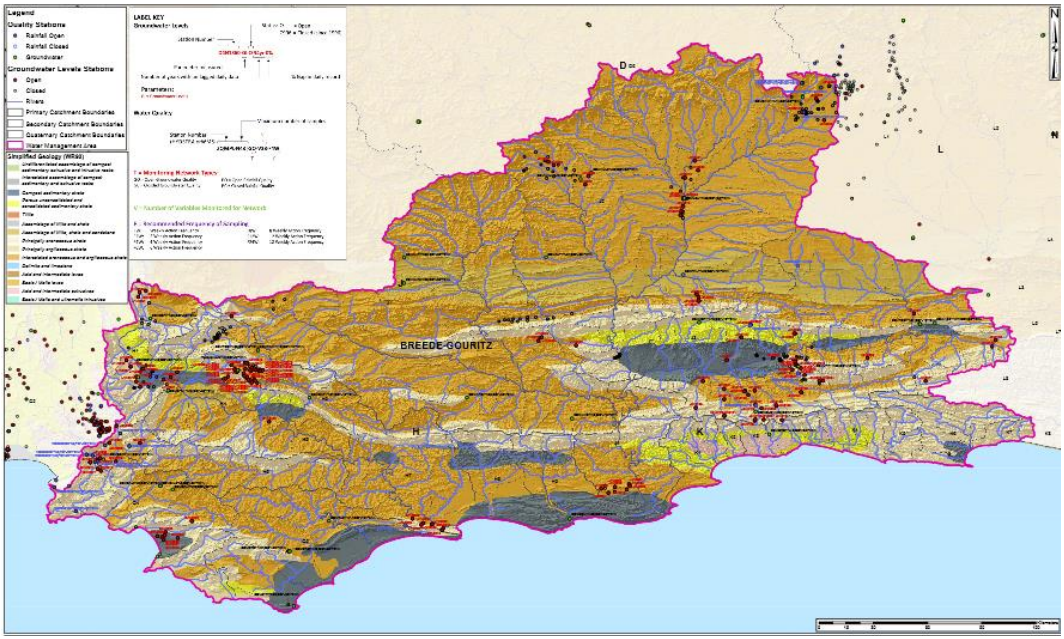

Figure 10: The Breede - Gouritz WMA (AECOM, 2015)

The Breede-Gouritz CMA roles and responsibilities include protecting, developing, conserving, managing and controlling water resources, while coordinating with national government and sector partners. The strategic focus of the CMA incorporates water resource planning, water use, management, institutional development, water resource protection, and water allocation reform. Further, the agency works closely with local government on water management and water-related services, also responsible for stakeholder engagement and maintaining and improving intergovernmental relations. One of the agency roles includes processing and maintaining water registrations and license applications.

3.4.7.3. The Beaufort West and Prince Albert Local Municipalities

The three towns considered in the study falls under two local municipalities – Beaufort West and Prince Albert Local Municipality. Both, these local municipalities are water service providers and water service authority within the area. The Beaufort West local municipality is responsible for providing the two towns: Beaufort West and Merweville with bulk water supply, while Prince Albert local municipality is responsible for the Leeu Gamka.

3.4.8. Oil and Gas

The northern part of the Karoo basin is known for economic oil shows, even though two small oil shows were observed in the Dannhauser and southeast of Wakkerstroom, but they were considered uneconomic (Johnson et al., 2006). Exploration studies conducted by Soekor in the Karoo basin between 1960s and 1970s discovered that only rocks located in the north of latitude 28^0S were under diagenesis and be regarded as oil reserves, excluding those which experienced dolerite intrusion. (Johnson et al., 2006) believes that, this was because the best oil shows were discovered in the upper part of Vryheid Formation and shales of this unit were probably the source. But, the primary porosity and permeability of the sandstones of Vryheid Formation were generally poor. Further, (Johnson et al., 2006) describe the intrusion of dolerite as the catalyst for conversion of oil to gas in the Karoo basin.

According to (Steyl et al., 2012) natural occurrence of gas has been reported by some studies (Rowsell and Connan, 1979) in the Karoo basin from data collected in boreholes drilled by Soekor. Gas analysis conducted on these boreholes revealed fluctuating gas quantities from the boreholes drilled on the Ecca Group shale (Steyl et al., 2012). Only the lower Ecca Group shales have dry gas with a total organic carbon that is comparable with the Marcellus shale (Steyl et al., 2012). The upper Ecca Group specifically the Tierberg Formation has a relatively low average total organic carbon (1.2%) which is lower compared to global producing shales (3 – 12%) and therefore not a viable source of shale gas.

3.5. DATA COLLECTION METHODS

Several methods are often used when investigating groundwater governance and institutional arrangements. Some of these methods include review of policies, legal and institutional frameworks, reports and peer reviewed articles (Pietersen et al., 2011a), also interviews of relevant stakeholders. This study made use of the following methods when addressing the research questions: interviews, reports review and field visits to collects primary and secondary data. The interviews were used to provide in-depth understanding of the processes involved in groundwater governance, institutional arrangements, and the current status of groundwater governance in relation to the proposed shale gas development.

3.5.1. Interviews

This study conducted interviews with relevant stakeholders and institutions involved in groundwater governance at local level in the south-western Karoo Basin. These include the Department of Water of Sanitation, and Beaufort West Local Municipality, Breede-Gouritz CMA, DEADP, and Beaufort West Farmers Union. The interviews conducted in this study were in-depth interview as the topic around shale gas exploration and production in the Main Karoo Basin is considered as a sensitive subject.

In-depth interviewing is a qualitative research approach that involves conducting intensive individual interviews with a small number of respondents to explore their perspectives on a particular program, research field, and situation among others (Boyce and Neale, 2006). These interviews are optimal for collecting data on individuals' personal histories, perspectives, and experiences, particularly when sensitive topics are being explored. Further, an in-depth interview is an open-ended, discovery-oriented method that is well suited for describing both program processes and outcomes from the perspective of the target audience or key stakeholder, and the end goal of the interview is too deeply explore the respondent's point of view, feelings and perspectives.

In-depth interviews mostly achieve high response rate, of which all the data is directly from the respondents. Further, it allows follow up when the interviewer is not satisfied with the response and still requires clarity, allows more detail questions to be asked and in many cases and provides an overview perspective of the respondent's regarding a subject matter. However, this method is subject to its own disadvantages, such as accuracy, reliability of data and cooperation of some parties. Furthermore, it is prone to bias and is considered time consuming, respondents tend to subjective and costly when not properly planned as they involve several steps such as; time for conducting interview, transcribing responses and analysing data collected (Boyce and Neale, 2006).

In-depth interviews involve not only asking questions, but the systematic recording and documenting of responses coupled with intense probing for deeper meaning and understanding of the responses. Thus, in-depth interviewing often requires repeated interview sessions with the target audience. Unlike focus group interviews, in-depth interviews occur with one individual at a time, or sometimes pairs of respondents, to provide a more involving experience.

