A theoretical analysis of possible geohydrological impacts associated with proposed hydraulic fracturing activities in the Karoo Basin of South Africa

by

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THESIS

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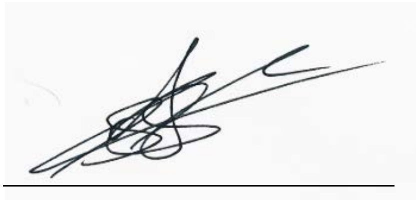
Promoter: Prof. P. D. Vermeulen

Declaration

I, S. S. de Lange, hereby declare that this thesis submitted in the fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Natural Science and Agriculture, Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa, is my own independent work. This thesis has not been submitted to any other institution of higher education. I further declare that all sources cited have been acknowledged by means of a list of references.



Fanie de Lange

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This final product of many years of toil and trouble is dedicated to my dear wife and companion along this journey. Thank you for not asking too many difficult questions and for taking up the slack for whenever so required…….which was most of the time. If not for you and the boys, this project would never have come to completion.

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Abstract

The decision to allow HF within the Karoo Basin of South Africa has raised many valid concerns regarding possible impacts on shallow groundwater resources upon which many communities and farmers are reliant to provide for their families.

Due to huge uncertainties on deep aquifer and groundwater behaviour, as well as possible long-term impacts because of HF, this thesis includes research and results focusing on the following two aims:

1. To evaluate possible impacts on shallow groundwater resources/aquifers in the Karoo; and
2. To produce a Groundwater Risk Assessment Tool (GW-RAT) that will assist decision-makers on quantifying possible risks to the groundwater regime at a specific location.

Internationally it is very difficult to quantify environmental impacts specifically on shallow groundwater resources due to a lack of information. No baseline information is available and many claims could not be validated due to this issue. In South Africa we have an opportunity to address this information gap that exists in the USA and Canada and it is critically important that regulators and government see to it that a database be created before any licences are awarded.

It is evident that HF in the Karoo Basin has several challenges on several levels. Not all work done to determine if a shale gas industry should be developed in South Africa would be negative or detrimental to the environment and we do have qualified geohydrologists with sufficient experience to assess the risks to shallow groundwater resources. It would also be possible to develop technical regulations and protocols for a fractured system environment.

Groundwater is a field of science with numerous sub-divisions, each with its own core scientific base e.g. aquifer mechanics, geochemistry, geophysical surveys and groundwater management. It is therefore important that each of these sub-divisions be appropriately utilised by experienced experts in each category to be able to create a conceptual model that will be able to assist in measuring, calculating and estimating parameters that will influence groundwater flow and quality as well as identify any possible risk from HF on shallow groundwater resources in order to facilitate sound groundwater governance.

The possibility of a HF industry should be seen as an opportunity in South Africa to enhance our knowledge on our deep aquifers and to develop analytical methodologies and solutions for such conditions or alternatively determine whether existing analytical approaches are still valid in a deep fracture system environment. As it is expected that numerical modelling would form part of any groundwater investigation, it would then be sensible to ensure that analytical solutions used for data interpretation should be of a standard in order to compile a conceptual model that is simple enough to allow for numerical modelling but as comprehensive and

accurate a reflection of the physical environment being investigated as possible. Numerical models can be regarded as a powerful tool in assisting geohydrologists and ultimately regulators in making better and well-informed decisions.

There are obvious concerns regarding water governance and specifically groundwater governance in South Africa. Currently the whole concept of governance can be considered as dysfunctional with no real leadership and example at the top echelons of government and regulators.

If groundwater governance is not developed in the sense of establishing local and regional monitoring networks and establishing an institutional environment where data and information are verified, validated and interpreted in a timely manner, there should not even be any thought of establishing a HF industry in South Africa.

Research has indicated that in all countries where HF has been allowed on large scale, information about frequency and severity record keeping and reporting has been horrendously neglected due to historical regulatory gaps and loopholes, either existing due to a lack of research skills or funding or even created as is evident by the “Haliburton loophole”. The development of a tool to assess and quantify, GroundWater Risk Assessment Tool (GW-RAT), was therefore regarded as an important aspect of this research project. Considerations were to keep it as simple as possible but to highlight specific aspects and/or activities that seems to be essential from a South African perspective.

Research for this theoretical analysis of possible impacts associated with HF on Karoo Basin geohydrology yielded various results. In some cases obvious impacts can be minimised by preventative and/or mitigation measures, while some other impacts that are more indirectly involved have been identified as more concerning.

From a technical perspective and available knowledge and skills within the South African geohydrological community, it is evident that we would be able to carry out site-specific investigations to generate enough information to conduct a comprehensive risk assessment with a high level of confidence.

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List of abbreviations

API	American Petroleum Institute
BTEX	Benzene, Toluene, Ethylbenzene and Xylenes
CBM	Coal Bed Methane
CIMERA	Centre of Excellence for Integrated Mineral and Energy Resource Analysis
DEA	Department of Environmental Affairs
DMR	Department of Minerals Resources
DWS	Department of Water and Sanitation
EC	Electrical Conductivity
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
FGWZ	Fresh Groundwater Zone
GMWL	Global Meteoric Water Line
GW RAT	Groundwater Risk Assessment Tool
HF	Hydraulic fracturing
IAP's	Interested and Affected Parties
IGS	Institute for Groundwater Studies
l/pad/d	liters per pad per day
l/pad/hr	liters per pad per hour
l/pad/s	liters per pad per second
m/d	meter per day
m^3/pad/a	cubic meters per pad per year
m^3/pad/d	cubic meters per pad per day
m^3/pad/mnth	cubic meters per pad per month
m^3/well/a	cubic meters per well per year
mamsl	meters above mean sea level
mbgl	meters below ground level
mg/l	milligrams per liter

M_L	Local Magnitude (Richter scale)
MPRDA	Minerals and Petroleum Resources Development Act
NEMA	National Environmental Management Act
NORM's	Natural Occurring Radioactive Material
O&G	Oil and Gas
OES	One Environmental System
PASA	Petroleum Agency of South Africa
SAOGA	South African Oil and Gas Alliance
SGWL	Static Groundwater Level
TDS	Total dissolved solids
UFS	University of the Free State
UNDP	United Nations Development Programme
USA	United States of America
USGS	United States Geological Survey
WRC	Water Research Commission

1. INTRODUCTION

1.1. Overview

In January 2012 a document: "***Shale Gas Report: A special report on economic considerations surrounding potential shale gas resources in the southern Karoo of South Africa***" was published (Twine et al., 2012). This document claimed to be a representation of information as well as analysis thereof that would detail the economic opportunities and benefits, should large enough quantities of shale gas be identified.

Arguments for or against hydraulic fracturing (HF) over the next four years would lead to many heated discussions between supporters of each viewpoint. Unfortunately without any substantiated available information and site specific data regarding geology and pressure gradients within deep aquifers, no side to these arguments could prove their claims. Possible volumes of gas estimated was based on too many assumptions and no prove existed that the gas is actually present in economical viable quantities, which should have been the focus of research studies from the start.

Unfortunately promises of vast economic injections into the struggling South African economy, led to an increase of political pressure as well as investment opportunities against which environmental aspects are usually a nominal concern. Prospecting corporations very quickly applied for Technical Cooperation Permits to PASA, which is mandated by the Minister of the Department of Mineral Resources (DMR) to receive and review all applications and make recommendations. Once a Technical Cooperation Permit was issued the corporations then applied for a conversion to an Exploration Right, in an attempt to move from theoretical desktop studies to field studies.

Internationally, especially in the USA, technological progress regarding HF advanced exponentially, which enhanced economic viability of resources previously deemed too expensive to access. A sense of self-reliance due to economic benefits associated with increased production, boosted the attractiveness of HF as energy source.

In South Africa petroleum exploration and production activities primarily focus on offshore development, with onshore activities located mostly in the Gauteng, Mpumalanga and Kwazulu Natal Provinces (Figure 1).

Offshore opportunities are still available for exploration but investigative exploration activities for HF will be focused in the Karoo Basin (Figure 2). Estimates of possible resources initially indicated potential that positioned South Africa fifth in the world but more recent estimates are much more conservative.

Up to date no permits and/or licences for exploration have been awarded by the DMR, which highlights the uncertainty by both government and investors on how to proceed as well as whether HF is a viable interim energy option. Nuclear power expansion in South Africa have also been identified as an option recently but government is evasive on the exact status of this possibility. It is very obvious that there are many political interventions behind the scenes on how to proceed with regard to energy solutions.

Today there is still a large amount of uncertainty on resource potential due to the unique environment in which exploration is expected to occur. The Karoo Basin of South Africa is highly intruded by dolerite dykes and sills as well as kimberlite dykes, which enhances the uncertainty of whether the target shales have been degassed due to the intense thermal environment when the lava intruded through the sedimentary rocks. Drilling to depths of 3 000 to 4 000 m might also be a lot more difficult in this intrusive environment, which supports arguments of gas wells[1] becoming conduits for pollutants to shallow aquifers supplying local farmers and communities with potable water.

Adding to the above uncertainty is the huge unknowns regarding aquifer behaviour at depths greater than 300 m. Very little geohydrological-specific information was gathered during the drilling of the SOEKOR boreholes in the 1960's to 1970's. At the time the SOEKOR boreholes were drilled to assess the possibility of onshore conventional oil accumulations being present in an effort by the government to establish energy independence. No thought was given to take any measurements regarding groundwater flows, chemistry or pressure gradients. Some pressure measurements were obtained but more for technical reasons, which helped with choice and viscosity of drilling fluids, than for understanding deep aquifer and groundwater behaviour when confining layers were punctured resulting in depressurisation of deep groundwater systems.

Impacts on shallow aquifers could be due to possible migration of deep groundwater towards surface along a pressure gradient – if it exists - and poor well construction. An upwards gradient could be the result of two possible reasons: 1.) Artesian conditions originating from an elevated recharge zone or 2.) Geostatic/Lithostatic pressure due to the effects of the entire overburden which includes the fluid and matrix.

While this document focuses primarily on possible geohydrological impacts on the Karoo environment due to HF activities, one cannot exclude economic gains from possible groundwater-related impacts or any of the other perceived impacts e.g. socio-economic, transport, sterilisation of agricultural land or environmental. A holistic approach needs to be kept in mind and contextualisation of geohydrology within this framework should be

[1] Throughout this thesis a "well" will be associated with oil and gas production, while "borehole" will be associated with groundwater.

attempted wherever possible.

While the fiscal benefits of HF for South Africa still need to be assessed in more detail from an energy and economical perspective, there should not be any reason why possible impacts on the geohydrological regime cannot be identified, assessed and quantified. South Africa's geohydrological community has individuals with the necessary experience, knowledge and skills to be able to develop protocols, strategies and management plans to investigate and make informed decisions accordingly.

Unfortunately groundwater investigations have been carried out superficially in the past with decisions made by individuals that are not qualified and therefore lacking a proper understanding of interactions between different components of a geohydrological investigation. This has often lead to instances where inaccurate estimations or poor management decisions were made.

Include insufficient budgets for comprehensive geohydrological investigations and one ends up with limited data gathering excursions, resulting in unreliable, sparse and often incomplete data sets. One of the main reasons for this is that during initial tender processes, no input is obtained from a qualified geohydrologist on what would be necessary to quantify and/or qualify possible groundwater impacts. Only once a project has been initiated, expert assistance is requested with a budget that is most often not adequate for all groundwater related investigations required.

The importance of a qualified geohydrologist with experience is supported by Mcintyre (2006) where he argues that an understanding of any subject remains inadequate without the perspective of an insider or practitioner. This observation is also included in a Water Research Commission (WRC) report by Seward and Xu (2015) on "***Key Interventions to Improve Local Groundwater Governance***". They decided to base their research on the definition of Moench et al. (2012) due to its consistency with mutual academic agreement on governance. According to Moench et al., groundwater governance is:

"***The process through which groundwater-related decisions are taken (whether on the basis of formal management decisions, action within markets, or through informal social relations) and power over groundwater is exercised."***

Which in turn leads to a definition of "good" groundwater governance:

"A 'good' groundwater governance environment is one where governance processes equitably reflect the voices and interests of stakeholders (including regional and global stakeholders with interests in resource sustainability) and where broadly supported courses of action can be implemented in an effective and equitable manner." (Moench et al., 2012).

Seward and Xu (2015) highlight that groundwater management is a part of groundwater governance and not a separate component. It is not a scale difference but two different processes and both should be included at local, regional, national and global scales.

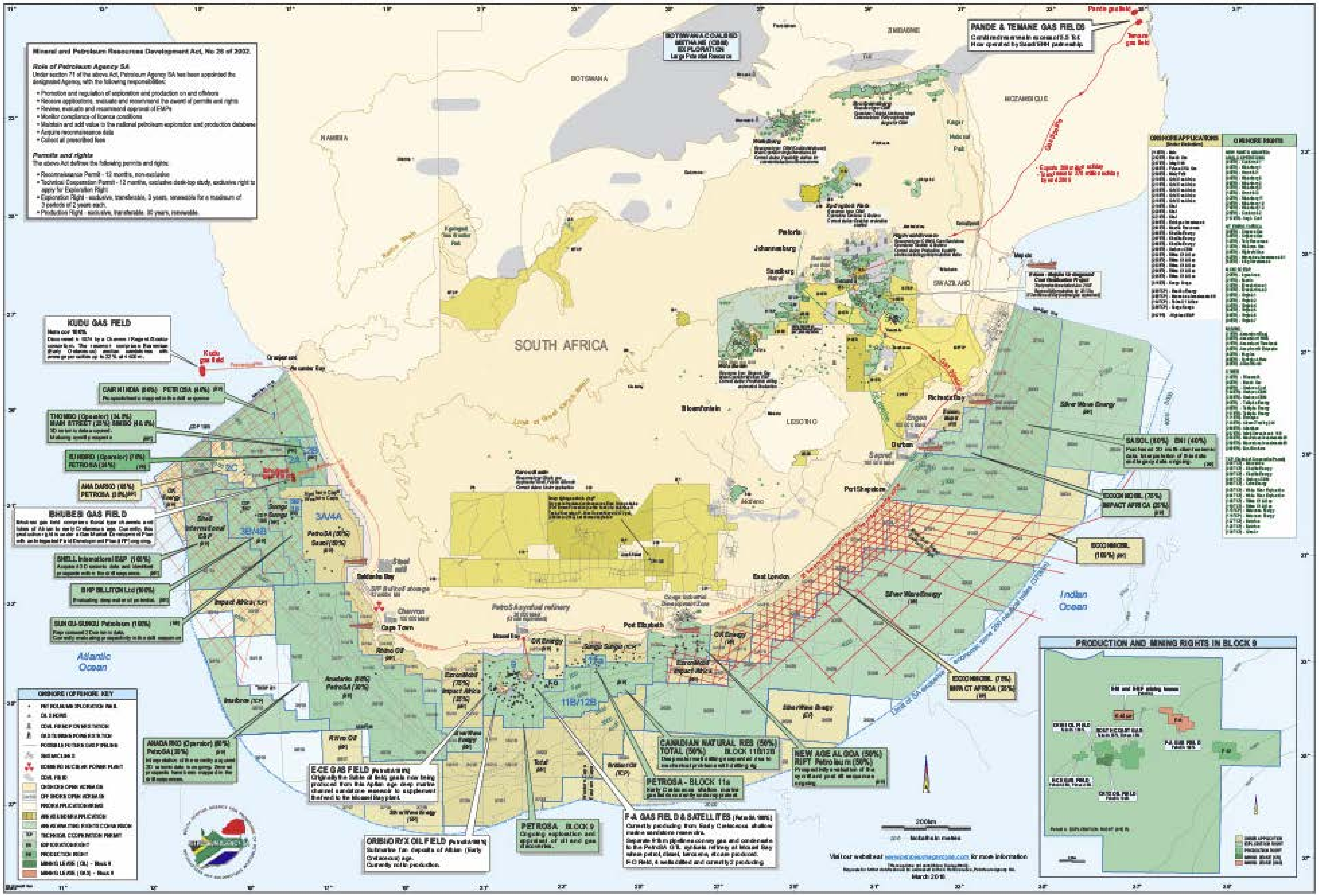

Figure 1: Petroleum exploration and production activities in South Africa, (PASA, 2016a)

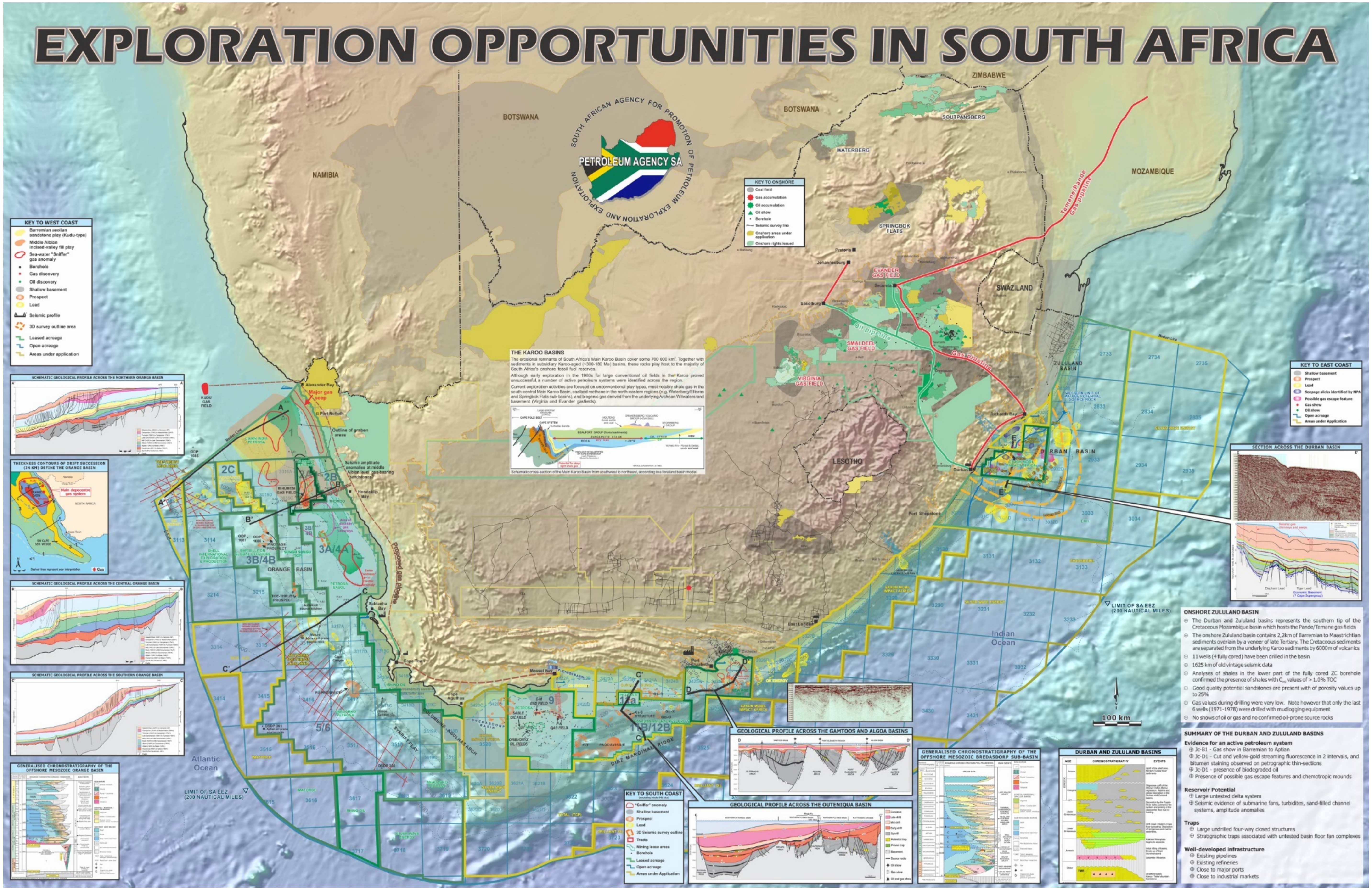

Figure 2: Exploration opportunities in South Africa, (PASA, 2016b)

1.2. Natural gas

Methane (CH_4) is the primary component of natural gas with smaller quantities of other hydrocarbons present in varying fractions.

Natural gas can be divided into two distinct categories:

- Conventional gas; and
- Unconventional gas.

Natural gas is mostly found in sedimentary basins in which the geological environment and rock types may vary. The rock type and trapping mechanism are the basis for distinguishing between conventional gas and unconventional gas (Cook et al., 2013) and not the composition of the gas.

1.2.1. Conventional gas

Historically most natural gas resources are associated with oil reservoirs and are considered conventional gas where oil and gas flow naturally towards surface due to a pressure gradient or can be pumped to surface without having to alter the formation in which the products are situated – no specialised technology is required to unlock its potential. Most of the gas that has been produced on a global scale to date is conventional gas.

Due to the fact that it is less technological intensive it is much easier and less costly to develop conventional gas plays.

1.2.2. Unconventional gas

Unconventional gas has a variety of origins, each with its own techniques of extraction. Examples of unconventional gas are:

- Shale gas;
- Tight gas;
- Coal seam gas (CSG) also known as coal bed methane (CBM); and
- Methane hydrates.

Technology for extraction of unconventional gas has seen an exponential increase in development of different techniques and consumables to minimise environmental impacts but industry has not yet found an effective way of dealing with social licence and local communities as well as environmental activists are still very sceptical about their claims of low risks associated with HF.

1.3. Hydraulic fracturing

1.3.1. Defining HF

HF involves the use of horizontal or directional drilling and stimulation of a given geological formation by means of a cocktail made up of mostly of water, sand and chemicals under high pressure.

In the oil and gas (O&G) industry HF is not a new phenomenon. In the 1930's the first horizontal well was drilled and by the late 1970's it was a common occurrence in the industry. Experimenting with fracturing started in 1947 and by 1950 it was accepted as a commercial process (King, 2012).

Due to arguments and statements made by parties for and against HF it seems fit to highlight the importance of terminology and perceptions regarding context. From an engineering perspective of the HF industry, HF relates to a precise stimulation activity, limited to the fluid action in initiating and extending cracks in the rock. Activists and concerned citizens on the other hand usually regard the term as related to all phases and activities including exploration drilling to production. Therefore industry will claim that HF has not contaminated any groundwater resource, while environmentalists will claim the opposite (King, 2012).

For the purpose of this document, the definition of HF will be regarded from the engineering viewpoint and will only be deemed relevant to the actual stimulation process of creating cracks and fissures under high pressure.

1.3.2. HF phases in a nutshell

Figure 3 represents a process chart that summarizes the different development activities as presented by King (2012). The time considerations for each phase can be measured in months and even years depending on the requirements by authorities and legislatures as well as the complexities involved in obtaining all relevant information.

A typical HF well consists of the following (Figure 4):

- The well head located on surface;
- A vertical segment to a certain calculated depth, which is known as the kick-off point; and
- A horizontal segment within the target formation.

The initial 300 m is usually periscoped to insert a succession of steel casing and cement layers (Figure 5) in order to serve as a barrier between any pollutant within the system and shallow fresh water aquifers being used by landowners and local communities as potable water source.

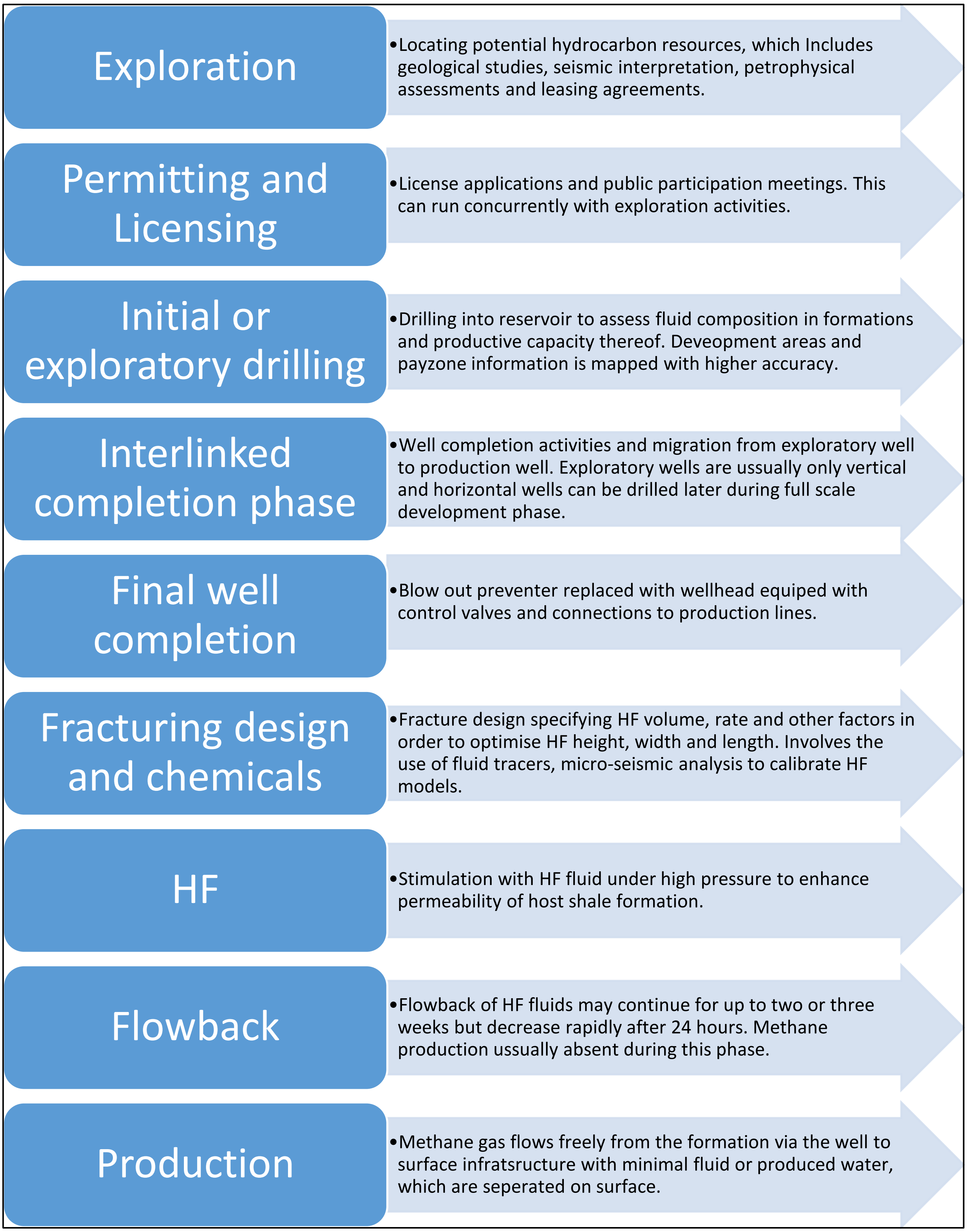

Figure 3: Well development activities summarizing process chart from (King, 2012)

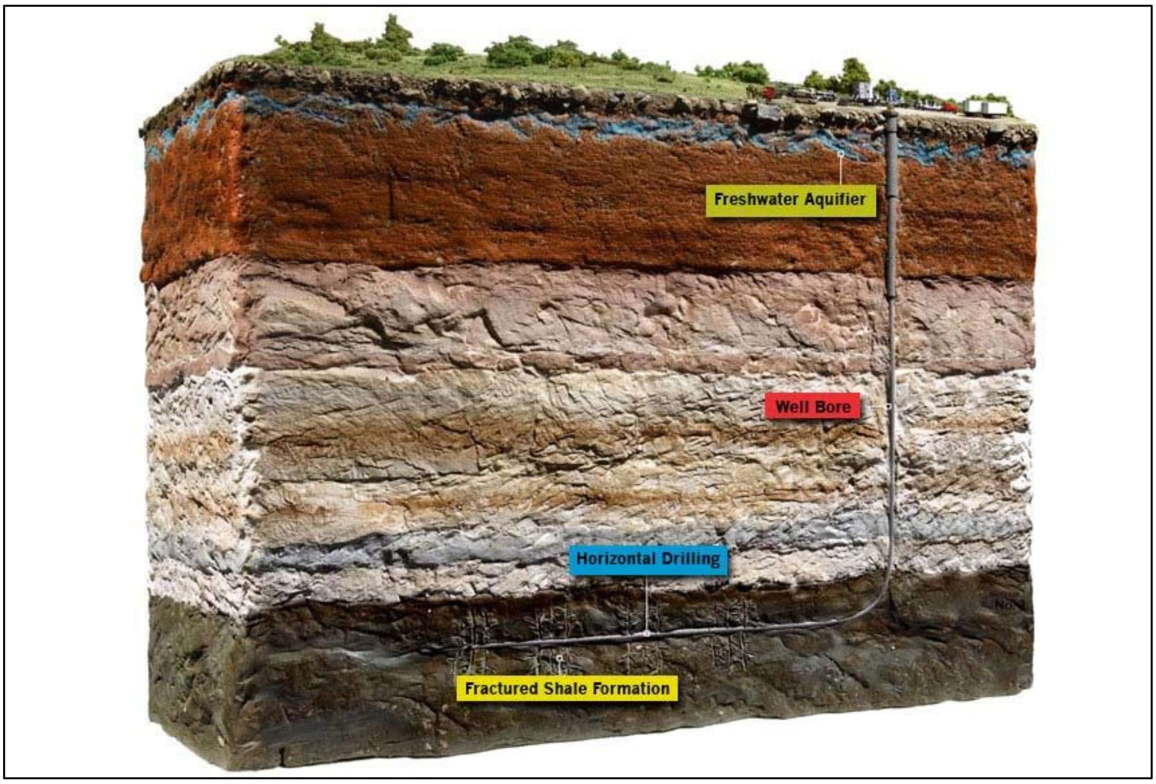

Figure 4: Simplified cross section with completed HF well (McGraw, 2016)

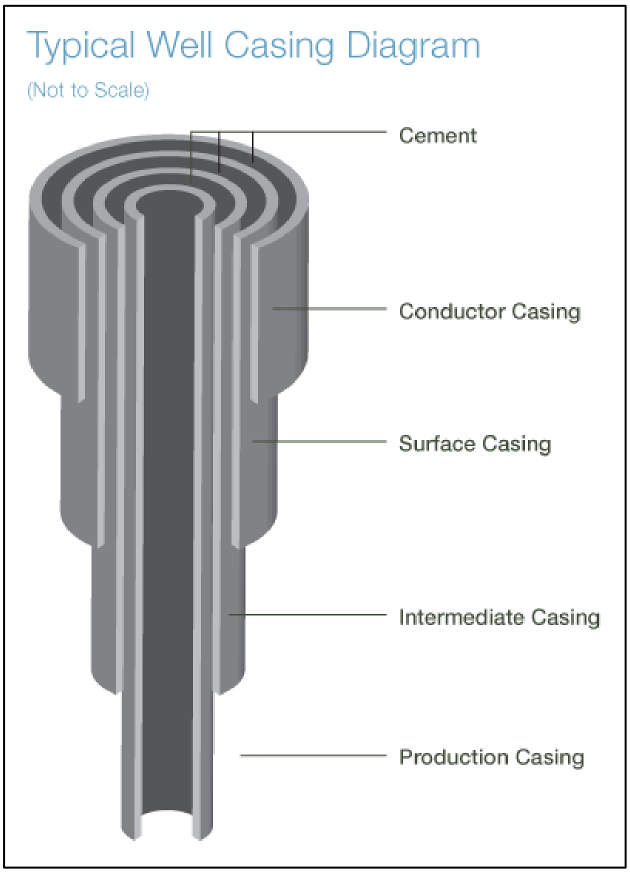

Figure 5: Typical well casing diagram (Sherman, 2014)

In very broad terms three distinct phases can be identified from cradle to grave for a shale gas well:

1. Exploration;
2. Production; and
3. Decommissioning.

For each of the first two phases it is expected that an intensive and detailed Environmental Impact Assessment be undertaken and an Environmental Management Programme be submitted in accordance with section 39(1) of the Mineral and Petroleum Resources Development Act (MPRDA) (DMR, 2002).

It is clear that extraction of unconventional gas resources is a highly advanced and technical activity, which requires accurate information and involves time scales measured in years. Initial capital inputs are also measured in millions or even billions depending on which currency is used.

1.4. Possible risks to water resources

A substantial volume of water is required during the HF process and estimations range between 7 600 and 15 200 m^3 with a maximum of even 49 200 m^3 per well (Freyman, 2014).

To add some perspective to possible requirements and using an example of one well pad with six wells, Table 1 summarises calculations based on the values mentioned in the previous paragraph.

Table 1: Possible water requirements per well pad

Unit	Average range		Maximum
m^3/well/a	7 600	15 200	49 200
m^3/pad/a	45 600	91 200	295 200
m^3/pad/mnth	3 800	7 600	24 600
m^3/pad/d	125	250	809
l/pad/d	124 932	249 863	808 767
l/pad/hr	5 205	10 411	33 699
l/pad/s	1.4	2.9	9.4

Where it is going to be sourced from is not very clear at the moment.

Possibilities include:

1. Local surface water, which is highly intermittent and unreliable throughout most of this arid part of our country. With the current extreme drought conditions, this option is highly unlikely;
2. Local deep aquifers, which are also an unknown and would be heavily regulated by the Department of Water and Sanitation (DWS);
3. Sourced from outside the local catchment by means of pipelines or using existing infrastructure; and
4. Sourced from elsewhere by rail or trucked in over large distances.

Once this water requirement has been addressed, the next challenge would be to address four potential risks on a site-specific and local scale, which according to Vengosh et al., (2014) are:

1. Hydrocarbon gases contaminating shallow aquifers, which have the associated potential to lead to shallow groundwater becoming saline due to leaking natural gas wells and subsurface flow;
2. Spills, leaks and/or inadequately treated shale gas wastewater being disposed of in an insufficient way, contaminating surface water as well as shallow groundwater resources
3. Toxic and radiative elements accumulating in stream sediments or soils near spill locations or disposal sites; and
4. Additional stress in already water scarce areas on water resources, which could lead to water shortages and conflict between contractors and other water users.

1.5. Challenges

Some of the challenges identified during this research were obvious and although protection of groundwater as a resource is a strong argument against HF activities, the knowledge and skills to ascertain whether the risk is just too high to allow HF are present within the South African geohydrological community.

One key factor to evaluating possible impacts on shallow groundwater resources is to include a reputable geohydrologist with sufficient experience from day one in the team that is responsible for the Environmental Impact Assessment (EIA).

Another element that might be the most crucial if a decision to continue with HF is made, would be groundwater governance. To date there have been numerous reviews on groundwater governance, indicating that there is a severe lack of adequate guidelines, sound methodology and protocols as well as implementation of existing institutional and regulatory procedures within the mining sector. If this is not streamlined and developed to acceptable best practice standards, HF should not be considered in a pristine environment like the southern Karoo Basin.