Relevant institutions such as Department of Water Affairs, Beaufort West Municipality, Breede-Overberg Catchment Management Agency (BOCMA) the Western Cape Government Department of Environmental Affairs and others were contacted to set up a date and time which they will voluntary agree to be interviewed about the subject matter of this study. Further, these interviews were conducted from the following institutions, namely Beaufort West Local Municipality, Beaufort West Farmers Union and the Breede - Gouritz CMA and the Western Cape EADP. Interviews followed a well prepared format that also enabled the interviewee to ask questions. Some questions were prepared in advance according to the developed framework (3.7) and in relation with the study research questions. Further, individual responses were recorded with individual's permission and later transcribed to assist with the analysis for the analytical framework.

Interviews with Western Cape EADP; this was done to identify the role and responsibility of the department on groundwater governance and protection within the Western Cape. This interview followed a formal focus group interview that involve interviewer asking questions and capture respondents. However, respondents were allowed to have a dialogue and ask more questions and request more clarity. Further, responses were recorded with interviewee's permission, and then later transcribed for analysis.

3.5.2. Document Review

Existing records often provide insights into a setting and/or group of people that cannot be observed or noted in another way. Document review is a qualitative method that gathers data by reviewing already existing documents, which can be peer reviewed journal papers, reports, minutes and so forth with an intention of collecting independently verified data and information (CDC, 2009). This method in this study is used to establish gaps that exist within the South African regulatory framework when compared to other countries.

This study made use of this method as currently, there is limited to no data available concerning groundwater governance in relation to shale gas developments in South Africa. Further, this method was used to review international and local policies and regulations regarding groundwater governance in relation to shale gas.

The document review method is however subject to its own advantages and disadvantages, less time consuming as it uses data from available literature to draw new conclusion and provide recommendation for future research as some studies have been conducted in some other parts of the world. However, this method in many cases contains data that is not reliable, unfinished documents, altered documents, lack accuracy and information drawn from other areas may not work in other environments, such as adopting regulations which are used in the U.S may not be effective in the main Karoo Basin, South Africa. To overcome such, data collected from this study was derived from peer revived articles, published reports, and government reports.

3.6. DATA ANALYSIS METHOD

To achieve the study objectives with the data collected above, the following data analysis methods were used.

3.6.1. Daily Interpretive Analysis and Thematic Analysis

Daily Interpretive Analysis (DIA) is one of the analysis methods used in this study. This method allows review and analysis of interviews on daily basis, records and notes were used to produce reports. However, this method becomes adequate when the interviewer takes recording and notes at the same time. Thematic Analysis on the other hand works with themes from the transcribed interviews where the interview selects themes which form patterns for analysis. (Braun and Clarke, 2006) define thematic analysis as "*identifying, analysing and reporting patterns (themes) within data. It minimally organises and describes your data set in (rich) detail.*"

3.6.1.1. Strength and Weaknesses

These approaches have their own advantages and disadvantages. One of the disadvantages is that it is time consuming, but its advantage is that the DIA can contain direct quotes from the person interviewed and this approach allows comparative responses between respondents and therefore, in this study enabled establishment of common practice gas exploration and production.

3.6.1.2. Procedure

The recordings and notes from the interview were reviewed, and then transcribed parts of the interview which were considered missing from the notes to produce tangible responses. Further, daily summaries and reports were produced from the material collected on that particular day. However, thematic analysis involves three stages which begin with transcription of the whole interview line-by-line, then organise the line-by-line codes into related areas to produce themes, then lastly development of analytical themes.

The transcripts of the interviews were reviewed line-by-line. Then, codes were established in relation to the data required for the framework analysis (Table 5). The selected codes were grouped into categories or themes to provide a better understanding of groundwater governance institutional arrangements. The developed themes were then later grouped into four capacity categories - technical, legal and institutional, cross-sector policy coordination and operational.

3.6.1.3. Motivation

One of the functions of the DIA is to document insight, or preliminary conclusions, that the interviewer might have while listening to a respondent. The tapes and notes are analysed to show the dynamic interrelatedness of the various pieces of information that the respondent presents. The respondent's discussion is therefore much more than a collection of "reality reports," that simply require the interviewer to list. While concrete informational items are critically important, so to list the ways in which the respondent assembles aspects of his/her reality. Thematic analysis enables determination of themes from different respondent's transcripts. Therefore, themes enable analysis of how respondents respond to questions, their perception regarding the subject matter.

3.7. Document and Content Analysis

Document analysis is defined by Bowen (2009) as a systematic process for reviewing or evaluating documents, and the object of content analysis can be all sort of recorded communication (such as transcripts of interviews, discourse, published and non-published reports). This method requires data to be examined and interpreted in order to gain knowledge and meaning to develop empirical knowledge. Further, document and content analysis are considered similar to how interview transcripts are analysed as it allows development of codes which are then translated into themes to enable analysis.

3.7.1.1. Procedure

The analytic procedure includes finding, selecting, making sense of the data and processing data that is contained in the document. Themes and categories for this study were developed in relation with the objectives to be achieved through content analysis (Bowen, 2009), of which included risks factors associated with shale, plausible groundwater-gas scenarios and the developed analytical framework for groundwater governance (Table 5).

3.7.1.2. Tools

There are three primary types of documents, namely public records (annual reports, policy manuals, student transcripts among others), personal documents (newspapers, calendars, e-mails) and physical evidence (flyers, posters, agendas among others). Further, documents for systematic review include journal articles, minutes of meetings, background papers, books and public records. However, this study used scientific journal articles, government reports and national legislation relating to groundwater management and protection.

3.7.1.3. Motivation

Document Analysis in many studies is combined with other qualitative research methods as means of triangulation. Further, the method is time efficient as it does not require data collection but data selection and most documents such as policies journal articles are available in the public domain.

3.8. ANALYTICAL FRAMEWORK FOR GROUNDWATER GOVERNANCE

There are several well established and well regarded analytical frameworks that exist for water. The European Union (Water directive) and the Organization for Economic Co-operation and Development (OECD) have developed holistic frameworks for water; however, even though the developed frameworks included provisions for groundwater through Integrated Water Resource Management (IWRM) principles, they lack adequate details for addressing specific groundwater governance requirements (Wijnen et al., 2012). Hence, the development of groundwater-specific analytical framework to measure groundwater governance at local level is critical. Analytical frameworks according to Knüppe and Pahl-Wostl (2011) are used to provide analysis of complex governance regimes and linkages between management and corresponding effects on the ecosystem. Further, analytical frameworks provide "better" understanding of how arrangements for water governance are shaped and they are mostly generated by insights from empirical data and current thinking about water governance(Franks and Cleaver, 2007). The analytical framework in this study follows the work of Foster et al. (2010), Pietersen et al. (2011a), Moench et al. (2012), Wijnen et al. (2012) figure 6 and Pietersen et al. (2016) for local level governance. The emphasis of the framework is groundwater governance at local level as it relates to shale gas development.

Data collected was used to determine gaps and barriers within groundwater governance at local level for the proposed shale gas development. Therefore, the 20 Benchmarking Criteria checklist by (Foster et al., 2010) served as best suitable method for evaluating groundwater governance provisions and capacity at local level. The 20 Benchmarking Criteria consist of typologies that can be used to determine groundwater governance status. Further, (Foster et al., 2010) recommends a pragmatic classification of groundwater bodies as the best typology for determining groundwater governance status- there being close linkages between the characteristics and status of groundwater bodies, with questions of how and why governance needs to be strengthen to achieve effectiveness on the ground implementation of agreed management and protection measures. Also, the documented typologies which are mainly focusing on groundwater pollution and quality can be altered to cater for other concerns for management. Therefore, this study amended the typologies set by (Foster et al., 2010) by adding other categories for investigating groundwater institutional and governance arrangements in relation to shale gas development and their effectiveness towards groundwater protection Table 5).

Table 5: Developed analytical framework

Capacity	**Theme**	**Criteria**
Technical	Baseline measurements and continual monitoring programmes	To detect groundwater pollution
		To determine resource status
		Protection of water resources
	Licenses	Review of licenses and setting conditions
		Zero discharge policy
		Use of alternative water sources

Capacity	Theme	Criteria
		Management of Water Use
		Water balance
		Full disclosure of fracturing fluids and other additives
	Prevention of pollution and / or over-abstraction	Mitigation options in place
		Management of flowback and produced water
		Management of fracturing fluids
		Management of spillage
		Post hydraulic fracturing report
Legal and Institutional	Transgressions	Dealing with non-compliant operators
		Mobilizing and formalizing community participation
	Empower to act on cross-sectorial basis	Setting-up water management institutions to deal with shale gas development
Cross-Sector Policy Coordination	Ensure 'real water saving' and pollution control	Government agencies as groundwater resource guardian
		Effective in control of exploitation and pollution
	To enable access to public information	Coordination with domestic and agricultural development
		Freedom of information and transparency
Operational	With measures and instruments agreed	Public participation in groundwater management
		Existence of groundwater management plan

Source: amended from (Foster et al., 2010)

3.8.1. Strength and weakness

One of the 20 benchmarking criteria advantage is that the criteria listed is specific, thus, enabling a systematic review of investigations and comparisons between one country or region on another (Seward, 2015). However, Seward (2015) argues that there is no evidence available that groundwater governance will be created or will be sustained, thus listing the following assertion as support:

(a) Groundwater governance and groundwater governance research are still in the infancy;

(b) The World Bank benchmarking criteria have not been adequately tested in empirical situation;

(c) Investigators such as (Wester et al., 2011) query whether any examples of good groundwater governance exist anywhere; and

The literature review for this report 'Seward study' found that few good examples of groundwater governance exist (Seward, 2015).

This study makes use of the benchmarking criteria as groundwater indicator not as an exact design criteria, as pointed out by (Pietersen et al., 2016). Which means, the more benchmarking criteria that are present, there more likely that groundwater governance will be effective (Seward et al., 2015). Thus, (Seward et al., 2015) argues that, the benchmarking criteria have an important value within research framework, but because there are limits on the topics and scales to be addressed they cannot constitute the whole framework. The main purpose of indicators – is to reduce the complex to one or small number of measurable parameters, so that an approximation indication of the system may be obtained.

3.8.2. Procedure

The analysis of groundwater governance focused on local level governance. The collected data from interviews was further used in the developed framework for the study. The themes identified from the analysis were used to provide information on the typologies set out by the framework. This information was used to evaluate the effectiveness of groundwater governance and institutional arrangements capacity and provisions at local level on the proposed shale gas development.

3.8.3. Motivation

The 20 Benchmarking criteria as described by (Foster et al., 2010) provides provisions for strengthening groundwater governance, measures for groundwater protection, enables determination of groundwater governance status, and provides ways of improving the effectiveness of groundwater governance. Further, enables evaluation of effectiveness of groundwater governance provisions and capacity.

3.9. QUALITY ASSURANCE/CONTROL

Qualitative research according to (Morrow, 2005) embraces multiple standards of quality, often referred to as validity, credibility, rigor or trustworthiness. Thus, maintaining such quality is crucial in qualitative research. Further, there are some criteria which are used in some studies (Bikitsha, 2015) to maintain rigor; these are: credibility, transferability, dependability and confirmability, however this study focused on credibility due to the nature of the study. Therefore, in order to achieve this quality of work, the steps below were employed throughout the study.

3.9.1. Credibility

Credibility involves the research overall and how well was the data conducted, analysed and managed throughout the research to address the study questions (Morrow, 2005). Further, in research, credibility deals with how well categories and themes cover data, that is, no relevant data have been unintentionally or systematically excluded or in case of irrelevant data included. Therefore, to improve credibility in this study, interview arrangements were made weeks prior via emails and telephone, whereby the institutions were contacted and provided with details of the study and what the study wants to achieve. All of the participants were given an opportunity to withdraw from participating in the study as this was voluntary, and so as to ensure the quality of data collected. Also, the use of purposive sampling allowed selection of the productive interview group that this study considers of value with the required information.

3.9.2. Triangulation

Triangulation was also used in this study, as data collected from interviews will be directly from workshops, interview guide and audio recordings. Triangulation is considered by Bowen (2009) as means of providing credible evidence by reviewing information produced from different methods. Further, all data collected went through data cleaning and management where all responses which were not directly required for the study will be removed to avoid change of focus as mentioned under credibility-section.

3.10. Ethical Clearance

Permission to conduct this study was sought out from the selected institutions. Further, information sheet was provided prior conducting interviews. Consent form were prepared, however, because of the nature of this study they were not mandatory and therefore not issued to interview participants, as this study does not require individual's response, rather an institutional representative on the subject matter. Ethical clearance from the University of the Western Cape was not obtained, as interviews in this study were used to gather more information and add value to the already existing reports and peer reviewed material for the analytical framework. However, memorandum of understanding (MOU) was reached between the interviewer and the participants, where all details of the projects including the benefits, risks and the study objectives were outlined and described in detail. Further, verbal acceptance within regard to entering property and interview participants was received prior.

With regard to data collected from the workshop that was held in 2015, ethical clearance was not required, as data from the workshop was obtained from the produced report. However, during the interviews, permission for audio recording of the whole interview was requested prior the interview, with the intension to fill in gaps from the notes.

3.11. LIMITATION

The proposed study limitations included lack of available data locally. Other limitations included lack of previous study on the subject (shale gas) in South African context. The proposed approach for the study (qualitative approach) has its own limitations, the approach in many cases lacks accuracy in data collection, and responses in interviews tend to be subjective rather than objective.

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

This section discusses the results and discussion part of the study. Shale gas exploration and production in South Africa potentially provides a bridge towards a low carbon future. However, the process of shale gas development requires measures to protect groundwater resources. This includes an effective regulatory regime with compliance and enforcement. Therefore, the conceptual approach of this study follows, in discussing the results, the risk associated with shale gas on groundwater, the resource settings, current and emerging issues on groundwater governance and shale gas, water management institutions within the south-western Karoo Basin and the analytical framework that was developed to assess gaps and barriers within the local groundwater governance system regarding institutional arrangements.

4.2 RISK FACTORS TO GROUNDWATER ASSOCIATED WITH SHALE GAS (MATSHINI ET AL., 2015)

Shale gas is a natural gas that is trapped within shale geological formation. The process of unconventional gas production includes hydraulic fracturing to produce the gas. The aim of hydraulic fracturing is to improve permeability of the host rock by creating (or reopening) a locally dense network of open and connected hydraulically conductive fractures (Healy, 2012). The risk posed by shale gas exploration and development to water resources has been discussed in many papers and forums e.g. (Vengosh et al., 2014) and (Pietersen et al., 2014). The risks can be summarized as (Pietersen et al., 2016): leakage of stray-gas from the target formation through faulty well casings (e.g., poorly joined or corroded casings) to contaminate groundwater; flowback and produced water from hydraulic fracturing operations poses a risk to groundwater resources; the wastewater residue deposits associated with shale gas production carries a risk of groundwater contamination; and the development of shale gas water use will be a competing water demand in already stressed water catchments.