A critical component to groundwater governance is monitoring and all its facets. It is therefore necessary to start with background/baseline monitoring projects to establish reigning geohydrological conditions that can be used to compare monitoring results during exploration and operational phases with. Long-term monitoring that includes observations during and after the closure phase should be considered and options must be included in any application for HF.

1.6. Aims and objectives

Due to huge uncertainties on deep aquifer and groundwater behaviour, as well as possible long-term impacts because of HF, this thesis includes research and results focusing on the following two aims:

- To evaluate possible impacts on shallow groundwater resources/aquifers in the Karoo; and
- To produce a Groundwater Risk Assessment Tool (GW-RAT) that will assist decision-makers on quantifying possible risks to the groundwater regime at a specific location.

Objectives of this research include:

- Assessing the unique geology of South Africa and the extent of fracturing along contact zones between sedimentary and intrusive rocks;
- Assessing the role of a qualified geohydrologist with at least 10 years' experience and their value and importance within the HF risk assessment value chain;
- Evaluating geohydrological information gathered from historical and recent deep boreholes drilled in the Karoo Basin;
- A critical review of current groundwater governance systems in South Africa and proposed technical regulations;
- Adapting existing monitoring protocols to include HF-related concerns;
- Construction of analytical and numerical models as predictive tools on possible migration scenarios; and
- Establishing an HF-specific risk assessment protocol.

1.7. Thesis structure

This thesis will follow the following structure:

- Chapter 1 is an introduction to HF with some basic specifics;
- Chapter 2 will review international HF activities and research and identify current best practice and state of the art technologies;
- Chapter 3 represents an overview of HF from a South African perspective from initial announcements to the current status quo;
- Chapter 4 deals with methodologies applied during research activities and data interpretation;
- Chapter 5 involves conceptual, analytical and numerical modelling in an attempt to predict possible migration of pollutants towards surface;
- Chapter 6 is a critical review of groundwater governance in South Africa;
- Chapter 7 represents the development of a South African specific risk assessment tool; and
- Chapter 8 entails conclusions arrived at during this research project.

1.8. Conclusions

The decision to allow HF within the Karoo Basin of South Africa has raised many valid concerns regarding possible impacts on shallow groundwater resources upon which many communities and farmers are reliant to provide for their families.

This research document started off with the obvious and a thorough assessment of all HF-related activities has yielded surprisingly easy solutions from a geohydrological perspective. A site-specific “**yea**” or “**nay**” can be easily arrived at by means of a comprehensive site evaluation and risk assessment. An essential element for the aforementioned evaluation(s) and assessment(s) should however be the employment of a qualified and Karoo experienced geohydrologist, which will add value as well as confidence in the outcomes of these investigations.

Another aspect that would need to be addressed is the matter of monitoring, which would establish geohydrological conditions prior to, during and after HF activities. This would fall under the realm of groundwater governance and should be considered as one of the highest priorities during any research, assessments and/or evaluations of possible impacts or risks.

Unfortunately a bigger concern lies with what happens afterwards when departments and regulators have to ensure that all HF activities and procedures are followed and adhered to. To date their record does not bode well for easing one’s mind that a HF industry can be introduced into the South African economy and more specifically "**Environment**" in a safe and responsible way. Political interference is a given, which means that transparency will be compromised and the benefits of HF will not achieve one of the most important aspects for a better South Africa; minimising the huge gap between rich and poor.

2. INTERNATIONAL CONTEXT – LITERATURE STUDY

2.1. Introduction

A huge emphasis is placed on groundwater resources due to it being the primary argument used by concerned parties when they question the rationale of allowing this intrusive method in the search to energy independence. Even after five years of research it is still a very vague and contentious subject because information and data are usually very restricted and no definite deductions can be made from it.

Available literature has been forthcoming since 2012 with numerous publications by the United States Geological Survey (USGS) and their Environmental Protection Agency (EPA). Extensive research has also been done in Canada. Two of the most comprehensive reports need mentioning here:

1. "*Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States*" (U.S. EPA, 2016a); and
2. "*Environmental Impacts of Shale Gas Extraction in Canada*" (Council of Canadian Academies, 2014).

The two abovementioned reports have been used as focus for this chapter due to the repetitive nature of information, issues and concerns forthcoming from reports published in Australia and European countries.

2.2. USA

HF was first done in the United States of America (USA) during an experiment in 1947 and by 1950 it was recognised on a commercial scale. Horizontal or directional drilling was already done in the 1930's and by the late 1970's it was a quite common activity in the conventional O&G industry (King, 2012). Lessons learned from the HF industry has therefore largely been forthcoming from the USA, where the influence of HF's possible impacts on the environment and especially the groundwater component thereof and the attempts to quantify these effects have been highly influenced by the presence of millions of conventional O&G wells distributed across the USA.

HF was initially used only in the conventional O&G industry as a mechanism to improve production of O&G from rock formations. The combination of HF and directional drilling at some stage was developed to such a degree that its potential to be used to produce O&G from hitherto unused unconventional rock formations was recognised (U.S. EPA, 2016b).

2.2.1. Water concerns

In the EPA report the attempt to quantify impacts from HF on drinking water resources was triggered when concerns regarding the quantity and quality of these resources were raised by the public. Changes in these two parameters were reported by residents living near O&G wells and they blamed HF as being responsible for these negative impacts. Additional concerns raised by the public were water availability in arid and drought-stricken areas as well as impacts associated with the disposal of wastewater, which is a by-product at any HF activity.

Researchers then introduced the term “hydraulic fracturing water cycle” and defined five stages within this cycle that include the following activities:

1. **Water acquisition**, which includes any withdrawal of surface or groundwater to be used in the next stage, chemical mixing;
2. **Chemical mixing**, where water and a proppant together with some other additives on site to produce hydraulic fracturing fluids to be used during the HF process;
3. **Well injection** when hydraulic fracturing fluid is mobilised throughout the O&G production well and injected under extremely high pressure into the target rock formation;
4. **Produced water handling**, which includes the supervision and on-site collection of water that returns to surface after the pressure is released at the end of the HF process as well as the transportation of this water for reuse or disposal; and
5. **Wastewater disposal and reuse** of wastewater.

In their final chapter, the researchers conclude that there is a possibility that activities in the hydraulic fracturing cycle have the potential to impact drinking water resources in some circumstances (U.S. EPA, 2016b). Depending on the combination of the cycle’s activities and whether local- or regional-scale factors are involved, these impacts can range in frequency and severity. More frequent and more severe impacts can be expected if some of the following listed combinations between activities and factors are present:

1. “Water withdrawals for hydraulic fracturing in times or areas of low water availability, particularly in areas with limited or declining groundwater resources;
2. Spills during the management of hydraulic fracturing fluids and chemicals or produced water that result in large volumes or high concentrations of chemicals reaching groundwater resources;
3. Injection of hydraulic fracturing fluids into wells with inadequate mechanical integrity, allowing gases or liquids to move to groundwater resources;
4. Injection of hydraulic fracturing fluids directly into groundwater resources;
5. Discharge of inadequately treated hydraulic fracturing wastewater to surface water resources; and

6. Disposal or storage of hydraulic fracturing wastewater in unlined pits, resulting in contamination of groundwater resources."

Table 2 summarises the synthesis of the EPA report. An attempt was made to reduce the content to issues mostly related to groundwater while the report is focussed on drinking water resources as a whole that includes both surface and groundwater.

Table 2: Summary of synthesis in EPA report – adapted to focus on groundwater issues, (U.S. EPA, 2016b)

Stage in hydraulic fracturing water cycle	Factors affecting the frequency and severity of impacts
Water acquisition, which includes any withdrawal of surface or groundwater to be used in the next stage, chemical mixing.	1. Most important factor to determine severity is to review local balance between water withdrawals and availability. Abstraction volumes not only criteria to be considered but balance between water withdrawals and availability in place and time should also be considered; 2. Declining groundwater volumes are essentially vulnerable to water quantity and quality impacts due to withdrawals; 3. If abstraction exceeds recharge, the net effect is a negative and declining groundwater levels; 4. Natural occurring chemicals e.g. uranium (NORM) in host rock(s) can be mobilized into groundwater resources; 5. Some state and local governments have asked O&G companies to source water only from surface water resources. This might not be an option in areas where surface water availability is inadequate. 6. Water availability can also vary over time due to seasonal changes and in the case of groundwater, precipitation would be one of the main parameters; 7. Water availability vs. water abstraction are highly influenced by long term or seasonal drought patterns; 8. Reuse of HF wastewater will reduce stress on fresh water resources but seems to be more driven by cost of disposal than by water scarcity; and 9. Using brackish groundwater can also be considered to reduce fresh water demand
Chemical mixing, where water and a proppant together with some other additives on site to produce hydraulic fracturing fluids to be used during the HF process. **Produced water handling**, which includes the supervision and on-site collection of water that returns to surface after the pressure is released at the end of the HF process as well as the transportation of this water for reuse or disposal.	1. Both these two stages impact on drinking water resources mainly through spills, therefore discussions are combined; 2. Spills can be from chemicals used to mix HF fluid, the HF fluid itself or produced water; 3. Spills can migrate towards surface and groundwater resources; 4. Spill frequency information is recorded but severity of spills is mostly not available; 5. Estimates from Colorado, North Dakota and Pennsylvania range between 0.4 to 12.2 reported spills per 100 HF wells; 6. Spill rates expressed on a per-active-well basis might be more appropriate as produced water spills can take place several years to decades after HF; 7. A data review of spills that occurred between January 2006 and April 2012 revealed that from 457 spills identified as related to HF, only 32 (7%) were reported to have impacted on surface or groundwater (U.S. EPA, 2015); 8. The estimate of possible spills reaching a drinking water resource range between 10 to 500 spills per year and is reflective of the very high uncertainty of these evaluations due to a severe deficiency of data on this subject; 9. Larger spills will be more likely to reach a drinking water resource and therefore spills due to well blowouts, pipeline leaks and storage failures will be more likely in reaching a drinking water resource than on-site spills that occur during chemical mixing and produced water handling; 10. Spills reaching the groundwater environment are considered to be more severe than those reaching surface water; 11. Higher permeability soils will allow for enhanced infiltration than soils with low permeability, which usually have a higher clay content; 12. Fractured rocks and karst environments will also facilitate a higher infiltration rate via preferential flow paths; 13. Spill prevention and response can be implemented to reduce impacts from spills, which can include spill containment systems consisting of primary, secondary and emergency containment systems; 14. Other spill remediation methods available are application of absorbent material, vacuum trucks, neutralization of spilled material(s) and

Stage in hydraulic fracturing water cycle	Factors affecting the frequency and severity of impacts
	using water to flush the area; 15. Diluted chemicals will have a lesser impact than chemicals that is very concentrated in spills with equal volume and the same holds true for produced water spills that has different brine concentrations; 16. Another factor that will influence the severity of the spill is toxicity and produced water containing NORM; 17. Groundwater movement through the matrix is usually very slow and in combination with multiple spills, this can lead to the accumulation of chemicals over time; 18. Installation of groundwater monitoring boreholes are expensive and very often neglected, which cause contamination of groundwater not to be detected as frequently and accurately as in the case of surface water; and 19. Groundwater remediation is costly and difficult which adds to the severity factor.
Well injection when hydraulic fracturing fluid is mobilised throughout the O&G production well and injected under extremely high pressure into the target rock formation.	1. During this stage impacts to drinking water resources are generally always groundwater resources; 2. Two fundamental pathways are potentially responsible for migration of contaminants with the potential to affect drinking water resources; a. Pathway #1 - migration due to defective in well casing and/or cement; and b. Pathway #2 - migration through the induced fracture network. 3. Pathway #1: a. The HF process is the time during which the system is exposed to the maximum stresses during the well's life; b. When pressures cannot be tolerated, either the casing or cement or even both can fail, leading to compromising the mechanical integrity with the unpremeditated migration of HF fluids into the surrounding environment; c. A 1%, of wells drilled, failure rate has been estimated but uncertainty with regard to whether these failures occurred during the HF stage or at some other time during the life of the well exist; d. The above culminates in approximately 100 to 125 failures per year on average but as with the spills, a lack of reliable information assigns a low confidence in these estimates, which is probably too low as it does not include failures outside the HF process or re-fractured wells; e. Well design and construction are two factors that will make the occurrence of mechanical failure more likely. More layers of well will enhance well integrity as well as cementing of casings throughout the entire fresh water aquifers(s); f. Design of casing, cement and other well components to a standard that it would be able to withstand expected stresses during the HF process is critical; g. Another factor to be considered is the corrosion of well components. New wells are less likely to experience mechanical failure than older wells where casing and cement jobs deteriorate with age; h. Performing pressure tests on casing prior to HF as well as monitoring of the annular space behind the casing that is used for HF during the process can identify failure in real time and an immediate shutdown can be implemented in time; i. The EPA's Well File Review study concluded that casing pressure tests were carried out in only 60 % of approximately 28 500 HF jobs and annulus monitoring was carried out during slightly more than 50% of these (U.S. EPA, 2016a); j. No evidence that the aforementioned frequencies have been improved upon since the review was done. 4. Pathway #2: a. This type of migration occurs indirectly via nearby wells intersecting the same fracture network or via natural fractures or faults, which could allow fluid to reach groundwater resources;

Stage in hydraulic fracturing water cycle	Factors affecting the frequency and severity of impacts
	b. It can also happen directly due to the fracture network extending beyond the production zone and into a fresh groundwater resource or by conducting HF into a drinking resource itself; c. The possible migration options are highly influenced by vertical separation distance between the production zone and drinking water resource, the physical characteristics of rock formations between the drinking water resource and production zone and the presence, distance and condition of nearby wells; d. HF fluid has been known to migrate between a production well and a nearby oil or gas well, which is referred to as "well communication events" or "frac hits"; e. The Well File Review (U.S. EPA, 2016a) indicated only 1% of wells experienced a frac hit and the spills report (U.S. EPA, 2015) indicated 10 spills attributed to well communication events. It is not known whether any fluid from these spills actually ended up in a drinking water resource; f. When any well communication events occur between a production well and any nearby active wells, it can be mitigated by shutting the affected nearby well in temporarily in order to reduce damage to their wells and the likelihood of spills; g. It has been determined that the probability of frac hits decrease as the distance between wells increase. One study indicated that the possibility of a frac hit is less than 10% in HF wells when the distance between them is more than 1 219 m but nearly 50 % when the distance is less than 300 m; h. Nearby wells in good condition will be able to withstand pressure better than wells with a poor well construction; i. Areas with a high frequency of abandoned wells, some of which have not been plugged properly, are more susceptible to possible occurrences of well communication events; j. Estimations of the amount of wells that was drilled prior to formal regulation is about 1 million and information regarding their status and location are unknown; k. Fluid migration between wells imply that any contaminant is able to bypass layers of intervening rock but even if this pathway does not exist, it could be possible for contamination of drinking water resources if the vertical distance between the production zone and resource is small; l. Davies et al. (2012) found that upward vertical fracture growth quite often was in the order of tens-to-hundreds of feet. A maximum fracture height of 588 m was recorded, while 1 % of fractures had a height of more than 350 m. A large vertical separation could prevent fluid migration. The study was only done in shale formations and it is necessary to note that fracture extension is not the only way drinking water resources can be contaminated from out of zone fractures; m. Numerical analysis (Kim and Moridis, 2015) suggested fractures not likely to extend all the way from production zone to shallow drinking water resources in a deep environment like the Marcellus shale; n. Other permeable subsurface geological features e.g. fault zones and fractured zones can connect with out-of-zone fractures, associated with HF, and act as link between them and a drinking water resource. This highlights the importance of the physical properties of intervening rock formations. During a study by Digiulio and Jackson (2016) in the Pavillion gas field in Wyoming, they observed upward flow at localised areas while subsurface fluids generally flow in a downwards direction; o. Cases where HF is done where no vertical separation exists between a production zone and a groundwater resource have been recorded but this is associated with Coal Bed Methane (CBM) plays and not really of importance in shale gas plays. It was recommended that this is unacceptable and poses too much a risk to groundwater resources over the short as well as long term; and p. Gas occurring in the subsurface can migrate along pathway #1 as well as pathway #2 due to its lower comparative density against

Stage in hydraulic fracturing water cycle	Factors affecting the frequency and severity of impacts
	fluids. This implies that groundwater resources can much easier become contaminated by gases e.g. methane (Li et al., 2016); 5. Very little-to-no data is available on factors that can influence the severity of impacts during the well injection phase of HF activities; 6. It is likely that factors such as the chemical composition of the fluid, volume, the delivery duration into the drinking water resource and the concentration of the fluid together with its specific components, will play a significant role in the severity of the spill; and 7. Pathway #1 is expected to yield the highest fluid volume migrating over the shortest time period, while pathway #2 will most likely result in lower volume and longer travel times. Although slower and being less in volume even pathway #2 can lead to severe impacts due to limited or non-detection and if left unaddressed.
Wastewater disposal and reuse thereof	1. This is the last stage in the HF water cycle and in the USA produced water is primarily disposed of in Class II wells; 2. Other methods of disposal include: a. Discharge to surface waters; b. Disposal in pits or evaporation ponds; or c. Reused in other HF operations. 3. Two identified activities that will impact on drinking water resources are: a. The discharge of inadequately treated wastewater to surface water; and b. The storage or disposal of wastewater into unlined pits or impoundments, which could influence both surface and groundwater resources. 4. Only produced water stored in pits or impoundments are considered to be able to contaminate groundwater resources; 5. Infiltration into soils from spills or overflows and percolation from pits through the underlying strata are considered to be the main mechanisms of groundwater contamination; 6. Lining of pits and impoundments is extremely important to minimize the frequency as well as severity from wastewater disposal and reuse activities; 7. If not monitored by regulators unpermitted unlined storage or disposal pits exist. Surveys by the California State Water Resources Control Board (SWRCB, 2016) and recommendations made on model criteria for groundwater sampling and testing (Esser et al., 2015) recorded about 1 000 unlined storage or disposal facilities in the Central Valley Region of California. 60 % of these were still being used since July 2016 and approximately 20% lacked the required permits (CA Water Board, 2016); 8. Organics e.g. benzene, toluene, ethylbenzene and xylenes (BTEX) as well as some others have been linked to unlined facilities in California and New Mexico; 9. High salinities (3 500 – 25 600 mg/l) down gradient of an unlined pit in Oklahoma as well as volatile organic compounds have been recorded (Kharaka et al., 2002); 10. Even disposal of wastewater with a low total dissolved solids (TDS) can cause severe impacts (Healy et al., 2008). High concentrations of TDS, chloride, nitrate and selenium was recorded in groundwater at a CBM wastewater impoundment in Wyoming's Powder River Basin. TDS concentrations exceeded 100 000 mg/l in one groundwater sample although concentrations from the wastewater that was discharged from the impoundment only measured 2 300 mg/l (Healy et al., 2011). It was concluded that the majority of solutes did not originate from the CBM wastewater but was a result of dissolution of previously existing subterranean salts and minerals. 11. Lined pits or closed-loop systems are important to decrease the frequency of impacts associated with wastewater disposal and reuse.

2.3. Canada

The Council of Canadian Academies released a report: "*Environmental Impacts of Shale Gas Extraction in Canada*" in 2014 and Chapter four that deals with water issues is focussed on groundwater due to the impacts of shale gas development being the most uncertain and controversial within this realm (Council of Canadian Academies, 2014). Most peer-reviewed studies seem to be focussing on groundwater as well.

Chapter four in the Canadian report deals with water and is expanded into the following sub-sections:

- Overview of potential groundwater impacts;
- Chemicals used in HF;
- Subsurface contamination pathways
- The assimilation capacity concept;
- Impacts of natural gas on shallow groundwater quality;
- Surface water concerns;
- Water use;
- Limits in knowledge and scientific understanding; and
- Conclusion.

The overview section is initiated by establishing the delineation of three zones of groundwater occurrence (Figure 6):

- The Fresh Groundwater Zone (FGWZ);
- The Intermediate Zone; and
- The Deep Zone.

These three zones are discussed in Section 2.3.1.

2.3.1. Water concerns

The depth to which the FGWZ reaches is undefined but is estimated at between 100 and 300 m below surface with maximum depths of up to 600 m in certain instances. Groundwater quality is considered potable or can be made potable by little effort and treatment. Chemistry is also used to define the depth of this zone for instance in Alberta this boundary is considered as the depth at which the maximum concentration of TDS reaches 4 000 mg/l. Due to the heterogeneous nature of geological formations between regions as well as differences in groundwater flow systems, natural groundwater chemistry varies considerably. Impacts due to shale gas activities are therefore challenging and present different challenges in different locations.

To be able to define the Intermediate Zone, it is first necessary to explain the concept of the Deep Zone. The Deep Zone has no actual scientific meaning or delineation. It is considered to include rock formations that include shale beds that can be targeted for gas extraction by means of HF. Between the FGWZ and the Deep Zone lies the Intermediate Zone. In this zone groundwater is brackish to saline and some formations may contain entrapped gases without any commercial value.

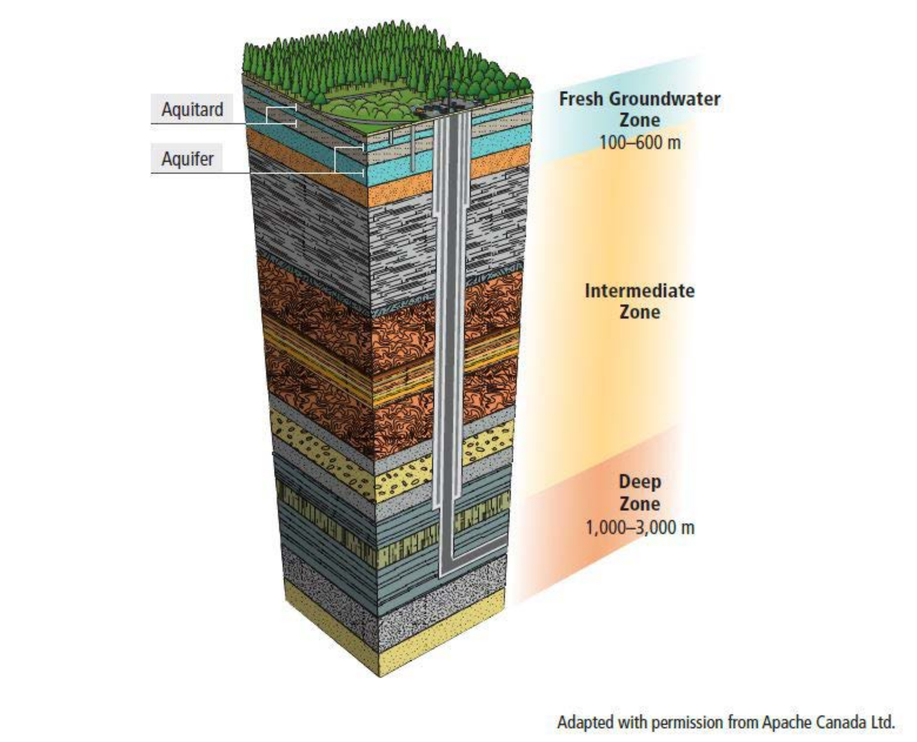

Figure 6: Depth terminology – schematic of a shale gas well illustrating the meaning of the terms Fresh Groundwater Zone, Intermediate Zone and Deep Zone (Council of Canadian Academies, 2014)

Threats to shallow fresh groundwater resources can be forthcoming from two sources of contaminants:

- Sources at land surface; and
- Sources from below the fresh groundwater resource.

Primarily pathways through which anthropogenic chemicals can reach groundwater are from accidental surface spills at shale gas pads where chemicals are stored to be used during HF activities or along transportation routes. Flowback water is another source for possible groundwater contamination from natural occurring contaminants or HF chemicals. It is stored and handled as well as recycled on surface and only removed when HF operations are finished. Flowback water is extremely saline and contains HF chemicals and natural contaminants from different formations it has come into contact with.

The Canadian O&G industry assesses impacts in two categories:

- Upstream impacts; and
- Downstream impacts.

Upstream activities are associated with exploration and production activities, while downstream impacts are considered to originate from refining and distribution activities. Upstream impacts on groundwater have been researched and assessed less than satisfactorily and it has become evident that this category of impact has been neglected by government and academia.

It is expected that the intensity of groundwater use may only become important in some areas after a relative long period of time has lapsed since shale gas development. Shale gas activities can also be considered as too recent for any contamination to be detected. Due to this, it was recommended by Jackson et al. (2013) that all upstream O&G activities should be considered as indicators of possible impacts from shale gas development, as they all have lifespans of decades or longer.

Table 3 summarises Chapter four dealing with water, Chapter six with specific reference to groundwater monitoring and Chapter ten that includes conclusions of the report that was prepared for the Council of Canadian Academies (Council of Canadian Academies, 2014).

Table 3: Summary of relevant water chapters – adapted to focus on groundwater issues, (Council of Canadian Academies, 2014)

Concern	Discussion
Overview of potential groundwater impacts	1. Shale gas impacts on groundwater can be considered in terms of: a. Range of contaminants; b. Different approaches; c. Various methods; and d. Groundwater conditions. 2. Contaminant types associated with HF covers a wider range and can be considered more toxic than those involved with the conventional oil and gas industry; 3. Natural contaminants from the host rock can also migrate to surface as part of the flowback after a fracking or stimulation event; 4. While well pads are considered as storage sites for hazardous chemicals during HF operations and appropriate measures put in place to prevent or mitigate any spills, current regulations do not classify produced water as hazardous; 5. Recalcitrant contaminants – contaminants not degrading effectively during natural processes – has the potential to migrate off-site into shallow groundwater sources: a. It is however acknowledged that not all effects due to recalcitrant HF chemical migrating off-site are significant; and b. It is also pointed out that some of these chemicals is undetectable by existing methods of analysis. 6. Groundwater flow is slow, which has the effect that it could take decades or even longer for any recognition of recalcitrant chemicals contaminating a resource; 7. Monitoring and analytical techniques at and around well pads were also inadequate in detecting emerging contaminants and only when a related public health issue was confirmed, were these issues addressed; a. This requires impacts of shale gas on groundwater to be considered in the context of decades, even centuries; and b. Impacts not even currently identified or observed should be anticipated because a search for evidence thereof is lacking. 8. A number of different pathways have been identified through which groundwater contamination may occur. These pathways can be grouped by sources which include: a. **Pad sources** – These sources include temporary or permanent vehicles, structures, buildings, storage dams or ponds, storage facilities for hazardous chemicals and/or lubricants and ablution facilities; b. **Non-pad infrastructure sources** – Some instances e.g. where only slickwater stimulations are done, where the stimulating fluid is approximately 99 % water, requires infrastructure that includes pipelines on surface or roads to allow for water to be brought to site or to remove waste fluids. Other types of infrastructure include water treatment facilities, storage tanks or ponds and in certain areas with suitable geological conditions, injection wells for disposal of surplus flowback water. Risks due to this infrastructure include: i. accidental spills of chemicals, oils, drilling muds, and fracture fluids during transportation, storage, or use; ii. spills of condensates (where these are present) or flowback water from the producing well; and iii. inadequate storage, treatment, or disposal of flowback water, which includes both fracturing fluids and saline formation water, and leaks from surface storage ponds or other storage facilities. c. **Deep sources** – These can be regarded as any source situated below the FGWZ and can be located within the

Concern	Discussion
	Intermediate zone on which research is limited to hydrocarbons and salinity characteristics or the deep gas bearing target zones. Technologies do exist to study the Intermediate zone but it has been neglected due to it being considered as only being a "passing through" zone in the HF industry. 9. It is noted that even with claims of "*more than a million hydraulic fracturing treatments…with only one documented case of direct groundwater pollution resulting from injection of hydraulic fracturing chemicals used for shale gas extraction*." There are private well owners in the USA that lodged claims against the HF industry who had their water supply replaced and losses compensated (Dutzik and Ridlington, 2012; Vidic et al., 2013); 10. Peer reviewed research into environmental impacts are heavily impeded due to confidentiality requirements and the severely expedited expansion of the HF industry. Limited funding exacerbate this trend. 11. The settled claims mentioned in 9 above have not been evaluated or assessed by government agencies or academia to determine the characteristics of impacts on domestic well water quality or the magnitude of the impacts; a. Considering the above, the following three issues are highlighted: i. No sufficient data to evaluate claims (for and against) contamination due to HF have been collected; ii. In order to understand the various possible pathways of contamination that may occur in future, sufficient data needs to be collected. This have not been done; and iii. The time frame to judge potential long term, cumulative impacts has been inadequate. 12. Of particular interest is the role the Intermediate zone below the FGWZ plays as not a lot of information is available: a. From a geological perspective the Canadian Intermediate zone consists of: i. Strata of fractured shale beds interlayered with other rock types that include sandstone, siltstone, limestone and dolostone; ii. It exhibits porosities and horizontal and vertical permeabilities across a large range; and iii. Detailed geological and geochemical characteristics have been poorly characterized due to its unimportance to the HF industry. b. If pathways exist within the shale layers, gas may migrate upward due to buoyancy or excessive pressure, potentially impacting upon the surrounding environment; c. These pathways are considered to have weak inter-connectivity and a greater source of concern is pathways associated with poor or missing cement seals along the wellbore; d. Migration of gas is considered a more likelihood than brine or saline water due to its buoyancy and the higher density of saline solutions; e. Isotopic tracing is suggested to confirm the origin of any stray gas observed during monitoring; f. Without establishment of baseline of dissolved or free natural gas in shallow groundwater it would be very difficult to determine if shale gas development is responsible for its presence; g. Even with depth of origin being determined it would be difficult to identify a clear pathway due to the complexity of natural subsurface fracture systems; h. Contamination might well go undetected due to non-existing monitoring and sampling of domestic wells, dedicated monitoring wells or other borehole sampling devices; i. It is suggested that the vertical hydraulic gradient of the layer of lowest vertical permeability will control migration rates but determining vertical permeabilities is technologically challenging;

Concern	Discussion
	j. The concept of effectively impermeable rocks in a shale gas environment should be very carefully considered as cross connection as a result of leaky well seals, abandoned wells and fluid along faults could enable migration; k. The ubiquitous nature of fractures within the subsurface environment adds to the uncertainty factor with regard to possible migration pathways. It is assumed that fracture apertures will be tight or closed at depth due to overburden stress but hydraulically active and fractured reservoirs have been recorded extensively in petroleum geological environments (Bjørlykke, 1989) l. The biggest risk for gas or fluid migration out of the production zone through existing faults and fractures occurs: i. During the stimulation process when pressure in the system is highest and new flow paths are opened; or ii. If a well is closed off indefinitely (shut-in) directly after fracturing has occurred because this allows the pressure to increase. m. Once production starts, the system is allowed to depressurise and gas and fluids follow the path of least resistance towards the wellbore and the risk of migration along natural pathways that might not be monitored becomes less; n. Due to its economic insignificance, facets of fracture formation and properties remain vague and it is unknown territory poorly understood; o. Initially, the significance of fluid migration along fractures and its associated contamination of groundwater was severely underestimated for certain types of contaminants e.g. chlorinated solvents (Kueper et al., 1992); p. Studies at the U.S. Geological Survey indicated hydraulically active fractures within low permeability rocks, which are mostly responsible for regional scale permeabilities of these rocks (Neuzil, 1986, 1994); q. Two primary methods have been identified as possible enhancemers of gas migration along fractures or faults due to HF activities: i. Development of pathways, through sections of the Intermediate zone because of cross connections, to leaky wells; and ii. Stimulation of minor earthquakes by HF or small deformation within the host rock, which could cause features to slip and activation of upward gas leakage along faults.
Chemicals Used in Hydraulic Fracturing	1. The shale gas industry is well known for its lack of transparency when it comes to declaring the exact chemical constituents in HF additives; 2. This has led to numerous jurisdictions requiring full or substantial disclosure; 3. Although some companies adhere to the full disclosure principle, many others claim proprietary rights and recipes should be protected as trade secrets; 4. In determining potential impacts and to be able to design effective monitoring strategies for both surface and groundwater systems: a. The exact chemical composition of HF additives is required; b. Toxicity assessments need to be conducted; and c. Persistence and mobility tests need to be carried out. 5. Surface spills of chemicals is a reality and of great concern as potential contamination source of surface as well as groundwater; a. The shale gas industry uses much greater volumes of water than the conventional O&G industry and if their performance

Concern	Discussion
	are used as benchmark, impacts from surface spills should be rating high on the risk assessment criteria.
Subsurface Contamination Pathways	1. Three major pathways are identified: a. Vertical fractures created by HF; b. Existing anthropogenic conduits; and c. Faulty practices during drilling or stimulation. 2. Studies indicated multiple contaminant pathways in numerous investigations; 3. According to Warner et al. (2012) there are evidence of existing pathways between deep shale formations and shallow drinking water aquifers unrelated to shale gas development; and 4. Baseline data, if they had any, would not be able to differentiate between pathways due to HF activities or natural existing pathways.
The Assimilation Capacity Concept	1. This concept relates to the issue of not whether groundwater impacts occur, but if they are significant to become unacceptable; 2. The term “Assimilation capacity” postulates that the groundwater zone has the capacity to assimilate contaminants to purify water; 3. Favorable conditions will result in a resilient environment being able to “renew” groundwater quality within an acceptable distance or volume over time; 4. The FGWZ could be a zone in which rejuvenation could occur; 5. In the long term, a high sub-terrain assimilation capacity could be the only factor preventing leakage from shale gas wells; and 6. No literature is available that contains an impact analysis that formally recognizes “assimilation capacity” in a natural gas context.
Impacts of Natural Gas on Shallow Groundwater Quality	1. Poor cement jobs may result in gas leakages along the annulus; 2. This problem is not just an issue in the shale gas industry but are observed in the natural O&G industry as well; 3. Impacts of natural gas has not been confirmed in field investigations; 4. Duke University researchers found that gas wells within 1 km of shale gas production activities yielded methane concentrations six times higher than wells situated at greater distances; and 5. Another study however concluded that topography and groundwater chemistry should rather be used to correlate with gas concentrations and not shale gas extraction.

2.4. Conclusions

Internationally it is very difficult to quantify environmental impacts specifically on shallow groundwater resources due to a lack of information. No baseline information is available and many claims could not be validated due to this issue. In South Africa we have an opportunity to address this information gap that exists in the USA and Canada and it is critically important that regulators and government see to it that a database be created before any licences are awarded.