4.2.1 Stray gas migration

When methane gas appears where it is not wanted it is called stray gas (USGS, 2013). For a well to leak, there must be a source of fluid, a breakdown of one or more well barriers, and a driving force for fluid movement, which could be fluid buoyancy or excess pore pressure due to subsurface geology (Davies et al., 2013). Shale reservoirs have very low permeability compared to conventional sandstone or carbonate reservoirs (typically between 3.9 x 10^6 and 9.63 x 10^6 millidarcy). Fluid movement through and from shales is likely to be extremely slow (Davies et al., 2014). Therefore, the potential for shales at depth to be the source of pollutants in the near-surface environment under natural conditions is low. Geological timescales would be required for significant quantities of hydrocarbons to migrate from a shale reservoir that has not been artificially hydraulically fractured (Davies et al., 2014).

Flewelling and Sharma (2014) review of the literature indicates that hydraulic fracturing affects a very limited portion of the entire thickness of the overlying bedrock and therefore is unable to create direct hydraulic communication between black shales (e.g., the Marcellus, Bakken, and Eagle Ford) and shallow aquifers via induced fractures. However, each shale gas plays unique and the detailed geometry of the shale formation in relation to local aquifers needs to be defined, and the risks of hydraulic connectivity between the two needs to be fully evaluated before hydraulic fracturing operations begin. 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. The targeted sources in the Karoo are overlain by very thick and tight shale deposits, such as the Tierberg Formation, up to 800 m thick that would prevent any natural gas from escaping (Steyl et al., 2012). Caution should; however, be taken especially since other artificial routes can be created for the gas to escape, e.g. along the dolerite dyke and sill systems. However, the most likely scenario for stray gas migration into shallow aquifers potentially occurs by the release of gas-phase hydrocarbons through leaking casings or along well annulus from abandoned oil and gas wells (Davies et al., 2012, Jackson et al., 2013). This conclusion is supported by (Darrah et al., 2014) who examined hydrocarbon abundance, isotopic compositions and comprehensive analyses of noble gases and their isotopes in groundwater near shale-gas wells in the United States (U.S). In general, their data suggest that where fugitive gas contamination occurs, well integrity problems most likely associated with casing or cementing issues was the cause. In contrast, [their] data do not suggest that horizontal drilling or hydraulic fracturing has provided a conduit to connect deep Marcellus or Barnett Formations directly to surface aquifers. In their opinion, optimizing well integrity is a critical, feasible, and cost-effective way to reduce problems with drinking water contamination and to alleviate public concerns accompanying shale gas extraction (Darrah et al., 2014). This conclusion is supported by the United States Environmental Protection Agency (EPA) in their assessment did not find evidence that hydraulic fracturing have led to widespread, systemic impacts on drinking water resources in the U.S (U.S EPA, 2015).

4.2.2 Flowback and produced water migration

Similar to stray-gas contamination it is unlikely that groundwater contamination will result in migration of salts or other dissolved constituents from deeper formations to shallow aquifers because of hydraulic fracturing. The necessary conditions for upward flow are an upward head gradient (Flewelling and Sharma, 2014). There are areas in sedimentary basins in which natural conditions create upward head gradients, and these are generated by one of two mechanisms—topography or overpressure (Flewelling and Sharma, 2014). (Flewelling and Sharma, 2014) show that in cases in the (Marcellus, Bakken, and Eagle Ford shale plays) where there is an upward gradient, permeability is low, upward flow rates are low, and mean travel times are long (often >10^6 years). Given the buoyancy of gas, the flow rate of denser saline water would be substantially slower than the flow of natural gas, and would depend on both the pressure gradients and hydraulic connectivity between the over pressurized annulus or leaking sites on the wells and the overlying aquifers (Vengosh et al., 2014). However, poorly constructed wells provide conduits for groundwater contamination with salts or other dissolved constituents. Existing wellbores, including abandoned oil and gas wells, old dry exploration wells and water wells represent primary potential vertical gas migration conduits (Miyazaki, 2009). (Miyazaki, 2009) concluded that most abandoned oil and gas wells develop leaks over time, even when plugged in accordance with current (US) government regulations. However, contamination from saline water has not been linked to date to hydraulic fracturing activities (Vengosh et al., 2014). This finding is supported by the (Darrah et al., 2014) study, which shows unlikely migration of contaminants from depth.

4.2.3 Waste residue deposits

The wastewater residue deposits associated with shale gas production carries a risk of groundwater contamination. Over time, metals, salts, and organics may build up in sediments, scales, and soil near wastewater disposal and/or spill sites (Osborn et al., 2011). (Ziemkiewicz et al., 2014) studied over fifteen well sites and impoundments and characterized, amongst other, liquid and solid waste streams generated by drilling and hydraulic fracturing and evaluated the integrity of impoundments used to store fluids produced by hydraulic fracturing. While most shale gas wells are completed with little or no environmental contamination, they found that many of the problems associated with shale gas development resulted from inattention to accepted engineering practices such as impoundment construction, improper liner installation and a lack of institutional controls (Ziemkiewicz et al., 2014). Therefore, it is how institutional arrangements work and how operational standard procedures are monitored that is more risky than waste residue deposits per se.

4.2.4 Competing water demand

The development of shale gas water use will be a competing water demand in already stressed water catchments. (Vengosh et al., 2014) reviewed reports and compiled data of the water consumption for shale gas development from the Marcellus, Barnett, Haynesville, Eagle Ford, Woodford Shale and Horn River in British Columbia showed that water use varies from 8000 to 100 000 m^3 per unconventional well (Table 6).

Table 6: Water Use and Wastewater Production per Shale Gas Well in Different Shale Gas Basins in the U.S.

Basin	Water use per well (m^3)	Wastewater per well (m^3)
Horn River Basin (British Columbia, Canada)	50 000	
Marcellus Shale, Pennsylvania (<2010)	7 700 – 38 000	
Marcellus Shale (2008 – 2011)	11 500 – 19 000	5 200
Marcellus Shale (2012)		3 500
Woodford Shale, Oklahoma	16 000	
Barnett Shale (Texas)	10 000	
Haynesville, Texas	21 500	
Eagle Ford. Texas	16 100	
Niobrara, Colorado (2012)	13 000	4 000

Source: Vengosh et al., 2014.

The widespread variability in use of water stems from distinctions in well borehole configuration, hydrocarbon type, target oil or gas reservoir, and the drill year of the well (Gallegos et al., 2015). Thus, according to (Gallegos et al., 2015) hydraulic fracturing is not a one-size fits all operation, assumptions and generalizations regarding water use in hydraulic fracturing operations and the potential for environmental impacts should be made with caution.