The most important issues that were identified by research reports in the United States and Canada, that would have a significant bearing on possible impacts in the Karoo Basin include:

1. Local balance between water withdrawals and availability. Abstraction volumes should not only be the only criteria to be considered but balance between water withdrawals and availability in place and time should also be considered
2. Surface spills are the major incident associated with surface as well as groundwater contamination;
3. Spills reaching the groundwater environment are considered to be more severe than those reaching surface water;
4. Fractured rocks and karst environments have the potential to facilitate a higher infiltration rate via preferential flow paths;
5. Installation of groundwater monitoring boreholes is expensive and very often neglected, which causes contamination of groundwater to go undetected;
6. Two fundamental pathways are potentially responsible for migration of contaminants with the potential to affect drinking water resources:
    a. Pathway #1 - migration due to defective in well casing and/or cement; and
    b. Pathway #2 - migration through the induced fracture network.
7. Very little to no data is available on factors that can influence the severity of impacts during the well injection phase of HF activities;
8. It is likely that factors such as the chemical composition of the fluid, volume, the delivery duration into the drinking water resource and the concentration of the fluid together with its specific components, will play a significant role in the severity of the spill;
9. Pathway #1 is expected to yield the highest fluid volume migrating over the shortest time period, while pathway #2 will most likely result in lower volume and longer travel times. Although slower and being less in volume even pathway #2 can lead to severe impacts due to limited or non-detection and if left unaddressed;

10. If pathways exist within the shale layers, gas may migrate upward due to buoyancy or excessive pressure, potentially impacting upon the surrounding environment;
11. Three major pathways are identified:
    a. Vertical fractures created by HF;
    b. Existing anthropogenic conduits; and
    c. Faulty practices during drilling or stimulation. and
12. In determining potential impacts and to be able to design effective monitoring strategies for both surface and groundwater systems:
    a. The exact chemical composition of HF additives is required;
    b. Toxicity assessments need to be conducted; and
    c. Persistence and mobility tests need to be carried out.

From the above it is clear that most of the possible ways that shallow aquifer contamination can become a reality, have already been identified internationally. Their lack of baseline information as well as incorrect monitoring methodology have allowed the HF industry to be able to argue that no conclusive evidence exists that they are responsible for any shallow aquifer contamination. Settlements between industry and some claimants were also handled as sensitive with non-disclosure agreements between the parties, which is indicative that decisions and agreements are not driven by any concern for the environment but rather with a focus on financial gain or losses.

Transparency as well as regulatory requirements would be absolutely critical in a decision whether a HF industry should be allowed in the Karoo Basin.

3. SOUTH AFRICAN CONTEXT

3.1. Introduction

One of the main criticisms against HF in South Africa is that it would impact on groundwater resources that are being utilized by farmers and local communities for potable water supply in an already water-stressed Karoo, which is an extremely valid argument when viewed against the background of the current water crisis experienced throughout the country.

Water availability is going to change drastically over the next ten years in Southern Africa and specifically South Africa according to predictive mapping using the Aqueduct Water Risk Atlas (Figure 7). The scenario depicted in Figure 7 does not take into account any additional stress on the system, but reflects a business as usual scenario.

Any increase in stress on the overall water budget will undoubtedly have an effect on groundwater availability due to the decrease in potential recharge. From the map it is also evident changes in water stress within the area of possible HF activity range between arid areas with low water use to areas with extremely high water use. This would influence the risk assessment and decision-making tool output for specific localities.

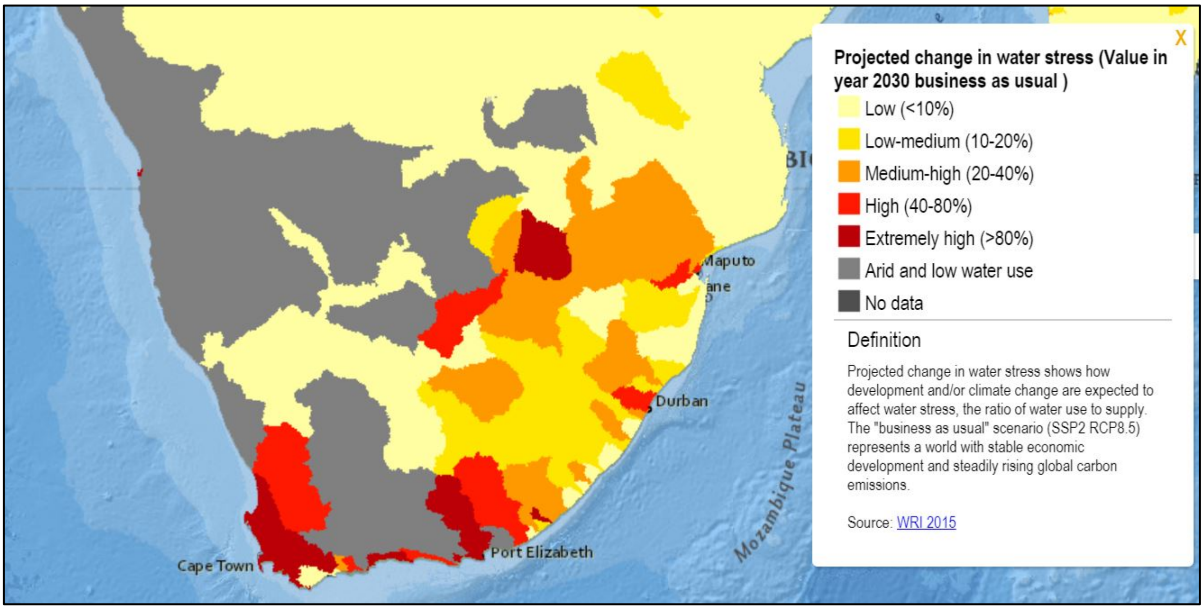

Figure 7: Projected change in water stress for Southern Africa (business as usual scenario - http://www.wri.org/applications/maps/aqueduct-atlas/)

From the same source, a map for groundwater stress in the same areas was developed (Figure 8) and stresses range from low to medium and medium to high with a very large portion where no data is available, which can be related to the importance of establishing baseline information by means of a well-planned monitoring system.

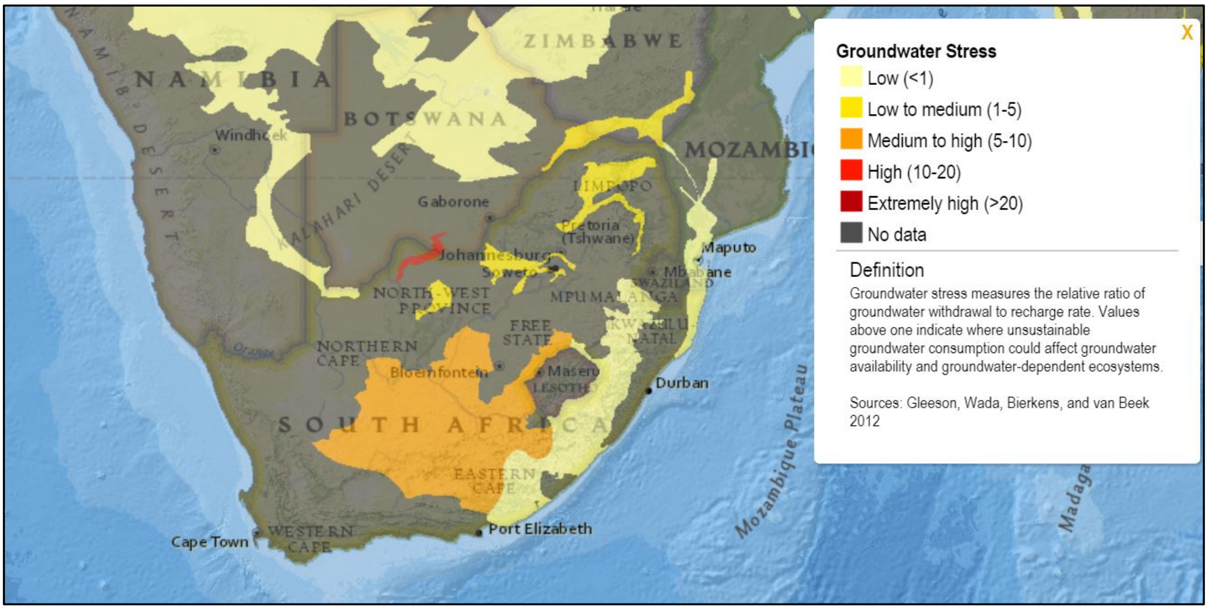

Figure 8: Current groundwater stress for Southern Africa
(http://www.wri.org/applications/maps/aqueduct-atlas/)

3.2. South Africa – Unique situation

Most of the estimations, predictions and potential impacts on groundwater due to HF is based on incidents and observations from a USA perspective and while some issues are analogous and can be used to assist in decision making, there are other distinct differences that are unique to the South African environment. In essence it can be summarised by the following:

- Water availability;
- Different geological setting;
- Possibility of an upward gradient at certain localities;
- Very little available information to depths greater than 300 m; and
- Opportunity.

The lack of knowledge regarding the issues mentioned above, can be regarded as an indicator of the low confidence in possible conceptual scenarios and the potential impact on groundwater resources. To be able to make informed decisions it would therefore be advantageous to consider each component carefully and develop proper methodologies supported by practical solutions to assess all aspects related to groundwater governance and management.

The current situation in South Africa is that a lot of noise is being made from different perspectives and role players based on very little knowledge and information. The main driver behind this uncertainty is probably the fact that all shale gas potential estimates have been done on paper without any exploration information being available. All efforts up to now is a kind of “cart in front of the horse” scenario. Some considerable budgets and time have been spent on evaluating possible potential, risks and outcomes without gaining any knowledge regarding the existence of a viable resource. Recent studies by academics indicate that the area in which shale gas production could be feasible is much smaller than the area that was used in initial calculations of resource potential (Chere, 2015; Cole, 2014). Other studies that extracted fresh core from the target formations yielded variable results and indications are that original estimates may have been much too high but that “sweet spots may exist where the target formation is at depths exceeding 1 500 m, has a vitrinite reflectance of less than 3.5% and contains less than 20% dolerite (De Kock et al., 2017).

One positive aspect of the sparsity of reliable information is that it opens up opportunities for research on the deep geohydrology of South Africa. One example that should trigger a positive response from state departments and research sponsors is the surprisingly good water quality that was encountered at depth when the KZF-01 borehole was drilled near Ceres as part of the CIMERA project. Who knows what other potable water reservoirs might exist at depth?

3.2.1. Water availability

Average water requirements for the HF process is estimated between 7 450 m^3 (ASSAf, 2016) and 10 500 m^3 (CSIR, 2016) per well, including drilling and HF activities. As none of the O&G companies have been able to indicate the scale of their operations, it is very difficult to estimate the volume of water that will be required should the licences be awarded.

Possible sources of water for HF activities can broadly be divided into two categories:

- Surface water; and
- Groundwater.

Depending on the location of a specific HF well pad, surface water can be:

- Piped; or
- Transported.

Groundwater sources can be identified during the exploration phase of HF activities and the target should be more saline aquifers situated at depth. Any potable resource that is encountered during these investigations should be reported and assessed by an independent institution to determine its size and potential. This would most likely also flag this specific location as a sensitive area for any HF activity, which would require additional levels of investigation before HF should be considered.

3.2.2. Geology

The South African geology associated with the areas over which most of the shale gas exploration licence applications fall can be considered as a totally different environment than most of the productive international shale gas plays. Within the Karoo Basin numerous intrusive rock structures occur, which in turn could influence the physical characteristics of the groundwater environment (Figure 9). These dolerite intrusions are of a much younger geological age than the sedimentary host rock formations and it has been observed that conditions during the cooling process will influence the contact zones between the dolerite and the sedimentary rocks.

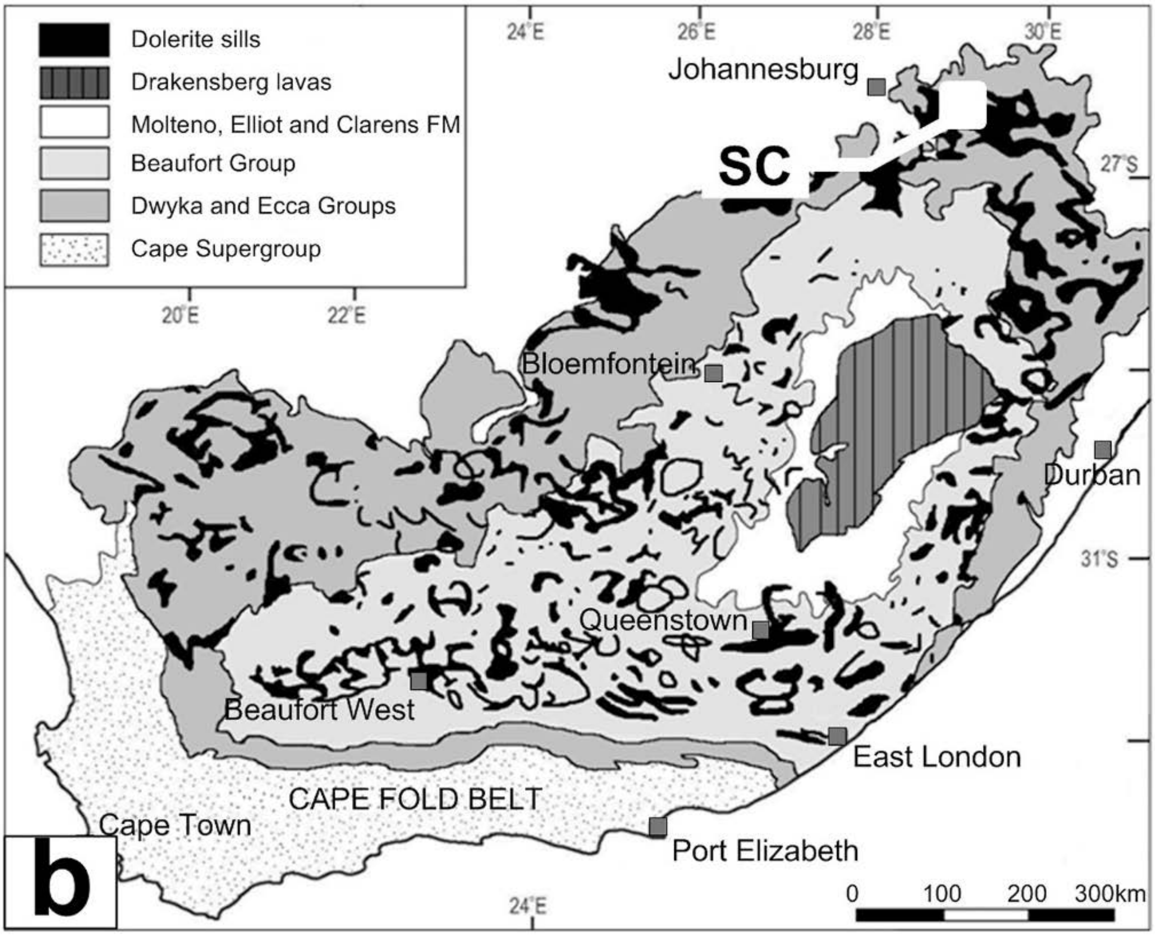

Figure 9: Schematic overview map of the main Karoo Basin showing the distribution of Karoo sediments and dolerite sills/saucers (Chevallier and Woodford, 1999)

Contact zones are usually targeted for groundwater abstraction due to the increased probability of zones with higher permeability being present due to these cooling processes. High temperature as well as high pressure conditions before the cool down period allows for the sedimentary rocks to be baked/metamorphosed and fracture development can occur when the magma cools down. Depending on aperture size within this fracture zone as well as interconnectivity between different fracture zones, the yield of a shallow groundwater borehole can be substantial as well as sustainable (Botha et al., 2002). This dual nature of crystalline igneous rocks in which primary porosity is tight but fracture networks do exist, causes unpredictable groundwater flow patterns due to their ability to form tight sealing, impermeable barriers under certain conditions (Thomaz Filho et al., 2008), highly permeable pathways at other times (Mège and Rango, 2010) and sometimes even both (Rateau et al., 2013).

Kimberlite intrusives have also been identified as structures along which preferential pathways may occur and this can be seen from the high influxes into the larger diamond mines e.g. Finch Mine in the Northern Cape Province (Silverton and Morton, 1994).

Factures along fault zones are responsible for many high-yielding abstraction boreholes in South Africa and concerns have been raised about these geological structures being able to allow any possible pollutants to migrate along these apertures to shallow aquifers. It has been observed that fault zones can increase or decrease permeability of rock formations and more research will be required to fully understand possible impacts from these structures at depths beyond 1 500 m.

Another geological occurrence that has been identified as a role player in potential impacts that might be associated with HF operations is the presence of seismic activities. Since 2000 there have been 84 occurrences of seismic events ranging between 0.3 M_L and 3.6 M_L. The possibility of a seismic event having a negative effect on well integrity has also been included in arguments by individuals and institutions that are against HF.

Assessments need to be made using accurate information and the importance of a sound knowledge of South African geology and its phenomena should be considered as extremely important when methodologies are developed to measure or calculate parameters that can influence its effect on HF activities.

3.3. Hydraulic head - Artesian conditions vs. Geostatic pressure

Various terms describing the level at which the water surface in an open borehole or well is measured exist, each with its own implication. One must understand that due to the hydraulic component inherently being part of any geohydrological concept, any measurement of a water level in a borehole represents a pressure or pressure head. This is why it would be important to develop regulations and guidelines, specifying how pressure measurements are obtained, in order to have an accurate level to which groundwater will rise in a specific aquifer system, which in turn will assist in determining risks associated with contamination migrating along these pressure gradients.

The Karoo Basin developed due to the reshaping of the continental interior of Gondwana where subsidence due to vertical motion of inelastic basement blocks and intervening crustal faults occurred (Tankard et al., 2009). Within this basin there are many occurrences of boreholes where artesian flow occurs. In many instances some boreholes only became artesian after a period of time has elapsed, while others have exhibited the opposite behaviour.

Artesian flow is considered to occur when the aquifer is under confined conditions with a recharge zone/area at a higher elevation than the topographical elevation of a borehole. If a borehole is drilled through the impermeable confining layer, the pressure gradient will force groundwater to either exhibit a piezometric level at a higher elevation than the water strike or if the pressure gradient is large enough, groundwater will flow freely from the borehole onto surface (Figure 10).

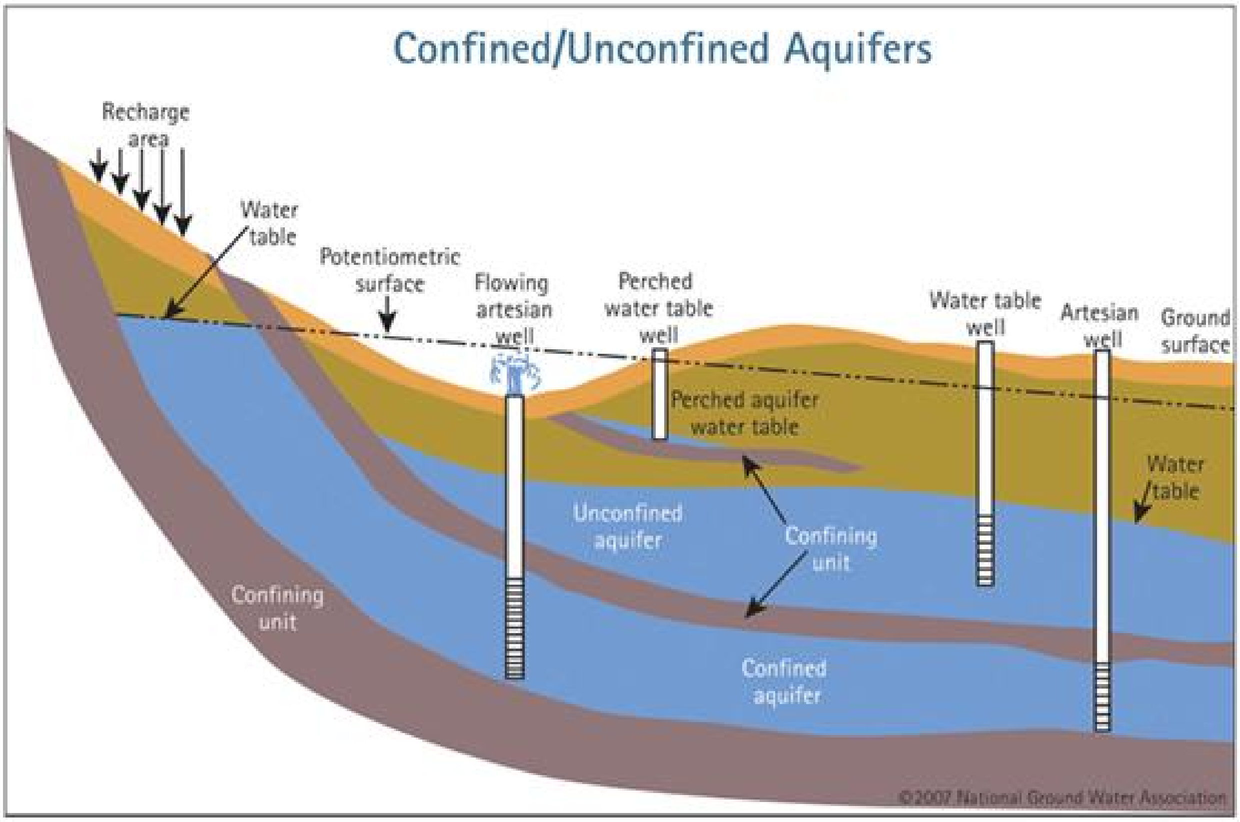

Figure 10: Image depicting difference between unconfined/confined and artesian flow (NGWA, n.d.)

Geostatic pressure can be considered the pressure that forces water contained within a certain geological setting to move, in other words potential energy is converted into kinetic energy due to a release in pressure on the system. In the case of a borehole or well being drilled the obvious direction would be upward towards surface.

The difference between geostatic pressure and artesian flow conditions are that the effect of groundwater movement due to geostatic pressure will at some point in time reach equilibrium and flow from the borehole/well will stop. Under artesian conditions, flow should continue for much longer and will continue as long as the pressure gradient between recharge zone and borehole/well is maintained. Artesian flow conditions will therefore be influenced by:

- Climatic conditions – Recharge volumes;
- Physical characteristics of the environment – Geological properties;
- Hydraulics – Pressure gradient; and
- Biological conditions – Biota has been recorded to be responsible for obstructing fracture apertures.

3.4. Fractured aquifer systems

Aquifers in the Karoo Basin environment is predominantly fractured systems with unique characteristics and properties, which makes it challenging to estimate sustainable yields of boreholes within these aquifers. This led to development of a Pump Test Manuel in a joint venture between the Institute for Groundwater Studies (IGS) and the WRC.

As part of this research project it became clear that although many analytical solutions exist, a certain amount of experience is required to make use of the different options to arrive at a sensible answer. Field data does not always fit in with theoretical results due to many assumptions being made with theoretical development of analytical solutions.

This once again underlines the importance of including a qualified geohydrologist with experience in the team that will be evaluating possible groundwater impacts associated with HF.

Research on flow velocities along fractures was done in the late 1990's in which the author of this thesis has been part of. Flow velocities of hundreds of meters per day were measured and in some instances even on a kilometers per day scale.

If a pressure gradient exists along which a pollutant can rise to surface in association with interconnected fractures with large enough apertures, any impact to shallow groundwater resources can occur at an alarmingly fast rate. Then the only defense between the HF system and shallow aquifers would be the casing/cement sequence around the gas well, which highlights the importance of monitoring the HF system continuously to have forewarning of any drop in pressure.

Determining fracture extent and interconnectivity is going to prove challenging for the HF industry in the Karoo environment and any applicant must show that they have sufficient capacity as well as sound methodology to be able to gather high quality data in order to deliver a conceptual model that will allow for accurate calculations and estimations.

The extent to which fracture geohydrology at depth can be researched and assessed will determine whether HF in our Karoo Basin should be allowed.

3.4.1. Flow velocities

Tracer tests along fractures in Karoo formations yielded variable results. On the campus of the University of the Free State (UFS), results yield a flow velocity of 54 m/day along a bedding plane fracture (Van Wyk, 1998). At Windhoek in Namibia a flow velocity of 5.18 km/day was measured in a fractured aquifer in a quartzite environment (Van Wyk et al., 2000) and more closer to home in the Beaufort West area, a tracer test along the Hansrivier Dyke yielded a flow velocity of 968 m/day (Van Wyk and Witthueser, 2011).

These tests were done in fractures that can be considered as near surface when compared with depths associated with HF activities.

At the moment there is no information available that can be used to calculate or estimate what can be expected in fractures at depths greater than 2 000 m. An attempt has been made in Chapter five to model three different scenarios in order to come up with some idea of what can be expected.

3.5. Opportunity

Even though possible groundwater impacts, especially with the current sparsity of reliable information, should be approached with caution, a healthy degree of objectivity should be part of the decision-making process. While HF is a new field of investigation in the South African context, mining has been the backbone upon which its economy has been built. Thousands of exploration boreholes have been drilled into the South African subterranean environment with minimal effect on the surrounding environment. Environmental and groundwater issues only become evident once mining activities start.

It is therefore necessary to point out that although actual HF, where subsurface geological zones are stimulated with a mixture of water, sand and chemicals under high pressure, has not been done in search of shale gas production, it was utilised by the Department of Water Affairs in the early 1990's to improve borehole yields by what was termed by Mr Bill

Williamson as “hydro jacking”. This process involved only water being forced into fractures under high pressure, which has the resultant effect of the apertures opening up and being kept open by natural ridges in the formation, improving the permeability of the fractured system (Less, 2019 – personal communication).

The possibilities for scientific research on deep groundwater systems in the Karoo should not be missed out on.

3.6. Status quo – Baseline information

An independent project sponsored by the IGS was done in an attempt to initiate a database of baseline information across the Karoo. The researcher was responsible for project management and supervised an M.Sc. student with the aim of developing a monitoring strategy and sampling protocols specific to HF activities in the Karoo Basin of South Africa.

All data collection, quality control and interpretation were guided by the researcher and a substantial document was the result of quite an extensive database covering a large area across the Karoo Basin.

Objectives to reach the aforementioned aim included:

- Establishment of a baseline data set against which arguments and different viewpoints can be tested before any hydraulic fracturing activities are allowed in the Karoo region of South Africa;
- Carrying out of a literature review in order to highlight all hydraulic fracturing aspects e.g. groundwater, geology, methane occurrences and to review existing sampling protocols and monitoring strategies;
- Characterising groundwater from specific areas based on their macro elements, trace and heavy elements as well as stable isotopes;
- Providing information on the groundwater levels, estimated yields and occurrences of methane at selected borehole locations;
- Evaluation of overall chemical and physical properties of the fieldwork results; and
- Interpreting fieldwork result to develop a long-term monitoring strategy for the HF industry within a South African context.

Nine areas were identified and fieldwork was carried out after attending numerous farmer union meetings at which our project was introduced and the purpose of our research explained. With one or two exceptions most farmers willingly participated and were essential in our ability to conduct field surveys and measurements.

The survey area was vast extending from Murraysburg in the north east part of the Western Cape Province to the Tankwa area in the west (Figure 11).

The farmers unions included in the research were:

- Murraysburg;
- Nelspoort;
- Rietbron;
- Nuweveld;
- Koup 4;
- Letjiesbos;
- Merweville; and
- Laingsburg.

The Tankwa area formed part of another project on which the IGS was requested to conduct a baseline geohydrological investigation before a deep borehole was drilled by the Centre of Excellence for Integrated Mineral and Energy Resource Analysis (CIMERA) on the Karoo Research Initiative (KARIN) project. CIMERA is hosted by the Department of Geology at the University of Johannesburg (UJ) and co-hosted by the School of Geosciences at the University of the Witwatersrand (Wits).

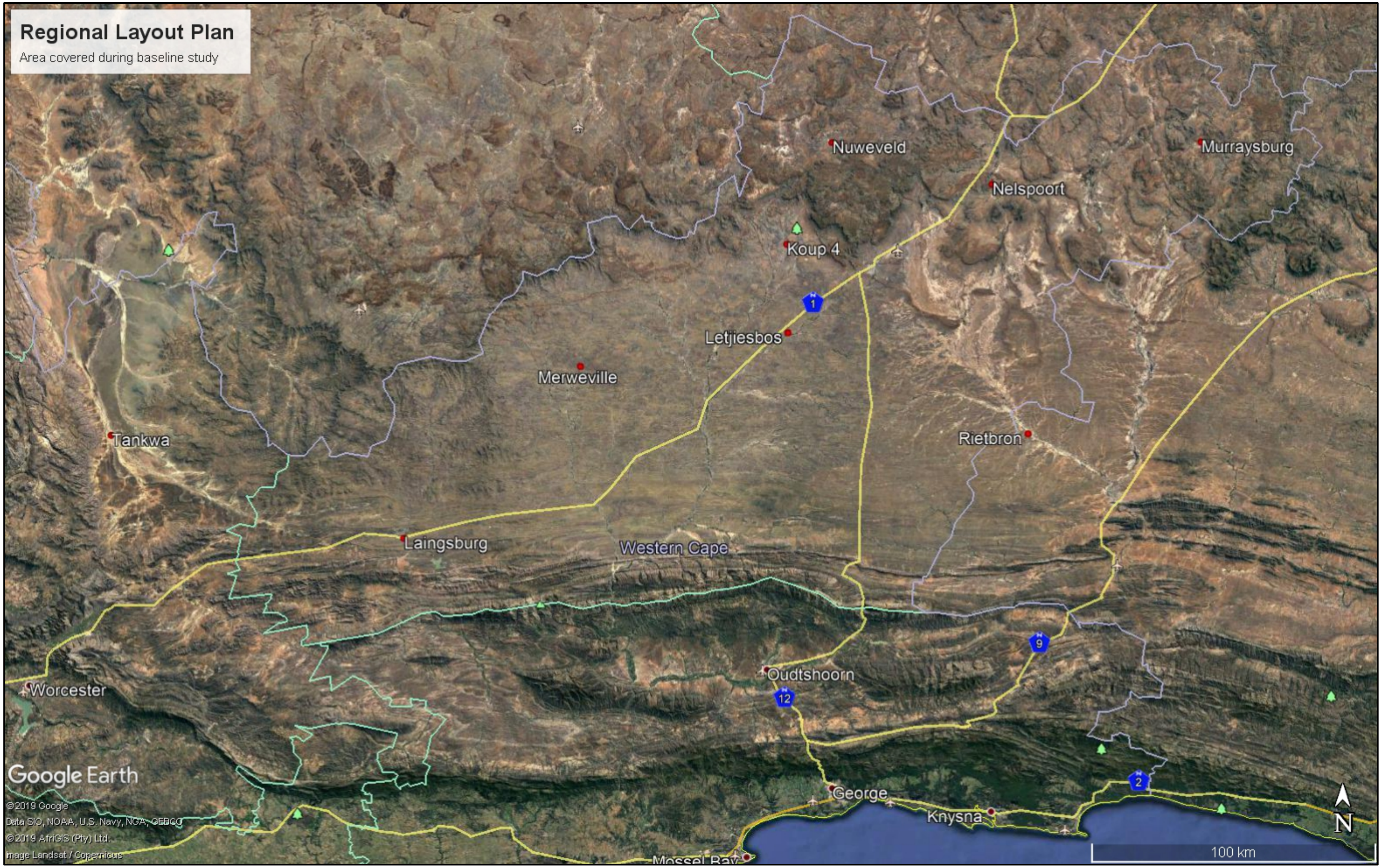

Figure 11: Regional layout plan indicating spatial extent of fieldwork

3.6.1. Methodology

In essence, the methodology for each area covered the following activities:

- **Hydrocensus** – This phase was an effort to cover as large an area in each farmers union's district in order to identify locations of high-yielding boreholes, springs and use of abstracted water. During the hydrocensus each farmer was allowed to indicate two boreholes that he or she would like to be sampled and analysed. This information was made available to the farmers when results were received from the laboratory. Typical field measurements were carried out and where open boreholes could be located, slug tests were done in an attempt to **1)** determine parameters and **2)** estimate potential yields across the area;
- **Aquifer characteristics and properties** – This was estimated by interpretation of slug test data obtained during the hydrocensus;
- **Groundwater level measurements – hydraulic head** – As with the slug tests, this information was gathered during the hydrocensus and where available, data and information from the farmers were copied. Groundwater level information assists in determining **1)** possible flow directions, **2.)** whether dolerite intrusive structures could be impermeable (compartmentalisation) and **3)** in combination with borehole depth, might be representing a piezometric head;
- **Hydrogeochemical investigation** – In order to assess baseline groundwater quality in general and investigate recharge mechanisms and possible percentage thereof to aquifer(s). Some surface water samples were also obtained to investigate possible groundwater-surface water interaction in support of stable isotope analysis that was included for selected sampling locations;
- **Stable isotope analysis** – Stable isotope signatures were used to evaluate climate conditions such as evaporation, condensation and transpiration at the time groundwater recharge occurred. This assist in determining possible sources of origin: local or regional or higher elevations. A trend of $\delta^{18}O$ values of precipitation develops as it has a maximum in the summer and a minimum in the winter. Seasonal variations of this isotope in precipitation can then be noted. If the variations are detectable in groundwater, groundwater residence times might be estimated (Craig, 1961); and
- **Methane gas occurrences** – In order to determine the presence of methane at sampling locations, a very basic methane detector that is used in the mining industry was deployed. A quick phase change from liquid to gas in a confined

space has the potential for methane to ignite at concentrations between 5% and 15% and it may result in an explosion if ignited by an electrical outlet, pump or match. A methane detector, Microtector II G460, was used to measure if any methane was present at borehole sampling locations. This methane sniffer was put on a high-range setting and measurements were taken in volume percentage. It was lowered into open boreholes as close as possible to the static groundwater level (SGWL) and equipped boreholes were measured by positioning the sniffer as close as possible to the top of the casing in a downwind direction.

3.6.2. Results and findings

As the data sets and measurements across the study area are large, our discussion will be reduced to conclusive indicators, trends and only selected graphical representations of a specific observation will be used.

3.6.2.1. Groundwater levels

Groundwater levels within one area can vary significantly. If the measurements for the Laingsburg area is considered, a minimum of 1.35 meters below ground level (mbgl) at the farm Ruggenskraal was recorded while a maximum of more than 45 mbgl was recorded at the farm Tweedside with an average of 15.95 mbgl (Figure 12).

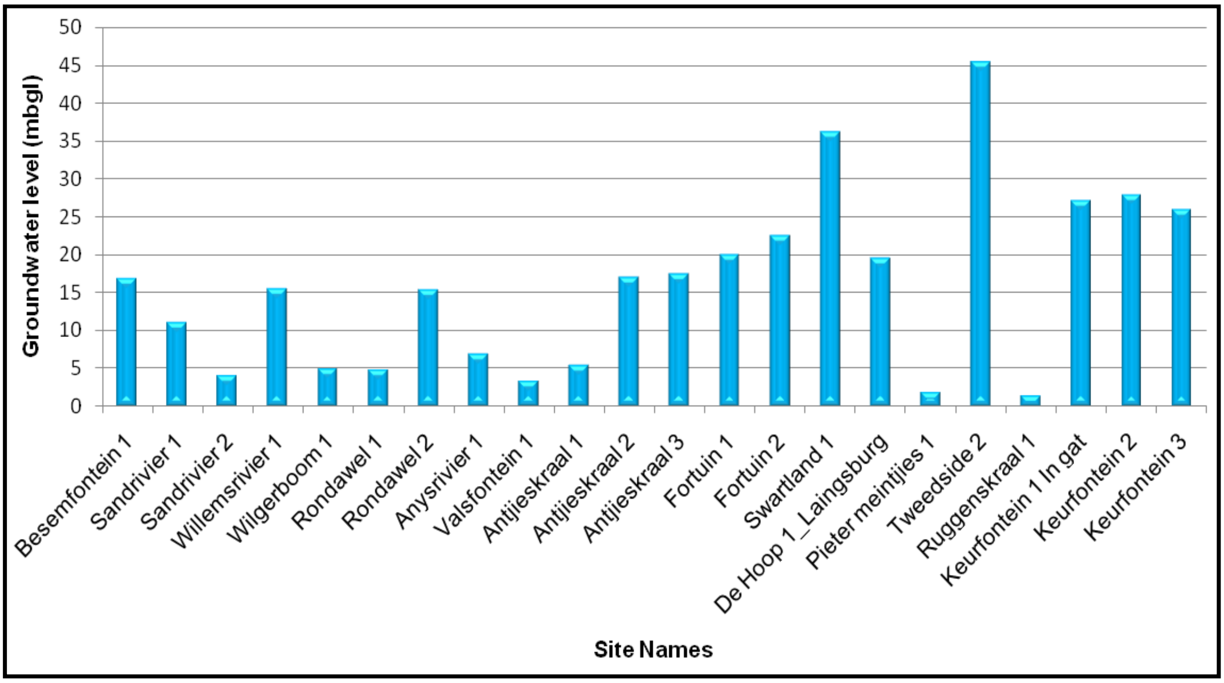

Figure 12: Groundwater level measurements for the Laingsburg area

This trend was observed in every union area. SGWL, borehole depth and water strike information would be critical when information regarding the thickness of the vadose zone is required to assess potential risks to shallow groundwater aquifers.

3.6.2.2. Aquifer properties

Slug tests were performed on numerous open boreholes across the study area. The majority indicated low-yielding boreholes usually adequate for livestock watering. Most boreholes indicating potential high yields were located along prominent geological structures that were outcropping above surface (Figure 13).

Figure 13: Borehole with potential high yield (12 s ≈ 3.9 L/s) in close proximity to dolerite dyke

Most aquifers in the study area can be described as secondary in nature. It is therefore not surprising that slug test results varies across quite a substantial range. From data evaluation it is obvious that permeability and porosity values will also then fluctuate substantially over short distances highly influenced by localized geology. It is not known if similar heterogenic conditions can be expected at depth and of great concern is that extrapolation of shallow aquifer properties cannot be done in a directly vertical downward direction. Very accurate geophysical information would be required to be able to delineate subsurface strata because drilling of additional core holes would be too expensive and also create addition preferential pathways to aquifers in both directions.

3.6.2.3. Hydrogeochemical processes

Physical and chemical interactions between groundwater and its surrounding environment i.e. geological formations, will influence the chemical composition. This will result in the seasonal, temporal and spatial variations of groundwater chemistry.

Samples were collected according to the sampling method suggested by Weaver et al. (2007), with some modifications at some boreholes where conditions were unique and did not adhere to normal field conditions. Accessibility and equipment as well as surrounding environment were challenging at some of the locations.

Electrical conductivity (EC) and pH were measured in field with a multi-parameter tester. Un-acidified water samples were collected and was analysed for inorganic chemistry. Samples were stored in containers, adequately labelled and preserved in a safe place until they could be taken to the laboratory for analysis. All samples were analysed within two weeks of collection. Inorganic groundwater chemistry analyses were conducted by the IGS Laboratory at the University of the Free State. Results of the chemical analyses are summarised in Table 4 by considering the distribution of the various chemical parameters across the study area.

Table 4: Summary of chemical distribution across the study area

Category	Constituent
General	1. pH pH values of the Karoo aquifers, in general, ranged between neutral to more alkaline conditions, with average values that ranged between 7.1 and 8. There were a couple of boreholes with pH values below 7 in the Murraysburg, Laingsburg, Nelspoort, Koup 4 and the Tankwa-Karoo areas. The highest pH was measured in one of the borehole groundwater samples in the Nelspoort study area, with a pH of 9.3. 2. Electrical Conductivity (EC) EC values ranged between 6 mS/m and 3 835 mS/m. The highest EC values were measured in the Tankwa-Karoo area. There were individual boreholes in Murraysburg, Nelspoort, Rietbron and Laingsburg with EC values as high as 500 mS/m. Each of these areas had boreholes that exceeded the standard value for EC, but the Tankwa-Karoo and Rietbron study areas were the areas where most of the EC values exceeded the standard value. 3. Total Dissolved Solids (TDS) TDS values of the study areas ranged between 56 mg/l and 25 592 mg/l
Major cations	1. Calcium Calcium and bicarbonate are usually dominant ions in recharged water, at the beginning of the groundwater cycle. The calcium average concentrations of the study areas ranged between 74 mg/land 167 mg/l. High calcium concentrations occurred in the Nelspoort, Rietbron and Tankwa-Karoo areas. Most of the groundwater samples of the Rietbron study area had a high calcium concentration. This might be because of the high evaporation/low recharge effect in these areas. 2. Magnesium Magnesium reveals the similar distribution pattern as calcium over the study area,

Category	Constituent
	with the highest concentrations in Rietbron, Nelspoort and Tankwa-Karoo, but does not occur in the same concentration levels as calcium. Magnesium is seldom more abundant than calcium, suggesting that magnesium minerals are not as readily soluble as calcium. Calcium and magnesium ions precipitate and therefore the total hardness of the groundwater can be determined. Groundwater in the Karoo was regarded as hard in most parts of the study area, with a few exceptions in Nelspoort, Tankwa-Karoo, Merweville and Laingsburg where some of the boreholes groundwater was classified as soft water 3. **Sodium** The concentration of sodium is more variable than calcium and magnesium. The sodium concentration in the whole study area ranged between 70.1 mg/l and 898 mg/l. Rietbron and Tankwa-Karoo were the areas with the most groundwater samples which sodium concentrations exceeding the standard value of 200 mg/l. There were boreholes in the other study areas also with sodium concentrations that exceeded the standard value, but Rietbron and Tankwa-Karoo had the most. It is only the Nuweveld area that did not have any borehole with a concentration level higher than the standard. 4. **Potassium** Most of the groundwater samples, except one in the Tankwa-Karoo area, potassium concentration levels were below the standard value of potassium. This might be because potassium is easily absorbed by the aquifer material and, therefore, can seldom reach significant concentrations in groundwater.
Major anions	1. **Bicarbonate** Bicarbonate and carbonate are represented by the total alkalinity. They are formed by introduction of carbon dioxide with rainfall and by the biological activities in the soil. Further dissolution of carbonates in the aquifer material introduces additional alkalinity into the solution until the solubility limit is reached. The average bicarbonate concentrations of the groundwater throughout the study area ranged between 296 mg/l and 467 mg/l. The highest bicarbonate concentrations were measured in Murraysburg and Laingsburg. 2. **Chloride** Chloride and sulphate concentrations seem to be well correlated. Chloride, however, dominates over sulphide in most areas. The chloride concentration measurements varied from the lowest value measured in Murraysburg, 2.3 mg/l, to as high as 14 432.4 mg/l measured in Tankwa-Karoo. Rietbron and the Tankwa-Karoo were the two study areas with the most boreholes which concentration levels exceeded the standard value. Murraysburg and Nelspoort areas both had one borehole with concentration levels higher than 2 000 mg/l. Rietbron and Laingsburg both had boreholes with chloride concentration levels higher than 1 000 mg/l. This is relatively high chloride concentration levels. Almost all the boreholes of the Tankwa-Karoo had chloride concentration levels that exceeded the standard value of 200 mg/l. Koup 4, Letjiesbos and Merweville had maximum chloride concentration values that ranged between 417 mg/l and 615 mg/l. It was only the Nuweveld study area that did not have any groundwater with chloride concentration levels that exceeded the standard value. 3. **Sulphate** Sulphate average concentration values of all the study areas ranged between 88 mg/l and 400 mg/l. There were some boreholes with quite a high sulphate concentration, even with values that exceeded 1 000 mg/l. Tankwa-Karoo and Rietbron were the two study areas with the most boreholes that exceeded the standard value of sulphate, 400 mg/l. The highest sulphate concentration of 2 313.5 mg/l was measured in one open borehole groundwater sample of the Tankwa-Karoo district. Letjiesbos study area was the only place where there was not any borehole with a sulphate concentration that exceeded the standard value. Murraysburg, Nelspoort, Merweville, Nuweveld and the Tankwa-Karoo areas all had one or two boreholes with a sulphate concentration value higher than 1 000 mg/l. The rest of the boreholes in the study area that have exceeded the target value of sulphate values ranged between 449 mg/land 961 mg/l 4. **Nitrate** Nitrate concentrations across the study area varied substantially. Almost in every

Category	Constituent
	study area there was a borehole or boreholes with a nitrate concentration that exceeded the standard value of 10 mg/l, except in the Merweville area there was not one borehole with a nitrate concentration level that exceeded the standard value. Average nitrate concentration values determined for all the study areas ranged from 0.1 mg/l to 6.1 mg/l. The highest nitrate concentration that was measured, 35.1 mg/l, was an open borehole in the Laingsburg district. Nelspoort and Rietbron were the areas with the most boreholes with a nitrate concentration that exceeded the standard value. Nuweveld and the Tankwa-Karoo only had one borehole each with a nitrate concentration that exceeded the standard value, and Murraysburg had two boreholes. The Koup 4 and Letjiesbos district around Beaufort West had both three boreholes with concentration levels that exceeded the standard value. 5. **Fluoride** The average value of the fluoride concentrations levels of all the study areas ranged between 0.4 mg/l and 1.5 mg/l. In every area that were visited during this study there were borehole(s) or springs which groundwater fluoride concentration levels exceeded the standard value of 1 mg/l. Nelspoort, Rietbron and Tankwa-Karoo had the most boreholes which groundwater exceeded the standard value. The highest fluoride concentration measured in Nelspoort, also the highest value in the whole study area, was an open borehole sample with a value of 13.1 mg/l. The highest fluoride concentration measured in Rietbron was an equipped borehole where a value of 3.3 mg/l was measured. The highest value of fluoride concentration levels of Tankwa-Karoo was an open borehole where a value of 8.5 mg/l was measured. The maximum fluoride concentration values of the other study areas ranged between 1.6 mg/l and 5.2 mg/l, but they do not have such a high number of boreholes which concentration levels exceeded the standard value as in the case of Nelspoort, Rietbron and Tankwa-Karoo boreholes and springs 6. **Phosphate** Phosphate was only present in a few boreholes throughout the study area. Included are two boreholes in the Nelspoort area, two in the Murraysburg area, three in the Laingsburg area and one in the Rietbron area. The highest phosphate concentration was in the Murraysburg area with a value of 1.2 mg/l, which is still below the standard value of 2 mg/l. This borehole is located next to crop farming activities and the high phosphate concentration might be a result of drainage of fertilisers. 7. **Bromide** Bromide concentrations throughout the study ranged between 0.3 mg/l and 21.9 mg/l. Tankwa-Karoo and Rietbron were the two study areas with the highest average bromide concentrations. The highest bromide concentration was detected in an open borehole in the Tankwa-Karoo district. There were quite a number of groundwater samples which bromide concentration exceeded the standard value of 3 mg/l in the Murraysburg, Nelspoort, Rietbron and Laingsburg areas. The highest bromide concentrations detected in these areas ranged from 4.1 mg/l to 8.7 mg/l. Bromide was detected in Koup 4, Nuweveld, Merweville and Letjiesbos groundwater samples, but the concentration levels were below the standard value. The highest concentration levels of these four study areas ranged between 1.2 mg/l and 2.7 mg/l. There is a good correlation between the sodium chloride concentration and the bromide. Throughout the study a trend was established that samples with high concentrations of sodium and chloride, also had a higher bromide concentration.
Heavy metals	1. **Uranium** During the study, uranium was detected in several boreholes and surface water samples. In some of the samples uranium was only detected, but in most of them the standard value of uranium in the water was exceeded. Murraysburg was the study area with the most samples that contained uranium. Tankwa-Karoo, Merweville and Rietbron only had one borehole each where uranium was detected, and one spring in Laingsburg where uranium was present. The rest of the groundwater and surface water samples (Koup 4, Nelspoort, Nuweveld and Letjiesbos) did not show any presence of uranium. Most locations (borehole, spring or river) where uranium was detected was located at the end of an intermittent stream. Uranium can thus be suspended in water as a muddy soluble uranium compound and end up in this position in the landscape. Phosphate was not present in any of the samples in which uranium was detected, which indicate that phosphate fertilisers can be excluded as possible source. A correlation between uranium and bicarbonate contents of the samples was

Category	Constituent
	observed; the boreholes, spring and surface water samples with uranium also indicate higher bicarbonate content. It could be that bicarbonate assist in mobilisation of uranium. Elim 2, a spring sample in the Laingsburg district, had the highest uranium content of 0.263 mg/l and also had the highest bicarbonate content of 1 344 mg/l. The locality of the boreholes at Murraysburg indicate that the uranium compounds could have been transported in the river, as it was present in the Buffels River sample, and Kareebosch River sample. It was also present in most of the boreholes next to the river. It can be concluded that uranium comes from soil and rock particles, but was transported with water. Koup 4, Nelspoort, Rietbron and Letjiesbos are the main uranium mining areas but there was no uranium present in borehole or surface water samples in these areas. It might be that uranium in these areas has formed compounds with soil material. 2. **<u>Arsenic</u>** Arsenic was detected in a couple of boreholes during the study. Laingsburg and Murraysburg were the two study areas with the most boreholes and springs with arsenic. In most of the Laingsburg boreholes, the concentration of arsenic had not exceeded the standard value of 0.01 mg/l. It was only Elim 2 (the spring) with a concentration exceeding the standard value. Most of the boreholes where arsenic was detected in Murraysburg concentration levels exceeded the standard value and the borehole (Fonteintjie 1) with the highest concentration arsenic of all the study areas where also in Murraysburg. Nuweveld, Nelspoort and Tankwa-Karoo all had only one borehole where arsenic was detected. Rietbron had three boreholes with arsenic. Not one of the Letjiesbos and Koup 4 boreholes or spring had shown any signs of arsenic. Arsenic was also not present in any surface water sample. The sedimentary rocks of the Karoo Supergroup are rich in silicate minerals such as quartz, pyroxene, plagioclase (mixture of albite and anorthite), feldspar and clay with traces of carbonate. These minerals may contain arsenic. 3. **<u>Iron and Manganese</u>** Iron was detected in most of the groundwater and surface water samples throughout the study. All Nuweveld, Merweville and Letjiesbos groundwater samples had iron, but not one had a concentration that exceeded the standard value of 0.2 mg/l. Most of Nelspoort, Koup 4 and Rietbron groundwater and surface water samples had iron, but not one with a concentration that exceeded the standard value, except for one borehole in the Nelspoort area. There were a few boreholes in these three areas with no iron. Laingsburg, Tankwa-Karoo and Murraysburg groundwater and surface water samples all had iron and also had one or more samples that exceeded the target value. The highest iron concentration was detected in one borehole in the Tankwa-Karoo area with a value of 1.416 mg/l. Manganese was detected in a couple of Nuweveld, Nelspoort, Koup 4, Letjiesbos, Rietbron, Laingsburg, Merweville and in all Tankwa-Karoo and Murraysburg groundwater and surface water samples and there were also in each of the study areas one or more samples which manganese concentration levels exceeded the standard value of 0.1 mg/l. The highest manganese concentration with a value of 15.087 mg/l was detected in an old borehole that was in use, but are not equipment anymore, in the Laingsburg area. There was also one borehole in the Merweville district with quite a high manganese concentration with a value of 3.133 mg/l. 4. **<u>Cadmium</u>** Cadmium was only detected at very low concentrations in groundwater samples of the Laingsburg and the Tankwa-Karoo areas. It was not present in any groundwater sample of the other study areas. 5. **<u>Copper</u>** Copper was detected at very small concentrations in almost all the groundwater and surface water samples of all the study areas, except for Merweville where there was no copper present. The highest concentration of copper was detected in an equipped borehole in the Nelspoort area and it had a value of 0.049 mg/l. 6. **<u>Aluminum</u>** Aluminium was detected in a couple of groundwater samples throughout the study, but at very low concentrations. There was only one surface water sample of the Murraysburg area and one groundwater sample of the Tankwa-Karoo area with a concentration level of 0.2 mg/l, but it was still below the standard value of 0.3 mg/l for aluminum. 7. **<u>Strontium</u>** Strontium was detected in all the groundwater and surface water samples, of all the

Category	Constituent
	study areas that formed part of this study, and in each there was one or more boreholes with a strontium concentration levels that exceeded the standard, except in the Nuweveld area, where there was not one borehole with a concentration level that exceeded the standard value of 4 mg/l. Nelspoort, Tankwa-Karoo and Merweville were the three study areas with the most groundwater samples which strontium concentration levels exceeded the standard value. The strontium maximum values ranged between 4 mg/l and 20 mg/l. The highest strontium concentration was detected in an open borehole in the Tankwa-Karoo study area with a value of 20.3 mg/l. 8. **Selenium** Selenium was only detected in groundwater samples of Nelspoort, Koup 4, Rietbron, Laingsburg and Tankwa-Karoo. Nelspoort and the Tankwa-Karoo area had four boreholes were selenium was detected. The standard concentration for selenium was only exceeded in one equipped borehole in the Laingsburg area, with a concentration level of 0.032 mg/l. 9. **Vanadium** Vanadium was only detected in groundwater and surface water samples of the Nuweveld, Nelspoort, Koup 4, Merweville and Murraysburg districts. Vanadium was present in most of Murraysburg groundwater and surface water samples. Nuweveld and Nelspoort areas also had a couple of groundwater samples with vanadium. Koup 4 and Merweville both only had one borehole with vanadium. Concentration levels of vanadium detected in these boreholes, springs and surface water samples have not exceeded the standard value for vanadium of 0.2 mg/l. The highest value was measured in the Nelspoort study area and it was 0.134 mg/l. 10. **Cobalt** Cobalt was not detected in any borehole, spring or surface water samples of the Nuweveld, Nelspoort, Koup 4, Letjiesbos, Rietbron or Merweville areas. Cobalt was detected in some boreholes samples in the Laingsburg, Murraysburg and Tankwa-Karoo areas. Cobalt was present only at very low concentrations in these boreholes. Low levels of cobalt in natural waters may be due to an adsorption reaction. 11. **Molybdenum** Low concentrations of molybdenum were detected in a couple of groundwater and surface water samples in Nuweveld, Nelspoort, Rietbron, Laingsburg, Merweville, Murraysburg, Tankwa-Karoo, Letjiesbos and Koup 4. Murraysburg and Nelspoort were the two areas with the most molybdenum samples and there were only three boreholes in Nuweveld area with molybdenum. The highest molybdenum concentration and the only one that exceeded the standard value of 0.07 mg/l, was one borehole in the Nelspoort area. 12. **Nickel** Nickel was detected in some of Nuweveld, Nelspoort, Koup 4, Letjiesbos, Rietbron and Laingsburg groundwater samples. There was only one borehole in both Merweville and Tankwa-Karoo areas where nickel was detected. The Murraysburg area did not have any borehole with nickel. Nuweveld and Nelspoort were the two areas with the most groundwater samples with nickel. Nickel was only present at low concentrations; the highest nickel concentration was measured in one of Nelspoort area boreholes with a value of 0.025 mg/l. 13. **Barium** Barium was detected in the groundwater and surface water samples of all the study areas. The barium concentration level of 0.7 mg/l was only exceeded in one spring sample, with a value of 0.784 mg/l in the Murraysburg area; the rest of the Murraysburg's groundwater and surface water sample values were far below this level. Together with these observations and the low sulphate concentration of the spring which is 14 mg/l, it can be concluded that the bedrock in the area had the proper anaerobic environment and food source to support sulphate-reducing bacteria, which are, in fact, removing sulphate from the groundwater. The sulphate is being removed and the barium increases in the solution. 14. **Silicon** Silicon was present in all of the groundwater and surface water samples. Since there is no standard value for silicon in drinking water, it will be classified according to values which were measured during the study. Nelspoort and Koup 4 were the two study areas with the highest silicon concentrations. The silicon concentrations of Nelspoort groundwater samples ranged between 6 mg/l and 43 mg/l, and for Koup 4 between 9 mg/l and 30 mg/l. The silicon concentrations for Nuweveld and

Category	Constituent
	Merweville ranged between 5 mg/l and 25 mg/l. Silicon concentrations for Laingsburg, Rietbron, Murraysburg and Letjiesbos groundwater and surface water samples ranged between 2 mg/l and 15 mg/l. The lowest silicon concentrations were measured in Tankwa-Karoo groundwater samples with values that ranged between 1 mg/l and 8 mg/l. **15. <u>Chromium</u>** Chromium was only detected in one equipped borehole in the Laingsburg area, but at very low concentrations. No other borehole with chromium was detected. **16. <u>Boron</u>** Boron was detected in all of Merweville, Murraysburg and Tankwa-Karoo boreholes, except in two boreholes in the Murraysburg area, and most of them had a boron concentration that exceeded the standard value of 0.1 mg/l. In Nuweveld and Letjiesbos there was only one borehole in both these areas where boron was detected and the rest have not shown any presence of boron. Boron was detected in most of the groundwater and surface water samples in the Nelspoort, Koup 4, Rietbron and Laingsburg areas, and quite a number of them had a concentration level that exceeded the standard value. The highest boron concentration was detected in the Tankwa-Karoo area with a value of 2.87 mg/l. There was also one borehole in Rietbron and one borehole in Nelspoort with a boron concentration level of above 2 mg/l. **17. <u>Lithium</u>** Lithium was only analysed for in Nelspoort, Koup 4 and Rietbron groundwater and surface water samples. Lithium was present in all the samples. The lithium concentration level of 2.5 mg/l was only exceeded in one open borehole in the Nelspoort study area. **18. <u>Zinc</u>** Zinc was detected in all groundwater and surface water samples of Nuweveld, Nelspoort, Koup 4, Rietbron, Letjiesbos, Merweville and Murraysburg areas, but at very low concentrations. Zinc was detected in most of Laingsburg area groundwater and surface water samples, but there were a few without zinc. Only one groundwater sample in the Tankwa-Karoo had zinc. **19. <u>Lead</u>** Lead was not detected in any of the groundwater or surface water samples that formed part of this study

Fieldwork for this research project yielded a substantial amount of information that might assist in shaping regulation and monitoring requirements and protocols. Unfortunately due to budgetary constraints only a once-off sampling collection excursion could be sponsored. Within the eight farmer associations and one area related to another project (Tankwa area) 440 sampling locations were visited, which included 313 equipped boreholes, 89 open boreholes, 20 springs, 5 rivers, 3 dams and 10 other sites e.g. boreholes where only methane measurements were done or a spring that was visited without any samples being collected. It covered a time frame of April 2015 to March 2016.

As a reference data set it should be considered too stand-alone and effort should be made to conduct follow-up excursions in order to develop a database populated with enough relevant information and data to be able to have verification data from which longer-term trends can be established.

3.6.2.4. Stable isotope analysis

Two groups of data could be identified, each with a distinct isotopic signature in most of the different areas. One group exhibited a heavier isotope signature indicating either **1)** mixing to some extent between groundwater and surface water or **2)** it had undergone evaporation before recharge occurred, with heavier isotope atoms migrating into the subsurface, or **3)** it was a surface water sample.

The other group, lighter in isotopic composition, included most of the groundwater samples. Depletion of heavier isotopes as precipitation events occur more inland can be observed from the data set. From the graphs depicted in Figure 14 to Figure 17 it is evident that a definite correlation exist between boreholes and springs, while surface water samples have a distinctly different signature.

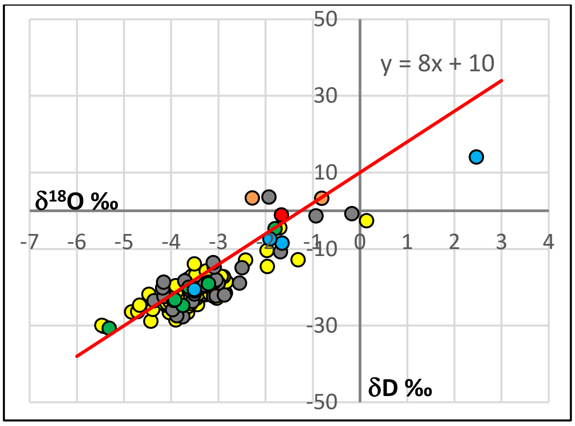

Figure 14: Plot of ^{18}O against D for Murraysburg water samples

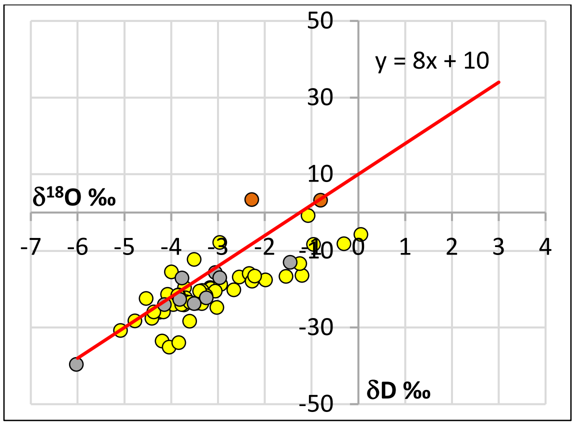

Figure 16: Plot of ^{18}O against D for Nelspoort water samples

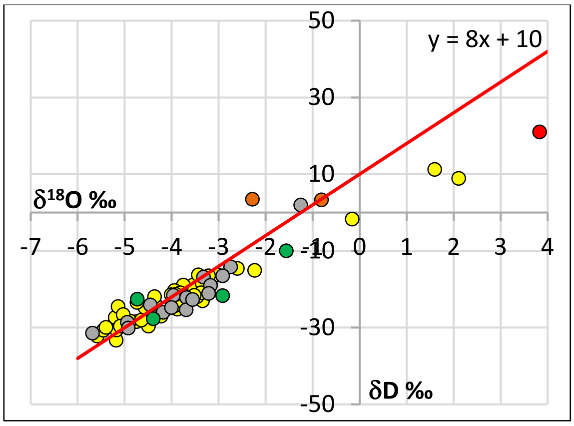

Figure 15: Plot of ^{18}O against D for Laingsburg water samples

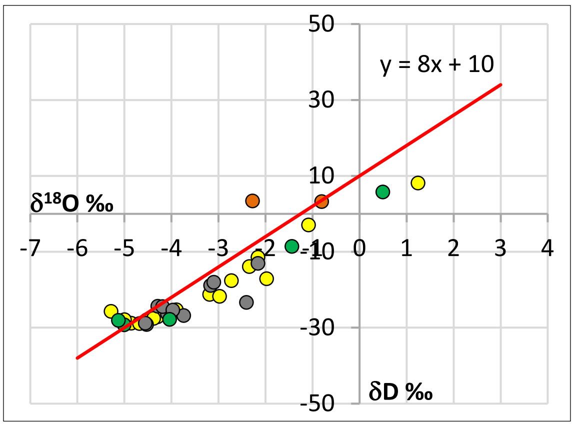

Figure 17: Plot of ^{18}O against D for Tankwa water samples

As expected in some areas definite evaporation signatures can be observed e.g. in the

Nelspoort area. At Murraysburg one river indicates severe evaporation and plots in the positive sector of the graph, while other river samples are spread decreasingly (lighter signature) along the Global Meteoric Water Line (GMWL), signifying possible mixing, which in turn could be indicative of groundwater/surface water interaction.

Detailed information on groundwater age can only be given if there is a time-series of the O^{18} content in precipitation and in the groundwater. The time-series of at least one hydrological year is required, which was unfortunately not possible for this project.

3.6.2.5. Methane gas occurrences

Out of all 440 sampling locations covering an approximate area of 28 000 km^2 only 28 locations yielded any results when methane measurements were done: 26 boreholes and 2 springs.

Elevated levels of methane gas were detected in four boreholes of these 28 sites throughout the study. The highest methane gas concentration was detected in an open borehole in the Murraysburg district, with a concentration of 8.4 Vol% Hi-range. Water levels of the boreholes with elevated methane gas ranged between 1.36 mbgl and 4.47 mbgl. The rest of the boreholes with elevated levels of methane gas concentrations, ranged between 1 and 2.022 Vol% Hi-range. Only very low levels of methane gas were detected at the rest of the boreholes and springs where gas was present. Concentration levels of methane gas in these boreholes and springs ranged between 0.02 and 0.28 Vol% Hi-range. Boreholes with low concentration levels of methane gas ranged from as shallow as 1.35 mbgl to as deep as 45.55 mbgl, but most of them had a water level that was deeper than 5 mbgl.

Chemical results of these boreholes and springs were grouped together to see if there is any chemical constituent(s) that could be related to the occurrence of methane gas, without any success. No chemical parameter was obvious in its presence where methane was present. Murraysburg and Laingsburg were the two study areas with the most boreholes where methane gas was detected. Most of the boreholes where gas was detected were situated in the Adelaide Subgroup of the Beaufort Group of the Karoo Supergroup, or on the contact between the Adelaide and dolerite or in the dolerite. It was only in the Laingsburg and the Tankwa–Karoo areas where some of the boreholes where gas was detected were situated in the Ecca Group of the Karoo Supergroup.

As mentioned earlier in the literature review Talma and Esterhuyse (2013) compiled a map of methane occurrence areas across South Africa, with the use of information from different sources. They also indicated with isotope data that the Karoo produces methane from both thermogenic sources (probably mature shales) and bio-reduction (probably coalfields). In this study there could not be distinguished between thermogenic and biogenic methane, but one recommendation will be to do a better analysis of Kareebosch 2 to see what type of gas is present and therefore some methane isotope analysis will be needed. Some authors also indicate that the H_2S smell, which is present at many places in the Karoo, is methane gas, but this statement does not agree with the results of this study since at very odorous boreholes the methane sniffer did not detect any methane gas.

3.7. Groundwater Governance

3.7.1. Introduction

Water governance can be most commonly described as:

"A range of political, social, economic and administrative systems that are in place to develop and manage water resources and the delivery of water services, at different levels of society." (Rogers and Hall, 2003).

As groundwater falls within this realm it can be expected from government to have an interactive system in place to decide who gets what water when and how and who has the right to water and associated services and their benefits.

South Africa does not have a very good track record of good groundwater governance and it would therefore be appropriate to carry out an assessment of South Africa's water governance structures and policies to assist in deciding on where HF should fit in within this framework. Three key components that should assist during the assessment due to their simplicity while remaining analytical are **1)** institutions and stakeholders, **2)** Governance principles and **3)** performance assessment.

3.7.2. Legal environment

The current legislative environment is a conundrum on how to include HF in existing Acts. Although the DMR is responsible for issuing the licence, the Petroleum Agency SA (PASA), which regulates exploration and production activities, has the mandate to act as agent for licensing in terms of the Minerals and Petroleum Development Act (MPRDA). This mandate includes two types of permits and two types of rights that they are allowed to issue:

1. Reconnaissance permits, in terms of section 75(1) of the MPRDA, which allows for only geological, geophysical or photo geological surveys and any remote

sensing techniques. It is valid for a period of one year and is not renewable or transferable;

2. Technical Co-operation permits, in terms of section 77(1) of the MPRDA, which allows a holder to carry out desktop studies, acquire existing seismic and other data from other sources, including PASA but does not include any exploration activities. The permit is valid for a period of 1 year and is not renewable or transferable;
3. Exploration Right permits, in terms of section 80 of the MPRDA allows a holder to carry out the entire value chain of petroleum exploration such as acquisition and processing of new geological/geophysical data, reprocessing of existing geological/geophysical data and any other related activity to define a trap to be tested by drilling, logging and testing, including well appraisal activities. The right is valid for a period of 3 years, renewable for three two-year term, transferable and can be encumbered by mortgage; and
4. Production Right permit in terms of section 84 of MPRDA allows a holder to conduct any operation, activity or matter that relates to the exploration, appraisal, development and production of petroleum. The right is valid for a period of 30 years, renewable for further periods each not exceeding 30 years, is transferable and can be encumbered by mortgage.

3.7.2.1. Applications

According to the South African Oil and Gas Alliance's (SAOGA) web page ("Upstream Oil & Gas in South Africa | South African Oil & Gas Alliance," n.d.), five technical co-operation permits have been issued for shale gas exploration in South Africa. Under "Other strategic matters addressed" in the PASA annual report for the year ended on 31 March 2019, shale gas is briefly mentioned where two data acquisition projects are mentioned of which final steps involving core sample analysis and the acquisition of an adsorber module for surface geochemistry were not finalized within the projects' specified schedule.

It seems as if the current economic and regulatory environment is not able to handle the next step in the shale gas endeavour in South Africa, which would be to explore the subsurface environment in an attempt to:

- Verify if there actually is any viable shale gas resources in the target formation(s);
- Gather geological information;
- Conduct geohydrological tests with measurements in order to be able to do a comprehensive risk assessment on possible impacts on shallow aquifers; and

- ❖ Verify if current extraction techniques will be applicable in a Karoo environment and if not, to gather information that might help in developing new techniques.

3.7.2.2. Risk Assessments

Currently risk assessments of impacts on groundwater resources have mostly been based on desktop studies that include historical data and very course maps with regard to geology and geohydrology. It is very seldom that information is gathered from exploration drilling and testing activities that would include vertical profile data of water strikes, yields and pressures. Packer testing is mostly not done and therefore an informed assessment with a high confidence is not always possible. Once again the importance of including an experienced geohydrologist is evident because the lack of the aforementioned information is often a result of a lack of knowledge regarding geohydrological assessments.

The level of certainty with HF assessment should be very high and this will require a comprehensive and rigid guideline on what is relevant and should be included in a geohydrological risk assessment. Current guidelines have been found wanting and different state departments have already started developing their own set of regulations without acknowledging other departments and regulators.

Sound risk assessment methodology exists but groundwater is a unique and valuable resource that should be considered in the long term as an alternative source of potable water during droughts. It should therefore be viewed as a strategic resource and a risk assessment methodology specific for groundwater should be developed. The GW-RAT tool developed as part of our research is a first attempt in establishing this concept.

3.7.3. Technical requirements

The only technical requirements for shale gas development in South Africa is still the Fracking Regulations made under the MPRDA (DMR, 2015). Its introduction into the environmental regulation mix has been a source of contention as well as confusion.