In the Karoo, the water use may conflict with drinking water supplies, livestock watering, irrigation and protection of groundwater dependent ecosystems. (Vermeulen, 2013) listed the following possible sources of water for shale gas development: development of local groundwater supplies – this includes exploiting the 4 000 breccia plugs in the Western Karoo, and the hydraulic fracturing of the aquifers of the Karoo; trucking in or piping surface water from elsewhere – by road, rail, pipeline or a combination thereof. This will put an additional burden on the roads and infrastructure. Transfer of water, either freshwater or seawater, clearly has a number of limitations and must be subject to a proper study; piping seawater or desalinated water from the coast – this will only be feasible if the water is purified and piped across the escarpment, which will be a very costly exercise; water from the Orange River – the excess water is already being allocated to previously disadvantaged farmers; and exploiting the deep saline aquifers for water. Under-utilised aquifers are thought to lay few hundred meters below the surface.

In addition, the following possible sources are identified: a blended solution incorporating contributions from all available water sources and maximising flowback water recovery and reinjection for continued hydraulic fracturing; procure grey water from municipalities that has been treated for disposal – this may be an additional source of income; and reallocation of water from other sectors that are not taking up their allocation.

4.3 GROUNDWATER GAS INTERACTION SCENARIOS

In order to fully assess the impacts of shale gas development on groundwater resource, one needs to identify the hazards or the risks, the pathway or pathways by which the potential risk will reach the shallow aquifers and the receptors that will be impacted by the certain event. This section provides discussion by which the identified risks in section 4.2 will impact on ground shallow aquifers of the south-western Karoo Basin.

4.3.1 Hazards

The potential hazards to groundwater have been described extensively in section 4.2.

4.3.2 Pathways/ Aquifer-Intrinsic Vulnerability

To adequately assess the risks poses by on the receptors, pathways by which an impact may propagate to the receptors must be identified. The intrinsic vulnerability of the system must be understood. This section aims to identify and discuss natural and artificial pathways that can contribute to the intrinsic vulnerability of the Karoo aquifers.

4.3.2.1 Proximity of Aquifers to Whitehill Formation

Stray gas as described in section 4.2.1 reaches groundwater in two pathways; natural and induced pathways. Stray gas can migrate to shale aquifers using natural fractures, faults and dolerite intrusions. The presence of dolerite intrusions as discussed by authors have the potential to act as conduits for gas migration as gas can escape along the dolerite dyke and sill systems. The depth to the focused area for shale gas exploration in the Whitehill Formation along the northern boundary of the Cape Fold Belt is ~4000m in the southwest Karoo and ~5000m in the southeast (Scheiber-Enslin et al., 2015), while shallow aquifers in the main Karoo Basin exist to the depth of 300m. Therefore, movement of fluid hydrocarbons from depth of about 5000m below the earth surface to shallow aquifers is still debatable, however dolerite intrusions and faults increases the potential of stray gas migration.

Aquifer properties play a crucial role in spatial distribution of impacts associated with shale gas exploration and production. These properties include hydraulic conductivity, storativity, and transmissivity to count the few, these properties are vital when assessing impacts from flowback and produced water.

Aquifer inter-connectivity is essential when assessing vertical movement of groundwater from deep aquifers to shallow aquifers. Movement of groundwater is governed by certain conditions such as hydraulic gradient, pressure and topography. Thickness of aquitards, hydraulic conductivity, storativity are key characteristics for vertical movement of groundwater and fluid hydrocarbons to shallow aquifers (WorleyParsons, 2013): Lower vertical hydraulic conductivity values of aquitards will lead to lower aquifer vulnerability. Further, the presence of aquitards reduces aquifer inter-connectedness, thereby reducing aquifer vulnerability.

4.3.2.2 Wellbore Pathways (Induced Aquifer Connectivity)

There are other pathways that exist to promote migration of deep saline water, flowback and produced water, and stray gas to shallow aquifers – these include artificial connections that exist through formations or potential develop in future from hydraulic fracturing processes. (WorleyParsons, 2013) highlights three main causes for increased aquifer connectivity:

- Poorly sealed groundwater observation or water supply bored, allowing groundwater or gas to migrate along the bore annulus across otherwise hydraulically confined aquifers;
- Poorly constructed or sealed petroleum or gas exploration wells, providing a migration pathway for fluids between discrete aquifer interval; and
- Old abandoned bores (i.e. oil and gas exploration or production wells, irrigation bores, stock and domestic bores), which may not been appropriately decommissioned or may have rusted or otherwise decay, allowing the free movement of water or gas between the formations.

4.3.3 Potential Impacted resource (Receptors)

Within the study area, there are ranges or resources (receptors) that have the potential to be impacted by effects of shale gas exploration and production. These include water users, groundwater dependent ecosystems and groundwater sustainability.

Exploration of shale gas resource involve a process of hydraulic fracturing which involve use of large volumes of water (Table **6**) pumped at high pressure to the targeted zone. The main Karoo Basin is presented with limited water resource, with most of its town depending solely on groundwater for domestic water supply, irrigation and stock farming. Therefore, any pressure that will be exerted on Karoo aquifers will render a threat on the groundwater resource, especially in towns such as Beaufort West which were recently hit by drought.

Groundwater has a crucial role in supporting terrestrial ecosystems, in particular in the extensive semi-arid parts of South Africa. Dependency of ecosystem on groundwater needs to be assessed in three ways – nature, extent and degree of dependency (Colvin et al., 2007). Degree of dependency ranges from totally or seasonal, extent: localised to widespread depending on the nature of the aquifer and the water table and nature of dependency is difficult to predict or may only be realised once an ecosystem has been stressed beyond a critical threshold (Colvin et al., 2007). Therefore, possibility of aquifer exploitation in the main Karoo Basin will affect groundwater dependent ecosystems as water tables will be lowered.

4.4 GROUNDWATER GOVERNANCE DISCUSSION

4.4.1 Resource settings

The area is underlain by rocks of the Karoo Supergroup. According to (Woodford and Chevallier, 2002) the target features for groundwater in the Karoo Supergroup are: groundwater associated with dolerite intrusions; groundwater associated with structural features other than those associated with dolerite intrusions; horizontal or near-horizontal fractures along bedding planes and formation interfaces; other fracture and joint systems; within more porous sedimentary successions; shallow groundwater associated with near surface calcrete layers; and in alluvial deposits associated with ephemeral rivers and streams. In the absence of these features the rocks of the Karoo Supergroup are considered poor aquifers (Meyer, 1998; King, 2002; Meyer, 2003). In terms of the deeper aquifer systems, there are many unknowns. However, deep (up to 4 692 m) exploration drilling by SOEKOR in the 1960s/70s indicated isolated occurrences of deep, saline groundwater in the Karoo formations and fresher groundwater from the underlying Witteberg Group (Rosewarne et al., 2013).

4.4.1.1 Beaufort West

All the towns in the study area rely in groundwater. Beaufort West obtains its water from both surface water and water reclamation plant which was put into place in 2011. Further, approximately 24% of the 2013/2014 water requirements is obtain from surface water, 17% from the reclamation plant and the remaining 59% from groundwater, boreholes located in Brandwag, Tweeling, Lemoenfontein and town wellfields, seeTable 7 (DWS, 2015). In addition, to increase Beaufort West water requirements, a license has been issued for four extra production boreholes (Quaggasfontein Compartment; QA2, SR4, SR5 and SR9), with a total yield of 294 336 m^3/a.

Table 7: Beaufort West various water resources and their volumes (m^3/a)

Water Resources	Volume (m^3/a)
Gamka Dam	373 000
Brandwacht	363 905
Springfontein	214 255
Lemoenfontein	105 485
Waterval Fountain	94 535
Gamka Vallei North	220 825
Gamka Vallei South	425 955
Town Boreholes	119 355
Hansrivier	812 855
Walkersdam	67 890
Reclamation Plant	441 650

NB: The Reclamation plant volume has 10% annual increase since 2014

Source: DWS, 2015a.

Beaufort West is one of relatively few towns in South Africa that uses reclaimed water. Further, raw water abstracted from the Gamka Dam and the boreholes is transferred to the water treatment before distributed to the public for consumption.

4.4.1.2 Leeu Gamka and Merweville

As highlighted above, Karoo dolerite dykes and sills that have intruded into the Adelaide Subgroup sediments turn to form target zones for groundwater. Leeu Gamka is currently supplied with groundwater from three production boreholes. The gently folded mudstones, siltstones and sandstones of the Abrahamskraal Formation (Adelaide Subgroup, Beaufort Group, Karoo Supergroup) underlie the town and settlement, with Quaternary alluvium being situated within the Gamka River course and floodplain. Merweville relies entirely on water supplied by seven boreholes through Merweville waste water treatment plant. Further, the recommended yields from the boreholes is 322 295 m^3/a (DWS, 2015b).

4.4.1.3 Current emerging issues

As mentioned above the low rainfall and the secondary nature of the rock type means that the Karoo aquifers can generally be classified as generally low productivity but locally moderate productivity (Pietersen et al., 2010). With depth, the productivity is expected to decrease. Any saline aquifer system will most likely relate to fault systems or deeply buried fracture systems are localized rather than regional. This means that the aquifer is susceptible to over-abstraction during drought periods. The advent of possible shale gas production will be a competing demand in already stressed water catchments as according to Stuart (2012) drilling a horizontal and vertical well requires about 400 - 4000 m3 of water in drilling fluids. Additionally, 7000 – 18000 m^3 of water containing drilling fluid is required for fracturing a formation that contains the unconventional resource. (Vengosh et al., 2014) further argues that, in small rivers such as those in Appalachian Basin, abstraction of water for hydraulic fracturing exceeds river flows during low flow period. Also, abstraction of water in rivers competes with other users downstream such as the case in Alberta, Canada. Therefore, alternate water use will be required such as desalination of saline groundwater, reclaimed water and so forth. In Table 8, provides an overview of the typologies and threats to the Karoo aquifers are given based on the (Foster et al., 2010) classification of groundwater issues.

Table 8: Typologies and threats to the Karoo aquifers in the Beaufort West, Leeu Gamka and Merweville areas.

Typology	Situation / process	High Risk	Medium Risk	Low Risk
Risk of extensive quasi-irreversible aquifer degradation and subject to potential conflict amongst users	Intensive exploitation (leading to land subsidence, saline or polluted water intrusion)	✓		
	Vulnerable to pollution from land surface (vulnerability, pollution)		✓	

Typology	Situation / process	High Risk	Medium Risk	Low Risk
	Depletion of non-renewable storage (in aquifers with low contemporary recharge)	✓		
Potential water use conflict but not at risk of quasi-irreversible aquifer degradation	With growing large-scale abstraction (especially in aquifers with high T/S ratios)		✓	
	Vulnerable to point-source pollution (vulnerability, pollution)		✓	
	Shared transboundary resource			
Insufficient (or inadequate use of) scientific knowledge to guide development policy and process	Potential to improve rural welfare and livelihoods (not fulfilling MDG potential)			✓
	Natural quality problems (e.g. As, F)			✓
	Scope for large-scale planned conjunctive use (urban W/S or irrigated agriculture)			✓

4.4.2 Water Management Institutions

The area falls within the Breede-Gouritz Water Management Area. A Catchment Management Agency has been established to manage the water resources. The towns fall within Central Karoo District Municipality. Beaufort West and Merweville fall within the Beaufort West Local Municipality whilst Leeu Gamka falls within the Prince Albert Local Municipality. The Central Karoo District is the responsible water services authority (for Murraysburg) and has monitoring networks in place to measure water quality throughout its areas of responsibilities. The Department of Water and Sanitation has embarked on a baseline monitoring program before shale gas development takes place. Other institutions with a water role include Western Cape Department of Environmental Affairs and Planning (DEADP) and Cape Nature. Besides the government agencies there are farmer associations operational in the areas.

Beaufort West Local Municipality, act as Water Services Authority and the Water Services Provider for Beaufort West, Merweville and Nelspoort according to (DWS, 2015a, DWS, 2015b), whilst Prince Albert Local Municipality act as Water Services Authority and the Water Services Provider for Leeu Gamka. Further, the local municipalities appears to be performing at "acceptable to good level" taking into account their size and the staff capacity, however, their management is sufficient as illustrated by their Blue Drop and Green Drop performances. Further, Beaufort West Local Municipality has improved since 2009 assessment of the Blue Drop; their Blue Drop score in 2011 achieved an average of 92% showing commitment in transforming drinking water quality

Breede-Gouritz Catchment Management Area is currently responsible for water-sue license authorization, this was delegated by the Minister from the Department of Water Affairs

4.4.3 The analysis of local level governance: Framework and Content analysis

With the use of the developed framework and content analysis, with regard to local governance, several groundwater governance arrangements for shale gas exploration and production were identified and discussed below.

4.4.3.1 Baseline measurements and continual monitoring programmes

Baseline monitoring data is vital prior to exploration and production of shale gas, as it enables early determination of groundwater contamination and this informs regulators if future activities have contaminated groundwater. Further, continual monitoring programs during and after exploration and production is vital for groundwater protection.

4.4.3.2 Licenses

Review of license and setting conditions are vital to cater for any changes during exploration and production of shale gas in terms of groundwater abstraction. Further, the license must explicitly stipulate a zero discharge policy for protection of groundwater resources. However, under license application, the applicant must provide alternative water resources that may be of use during shale gas developments

4.4.3.3 Prevention of pollution and/ or over-abstraction

Prevention of pollution of groundwater from shale gas exploration and production involves several mitigation options, such as baseline and continuing monitoring for early indications of groundwater contamination. However, with regard to mitigations relating to over-abstraction from fresh water resource, Pietersen et al (2015) highlighted the use of (a) alternative water such as brackish or saline water; (b) disclosure of chemicals used during hydraulic fracturing (fracturing fluids); (c) recycle of produced water and flowback for further hydraulic fracturing of other wells.

4.4.3.4 Transgressions

According to (Pietersen et al., 2016) in case of perceived transgressions, certain procedures or methods need to be developed to deal with such cases. These cases need to be dealt with in a thorough manner for protection of groundwater resources from contamination. Further, mechanism that enable review of administration decision need to develop, these include review of judicial so as to enforce groundwater protection.

4.4.3.5 Empower to act on cross-sectorial basis

Setting water management institutions to deal with shale gas development will improve protection of groundwater from shale gas development. This will remove the load from the already existing institutions, as some institutions do not have adequate capacity to manage impacts of shale gas on groundwater resources.

4.4.3.6 Ensure 'real water saving' and pollution control

The south-western Karoo Basin depends mostly on groundwater for basic water supply. The area has limited surface water resources as some rivers are dry most of the year. Therefore, conserving this type (groundwater) of resource is crucial for all life in the area, further prevention of any form of contamination to groundwater is vital.