Experts in the field of law consider the format as well as specific regulations to be *ultra vires* (beyond the powers) of the Minister of Mineral Resources due to its intrusive nature into mandates of other departments, with specific reference to the DWS and DEA (Glazewski and Esterhuyse, 2016).

Many technical aspects of HF is covered by the technical regulations. Unfortunately it seems as if it was largely a copy and paste effort from information that was already available without taking a South African and more specific, a Karoo context into consideration. Research and development of technical regulations specific for Karoo conditions can also be considered to fall within the context of “opportunity” and while there seems to be a lull in appetite for data acquisition and desktop studies from industry, it would be fitting for government to consider funding research for further development.

3.7.4. Monitoring

Monitoring might be mentioned last in this chapter, but it most certainly is not the least important component of groundwater governance. Without data and information there would be no groundwater governance.

At the moment groundwater monitoring in South Africa can be considered as non-existing. Data shown by the DWS at the Lower Orange River Forum meeting that took place from 30 September 2019 to 1 October 2019 did not include any information for the past four years. The reason that was provided was that they did not have a budget to collect samples or to analyse the samples.

If a government department, whose mandate is to protect water resources for the benefit of all citizens, does not have any funds to carry out this mandate, it is highly unlikely that there is any water governance being done.

Another point of contention is the volumes of water, surface as well as subsurface, that are illegally obtained by users and with the authorities not being able to do anything about it. There are many employees at the DWS that are competent as well as willing and able to do their work. Unfortunately decisions with regard to budgets and high-level appointments are highly influenced by a political system that has been shown to have lost any sense of responsibility for their people. Disappearing funds as well as a culture of unaccountability has left the state regulator in a shambles and if there is one lone standing reason why HF should not be allowed in South Africa, it would be a severe lack of water governance - the implementation part - due to the absence of reliable data and information.

3.8. Conclusion

It is evident that HF in the Karoo Basin has several challenges on several levels. Not all work done to determine if a shale gas industry should be developed in South Africa would be negative or detrimental to the environment and we do have qualified geohydrologists with sufficient experience to assess the risks to shallow groundwater resources. It would also be possible to develop technical regulations and protocols for a fractured system environment.

A preliminary investigation across a large section of the Karoo yielded some base line information regarding groundwater levels, quality, recharge as well as uses. What became clear from the research was that initiating information gathering can be done with relatively small budgets and time frames. Local communities are prepared to take an interest in activities that might have an influence on a scarce and hugely important resource they are dependent upon for survival, but only if their trust can be won. It is the author's personal view that any interaction with farmers and communities should be dealt with in association with independent academic researchers with no affiliation with state organisations or O&G companies as they are viewed as untrustworthy with only profit margins influencing their interests and decisions.

Physical and chemical data indicated that water quantity and quality vary across short distances in the same area. This is significant as monitoring in preparation of a possible HF industry would require accurate data in order to establish whether any impacts can be attributed to their activities at a later stage. Without reference data, any individual or regulator would not have any legal claim in a court of law.

Very simple established scientific methodologies can be deployed to assist in gathering enough data and information to establish a status quo image before HF activities are undertaken. It would however be a good idea to allow more than one institution to develop an independent database with some form of cross-referencing in order to maintain a reliable, transparent set of information that will allow for updated and well-informed decision making. A typical scenario would be where the DWS includes the information into their own national database and an academic/research institution or a collective of experts from different academic/research institutions develop their own database with interaction between the groups and Interested and Affected Parties (IAP's) at a quarterly frequency.

All of the above could be regarded as an opportunity to develop a South African geohydrological community that can add value not only to a local HF industry but with research on our deep systems we would be able to have a more realistic conceptual model as well as better knowledge on deep aquifer system behaviour and groundwater quality.

The only obstacle between moving forward with regard to knowledge, development and a possible contribution to our energy crisis would be continuing along the current path of water governance.

4. PROPOSED METHODOLOGY FOR INVESTIGATING POTENTIAL GROUNDWATER IMPACTS FROM HF ACTIVITIES

4.1. Introduction

Over the past five years, research and associated publications on HF increased exponentially due to this activity being made a very public scapegoat for especially contamination of shallow groundwater resources and associated human health concerns. Typical arguments against HF would include environmental impacts on groundwater, air, fauna and flora as well as transport-related issues.

The main focus of this thesis being geohydrological aspects, methodology related to regulating, quantifying and qualifying possible groundwater impacts will be the primary discussion point but wherever possible it will be contextualised within the broader framework of environmental issues as well as economic, socio-economic and legislative matters.

A geohydrological investigation entails in very broad terms determining physical characteristics of the environment (geology) in which groundwater occurs as well as measuring hydraulic parameters (pressure gradient) existing within this environment. Due to its invasive nature as well as the extent within this environment to which HF has an influence, basic geohydrological methodologies still apply but due to extreme temperatures and possible corrosive environment, equipment and measuring apparatus would be costly and should be robust. One should also be prepared to extend field work that is usually conducted over days into possibly months, in other words, a different scale of investigation as well as level of confidence and accuracy is involved in any geohydrological investigation related to HF. Measuring techniques as well as protocols should also be adjusted and revised to make sure that it would still yield reliable results within this environment.

4.2. Environment – Geology

Since the Karoo geology has been discussed and described by many authors in the past, the geology description will be basic with regards to general lithology. For the purpose of this research, it would be much more fitting to focus on the different geological aspects that have been identified as factors that will increase the risk of contaminants migrating from depth into shallow aquifers that are used by farmers and local communities.

It is an established fact that the Karoo geology is highly heterogenic, with subsurface conditions changing over short distances as well as with depth due to deformation and intrusive rock formations. Information regarding shallow aquifers has been well documented but very little information to depths greater than 300 m is available to researchers and within the public domain. Most of this information resides within the mining houses, which makes it proprietary information.

Another factor that should be kept in mind is that any geological drilling seldom considered any groundwater-related information and very little data has been recorded on geohydrological conditions at great depth except for some estimations of general pressures encountered during drilling activities by SOEKOR in the 1960's.

The SOEKOR borehole information will be the bulk source of information together with more recent work that was done by the Centre of Excellence for Integrated Mineral and Energy Resource Analysis (CIMERA) at two locations in the Karoo Basin.

As has been indicated in the South African context chapter, the Karoo geology is complex, and a groundwater investigation and risk assessment together with a comprehensive groundwater monitoring strategy should be one of the highest ranking requirements when applications from O&G companies are considered.

The geological component will be a prominent indicator in the risk tool that will be developed and a comprehensive breakdown into different components is envisaged for each of the phases of HF i.e. 1) exploration, 2) production and 3) closure.

Aspects associated with geological formations and their influence on groundwater flow in terms of direction and rate will be extremely important to assess possible impacts on a local as well as a regional scale. The role of the geological setting at any HF site will have to be very well defined as part of any conceptual model of the area as well as its interaction on a larger scale with the regional subsurface environment.

The above criteria and concerns should be the basis from which any technical, information gathering as well as monitoring guidelines and/or requirements be developed and should be reflected in the conditions stipulated by any licence awarded to an applicant.

4.3. Groundwater hydraulics

Not only is the purpose of any geohydrological investigation to determine physical parameters associated with the environment (geology) as well as its extent but measurements of hydraulic potential and possible sustainable yields due to a pressure gradient that may or may not exist within the system are also evaluated. Although this could be time consuming and would rely on highly specialized equipment as well as reliable and scientifically researched techniques, on the overall scale and costing of the HF industry, this could be seen as negligible as well as very important when environmental concerns are considered.

To be able to expand a conceptual model of any potential HF site, very detailed information with regard to the groundwater flow regime will be required. This should include:

- Detailed lithological information at positions where waterstrikes, air/gas pockets, fractures and contact zones between different geological formations occur;
- Visual information of the lithology of each borehole should be recorded;
- Record of different aquifers along the drilling pathway;
- Below depths of 100 m, it can be expected that any aquifer system would be confined and a piezometric head for each of these aquifers should be determined;
- Measurement of any flows from the well, should any occur;
- Temperature measurements; and
- Groundwater quality information at different depths and specified locations as determined by a qualified geohydrologist with relevant experience.

High-yielding boreholes in Karoo aquifers usually intersect a well-developed fracture network. This observation is based on boreholes that are 90% not deeper than 100 m. As there is not a lot of information available on the behaviour of deep contacts and fracture zones, depth-specific information should be required by making use of e.g. cameras and packer systems to seal off a section of the well in order to conduct falling head test or slug tests in an attempt to determine transmissivity (T) values (Lubbe et al., UP[2]). Tracer tests can also be used to determine flow velocities and some of the other parameters associated with fracture flow.

There is a high probability that the HF industry already has technology available as part of their drilling process that they should be able to collect data as per requirements mentioned above. It would therefore be important to only issue licences to applicants that can prove that they will be capable of meeting all requirements and conditions as specified by their licence conditions.

There are numerous techniques and tests that can be applied and these should form part of any technical requirements developed for an HF industry in South Africa.

[2] UP indicates an unpublished article

4.4. Monitoring

The lack of sufficient information from a South African perspective was highlighted previously in this document. One of the most important aspects in addressing this limitation is by establishing an accurate monitoring system that includes all processes of problem definition that forms the monitoring cycle (AGW-Net, 2015). These processes include (Figure 18):

1. Management objectives;
2. Information needs;
3. Data acquisition;
4. Data storage;
5. Interpretation; and
6. Dissemination.

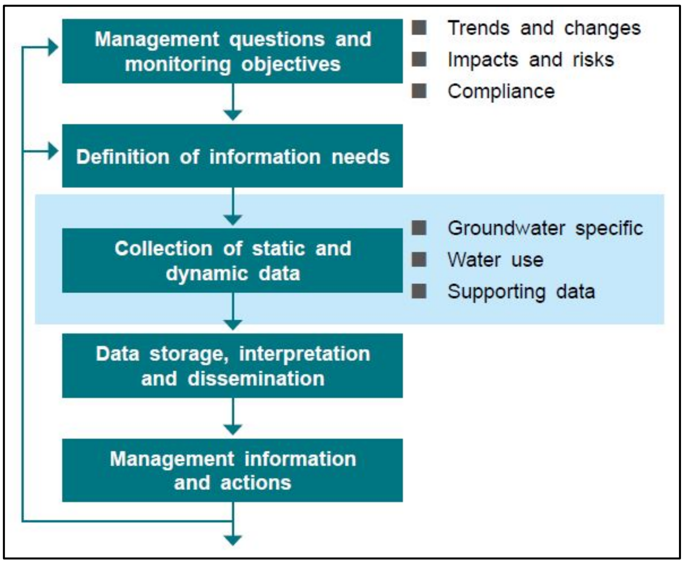

Figure 18: Monitoring cycle (AGW-Net, 2015)

The monitoring of groundwater in South Africa is the mandate of the DWS. At the moment funds are made available for "drought relief" throughout the country. One can only hope that some portion of this funding would go towards developing new and upgrading existing monitoring networks that can be used to develop a pre-HF picture (status quo) as well as identifying any impacts if HF is allowed in a future South Africa. This will assist regulators to determine if any impacts can be related to a certain HF activity in order to take action and see to it that it is remediated.

Considering all the aforementioned processes, one must then take into account the five basic objectives for establishing a monitoring system:

1. Baseline monitoring;

2. Resource monitoring;
3. Compliance monitoring;
4. Protection monitoring; and
5. Pollution containment monitoring.

Table 5 summarises four basic objectives with typical reasons/examples for each objective.

Table 5: Summary of basic objectives when establishing a monitoring system

Objective	Reason/Example
Baseline monitoring	Baseline monitoring assist in establishing ambient groundwater conditions in terms of hydraulic pressure gradient, estimated sustainable yield, abstraction volumes and chemical constituents (quality). Without baseline information no impacts can be identified as no reference information will be available for comparison.
Resource monitoring	To better understand a groundwater system with regards to recharge, discharge, groundwater/surface water interaction and to be able to determine groundwater quantity and quality behaviour over time.
Compliance monitoring	This can be sub-divided into two main dimensions. 1. Measurement of groundwater use and aquifer response to provide information on management related to quantity. This typically will allow for decisions on number of boreholes that can be allowed, abstraction rates and distances between boreholes. A specific reference groundwater level can then be estimated against which groundwater levels can be assessed; and 2. Measurement of groundwater quality parameters for assessment against prescribed maximum levels.
Protection monitoring	To assess potential impacts on specific groundwater infrastructure or aquifers. Examples can include: 1. Well fields or springs for public water supply against depletion and quality hazards; 2. Urban infrastructure against land subsidence; 3. Strategic water reserves against depletion or quality hazards; 4. Archaeological sites against rising water tables; and 5. Groundwater dependent ecosystems against undesirable changes in water quantity and/or quality
Pollution containment monitoring	Early warning on impacts of potential pollution hazards i.e.: 1. Intensive agricultural land use; 2. Industrial sites of specific industries;

	3. Solid waste land fill sites; 4. Land reclamation areas; and 5. Quarries and mines

4.5. Risk assessment

Risk assessments are usually done by an expert in a specific field of science. The expert determines a risk based on existing information available as well as information he or she gathers during field work excursions. By evaluating and interpreting the data, the expert can:

1. Characterise the risk;
2. Indicate mitigation measures to manage and reduce the risk; and
3. Communicate and inform others about the identified risk.

Once a comprehensive data set has been generated, in the case of a geohydrological investigation it should culminate in the construction of a conceptual model, the expert can assign risk associated with certain aspects of an activity. There are numerous ways in assigning risks but the underlying basics of assessment are universally more or less the same and only differ in the extent to how much detail is to be included.

One of the aims of this research is to produce a decision-making tool to assist experts, either appointed as consultants by applicants for a HF licence or working in government and regulatory departments, to be able to consider all impacts on our country's groundwater resources and to make informed decisions on whether an investigation has been properly carried out or whether the proposed activity should be allowed, after giving due consideration to the outcome of a risk assessment.

Research will focus on risk assessment techniques currently being employed by the O&G industry and Karoo Basin specific activities will be identified as well as which best practice technique(s) are available to investigate them.

4.5.1. Geology

As mentioned previously, several geological structures are used as arguments for preferential flow in an upwards direction along a pressure gradient due to the basin shape of Karoo sediments. These structures include:

- Dolerite dykes and sills;
- Fault zones; and
- Kimberlite pipes.

To be able to assess any risks associated with any of these structures it would be pertinent to conduct studies on their:

- Distribution on a regional scale;
- Interconnectivity;
- Distribution with depth;
- Contact characteristics; and
- Geohydrological characteristics.

With the lack of drilling information or rather the information being regarded as proprietary information of industry, it might necessitate that an EIA should cover a larger area than just the target site to be able to assess any possible regional impacts. The scale of investigation for an EIA should be pre-determined by a specialist group for each application to ensure that all geological information is considered.

4.5.2. Groundwater hydraulics

Determining groundwater parameters e.g. transmissivity (T), storativity (S) and effective borehole radius (e_r) is already complex and based on imperfect analytical as well as numerical solutions. It is also left to the geohydrologist to include supporting data, which could be considered subjective – one more reason to make use of senior geohydrologists who are considered as experienced enough by their peers.

When groundwater hydraulic data is considered, it would be important that the information should be from a reliable source and in most cases it should be peer reviewed for a second opinion. This should also apply for the data interpretation.

Employing and developing scientific hydraulic tests that will be able to assist in determining the parameters of groundwater system(s) encountered on the way down to the target formation would be critical and should be included in any technical requirements and form part of licence conditions to applicants. Independent observers representing regulators should be considered to ensure that tests are carried out as per specifications and data quality is not compromised.

4.5.3. Technical requirements

From a groundwater perspective, although the environment includes a host of sub-divisions, the primary concern would be subterranean formations and specifically this physical environment's ability to store and allow water to flow throughout this system due to differences in pressure and connectivity between pathways in a fractured system. During any investigative activity related to HF, it would therefore be critical to be able to assess/estimate physical properties i.e. T-values, S-values, and effective porosity (n) of different rock layers.

Different methods to determine the abovementioned properties will be put forward when proposed technical requirements by the Minister of Mineral Resources for HF are reviewed and recommendations are made. It is the opinion of the researcher that the current proposed technical requirements need to be adjusted to make provision for the unique South African geological context in which these activities are to be undertaken by a successful applicant.

4.6. Groundwater governance

Shale gas development as a whole will involve different role players on different levels, which will complicate groundwater governance with respect to HF activities. These include national, provincial as well as local government agencies. If one considers the disastrous communication history between different levels in just one department, imagine the confusion if all the different departments and regulators come into play.

Groundwater governance in South Africa clearly lacks implementation and high ranking individuals with sufficient knowledge and skills. Regulators and state departments whose mandate it is to protect the groundwater resources of South Africa are currently failing dismally in their attempts with impacts on our natural resources continuing to increase as well as maintenance on infrastructure not being done at all. At this moment in time, it is very hard to imagine a future where the above trends in groundwater governance will be turned around and our resources be managed in a way that is beneficial to all the citizens in South Africa.

A critical review of groundwater governance in South Africa will therefore form part of this research and conclusions made on whether HF should be allowed within the current situation in South Africa.

4.7. Modelling

There are different types of models that can be used to assist in making decisions regarding groundwater flow, interactions and impacts. Any information-gathering activity is usually in order to ascertain the physical environment and associated parameters that can be used to build a conceptual model of existing conditions of the subsurface and hydrological pressure gradients. Analytical solutions are usually employed to determine or estimate groundwater parameters e.g. T-values and S-values and recharge from precipitation to be used as input to the conceptual model. In complex situations, such as HF activities, this conceptual model can then be expanded into a numerical model to assess whether measured, calculated and estimated values are valid by running the numerical model and comparing output values to measured values. If any discrepancies are observed additional information should be generated by further investigation to make adjustments to the conceptual model.

Once the calibration phase has been successful, a different set of data, kept separate from the calibration data set, should be used to verify if the numerical model is able to accurately represent the natural environment. During exploration a verification data set is not available and any numerical modelling will only be done with a once-off data set for calibration, which would have the effect that the confidence from any modelling output should be considered as low and models should be required to be updated every two years with monitoring data.

After calibration the numerical model is also used for predictive modelling and once again the quality and amount of available data should be considered and a degree of confidence should be specifically mentioned by the modeller.

4.8. Conclusions

Groundwater is a field of science with numerous sub-divisions, each with its own core scientific base e.g. aquifer mechanics, geochemistry, geophysical surveys and groundwater management.

It is therefore important that each of these sub-divisions be appropriately utilised by experienced experts in each category to be able to create a conceptual model that will be able to assist in measuring, calculating and estimating parameters that will influence groundwater flow and quality as well as identify any possible risk from HF on shallow groundwater resources in order to facilitate sound groundwater governance.

5. ANALYTICAL, CONCEPTUAL AND NUMERICAL MODELS

5.1. Introduction

Modelling of groundwater resources and phenomena that could influence this environment has been with us since the first attempt by Darcy. A numerical model is usually the culmination of intensive research and field work to generate information and data, which are then in most instances first evaluated and assessed by means of simple analytical models. This output can then be evaluated and if it is accurate and representative of a specific system, a conceptual model is developed. From this conceptual model a decision can then be made on whether it is comprehensive enough to warrant constructing a numerical flow model. If required, a mass transport model can be added once the flow model has been calibrated and verified.

Numerical modelling is an important tool in the HF industry to assess different scenarios with regard to impacts associated with fracture propagation during stimulation activities (Kim and Moridis, 2015).

5.2. Analytical models

Analytical models are usually employed to determine certain parameters associated with groundwater flow and distribution over time. Some analytical methods frequently used by geohydrologists include:

- Theis (Theis, 1935) and Cooper-Jacob (Cooper and Jacob, 1946) methods for confined unsteady state conditions;
- Moench (Moench, 1985) solution for unsteady state flow in a homogeneous, isotropic leaky confined aquifer;
- Barker (Barker, 1988) radial flow solution for isotropic, single- or double-porosity fractured aquifers; and
- Gringarten and Ramey (Gringarten and Ramey, 1974) solution for unsteady state flow in a single uniform-flux horizontal fracture in an anisotropic confined aquifer.

It is evident from the above that one should be careful when applying analytical solutions as the above mentioned four solutions are some of the more familiar techniques for very specific conditions. From a quick search on the internet 35 analytical solutions could be identified, each developed for a specific type of environment. With the depths at which HF is going to be done in the Karoo, it can be expected that a combination of these environments will be encountered and will influence each other as well as any analytical approach to evaluate data.

The idea of being able to seal off certain sections of a well to conduct tests within a single aquifer layer should therefore be an important component of any technical requirements for applicants.

5.2.1. HF research

Atangana and van Tonder (2014) investigated the potential risk of groundwater pollution by HF by employing groundwater flow and mass transport equations, which in essence can be considered as analytical solutions at a certain point in a time domain.

One of the arguments by the anti-fracking community is that an upward pressure gradient exists and therefore groundwater carrying pollutants will migrate to surface and if there are any leakages this will have a negative impact on shallow aquifers that are used by local farmers and communities.

As the position and extent of subsurface fractures are very difficult to determine, if not impossible, in most subsurface environments, Atangana and van Tonder (2014) used Monte Carlo and Latin hypercube sampling to carry out an uncertainty analysis of the apertures of the fractures.

They concluded that their approach of using mathematical equations to describe the relationship between aperture gap size and T-values for each aperture, seepage velocities and discharge rate indicate that they were successful in establishing a relationship between aperture size and travel time of a pollutant against a given pressure head.

They suggested that this methodology can be used to investigate possible risks in an uncertain environment when groundwater investigations are done in areas where HF licences have been awarded. They indicated that there is also a long-term concern and that not only wells should be plugged with e.g. cement but that the total fracked reservoir should also be cemented closed to minimise any possible migration along fracture apertures.

Their view to plug the whole fracked system, although one from several options during the decommissioning phase, is not necessarily shared by the author and some additional options will be discussed in a section dealing with closure options.

Figure 19 depicts the relationship between travel time and aperture size of a pollutant along a gradient. Migration in an upward direction, if the pressure gradient exists, could be quite fast in an aperture of more than 1 mm. This specific scenario was done for a period of 47.5 years. It is evident that it is possible for a pollutant to reach shallow groundwater aquifers within this time in cases where larger diameter apertures are present.

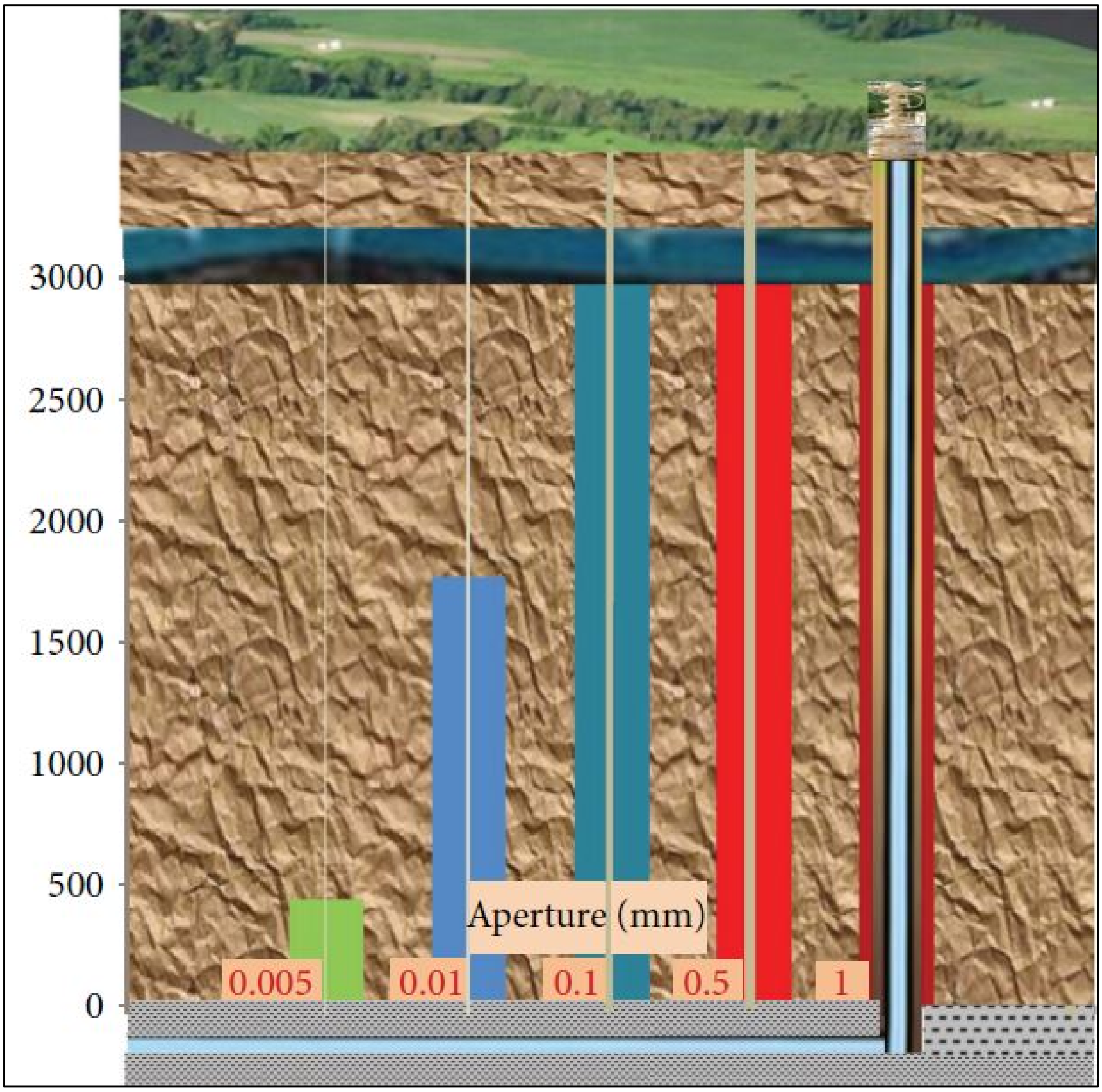

Figure 19: Image depicting flow velocities along various aperture sizes (Atangana and Van Tonder, 2014)

5.3. Conceptual models

As has been indicated before, a conceptual model is a simplified representation, 2D or 3D, of a given scenario. From a groundwater perspective, this will relate to a conceptual model that will include:

- Geological information;
- Physical parameter information associated with each geological layer;
- Presence of any intrusive rock formations;
- Presence of any fracture positions;

- ❖ Indications of whether a specific geological formation can be considered an aquifer, aquitard or aquiclude;
- ❖ If an aquifer is identified whether it is unconfined, leaky or confined;
- ❖ Groundwater level information – important to note if it is a groundwater level (unconfined conditions) or a piezometric level (confined conditions);
- ❖ Any areas of higher recharge from precipitation;
- ❖ Any areas where surface water/groundwater interaction occurs; and
- ❖ Groundwater quality information.

Depending on the volume and quality of the above data as well as its spatial representation of a specific area, the confidence associated with any conceptual model can be low or high in the case of a conceptual model which is more comprehensive.

In the case of HF and the possible risks involved, it would be a very good idea to err on the side of caution and be as comprehensive as possible. Once again it is important to point out that a high degree of effort should be put into establishing the interaction between site-specific information from exploration around a well pad and its setting within the regional groundwater regime.

A conceptual model is a "growing" model and should be developed in stages as work on site progresses. Lithological logs should be able to assist in grouping certain geological sequences with similar characteristics together in an attempt to keep the conceptual model as simple as possible, especially if the model is going to be used as foundation for numerical modelling. Once the physical representation has been developed, analytical solutions (models) are usually employed to determine parameters from specialised tests and measurements.

Once a conceptual model has been developed, a decision can be made on whether to continue with a numerical model. In the case of HF a numerical flow as well as mass transport model should be a requirement and it should also be used in conjunction with fracture propagation models being used by the O&G industry.

There are existing software packages that can be used to import lithological logs and all the physical geological information to build the conceptual model. One that is used by many international companies as well as by the researcher is LEAPFROG GEO that is workflow based and updates dynamically as new data is added to the project.

5.4. Numerical models

Numerical models are very useful to assist in making decisions where some margin of uncertainty exists. To construct a numerical model that will yield results at a high confidence level, high quality data and information as well as a sound knowledge of the limitations of a specific software package and/or solution that is selected, are required. Output of any numerical model is just as reliable as the quality of the input into the model.

Considering the above it would be appropriate to point out the following:

- ❖ No data or information from deep aquifers in the Karoo Basin were available;
- ❖ Outcomes of analytical solutions were used as basis for construction of the model;
- ❖ Input values were based on literature as well as analytical solutions;
- ❖ Conceptual models are oversimplifications of reality;
- ❖ Output values and visual representation thereof must be seen as an exercise to explain certain concepts and expected behaviour under certain conditions that might not be reflective of the actual subsurface environment; and
- ❖ Only worst-case scenarios were modelled.

5.5. Fracking model

Two models were constructed in an attempt to get an idea of what could be the result if any pollutant migrates along a gradient in an upwards direction towards surface.

The first model was a simple vertical fracture from a depth of 1 500 m to continue from the analytical model depicted in Figure 19. A second more comprehensive model was constructed based on a conceptual model presented in the *Karoo Groundwater Atlas* (SRK, 2012).

5.5.1. Vertical fracture model

This model was developed to see if it is possible to represent the analytical results as concluded by Atangana and van Tonder (2014) to estimate travel times along fractures with different aperture sizes.

5.5.1.1. Conceptual model – Vertical fracture

The conceptual model depicted in Figure 20 is an overly simplified representation of an area 2.5 km by 1 km with a fracture running across the model domain. A depth of 1 500 m was selected, which is similar to the expected depths of HF in the Karoo.

A homogeneous geological environment was assumed for the whole model domain except for the fracture zone, which was assigned a different vertical hydraulic conductivity (K_zz) value.

In the numerical model it was also decided that it would be representative of a fault zone, which is assumed to be fractured through all the slices and layers. The aperture size was also increased to 10 m to be more representative of known fault zones where the fracture zone can be much wider than the analytical solution's aperture widths.

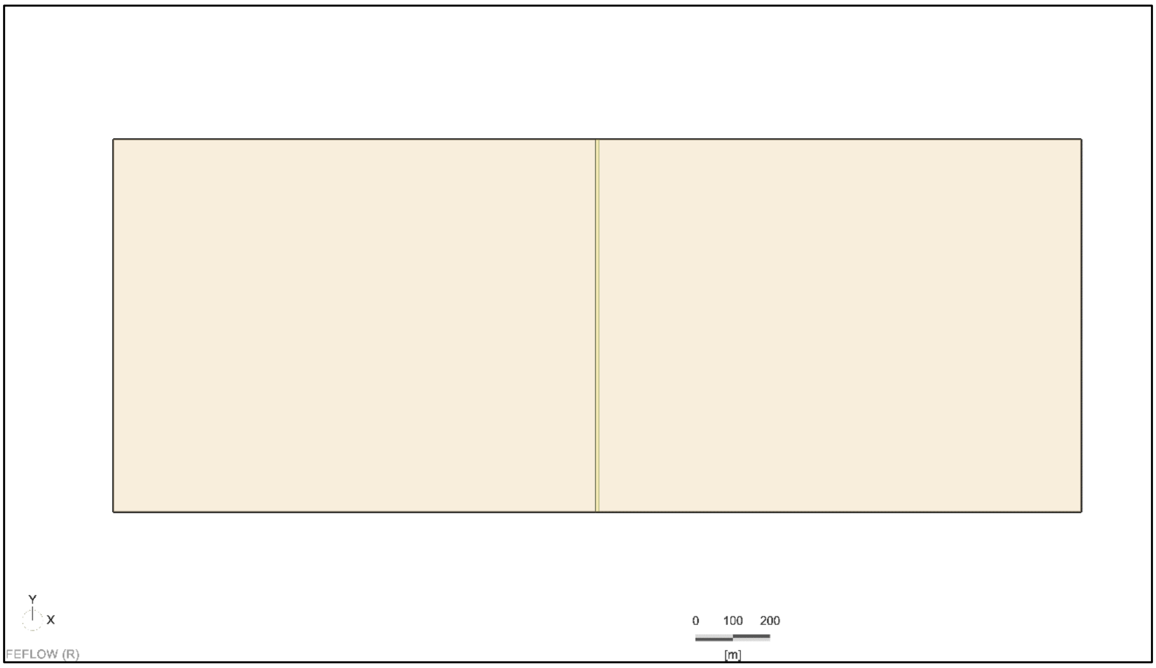

Figure 20: Conceptual model of vertical fracture model

The model network was generated by making use of a 3D finite element groundwater modelling software package Feflow, developed by the Germany based DHI WASY Institute for Water Resources Planning and Systems Research GmbH.

The basic premise on which all numerical models are based is that the area in question can be discretised into smaller areas, also referred to as elements. In the case of the fracture model, the area was discretized into 247 590 elements (8 253 elements X 30 layers), with 130 572 nodal positions (4 212 nodes X 31 slices). Different zones and layers were assigned in order to compensate for geohydrological differences in characteristics over the area due to geology and/or gradient at depth (Figure 21).

A flat topographical model domain for the first slice of the model was assigned a value of 1 500 mamsl across the whole area and the thickness of the successive layers (Figure 22) were subtracted from slice 1 to a final elevation of 0 mamsl.

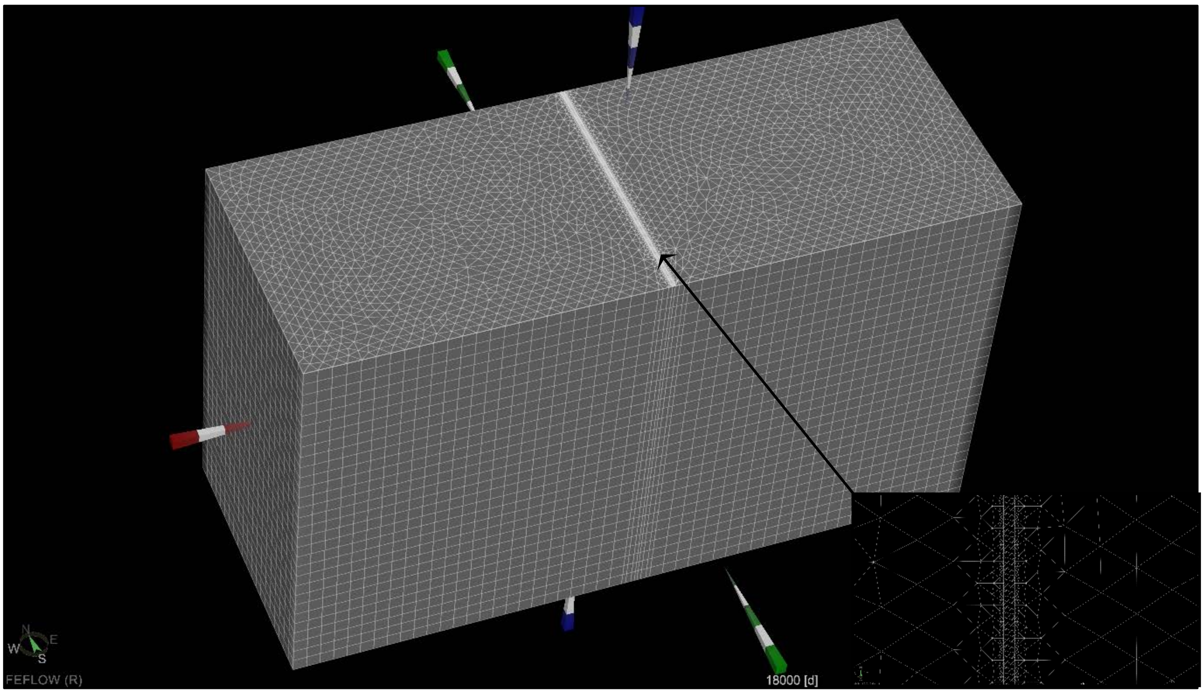

Figure 21: Finite element mesh constructed for the simplified fracture model

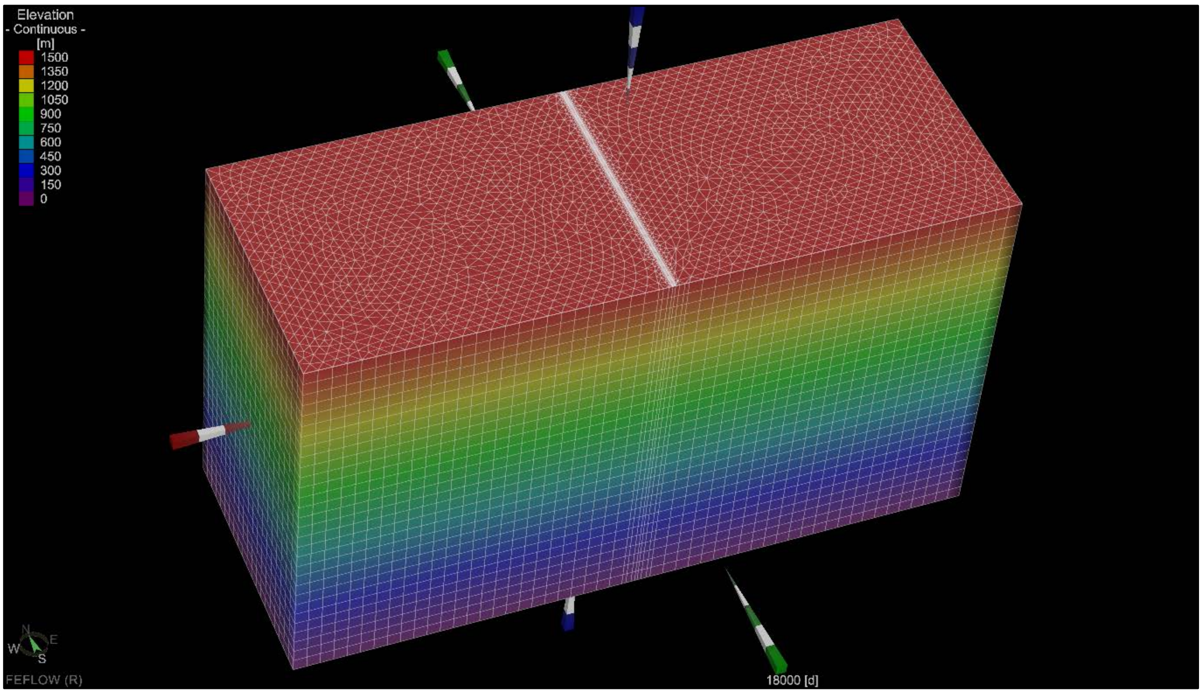

Figure 22: Elevations assigned to the different slices in the model

To create a hydraulic gradient a value of 1 530 m was selected for the bottom slice of the model and a value of 1 500 m for the top slice in order to create an upwards gradient. The model was run in steady-state to distribute the pressure evenly across the entire depth of the model domain (Figure 23). All the nodes of Slice 1 and Slice 31 in the model were converted to constant head boundaries in order to keep the gradient across the model domain constant for when the mass transport model was run.

Input values for K-values in all three dimensional directions were awarded a value of 1 meter per day (m/d) across the whole model except for the “fracture” which was assigned a value of 10 m/d along the K-zz axis.

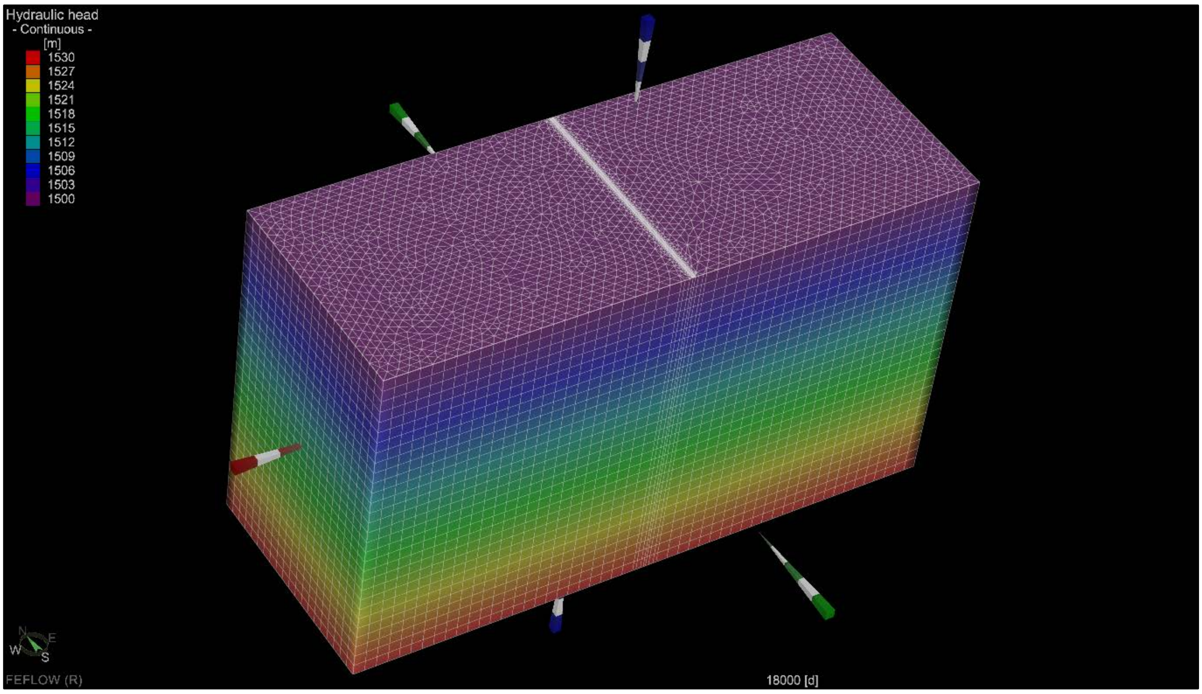

Figure 23: Initial hydraulic heads after steady-state simulation

5.5.1.2. Numerical model – Vertical fracture

The model was subsequently run in transient state for 18 000 days (50 years) with output intervals at:

- 360 days   1 year;
- 1 800 days   5 years;
- 3 600 days   10 years;
- 7 200 days   20 years;
- 10 800 days   30 years;
- 14 400 days   40 years; and
- 18 000 days   50 years.

Figure 24, Figure 25 and Figure 26 indicate the migration along this gradient of 0.02 for 1 year, 20 years and 50 years respectively. No specific pollutant/chemical compound was used for the mass transport model but a value of 100 mg/l was used as a continuous mass-concentration boundary condition. This allows for data output to be analogous to a percentage of the initial concentration of 100 mg/l.

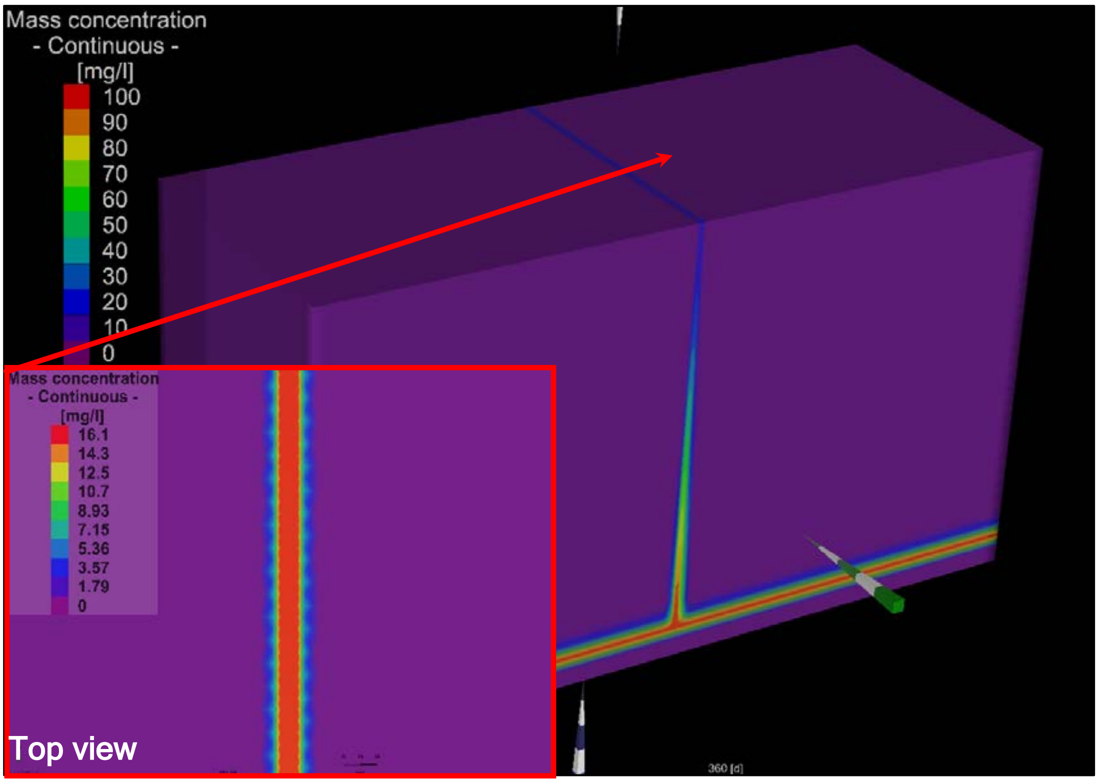

Figure 24: Potential pollutant migration after 360 days (1 year)

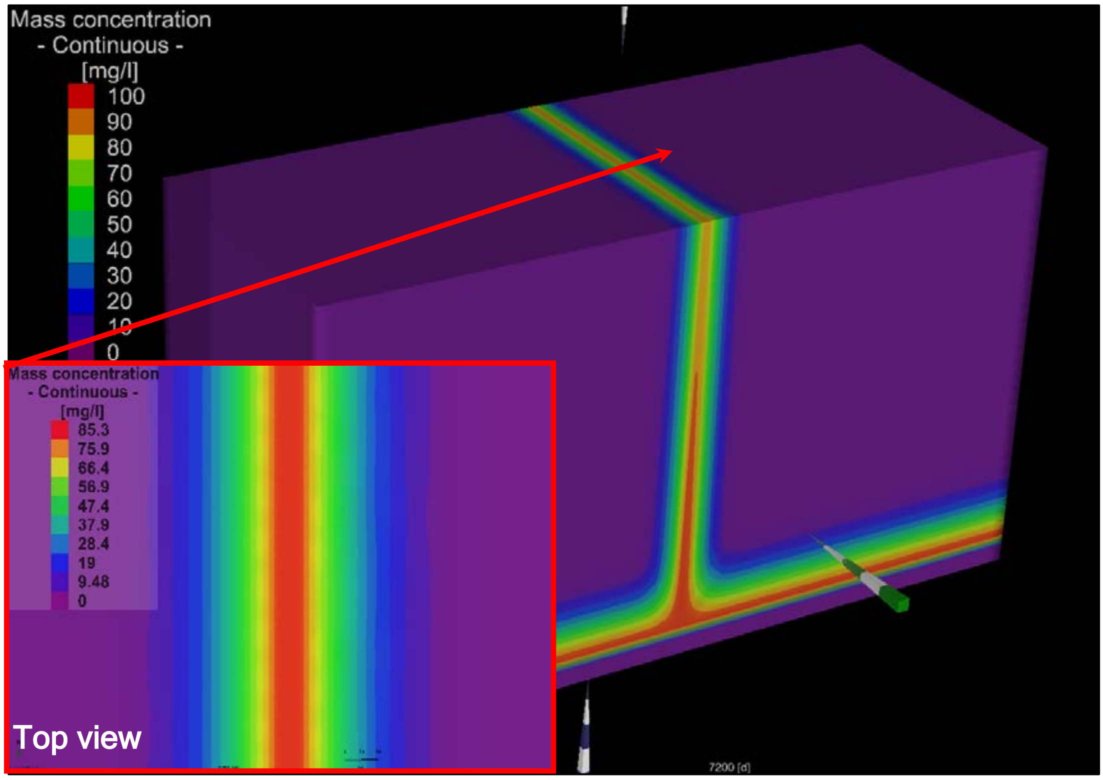

Figure 25: Potential pollutant migration after 7 200 days (20 years)

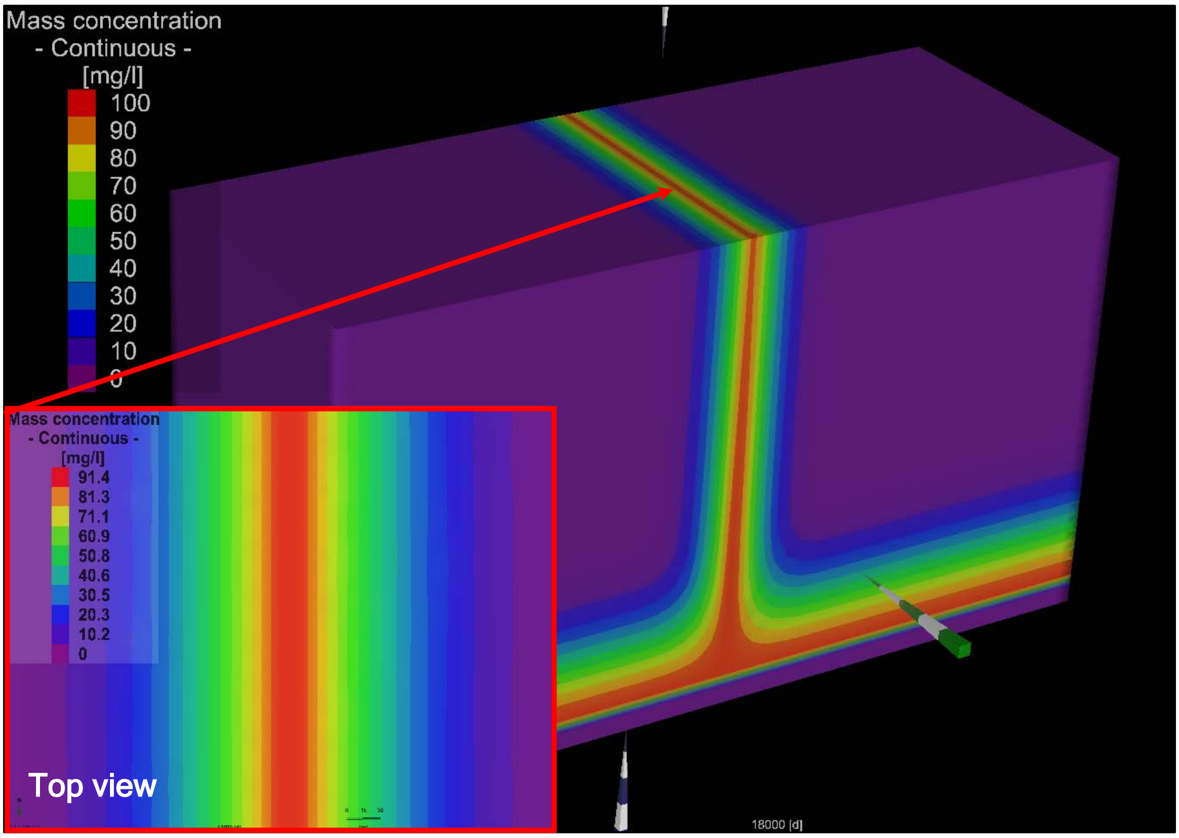

Figure 26: Potential pollutant migration after 18 000 days (50 years)

Figures representing the complete output set as mentioned in the list (p. 56) are included in **APPENDIX B**.

One more assumption regarding the pollutant was that it would be conservative and will only be influenced by advection with no adsorption, sorption, degradation or attenuation. Only the transversal to longitudinal dispersion ratio was specified at 1:10.

It is obvious that the plume migrates quite rapidly along the pressure gradient and reaches the top of the model at a concentration of 16 mg/l after only one year (Figure 24). After 20 years a concentration of 85 mg/l is predicted and the plume has migrated a distance of approximately 50 m away from the fracture into the matrix surrounding the fracture zone at a concentration of 50 mg/l. At 50 years a concentration of 91 mg/l is predicted and the migration extent into the neighboring matrix is an estimated 70 m from the fracture zone in both directions.

Another significant observation is the migration of the plume across the whole model domain from its level of origin. This highlights the following concerns with regard to information and data gathering:

- Most boreholes at a specific well pad are closely spaced and any lithological information of deep geological conditions will be limited to an area similar in size below the pad;

- ❖ Horizontal drilling can continue to distances of 5 to 7 km away from the well pad but lithological information will be limited to a narrow section of subsurface geology;
- ❖ It is a known fact that Karoo geology is significantly heterogenic and changes in formation thickness, contact zones and their characteristics as well as the occurrence of intrusive rocks can vary considerably over short distances; and
- ❖ Geohydrological conditions are highly influenced by the surrounding environment.

Bearing these concerns in mind it would then be very valid to find out from the HF industry what their methodology is to address this possible information gap.

This exercise in modelling by making use of research that was done to find an analytical solution for plume migration along fractures has been useful in three ways:

1. It supports the findings by Profs Atangana and van Tonder that a pollutant can travel towards surface very rapidly under specific conditions;
2. It has shown that numerical modelling can be used as a tool to assess geohydrological scenarios for predictive modelling in fractured environments; and
3. It has also highlighted the importance of sufficient, reliable and accurate data and information to be confident in model output.

5.5.2. Karoo Groundwater Atlas model

As a continuation of exploring the use of numerical models in predicting possible impacts on shallow groundwater aquifers due to HF activities, it was decided to use HF-related information to construct a numerical model and then, applying the methodology that was used for the analytical model and vertical fracture model, to run a more comprehensive model.

5.5.2.1. Conceptual model

The conceptual model that was used as basis for the numerical model was suggested by SRK Consulting as part of their *Karoo Groundwater Atlas* (SRK, 2012) (Figure 27). It can be regarded as very generalised and in the text description it is evident that the "*liberal use of question marks and subdued colours to denote uncertainties*" covers most of this model for the area below 300 m. This document saw the light in February 2012 and no other attempts have been made to construct a more comprehensive model.

Later research has produced very valuable information as well as significant contributions in understanding the Karoo geology, keeping possible HF activities in mind. One of these publications by Scheiber-Enslin et al. (2016) indicates that in certain areas in the Karoo dolerite sills are not as prevalent as previously anticipated. This will have serious implications on **1)** whether there are viable shale gas resources within the Whitehill and Price Albert Formations and **2)** what the physical characteristics of the subterranean environment is.

If there were no dolerite to contribute to producing a high temperature environment, which could cause methane gas to be gassed off into the surrounding matrix or along fracture pathways, there might still be a possible resource present. If there is methane gas within the formation and no dolerite in close proximity, it suggest less opportunity for fracture formation due to intrusive rock activity, which in turn suggests less opportunity for fractures and therefore minimising the risk of migration pathways being present. The issue of interconnectivity of fractures associated with contacts between dolerite and sedimentary rocks can also then be considered moot.

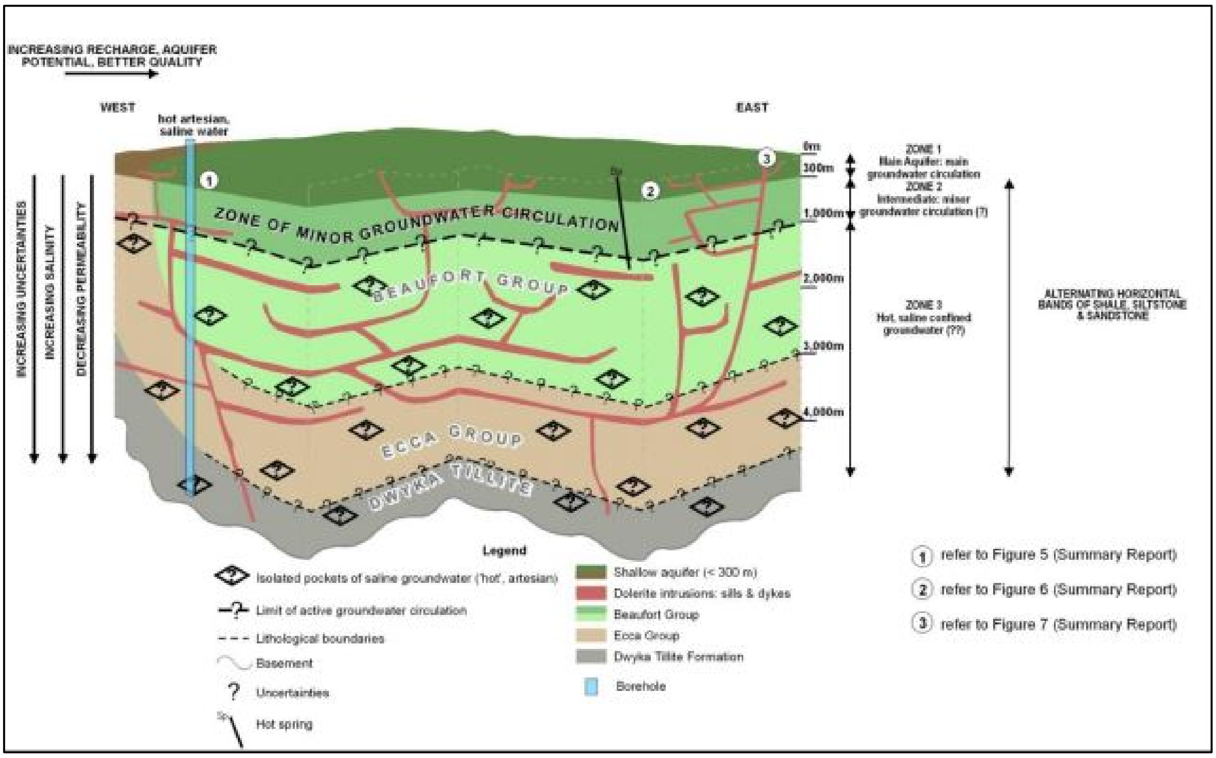

Figure 27: Conceptualised 3D block model (SRK, 2012)

Figure 28 represents only the dolerite intrusive structures as presented in the SRK Consulting model. It is assumed that a fracture zone is associated with each dolerite structure and that these fractures are interconnected. The whole model domain was considered as homogeneous and no differentiation was made between the different geological groups.

It was decided that only a 2D model would be constructed as there was no information to populate the area of 11 000 m wide by 4 000 m deep. Adding an extra dimension for a model that was already populated with information that was obtained from literature and expert opinions, wouldn't have added any value and the additional elements and nodes would have increased run-time during simulations.

Two "fracked" zones were entered at a depth of 3 500 m with a well from each section towards surface (Figure 28).

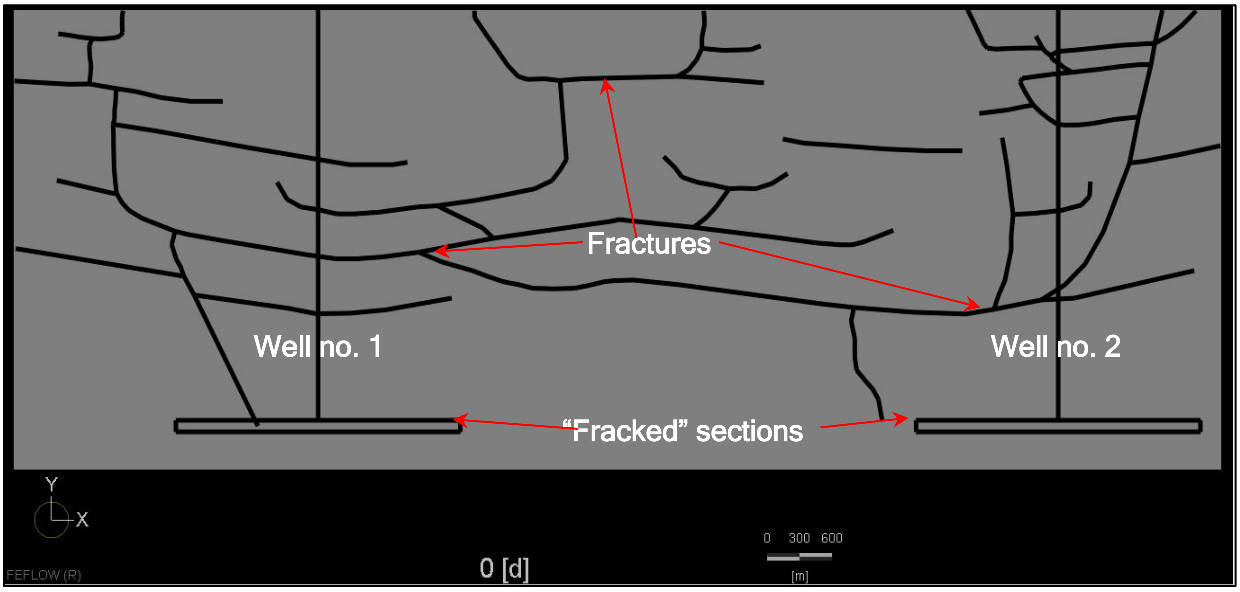

Figure 28: Conceptual model of Karoo Groundwater Atlas model

The model network was again generated by making use of a 3D finite element ground water modelling software package Feflow. In this 2D model, the area was discretized into 130 860 elements with 65 727 nodal positions (Figure 29).

It was decided to use a lesser gradient of 0.009 across the 3 500 m distance to surface from the "fracked" sections. However, higher K-values were used than in the vertical fracture model. A K-value of 0.01 m/d was assigned to the matrix part of the model domain, while a K-value of 1 000 m/d was assigned to the fractured component. The seemingly excessive K-value for the fracture system is an attempt to model a possible worst case scenario and based on tracer experiment results obtained during the author's M.Sc. research where a travel time of 54 m/d (Van Wyk, 1998) was estimated in a bedding plane fracture at the IGS Campus Test Site on the premises of the UFS. Dr. R. Murray's tracer tests at Windhoek in Namibia yielded flow velocities of slightly over 500 m/d (Van Wyk et al., 2000) and a tracer test along the Hansrivier Dyke in the vicinity of Beaufort West yielded a flow velocity of 968 m/day (Van Wyk and Witthueser, 2011).

To create the hydraulic gradient of 0.009, the same values of 1 530 m was selected for the bottom slice of the model and a value of 1 500 m for the top slice as was done for the vertical fracture model. A steady state simulation was run to distribute the pressure evenly across the entire depth of the model domain (Figure 30). All the nodes throughout the model were assigned a constant head boundary in order to keep the gradient across the model domain constant for when the mass transport model was run.

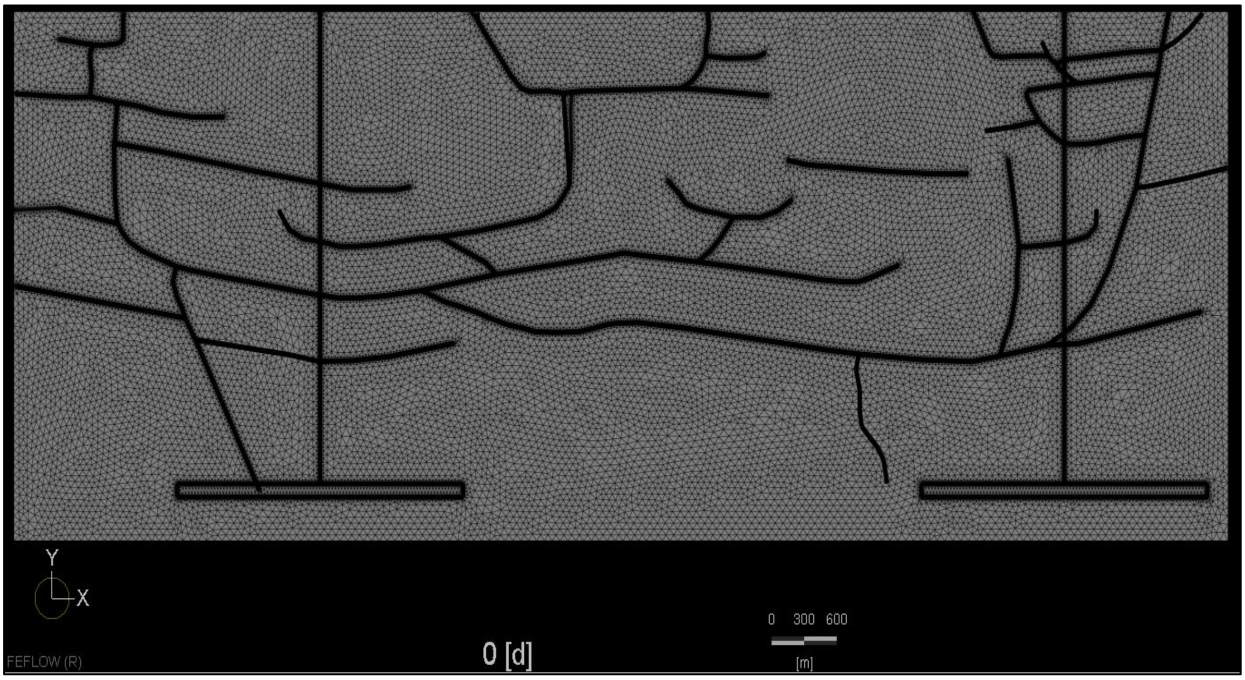

Figure 29: Finite element mesh constructed for the Karoo Groundwater Atlas model

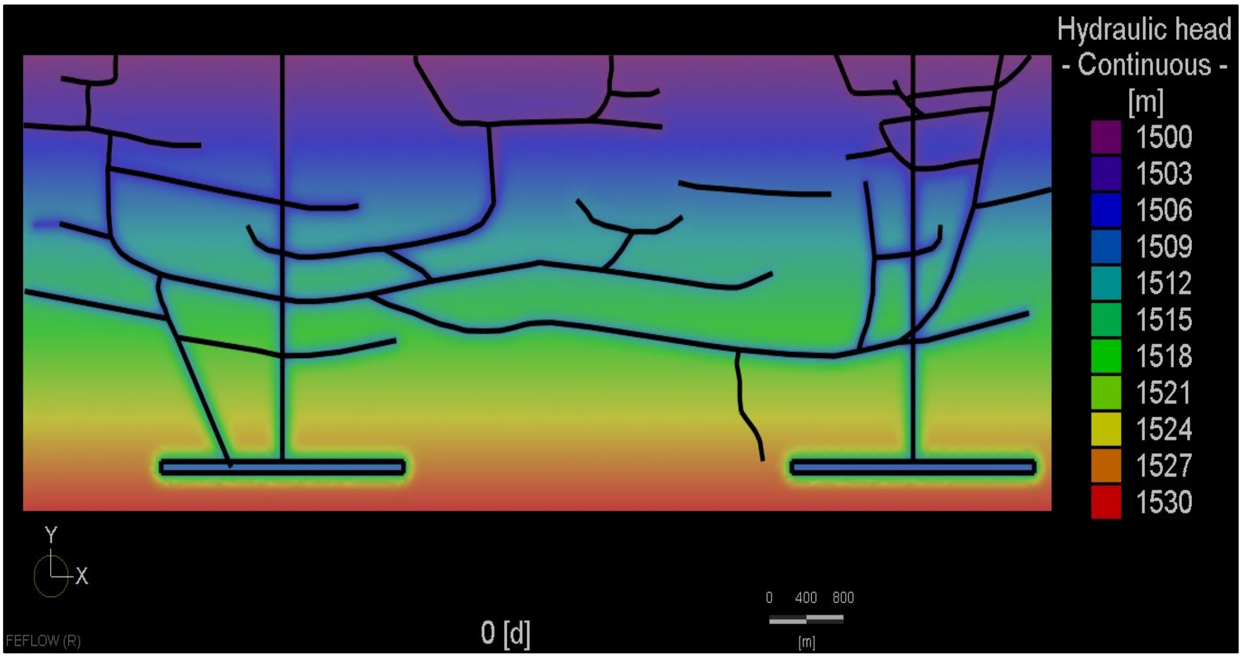

Figure 30: Initial hydraulic heads after steady-state simulation

5.5.2.2. Numerical mmodel

As with the vertical fracture model, an arbitrary value of 100 mg/l was assigned to the nodes of the “fracked” zones as a continuous mass-concentration boundary condition. Once again the migrating pollutant was assumed to be conservative.

The model was subsequently run in transient state for 18 000 days (50 years) with output intervals at:

- 365 days 1 year;
- 1 825 days 5 years;
- 3 650 days 10 years;
- 7 300 days 20 years;
- 10 950 days 30 years;
- 14 600 days 40 years; and
- 18 250 days 50 years.

Figures representing plume migration for all the intervals above is presented in APPENDIX B and only the 365 days (1 year), 7 300 days (20 years) and 18 250 days (50 years) images form part of this section’s discussion.

From Figure 31, Figure 32 and Figure 33 the immediate observation is that migration is rapid along prominent fractures orientated in a vertical direction. Not a lot of migration occurs along the horizontal fracture zones.