4.4.3.7 To enable access to public information

Cross-sector policy coordinating between groundwater governance institutions improves the effectiveness and implementation of regulation for groundwater protection. Further, license application does provide a room to consider other institutions and assessing the potential impact that the proposed hydraulic fracturing will have on water resources. Transparency within institution and the public improves public trust between the public and state entities, which results in an effective regulatory regime and enforcement.

4.5 ANALYTICAL FRAMEWORK FOR GROUNDWATER GOVERNANCE

Governance provisions at local level for the study area appear to be to be insufficient to deal with the proposed shale gas, even though there are some provisions, implementation and capacity seem to be lacking in many area. The above table (Table 9) provides analysis of effectiveness of governance provisions and institutional capacity at local level for shale gas using a framework developed from the 20benchmarking criterion by (Foster et al., 2010). The collected data analysed using the developed framework combined with content analysis. Further, the table makes use of codes to provide a better analysis of the data collected; 0 = non – existent, 1 = incipient, 2 = fair, and 3 = excellent.

Table 9: Effectiveness of groundwater governance provisions and institutional arrangements in the study area.

Capacity	Context	Criterion	Provision	Inst. Capacity
Technical	Baseline measurements and continual monitoring programs	To detect groundwater pollution	0	1
		To determine resource status	2	1
		Protection of water resources	0	0
	Licenses	Review of licenses and setting conditions	2	0
		Zero discharge policy	0	0
		Use of alternative water sources	1	1
		Management of Water Use	1	1
		Water balance	1	1
		Full disclosure of	0	0

Capacity	Context	Criterion	Provision	Inst. Capacity
		fracturing fluids and other additives		
	Prevention of pollution and / or over-abstraction	Mitigation options in place	0	0
		Management of flowback and produced water	0	0
		Management of fracturing fluids	0	0
		Management of spillage	0	0
		Post hydraulic fracturing report	0	0
Legal and Institutional	Transgressions	Dealing with non-compliant operators	1	0
		Mobilizing and formalizing community participation	0	0
	Empower to act on cross-sectorial basis	Setting-up water management institutions to deal with shale gas development	0	0
Cross-Sector Policy Coordination	Ensure 'real water saving' and pollution control	Government agencies as groundwater resource guardian	1	0
		Effective in control of exploitation and pollution	0	0
	To enable access to public information	Coordination with domestic and agricultural development	1	0
		Freedom of	2	1

Capacity	Context	Criterion	Provision	Inst. Capacity
		information and transparency		
Operational	With measures and instruments agreed	Public participation in groundwater management	0	0
		Existence of groundwater management plan	0	0

Governance provisions at local level for the study area appear to be to be insufficient to deal with the proposed shale gas, even though there are some provisions. Implementation and capacity seem to be lacking in many area. Table 9 provides analysis of effectiveness of governance provisions and institutional capacity at local level for shale gas using a framework developed from the 20benchmarking criterion by Foster et al (2009). The collected data analyzed using the developed framework combined with content analysis. Further, the table makes use of codes to provide a better analysis of the data collected; 0 = non – existent, 1 = incipient, 2 = fair, and 3 = excellent.

Baseline measurements of groundwater and continual monitoring program within the study does exist, but only for determining groundwater resource, and that only occurs within the municipal wellfields. Further, farmers around the study area are responsible for protecting and managing their groundwater resources. However, the DWS has recently embarked on a monitoring program around the area, but only limited parameters are off concern. But, the district municipality and local municipality does not have adequate capacity in terms of highly skilled professionals such as hydrogeologist, as they only have engineers to deal with all issues around water resources, unless outsourced.

The minister of Water and Sanitation has delegated the Breede-Grouritz CMA to deal with all water user license applications through the National Water Act (Act of 1998). However, at present, the Breede-Gouritz CMA does not have adequate knowledge and understanding of shale gas exploration and production, this include knowledge on water acquisition for exploration, treatment and discharge of flowback. Also, the current requirements in water-user license does not address shale gas exploration and production processes. Therefore, such requirements like zero discharge policy, does not exist. But, are currently proposed to be added on the water-user license. Further, use of alternative water resources is also suggested in the license application, but currently the area has limited water resources, depending mostly on groundwater, excluding Beaufort West depending on groundwater and water reclamation plant.

Within the study area, there are currently no mitigation options in place for groundwater pollution as there are no major threats on groundwater from activities such as industrial, discharging of untreated effluent or mining activities. Further, some parts of the area such as Leeu Gamka and Merwewille does not possess wastewater treatment plants and for those that do, such as Beaufort West, they are currently struggling with treating normal waste as documented in the Blue, Green Drop report. Therefore, to be able to treat or manage flowback these treatment works will either require upgrade or new treatment works will need to be developed to ensure proper treatment of flowback for further fracturing.

At present, the groundwater institutions within the south-western Karoo have no measures in place for management of fracturing fluids, management of spillage. However, these are only proposed to be one of the requirements when applying for water acquisition license. Further, post hydraulic report is also proposed as one of the requirements when obtaining water-user license, however, at present there are currently no requirements for post hydraulic report.

The NWA (Act no 36 of 1998) does provides provisions and measures of dealing with non-compliant operators under section 53 and54. However, these regulations do not directly address impacts associated with unconventional gas, also the NWA provides a good regulatory system of protection of water resource but, lacks proper implementation. Further within the study area there are no community involvement regarding protection of groundwater resources, but the CMA believes that people's negligence to participate in groundwater management is caused by lack of water issues. However, the local municipality and Breede-Gouritz WMA believe that when groundwater issues appear, people will mobilize towards groundwater protection.

Existing water management institutions within the study area range from local municipality, district municipality, catchment management agency, provincial government and so forth. But, South African waters are controlled, managed and protected by the DWS, however the minister can delegate certain duties to the CMA, these include water user application, management of water resources at catchment level and so forth. Even though these responsibilities are delegated to CMAs, the final decision is still made by the DWS.

The roles and responsibilities of the institutions present within the study area are not adequate to deal with shale gas developments, according to the data collected. Further, the local municipality within the study area are responsible for bulk water supply, not activities such as water acquisition for exploration and production of shale gas, possible contamination of water resources from shale gas developments, and all other activities associated with shale gas exploration and production. Further, some local municipality currently, struggle with their roles and responsibilities due to factors such as budget cuts to implement and strengthen regulations. Therefore, it is recommended that new institutions such as council or institute and others be established to deal with the proposed shale gas developments, an institution that will be entitle to administer, manage and regulation shale gas developments. However, existing institutions can be developed through training, knowledge and skills that are crucial in shale gas industry.

As mentioned above, the DWS is the custodian of South Africa's water resources according to NWA (Act 36 of 1998). Further, the DWS is responsible of developing policies, regulation and strategies of how the quality and quantity of water can be managed and protected, but implementation of such, depends on the local government. But, with issues such as budget cuts and lack of skills and knowledge hinders proper implementation of developed regulations (Pietersen et al., 2011).

Groundwater in the south-western Karoo Basin towns such as Beaufort West, Merwewille and Leeu Gamka is the most vital source of fresh water, therefore its use is of vital concern. Coordination between water users such as agriculture, stock farming among others in the study area is not adequate or at the bottom stages, as farmers in the area are responsible for their own drilling of wells to access groundwater and monitoring of wells as the Beaufort West Local Municipality does not provide farmers and industries with water. Further, because there are no major industrialisation occurring in the area, could provide a reason of small coordination between the water users in the area because there is no major threat to water resources.

Local groundwater management institutions in the area does promote access to public information, the local municipalities publishes the water quality on the local community newspaper also on the local radio station in Beaufort West. Other institutions such as the Provincial Government (EADP), Breede- Gouritz CMA publish their reports on local libraries and documents can be downloaded online.

Currently within the investigated areas, there is no public participation for groundwater management, only government institutions responsible for protecting and managing groundwater resources. However, with a notion that, the water in the area is currently not under threat, therefore the public does not feel obligated to manage or protect groundwater resources. Further, with regard to groundwater management plan, the towns in the study area does not have groundwater, but due to the proposed shale gas development the area will be required to develop one that will ensure protection and management of groundwater.

5 CONCLUSION AND RECOMMENDATION

5.1 CONCLUSIONS

South Africa relies on coal and imported crude oil for most of energy. The possibility of production of shale gas in the main Karoo Basin of South Africa provides a potential opportunity to diversify South Africa's primary energy mix. However, the development of shale gas may in some cases pose a potential hazard to groundwater resources. To ensure protection of groundwater means an effective governance regime must be in place to regulate impacts on the resource. This study investigated groundwater governance arrangements for shale gas exploration and production in south-western Karoo Basin. Further, this study aimed at improving knowledge and understanding on groundwater institution and groundwater governance arrangements that promote groundwater protection during shale gas exploration and production.

To achieve the above aim, this study reviewed risks associated with shale gas exploration and production on groundwater resources, because groundwater protection is the main concern in the selected study area, as the area depends mostly on groundwater. The review also included possible ways in which groundwater contamination could occur through stray gas migration; flowback and produced water; waste water residue deposits associated with shale gas development and shale gas as the competing water demand in the area.

Stray gas migration is considered as one of the major risks to groundwater resources. For a well to leak, certain conditions are required, and these involve source of fluid, breakage of one or more well barriers, driving force for fluid movement (fluid buoyancy or pore pressure). Also, shale formations are relatively low permeable causing the fluid movement to be relatively slow. The targeted source in the Karoo is overlain by thick and tight Tierberg Formation that has an ability to restrict any movement of fluid. However, some basins geological settings such as topography and hydraulic conditions, artesian and sub-artesian pressure enable occurrence of stray gas migration, therefore caution should be made since artificial routes can be generated and the above mentioned conditions propel the upward movement of fluid hydrocarbons. But, leaking well casings are still considered as the major threats for stray gas migration.

Waste residue deposits carries risk to groundwater contamination, as overtime the metals and organics associated with shale gas developments build up along soils and sediments. Even though most wells are finished up with little or no problems, often problems associated with shale gas wells lies on the inattention of engineering practices, lack of proper installations, lack of proper institutions controls and so forth. Therefore, in the case of waste residue, lack of proper institutional arrangements is the main concern.

Development of shale gas water use will be a competing water demand in the main Karoo Basin, as shale gas exploration and production has been classified by some authors as using large quantities of water. The south-western Karoo Basin is classified as one of the arid regions in South Africa, with limited water resources and low amounts of rainfall. Therefore, the occurrence of shale gas exploration and production without alternative water sources will result in bulk water shortages, exploitation of aquifers and lowering of water tables.

Groundwater in the main Karoo Supergroup is associated with dolerite intrusions horizontal or near-horizontal features along bedding planes and formation interfaces, fractures and joint systems. While in some areas, shallow groundwater is associated with near surface calcrete layers, alluvial deposits associated with Ephemeral Rivers and streams. However, knowledge about deep aquifers is still inadequate. Further, without the above features, Karoo aquifers are generally classified as poor production.

This study described plausible groundwater – gas interaction scenarios or pathways in the south-western Karoo Basin: natural and induced pathways. Natural pathways include groundwater – gas interaction through dolerite intrusions, existing faults and fractures which have the potential to act as conduits for fluid hydrocarbons. However, conditions such as sub-surface pressure and artesian pressure for upward movement of fluid to shallow aquifers will be required for such to occur. Induced pathways included poor well construction resulting into leaking of well casing and well failure, which are considered as preferential pathways for stray gas migration. Possibility of groundwater – gas interaction will have an impact on these identified receptors: water use, groundwater dependent ecosystem and groundwater sustainability.

The study developed and tested an analytical framework to assess groundwater governance and institutional arrangements at local for the proposed shale gas developments in south-western Karoo Basin. The approach allowed an understanding of complex groundwater governance issues and their relationship to be investigated. The framework evaluated the effectiveness of existing groundwater governance provisions and capacity with regard to the proposed shale gas development areas.

From a groundwater governance point of view, the groundwater governance institutions within the south-western Karoo Basin lack the knowledge and capacity to manage the proposed shale gas development. The available regulations and license requirements for water acquisitions does not address shale gas or any activity related to shale gas development, this includes discharge policy, water use management, disposal of flowback and produce water, recycle of produced water for further fracturing to count the few. It should also be noted that local groundwater institutions such as municipalities are currently struggling with their roles and responsibilities due to factors such as budgets cut, therefore, managing hydraulic fracturing and protecting groundwater will add more stress on currently struggling institutions. Also, the Breede-Gouritz CMA lacks knowledge and understanding of some of the factors and risk associated with shale gas on groundwater resources.

5.2 RECOMMENDATIONS

To prevent contamination of groundwater from stray gas, this study recommends intensive groundwater monitoring from nearby wells. Therefore, development of a proper monitoring system is essential to develop a strong baseline data and also to detect any changes on water quality prior, during and after shale gas exploration. South African regulatory framework for groundwater governance at local is considered not adequate for shale gas exploration and production. This study recommends a goal-based regulation approach rather than a prescriptive, as the shale gas environment is considered innovative. Therefore, a goal-based regulatory regime will enable review of license conditions, adaptation to new technology and promote innovation.

To promote good governance, cross-sector coordination between different institutions (local to national) responsible for protection and management of groundwater resources is crucial with regard to the proposed shale gas development and to prevent or minimize groundwater contamination from fugitive gas while promoting effective management of water resources. Further, involvement of other stakeholder such as public or civil society within the area is vital and promotes good governance.

Local water management institutions knowledge and understanding of hydraulic fracturing and its possible impacts on groundwater resources needs to be constantly improved, to enable regulators to be at the forefront on groundwater contamination, as currently it is lacking.

Any roles and responsibilities of local water management institutions on hydraulic fracturing needs to clearly defined prior exploration and production of shale gas.

Further, requirements such as zero discharge policy are crucial for protection of water resources, also use of alternative water resources is mandatory as the area is considered as a water scarce environment, therefore are required in the license application. In areas such as south-western Karoo Basin, water balance is vital, and use of alternative water resources such as deep brackish water, desalinization of seawater and so forth to minimize impacts on local fresh water resources

Zoning of areas is mandatory to protect groundwater resources, areas of exclusion need to be determined. This includes, areas close to local wellfields, areas with complex dolomite intrusion that has not been studied completely.

This study recommends more studies to be conducted to determine the plausible groundwater-gas interactions and improve the country's understanding of deep aquifers (>300 m) in the main Karoo Basin.

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