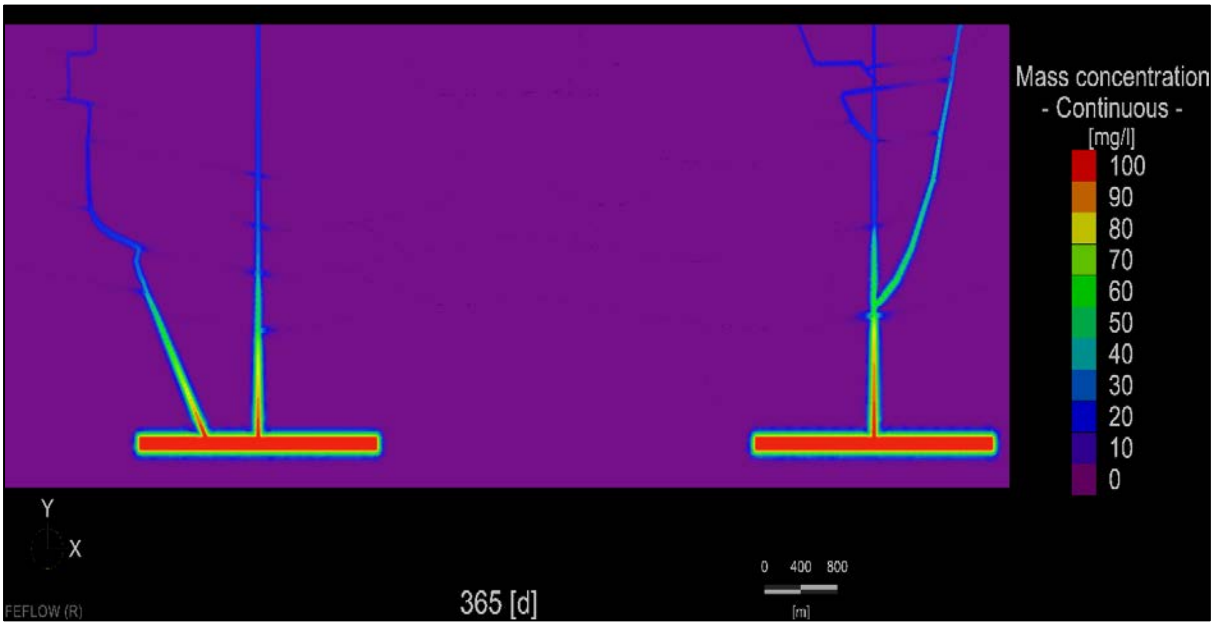

Figure 31: Potential pollutant migration after 365 days (1 year)

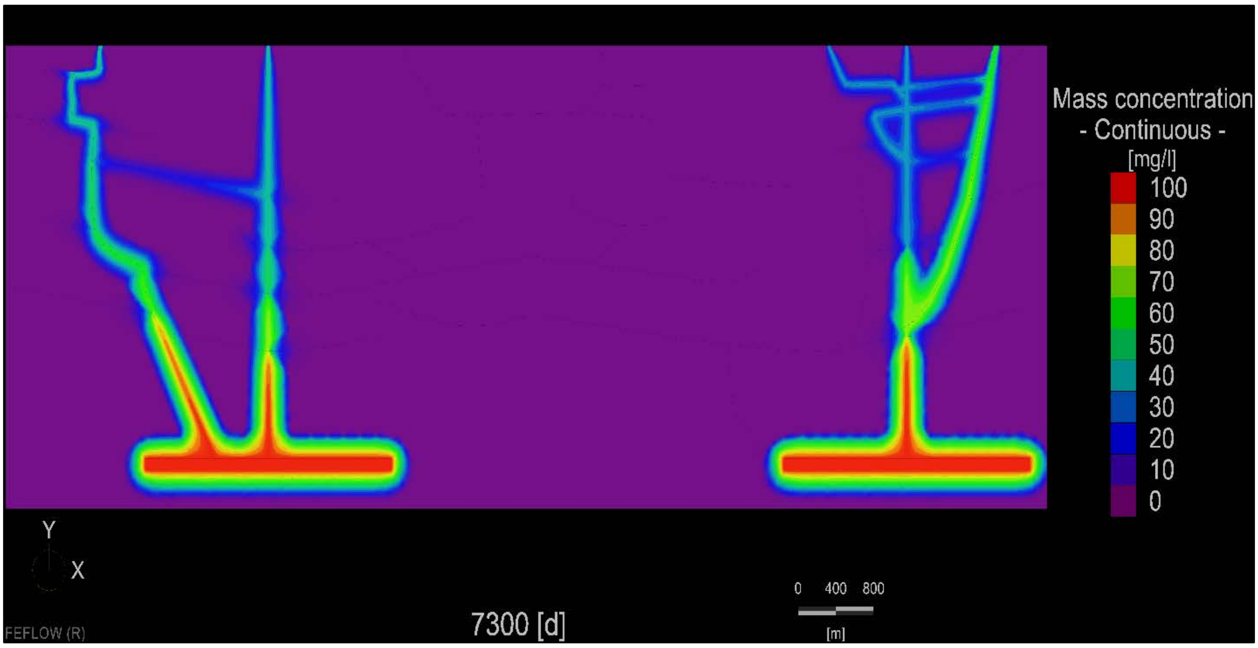

Figure 32: Potential pollutant migration after 7 300 days (20 years)

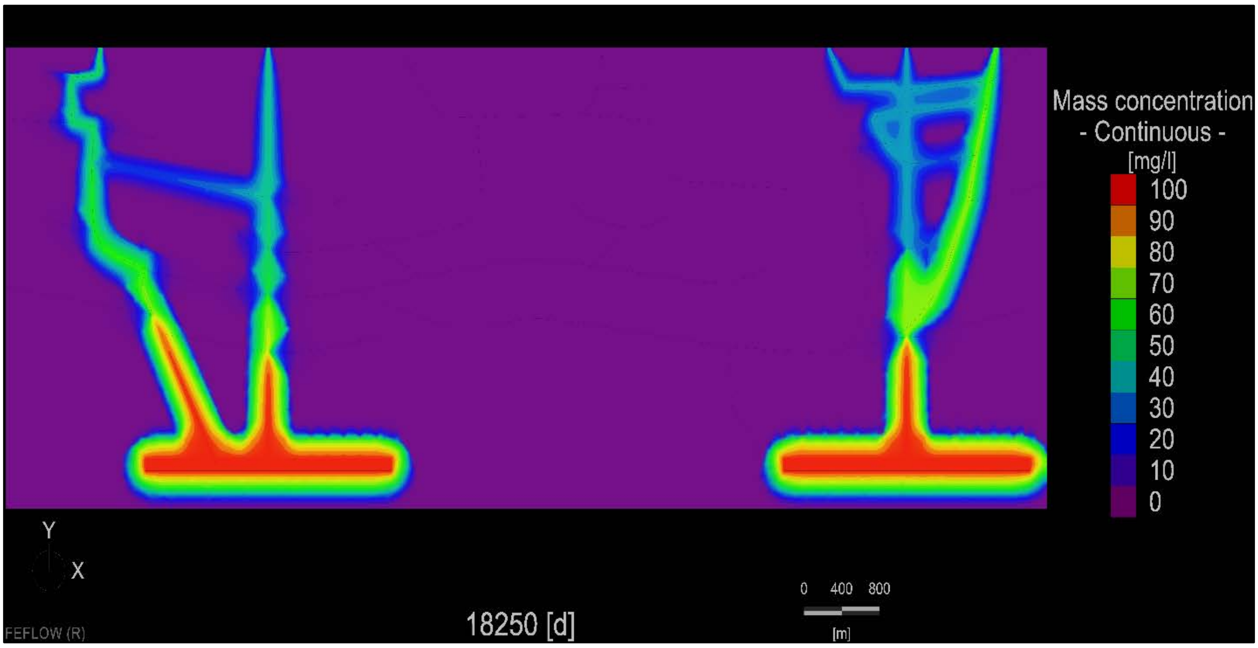

Figure 33: Potential pollutant migration after 18 250 days (50 years)

Over time plume migration remains mostly associated with preferential pathways vertical in orientation with some ingress into the surrounding matrix.

The "fracked" zone on the left hand side had besides well no. 1 an additional fracture feeding directly into it, while the "fracked" zone on the right only had well no. 2 intersecting it. From this it is obvious that any fracking (stimulation) activities should not be allowed in subsurface conditions where dolerite intrusive rocks are present. This supports the inclusion of dolerite in the "possible fatal flaws" section of the GW-RAT tool.

5.6. Conclusions

Analytical models in groundwater have been around since Darcy conducted his first experiments. Since then numerous analytical solutions for various subsurface conditions have been developed and successfully used to determine certain geohydrological parameters, predicted drawdowns and sustainable yields from aquifers.

The possibility of a HF industry should be seen as an opportunity in South Africa to enhance our knowledge on our deep aquifers and to develop analytical methodologies and solutions for such conditions or alternatively determine whether existing analytical approaches are still valid in a deep fracture system environment. As it is expected that numerical modelling would form part of any groundwater investigation, it would then be sensible to ensure that analytical solutions used for data interpretation should be of a standard in order to compile a conceptual model that is simple enough to allow for numerical modelling but as comprehensive and accurate a reflection of the physical environment being investigated as possible.

The requirement for a comprehensive and accurate conceptual model of any given HF site, should be a prerequisite to any applicant for a licence to produce shale gas. Not only in the Karoo but anywhere in the world. It should be populated with site specific information from geological and geohydrological information. Input should be accurate from measurements, calculations as well as estimates from analytical solutions that is suitable for geohydrological conditions at the site.

Numerical models can be regarded as a powerful tool in assisting geohydrologists and ultimately regulators in making better and well-informed decisions. Due to the fact that model output can be wrong and totally inaccurate in the hands of someone that does not understand the limitations and/or assumptions under which numerical models operate, it is really important that the modeller that is part of a team investigating potential HF-related impacts on shallow aquifers be someone that understands the mathematical limitations and assumptions associated with a specific algorithm that is selected as solution on a given modelling exercise. Someone with an understanding of the physical and practical side of groundwater investigations would be preferred above a modeller that has a mathematical background only no matter how strong.

An analytical solution put forward by Atangana and van Tonder (2014) has indicated that travel times for pollutants can be quite rapid if an upward pressure gradient exists and a fracture or interconnected fractures with sufficient aperture width are present. This could put any pollutant in close proximity to shallow groundwater resources with only a sequenced combination of steel casing and cement jobs between the resource and pollutant.

A single vertical fracture numerical model supports their research. Across a gas well with a depth of between 3 500 m to 4 000 m, many different matrix environments would be intersected, each with its own set of physical characteristics. Delineating sections with similar characteristics would be important for construction of a numerical model that will yield sensible and accurate output.

By making use of an existing conceptual model, put forward by SRK consulting as part of their *Karoo Groundwater Atlas*, an additional model was constructed, which yielded another set of supporting results. In this case two prominent trends could be identified. One was that plume migration could occur primarily in fractures orientated vertical and secondly the zone in which stimulation/fracking of the formation is done should not be intersected by any dolerite intrusive structures.

As a penultimate concluding remark the author feels it prudent to point out that all models were based on the assumption that an upward hydraulic gradient towards surface exists and K-values assigned to the different components – matrix and fracture zone – were based upon literature values and personal communications with several groundwater experts with a comprehensive knowledge of Karoo Basin geohydrology.

This chapter has proved that models can be useful in using field measurements and calculated or estimated data in an attempt to evaluate possible impacts on the groundwater system at any given location. The effectiveness of numerical however, would be greatly dependent on skilled software operators and reliable and accurate data and information.

6. GROUNDWATER GOVERNANCE

6.1. Introduction

Four fundamental dimensions of governance dynamics are identified by the United Nations Development Programme (UNDP, 2013) in their *"User's Guide for Assessing Groundwater Governance"*:

1. Social dimension;
2. Economic dimension;
3. Political dimension; and
4. Environmental dimension.

The complexity of governance dynamics is depicted in Figure 34 where the four dimensions of water governance and their different focus areas as well as the continuous internal links/communication are presented.

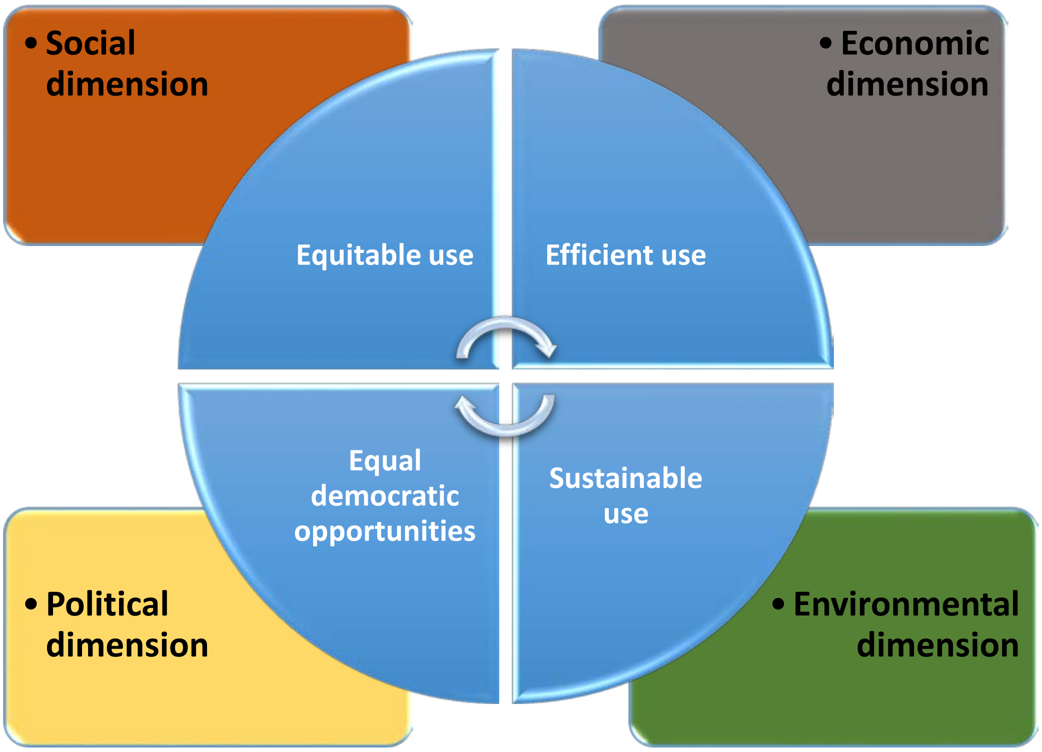

Figure 34: Water Governance Challenges (Tropp, 2005)

It happens very often that water governance is perceived as being synonymous with water management where in actual fact they are both independent components that are linked in a way that efficient governance should yield efficient and practical management tools. Water governance is the process of determining rules, while water management is the process of implementing these rules. Governance is decisions that are made and management is implementing these decisions. One process is not of any use without the other. In order to be able to formulate rules as part of water governance, reliable monitoring information is required, which again highlights the importance of developing local and regional monitoring networks. Monitoring is a physical action that would be included under water management. The interplay between governance, management and monitoring (Figure 35) can then possibly be described as a cycle of "development" in a society that is serious about their resources. Note that monitoring will influence governance decisions as well as management options.

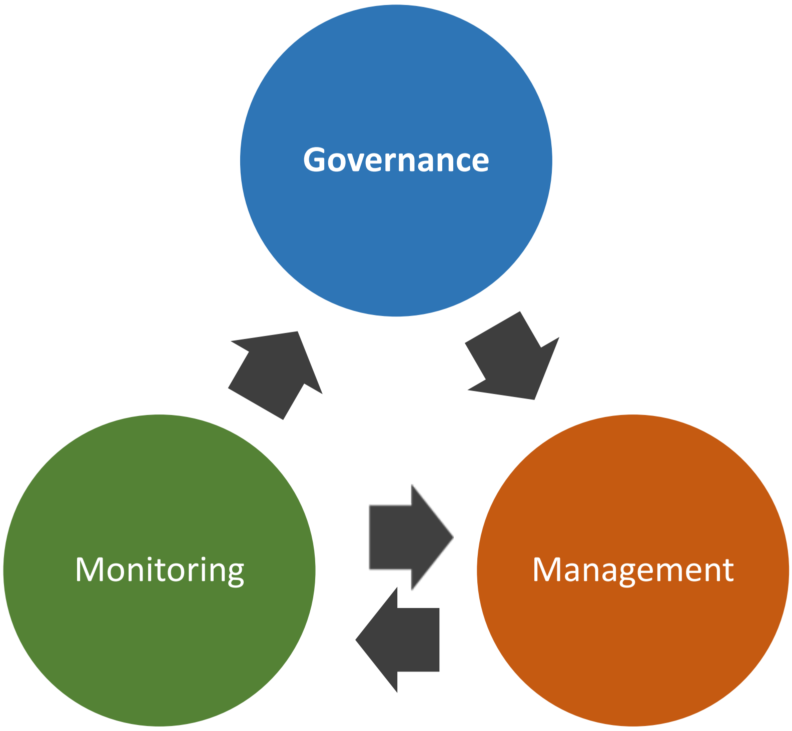

Figure 35: Flow diagram indicating the interaction between governance, management and monitoring

There is no blueprint for water governance. There are just too many aspects that can influence any one of the four dimensions of water governance at a certain point in time. Different challenges are experienced by many countries at different levels in their attempts for optimised water governance.

Groundwater governance encompasses numerous aspects and elements of which some have been introduced into the mix only recently. Some of the aforementioned often included are:

- Decentralisation;
- Integrated and coordinated decision making;

- Stakeholder participation;
- Catchment management; and
- Increased involvement by the private sector.

Current trending changes in groundwater governance include:

- Moving from state-centric to more pluralistic forms of governance; and
- Recognition of water as a human right.

South Africa is one of the first countries in the world to acknowledge water as a human right in our constitution.

Technical regulations for HF proposed by Minister Susan Shabangu of the DMR (DMR, 2015) have been reviewed by numerous institutions as well as other state departments and the general consensus was that the document was compiled in haste by cherry picking from international regulations without considering Karoo-specific requirements. Many state departments decided to draw up their own regulations, which indicates the lack of efficient groundwater governance.

Effective water governance should include development and management of resources as well as delivery of water services across all levels of society (Rogers and Hall, 2003).

6.2. Status quo

In South Africa water governance and therefore groundwater governance is currently in dire straits because existing rules are not implemented due to various reasons. Almost everyday reports of empty taps and broken infrastructure is included in newspapers. The fact that no spare parts or equipment are available at local municipality level causes additional delays in solving the problem.

Many towns in the Karoo are currently experiencing water shortages due to the extended drought as well as a lack of knowledge and skills where groundwater is concerned. Technical staff usually does not understand why groundwater monitoring is important and budgets for maintenance are mostly non-existent due to salaries making up the brunt of these municipalities' budgets. No additional funds are available for maintenance and if any becomes available it is not always spent on water-related issues.

The National Water Policy Review (NWPR) (DWS, 2013a) had the purpose to identify and address gaps and omissions from past policies in order for the aforementioned gaps and omissions to be included in subsequent legislation.

Seward and Xu (2015) very eloquently sum up the conundrum of water governance by pointing out that just by considering all the role players involved in groundwater governance it is obvious from the start that tension between different agents will exist. I quote:

"*Regional, national and global 'hydrocrats' who are concerned about groundwater over use and pollution, want to make rules to stop this and expect local users to either comply with or even implement these rules.*

vs.

Individual groundwater users who are concerned about getting their fair share of the resource and/or being able to use that resource for economic gain."

From the very brief description attempting to describe the current groundwater governance situation in South Africa, it is evident that we are hugely lacking in our ability to execute any one of the components of the cycle of development mentioned earlier. Numerous reasons can be mentioned as to why we find ourselves in this situation but it is the opinion of the researcher that high-level decision makers, who lack the skills to comprehend what their role should be in enabling their personnel, are influenced in various ways to make certain decisions that are detrimental to water governance. Most groundwater personnel at local-scale levels are extremely competent and understand what needs to be done to carry out their mandate as regulators. Unfortunately they do not have the backing of their minister and/or director generals.

6.3. Way forward?

Up to now a centralised hub from where decisions and policies are forwarded along a chain of command to local municipalities – grassroots level – has not been successful. Planning on a national scale has not benefitted any of the small- to mid-sized communities up to now and water governance is rapidly deteriorating in large metropoles e.g. Mangaung and Nelson Mandela Bay.

From a groundwater point of view it is time to initiate implementing existing rules on a local scale. Educating individuals to assist in monitoring and repairs on municipal level would be front and foremost in getting things started, while long-term maintenance could be outsourced to local contractors under the supervision of an experienced and accredited service provider.

Government, industry and tertiary educational institutions should combine and form a knowledge hub that will be able to assist good governance, which will lead to better management of groundwater resources. Following is a summary list of possible methods to improve groundwater governance as described in a document compiled as product implemented in 2011 and sponsored by the World Bank (Food and Agriculture Organization of the United Nations et al., 2016).

1. Adoption of principles for governance of groundwater which will include the following aspects:
    a. Equitable access
    b. Sustainability;
    c. Transparency;
    d. Participation and representation;
    e. Accountability;
    f. Functional integration with water policy and management;
    g. The precautionary principle; and
    h. Knowledge management principle.
2. Desirable institutional responses by ensuring:
    a. Accessible groundwater information;
    b. Establishing an institutional home for groundwater;
    c. Removing constraints; and
    d. Facilitating investment in groundwater.
3. Promoting viable institutional strategies by:
    a. Engaging with users at aquifer scale;
    b. Anticipating the evolution of groundwater quality;
    c. Defining mutually acceptable levels of depletion and degradation;
    d. Spreading production and environmental risks;
    e. Strategy when access to groundwater disappears; and
    f. Structuring investment in groundwater governance.
4. Anticipating climate change by taking into account;
    a. Accelerated geohydrological cycles and groundwater circulation; and
    b. Changing patterns of land use and recharge.
5. Anticipating the impact of technologies and groundwater "frontiers" in the fields of:
    a. Geophysical exploration;
    b. Drilling and pumping technology;
    c. Further impacts on the built environment;
    d. Implications of crustal encroachment; and
    e. Evolution of environmental instruments and aquifer protection.
6. Stressing and promoting the benefits of good governance by highlighting:
    a. Livelihoods outcomes and groundwater transactions;
    b. Macro-economic outcomes and setting the incentive structure; and

c. Environmental outcomes.

6.4. Conclusion

There are obvious concerns regarding water governance and specifically groundwater governance in South Africa. Currently the whole concept of governance can be considered as dysfunctional with no real leadership and example at the top echelons of government and regulators.

If groundwater governance is not developed in the sense of establishing local and regional monitoring networks and establishing an institutional environment where data and information are verified, validated and interpreted in a timely manner, there should not even be any thought of establishing a HF industry in South Africa.

HF should be considered to have the potential to harm a very valuable and sensitive resource until such a time that more information is available. Without good groundwater governance this will not be possible.

All the information on good groundwater governance is available, ready to be combined into a set of principles, requirements and protocols for a South African context but it will take champions on local governance levels to break the ice and take ownership of their groundwater resource. It will also require government, industry and educational institutions to assist local councils and municipalities and to become involved with their groundwater governance on a much higher frequency than what is currently the case.

7. DEVELOPMENT OF A RISK ASSESSMENT TOOL FOR HYDRAULIC FRACTURING OPERATIONS

7.1. Introduction

Geohydrological investigations have over time been highly neglected with only minimal information and data gathered during the EIA process. Projects are many times assigned to engineering companies or even contractors without in-house capacity to evaluate groundwater impacts. Budgets allowed for investigations are most of the times not adequate to allow for inclusion of highly technical activities/tests that are generally costly but would add value to reliability and confidence, by orders of magnitude, in output results upon which much better management decisions can be made.

The primary focus of any geohydrological investigation should be the compilation of an acceptable conceptual model of the specific system on which an impact is being assessed. Due to the potential of HF being extremely disadvantageous to the groundwater environment, additional compulsory checks and balances should be required by regulators to determine possible impacts.

Research has indicated that in all countries where HF has been allowed on large scale, information about frequency and severity record keeping and reporting has been horrendously neglected due to historical regulatory gaps and loopholes, either existing due to a lack of research skills or funding or even created as is evident by the "Haliburton loophole". This refers to a very dubious provision in the USA's energy bill in 2005 and was championed by the then-Vice President Dick Cheney, which used to be a former chief executive of Haliburton. The EPA was effectively stripped of its authority to regulate HF because industry argued that the chemicals used in the process are proprietary secrets and by revealing this information their competitive edge would be compromised (The Scientific American, 2011).

The development of a tool to assess and quantify, GroundWater Risk Assessment Tool (GW-RAT), was therefore regarded as an important aspect of this research project. Considerations were to keep it as simple as possible but to highlight specific aspects and/or activities that seems to be essential from a South African perspective.

The overall layout of the tool should be simple and user-friendly to allow for minimising decision-making errors. Guidelines were developed to inform the user on how to choose an option and a simple scoring system forms the basis to arrive at a score that is underlain by a comprehensive inclusion of all possible identified impacts based on activities associated with the HF process but will also include other associated activities before and after the stimulation phase of operations.

7.2. Risk features

A huge concern from a groundwater perspective when it comes to HF is the potential for any pollutant or saline groundwater from deeper aquifers to migrate along a pressure gradient towards surface.

From a purely natural environment perspective any attempt to determine subsurface fracture positions, extent as well as inter-connectivity would prove challenging, which highlights the importance of having a set of regulations and guidelines that will assist in compelling any licensee to gather high quality data and having a regulator that has the knowledge, skills and authority to enforce these regulations. Seismic activity can change a specific setting and any effort to predict the probability of such an event occurring in the surrounding area of a well pad will prove difficult.

Man-made conduits, of which a HF well is front and foremost, will also be introduced into this natural environment and information gathering during any subsurface activities would be vital to ensure that the integrity of the system is kept in place and that any changes are identified at an early stage to prevent structural breakdowns that could allow contaminated backflow or produced water to migrate into the shallow fresh water aquifer system(s).

Shallow groundwater resources are in some areas the only means of potable water supply and therefore it is extremely important that aquifer systems and pressure gradients be recorded accurately to determine risks involved.

Activities that might have an effect on shallow groundwater resources can be divided into two categories:

1. Surface activities; and
2. Subsurface activities.

This will also be the main division for each of the three phases upon which the risk assessment tool, GW-RAT is developed.

7.2.1. Surface activities

Surface activities are going to take place at a much closer distance to shallow groundwater resources than the actual fracking phase after the well has been drilled and constructed. With gravity adding an additional force to be considered, groundwater contamination from surface activities is a definite concern during all three phases of a gas well's life span.

Fuel and chemical spills on a well pad are very possible and great effort should be made to minimise any ingress into the subsurface should one occur. During site visits to several sites in and around Pittsburg, Pennsylvania, a liner stretching across the whole well pad area (Figure 36) was observed and communications with operators indicated that specialized HAZMAT teams and equipment were on site to be deployed if any spill occurs.

Figure 36: Well pad liner to prevent any contamination from surface spills (courtesy of D. Vermeulen, 2011)

There are numerous activities that take place during all three phases when a well pad is developed. Some of them will be present during all three, while others will only be specific to a single phase. Geophysical investigations are an example of an activity that is only relevant during the exploration phase, while access control will be an activity that will take place during all three phases.

For the risk assessment, surface activities that were identified are:

1. Exploration phase:
    a. Geophysical investigation;
    b. Well pad construction;
    c. Site offices/Ablution facilities;
    d. Heavy machinery;

    e. Lining;
    f. Water sourcing/acquisition (surface water);
    g. Reservoirs/Storage/Holding facilities;
    h. Access control;
    i. Blasting;
    j. Drilling; and
    k. Drill cuttings.
2. Production phase:
    a. Data recording;
    b. Chemical mixing;
    c. HF;
    d. Flowback;
    e. Produced water;
    f. Well pad construction;
    g. Water sourcing/acquisition;
    h. Drilling; and
    i. Drill cuttings.
3. Closure phase:
    a. Well pad;
    b. Well head;
    c. Monitoring equipment;
    d. Access control; and
    e. Rehabilitation.

Each of the activities above are included in the GW-RAT tool and for each one a hyperlink has been created to link to a separate document with additional information regarding consideration to take note of in deciding a specific score for each activity as well as some information as to possible mitigation measures for each activity.

7.2.2. Subsurface activities

Subsurface activities will be much more difficult to assess than surface activities where visual observations can assist in determining the extent and gravity of a situation. Specialised techniques and equipment will be required to monitor processes and integrity during well construction, production and closure phases. Once again the question arises on how long monitoring should continue after a specific site has been closed down. It is recommended that some way be found that a well should never be allowed to be abandoned due to the fact that at some stage casing and cement jobs will deteriorate and if there is a pressure build-up in the system, this could allow pollutants to find their way into shallow aquifers. A long-term monitoring strategy is going to be a critical component in limiting and mitigating possible impacts on life-sustaining resources. Risk features included in the GW-RAT tool are:

1. Exploration phase:
    a. Excavations;
    b. Water sourcing/acquisition (groundwater);
    c. Drilling;
    d. Data recording;
    e. Blasting;
    f. HF;
    g. Flowback;
    h. Produced water; and
    i. Monitoring.
2. Production phase:
    a. HF;
    b. Flowback;
    c. Produced water;
    d. Methane - Stray gas contamination;
    e. Migration of salts or other dissolved constituents;
    f. Natural Occurring Radioactive Materials (NORM')s; and
    g. Casing integrity.
3. Closure phase:
    a. Closed well;
    b. Casing;
    c. Cement job; and
    d. Monitoring probes.

As with surface activities, hyperlinks for each of the abovementioned risk features are included for guidance and additional information to be able to make an informed choice of selection when populating the risk assessment sheet in the tool.

7.3. Possible fatal flaws

While the RA sheet in the GW-RAT tool allows for HF activities around a well pad during the different phases, some thought must also be put into conditions that could influence groundwater flow: volume as well as direction. Provision has been made for this in the calculation sheet of the tool. Once a score has been awarded, the user is required to select options from dropdown boxes from the section on the sheet where possible fatal flaws are listed. Although the word “Fatal” is used, it does not necessarily imply that the site should be abandoned and the idea of HF at the specific location be scrapped. Any further use of the word “fatal” should be viewed in light of this. This function in the tool should be regarded as a warning system of potential flaws within the geohydrological environment that require further investigation. The applicant for the HF licence should be given the opportunity to carry out additional research to verify if the anticipated risk associated with a specific “flaw” is applicable at a specific location.

An example would be if a fault zone is identified and flagged in the GW-RAT tool but no additional data is available. The only information available is that a fault zone is present across the area. The applicant can then be allowed an opportunity to determine whether the zone was influenced by permeability enhancing or reducing processes. If it is found that the formation permeability has been enhanced, the fatal flaw has been confirmed and no HF activities should be allowed. If the formation permeability is found to be reduced, it should not be regarded as a fatal flaw although the presence of the fault zone should require a higher level of monitoring.

If the risk can be reduced by pre-HF mitigation measures, it could also allow HF activities to continue if adequate monitoring requirements are put in place.

7.3.1. Geology

Assessing the environment in which groundwater occurs and HF activities might take place is going to be critical. A high degree of accuracy is going to be required to determine risks involved and specifics on how to go about it should be in place before any company should be allowed to continue with exploration.

Criteria specific to the geological environment that were deemed important are:

- **Target depth** – which refers to the depth from surface to the Whitehill and Prince Albert shale layers of the Ecca Group at any given location;
- **NORM’s** – Natural Occurring Radioactive Material could be present in deeper-situated sandstone layers and if a pressure gradient exists to surface, it could migrate towards shallow aquifers and potentially affect human health;
- **Dolerite** – As mentioned throughout this document, contact zones between dolerite intrusive rocks and the sedimentary host rock could be conduits of higher permeability, which would allow for rapid migration along pressure gradients. The occurrence of dolerite at any potential HF site should be cause for additional studies to determine if there zones of higher permeability exist and what the effect

and risks involved would be;

- **Kimberlite** – As with dolerite this intrusive rock formation could lead to high permeability conditions along contact zones and be cause for rapid migration of pollutants along a pressure gradient;
- **Fault zones** – Areas where movement of geological formations occurred, could be open or closed. Open faults could have high permeabilities and allow for migration within these zones. A zone that might be vertically orientated that could lead to migration taking place towards surface and shallow aquifer(s); and
- **Seismicity** – Seismic events could lead to compromising the integrity of a gas well. This in turn could allow gas and fluids to escape the well into the surrounding environment, which have the potential to impact potable groundwater resources should this occur at shallow depths. A Google Earth image with seismic events across the Karoo Basin, indicating year and magnitude of each event, is included as hyperlink to this flaw.

Any one of the fatal flaws mentioned above within the geological environment could have the potential to affect shallow groundwater resources if not researched sufficiently.

7.3.1.1. Target depth

It is expected that most target zones for HF would exceed a depth of 3 000 m. A conservative approach was followed throughout the development of the GW-RAT tool to add an additional confidence aspect to the methodology suggested. For this reason it is suggested that a depth of 2 000 m should be the criteria used to flag this component as a fatal flaw.

If the target depth is less than 2 000 mbgl, it is suggested that additional precautionary measure be put in place to minimise any risks. Monitoring requirements should also become more stringent.

7.3.1.2. NORM's

The presence if NORM's will add additional requirements into the mix as it could have impacts on human health and require specialised personnel and protocols with regards to hazardous waste handling. The ability of regulators to monitor transportation and disposal of hazardous waste must be established before this fatal flaw can be ignored and mitigation measures be accepted as sufficient to continue with HF activities at the location. With the current lack of sound groundwater governance, no HF should be allowed if NORM's are detected in drill chips, backflow or produced water.

7.3.1.3. Dolerite

Dolerite intrusive structures are part of the Karoo landscape and cover a major part of the area considered. One concerning aspect of these dolerite structures is the variability in their orientation over short lateral distances (Chevallier and Woodford, 1999) causing a very heterogeneous environment, which in turn would be very difficult to monitor and therefore manage. Current risk assessment methodology of groundwater resources is usually more a matter of an expert opinion based on experience and assumptions without actual measured data and/or a scientifically sound underlying hypothesis. Cross-cutting relationships where dykes and sills of different age intersect each other, increase the complexity of the Karoo dolerite formations and necessitate a groundwater assessment strategy that includes all possible outcomes. To further complicate matters, the fact that very little is known about the interrelationship between dolerite structures at depth is on one hand a cause for great concern and on the other hand an opportunity for research to understand our deep geology and geohydrology. It is therefore important that government takes the lead in funding and research on our deeper groundwater systems.

If any dolerite dykes or sills are identified during site assessment and/or drilling activities, great care should be taken in measuring geohydrological parameters. Important information should include pressure measurements at contact zones by means of packer testing, flow velocities along contact zones by means of tracer tests and any information regarding extent and interconnectivity with other fracture zones.

A recent study included in a book edited by Linol and de Wit (2016) revealed very interesting information. If Figure 37 is considered, it seems as if SOEKOR well (triangles) data can be divided into two distinct groups. One group of red triangles located in the north east and west of the Karoo Basin represented by the thick black outline in the top image (a), and a second group of green triangles situated more central and towards the south of the basin.

Considering the cross section shown in Figure 37(b), it is clear that dolerite has intruded only the Beaufort (BF) Group for the green triangle boreholes. Red triangle boreholes have dolerite intrusion throughout the whole stratigraphic sequence: Dwyka (DW), Ecca Shales (ES), Ecca (EC) and Beaufort (BF) Groups.

The above is important because it means that in certain areas dolerite might not be as prominently present, which in turn minimise risks associated with these structures and therefore the possibility to allow HF in these areas if shale gas is present in economically viable quantities.

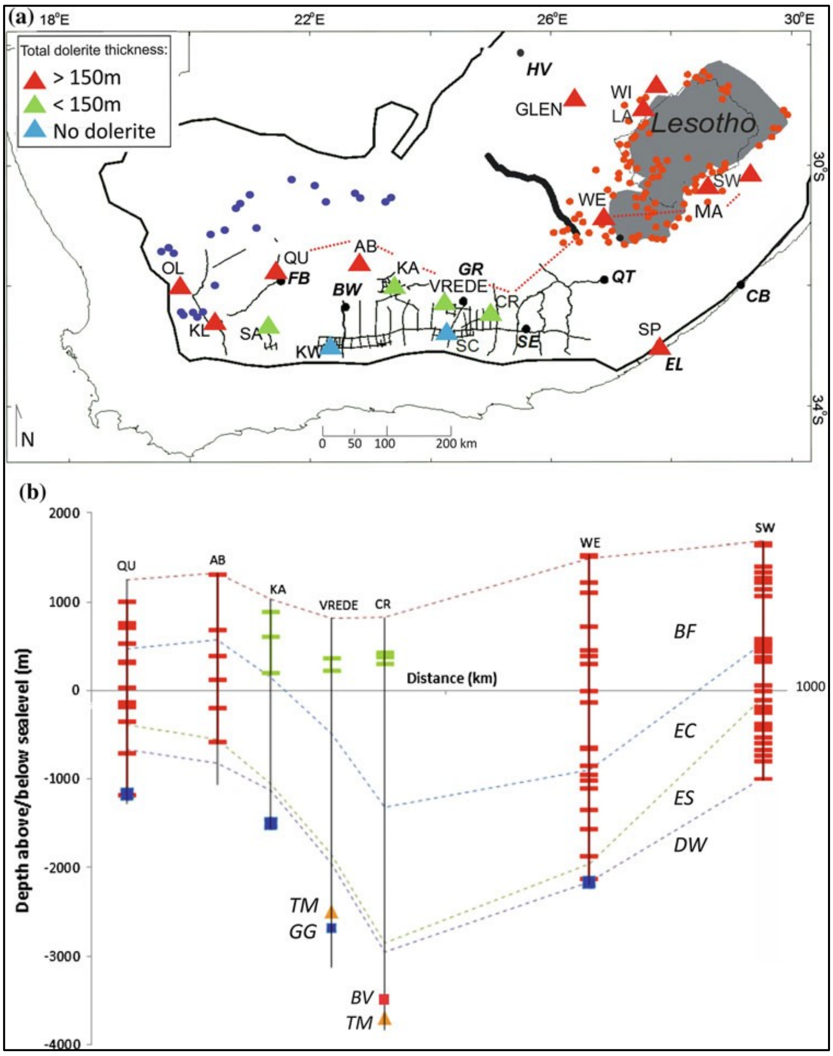

Figure 37: Location map and profile of dolerite occurrences in deep SOEKOR wells (Linol and de Wit, 2016)

7.3.1.4. Kimberlite

Kimberlite is another type of intrusive formation that is encountered within the Karoo geology. Due to its volatile origin, which caused a rapid expansion into the earth crust to form mostly pipe structures, a highly fractured contact zone with surrounding host formations can be expected. This is evident in some areas in the Free State where the towns of Jagersfontein and Fauresmith originally received all their water from an abandoned mine at Jagersfontein (Botha et al., 1998). Overall kimberlite pipes do not add much in terms of groundwater yields on a regional scale but the potential of their highly fractured nature to migration of pollutants to within close proximity of shallow groundwater resources should be considered as a matter of high risk whenever a risk assessment is conducted.

Arsenic has also been associated with the natural composition of kimberlite and any presence of this magmatic formation should be investigated with great detail if any HF activities are carried out in close proximity to it. If kimberlite pipes or fissures are identified during geophysical surveys, site assessments and/or drilling activities, pressure gradients, flow velocities, extent and interactions with other zones of high permeability should be investigated by making use of sound scientific methodology and Best Practice protocols and equipment.

7.3.1.5. Fault zones

Bense et al. (2013) published an article where two different approaches are evaluated, which should be evolved into an inter-disciplinary collaboration to yield better results. In their document they identify:

- Surface-focussed studies by structural geologists; and
- Subsurface-based studies by geohydrologists;

as both being integrally situated in a specific location but largely concentrating on different field areas, using different field methods over different timescales.

They continue to indicate that fault zones can both enhance permeability by the following primary fault processes:

- Particulate flow;
- Fracturing; and
- Brecciaton.

or reduce permeability by:

- Particulate flow;
- Phylosilicate smearing;
- Cataclasis; and
- Brecciation/cataclasis.

Secondary and other geological processes can also either enhance or reduce permeability. These include:

- Fluid flow controlled dissolution and cementation;
- Pressure solution;
- Sediment infilling; and
- Fault growth.

If fault zones are identified as part of geophysical surveys, site assessments and/or drilling activities, additional information regarding their impact on groundwater flow should be investigated and assessed. Investigations should be carried out comprehensively as fault zones can increase or decrease permeability of rock formations.

7.3.1.6. Seismicity

If seismic events have occurred in the area before, it is advised that a structural geologist be included in the investigation team to assess stresses in the immediate area as well as on a regional scale. Seismic events could impact on existing infrastructure of which the gas well should be the primary consideration

7.3.2. Geohydrology

Geohydrological concerns viewed as important enough to flag a fatal flaw if identified include:

- **Shallow aquifer type** – Shallow aquifers can be classified as major, minor or poor according to the "*Aquifer Classification of South Africa*" map developed by the DWS. The colour coded map is linked through a hyperlink to the GW-RAT tool to assist users in making their selection. If a shallow aquifer is a major or only source of potable water supply, any HF incidents could have long-term detrimental effects, influencing the livelihood of communities that are already experiencing severe poverty conditions;
- **Aquifer vulnerability** – As with the aquifer type, this concern is supported by a hyperlinked map by the DWS: "*Aquifer Vulnerability of South Africa*". If an aquifer is considered vulnerable, HF activities will increase risks to this aquifer and it should not be allowed;
- **Aquifer supply recipient(s)** – HF activities within a radius of 5 km of any groundwater abstraction point for potable water supply from a shallow aquifer should not be allowed;
- **SGWL** – A shallow SGWL should be cause for concern, especially for the fact that surface spills are quite often reported at HF sites. Great consideration should be given to the ability of the vadose zone to act as buffer to prevent any pollutant to enter shallow aquifer systems; and
- **Groundwater quality** – Good groundwater quality is a commodity in the Karoo with its history of brackish water. If shallow groundwater with a low salinity is present at a proposed HF site, the advantage of having such a good quality resource

should be carefully weighed against a risk of contaminating it with HF-related chemicals or natural pollutants being mobilised by HF fracking activities in the subsurface environment. The "*Groundwater Quality of South Africa*" map by the DWS is attached through a hyperlink to assist the user.

7.3.2.1. Shallow aquifer type

If a major aquifer is identified in the zone of possible impacts around a proposed HF site, it should be considered as a fatal flaw and no HF activities should be considered.

7.3.2.2. Aquifer vulnerability

If any information indicates that the proposed activities fall within a "moderate" or "most" category when aquifer vulnerability is considered, it should be deemed a fatal flaw and no HF activities should be allowed.

7.3.2.3. Aquifer supply/usage

If any groundwater is abstracted from a shallow aquifer within a radius of 5 km from any HF activities to provide potable water to a community, irrigation scheme, animals or homesteads, it should not be allowed and flagged as a fatal flaw.

7.3.2.4. Static groundwater level

A static groundwater level (SGWL) is a measurement of the water level in a borehole or well that is measured from a specific datum on surface. This measurement is considered to represent the hydraulic head of the system. It does not necessarily represent the groundwater level of the unconfined aquifer because pressure within a deeper confined system could be high enough to result in a measurement that is shallower but representing the confined aquifer's potentiometric or piezometric head.

From a groundwater perspective it is important to know what the hydraulic head is at a specific location as well as point in time. Due to the different conditions encountered is the subsurface environment e.g. unconfined and confined, information should be well-recorded in order to determine the cause of a specific pressure head. In the case of groundwater it would be called a hydraulic head. According to the Groundwater Dictionary of the DWS ("DWS: Groundwater - Groundwater Dictionary," n.d.) the definition for hydraulic head is: "…the height above a datum plane such as sea level of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system." They describe it as the elevation to which water will rise in a borehole connected to a point in an aquifer under pressure. From hydraulic head measurements, flow directions as well as possible interaction between aquifers at different depths can be estimated.

If a SGWL of less than 50 m is measured, it will be possible for any surface activities during HF activities to be able to impact on shallow groundwater aquifers. Care should also be taken to determine whether the measured SGWL is representative of the unconfined system or a piezometric level representing a confined system.

7.3.2.5. Groundwater quality

Groundwater quality across the Karoo Basin has been known to vary and in certain areas brackish water high in salinity is problematic. As EC is an indicator of the salinity of groundwater, it is proposed that it should be the standard for groundwater quality in the GW-RAT tool. For the risk assessment six levels are proposed:

- 0 – 70 mS/m:
  - If EC measurements fall between 0 and 70 mS/m, the groundwater resource should be regarded as a potable water resource and HF activities should not be allowed within this area.
- 70 to 170 mS/m:
  - If EC measurements fall between 70 and 170 mS/m, the groundwater resource should be regarded as a potable water resource and HF activities should not be allowed within this area.
- 170 to 370 mS/m:
  - If EC measurements fall between 170 and 370 mS/m, the groundwater resource should be regarded as water resource for certain crop and stock watering and HF activities could be considered within this area only if an alternative source/supply can be provided by the HF operator and strict construction and monitoring conditions should be imposed.
- 370 to 520 mS/m:
  - If EC measurements fall between 370 and 520 mS/m, the groundwater resource should be regarded as water resource for stock watering under certain conditions and HF activities could be considered within this area only if an alternative source/supply can be provided by the HF operator and strict construction and monitoring conditions should be imposed.
- 520 to 4 000 mS/m: and

- o If EC measurements fall between 520 and 4 000 mS/m, the groundwater resource should be regarded as water resource for stock watering under certain conditions and HF activities could be considered within this area only if an alternative source/supply can be provided by the HF operator and strict construction and monitoring conditions should be imposed.

❖ > than 4 000 mS/m

- o Not many animals will be able to use this water and impacts due to HF activities would not be considered to have the potential to negatively influence any users of this groundwater source. HF could therefore be considered.

7.3.3. Regulation

Water uses are defined in the National Water Act, 1998 (Act No. 36 of 1998) (NWA) and include the following activities as described in Section 21 of the NWA:

1) Taking water from a water resource;
2) Storing water;
3) Impeding or diverting the flow of water in a watercourse;
4) Engaging in a stream flow reduction activity contemplated in section 36;
5) Engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1);
6) Discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;
7) Disposing of waste in a manner that may detrimentally affect a water resource;
8) Disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process;
9) Altering the bed, banks, course or characteristics of a watercourse;
10) Removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people; and
11) Using water for recreational purposes.

In terms of Section 22(1), a person may only undertake the abovementioned water uses if it is appropriately authorised.

A person may only use water

a) without a licence
   i. if that water use is permissible under Schedule 1 (of the NWA);
   ii. if that water use is permissible as a continuation of an existing lawful use; or

iii. if that water use is permissible in terms of a general authorisation issued under section 39;

b) if the water use is authorised by a licence under this Act; or

c) if the responsible authority has dispensed with a licence requirement under subsection (3).

Each HF applicant will have to apply for a Water Use Licence (WUL) by means of a Water Use Licence Application (WULA). If this is not in the process or in place, any activities can be considered illegal and definitely be flagged as a fatal flaw due to non-compliance to the NWA.

7.3.3.1. Water Use Licence Application (WULA)

If no WULA has been submitted to the DWS, this should be regarded as a fatal flaw and any activities on the proposed site should immediately be terminated, while the DWS should be informed.

7.3.3.2. Water Use Licence (WUL)

If no WUL has been issued by the DWS, this should be regarded as a fatal flaw and any activities on the proposed site should immediately be terminated, while the DWS should be informed.

7.4. GW-RAT

The *GroundWater Risk Assessment Tool* (GW-RAT) is based on a scoring system through which a qualified geohydrologist with sufficient experience of Karoo geohydrology will populate a spreadsheet in MS Excel with numerical options from dropdown boxes.

As mentioned previously within this document (section 1.3.2, p 7), the whole life of a HF project consists basically of three phases:

1. Exploration;
2. Production; and
3. Closure.

It was decided that the tool will allow for an assessment of all three phases mentioned above. This tool has also been developed to be able to be adjusted should any additional criteria be required to be included. Any suggestions would be welcome and if it is deemed important to be included, the developers will make the necessary changes and make an update available with an updated guideline as well since it would influence the scoring system.

The workbook consists of four work sheets:

1. **GW-RAT**, which is the title sheet;
2. **RA**, which is where the risk assessment scoring sheet is populated;
3. **Calculation**, where the score is calculated and some additional information with regard to possible fatal flaws can be included; and
4. **Risk assessment criteria**, which is a hidden sheet only accessible to the developers on which information is uploaded to be used in the background by the equations in certain cells.

All four sheets are password protected so that the user can only populate the light yellow cells in order to avoid possible changes to background formulas and equations.

7.4.1. Title sheet

When the Excel Workbook is opened, it will show a Title sheet with some guidelines - **Points to Ponder** - as well as basic instructions on how to initiate the risk assessment - **Instructions**.

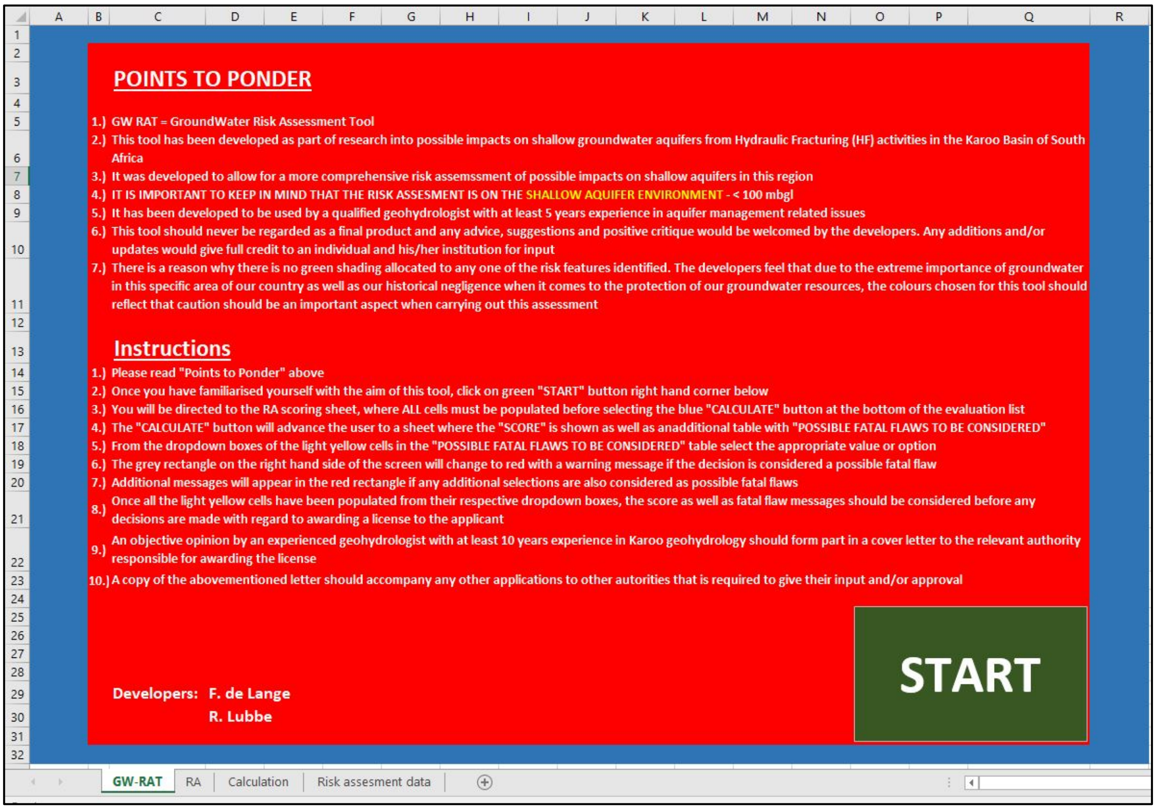

Figure 38: Title page of the GW-RAT tool

It is advised that the user reads carefully through the guidelines and instructions. Once he or she is familiar with what is expected of them, the process can continue by clicking on the green “START” button on the bottom right hand of the title sheet.

The user can access the title sheet again from the RA sheet by means of the red "TITLE PAGE" button on the top left hand side of the sheet.

7.4.2. Risk assessment sheet

7.4.2.1. Risk assessment methodology

As previously stated, the assessment methodology is based on a scoring system with a negative value indicating that the nature of a specific risk feature is negative.

Specialist information will be used as input and an overall impact score will be calculated by multiplying the product of the nature, magnitude and significance of a specific risk feature by the sum of the extent, duration and probability (Equation 1). It is important to note that each risk feature should be considered carefully before any selection is made (Table 6).

$$\boldsymbol{SCORE} = (\boldsymbol{N} \times \boldsymbol{M} \times \boldsymbol{S}) \times (\boldsymbol{E} + \boldsymbol{D} + \boldsymbol{P}) \qquad \textbf{Equation 1}$$

With:

N = Nature

M = Magnitude

S = Significance

E = Extent

D = Duration

P = Probability

Table 6: Table summarising impact methodology

Parameter	Score	Description
Nature	-1	Negative impact
	1	Positive impact
Magnitude	1	Low: GW resource(s) not impacted or minimally minimal impact
	2	Medium: GW resource(s) notably impacted although low in severity
	3	High: GW resource(s) severely impacted either temporarily or permanently
Significance	1	Impact will not affect GW resource(s). No mitigation necessary
	2	No impact after mitigation

Parameter	Score	Description
	3	Residual impact after mitigation
	4	Impact cannot be mitigated
Extent[3]	1	Local - extent to the site and its immediate surroundings
	2	Regional - impact on regional scale but within province
Duration	1	Short term - 0 to 5 years
	2	Medium term - 5 to 11 years
	3	Long term - GW resource(s) slightly contaminated and requires treatment before use
	4	Permanent - GW resource(s) contaminated with no probability of rehabilitation
Probability	1	Unlikely- GW impacts could occur some time
	2	Moderate- GW impacts should occur some time
	3	Likely- GW impacts likely in most circumstances
	4	Almost certain- GW impacts expected in most circumstances

Table 6 summarises the impact methodology and explains in brief terms what a certain score would indicate.

7.4.2.2. RA sheet

The RA sheet has been set up in such a way that all three phases of the HF life cycle can be evaluated. Each of the phases i.e. 1) “Exploration”, 2) “Production” and 3) “Closure” has been subdivided into 1) “Surface activities” and 2) “Subsurface activities”. A list of risk features have been identified for each phase and location to be evaluated against the criteria as set out in the impact methodology (Table 6).

As the GW-RAT tool is populated, a value is calculated for each one of the risk features that is included in the RA sheet. Once the whole sheet has been populated the blue “CALCULATE” button below the table can be selected and the user will continue to the final sheet where the score will be calculated. This final score is the average of the final score for each of the risk features – all the grey cells at the right hand side of the RA table (Figure 39). Two other red buttons are also available on the RA sheet; 1) a “Reset” button on the left hand side of the Score equation, which and be used to delete all the selected

[3] If a positive 1 is selected for the “Nature” parameter, 1 should also be selected for the “Extent” parameter

values if so required, and 2) a “TITLE PAGE” button on the top left corner of the sheet, should a user have need to return to the Title page.

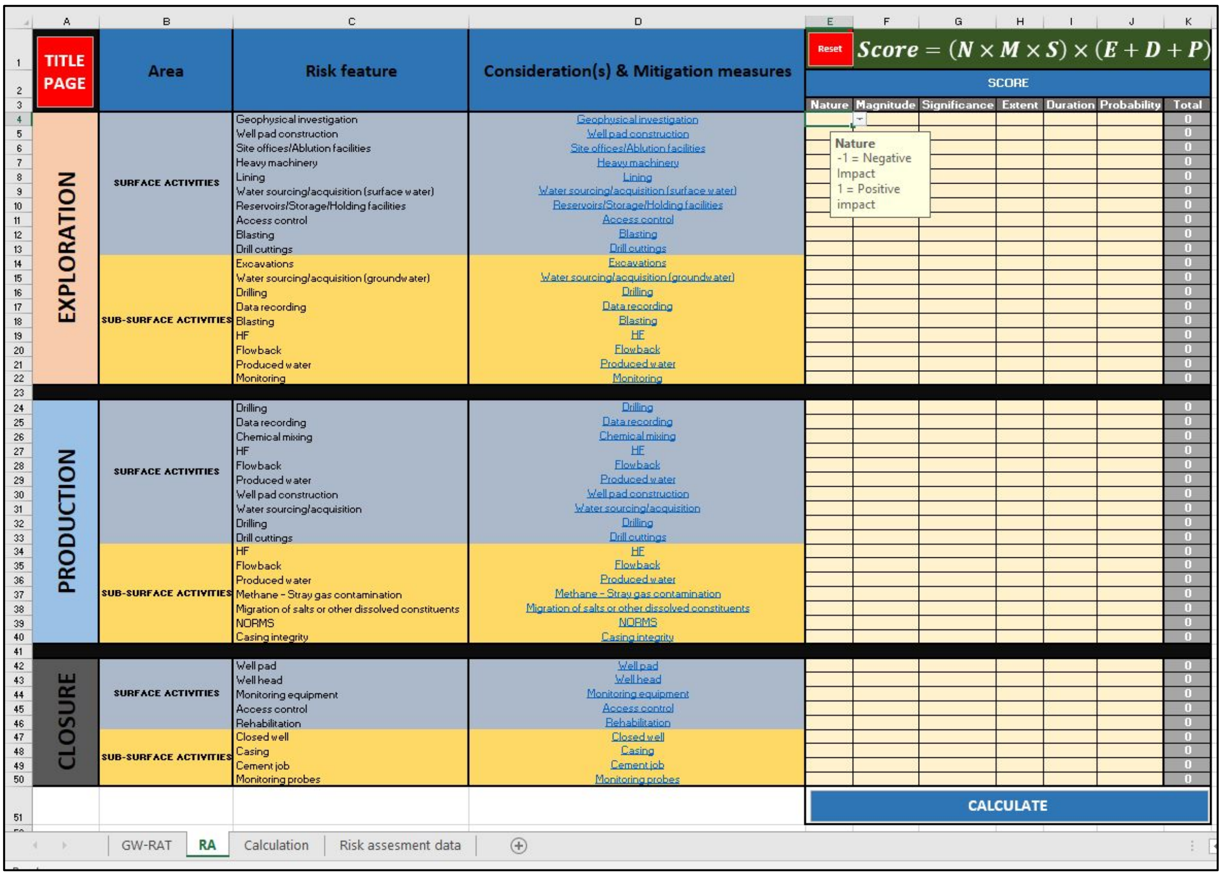

Figure 39: Risk Assessment (RA) sheet of the GW-RAT tool

It is very important that the light yellow cells be populated by means of selecting a value from the dropdown box. An effort has been made to prevent a user from making a mistake by typing in an invalid number. If a value that falls outside the range for a specific parameter is incorrectly typed in, a pop-up message will appear on the screen indicating to the user that he or she should use the dropdown menu (Figure 40).

A column with “Consideration(s) and Mitigation measures” also forms part of the RA sheet. This column has hyperlinks to additional information that will guide the user to make a more informed decision while populating the scoring sheet. If a hyperlink is followed, a PDF document is opened on an index page with a similar layout than the RA sheet. For each of the risk features an additional two hyperlinks will be available. One hyperlink to “Considerations” for additional information that can assist in making the correct decision on the score sheet and another hyperlink to “Mitigation measures” to be able to gain knowledge on how to minimize a specific impact. The supporting document is based on technical regulation documentation and Best Practice guides in the HF industry.

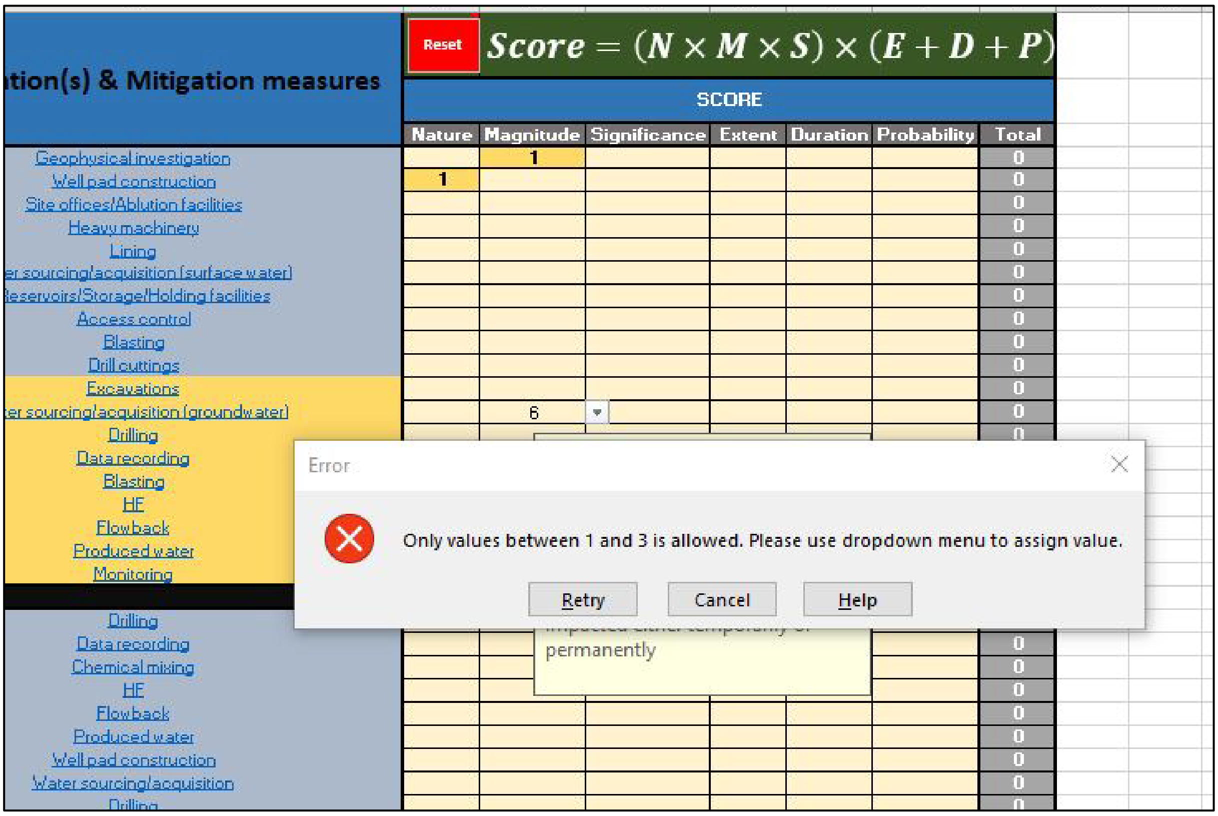

Figure 40: Screen capture image with pop-up error message

7.4.3. Calculation sheet

7.4.3.1. Scoring value

The "Calculation" sheet is the final sheet where the average score is calculated and displayed to indicate a YES, MAYBE or NO.

Hypothetically, if not one of the risk features are considered to have a negative impact on the environment with all the low scores selected for all the other parameters a final average score of 3 is possible. It is obvious that the probability for this to occur within a HF environment is negligent and it can be well expected that the final score would have a negative value. When all risk features are considered as possibly having a negative impact and if all the high scores are selected for each of the risk features a minimum final average score of -120 is possible. Theoretically it is then safe to say that values will always range from a maximum of 3 to a minimum of -120.

It was decided to rank the average impact score by dividing the absolute minimum value by 3 and to use the ranges as criteria to determine if groundwater impacts should be considered as low, medium or high.

The following rankings are therefore proposed:

1. 3 to -40 Possible impact can be considered as low and acceptable under specific conditions decided by the regulator in consultation with its experts;
2. -40 t0 -80 Possible impact should be considered as medium and it would probably necessitate additional assessment criteria and research if the licencee want to continue with the project; and
3. -80 to -120 Possible impact is considered as high and no HF should be allowed.

Figure 41 represents the "clean" spreadsheet before any calculation is done in the RA sheet with a score value of 0.

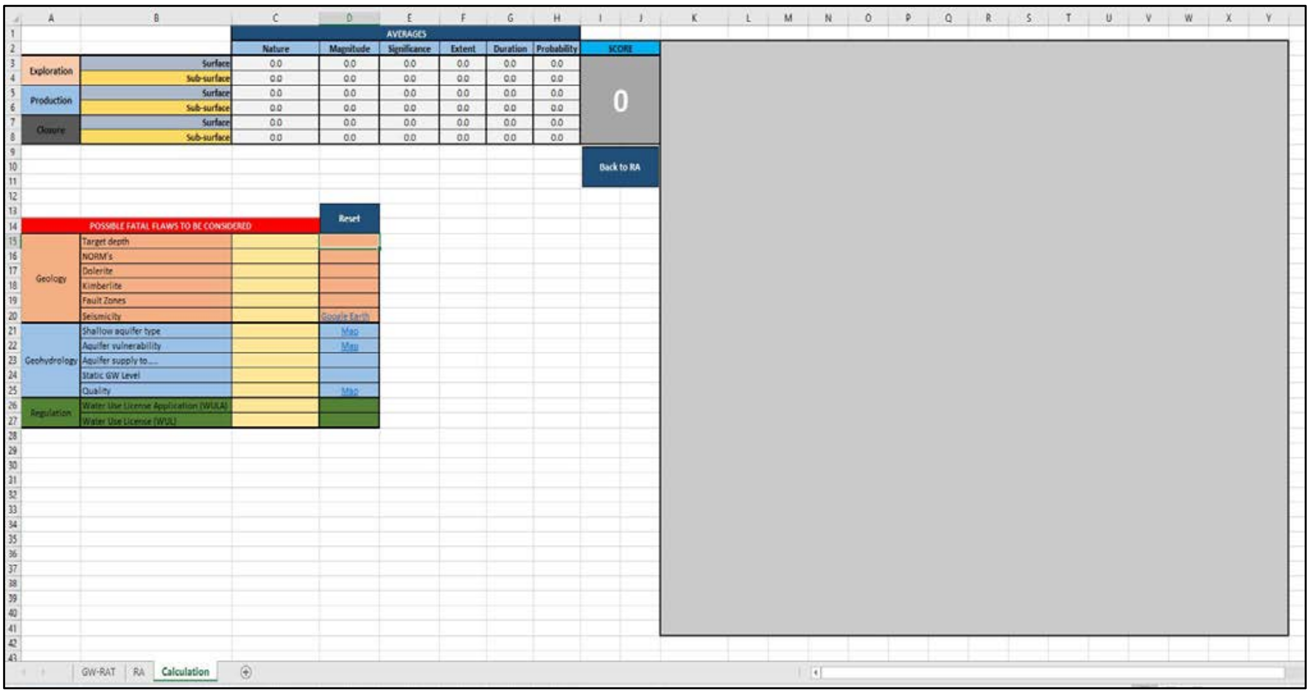

Figure 41: Calculation sheet of the GW-RAT tool

Colour codes have been added throughout the tool and access has been restricted to only the cells that should be populated as indicated on the Title page.

Values between 3 and -14 would be acceptable depending on the outcome of the additional selections in the "POSSIBLE FATAL FLAWS TO BE CONSIDERED" table just below the Score value on the Calculation sheet. If Score value of between 3 and -40 is calculated, the Score value will be bold white digits on a green background as indicated in Figure 42 on the next page.

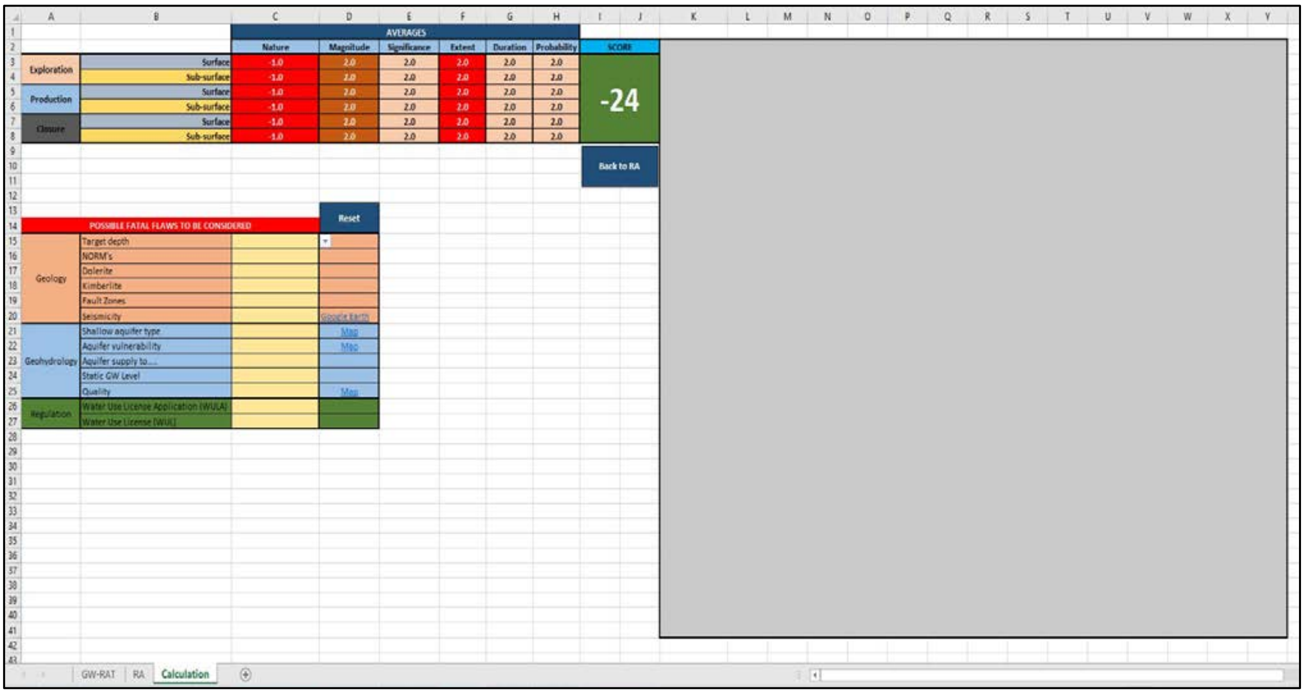

Figure 42: Calculation sheet indicating a scoring result between 3 and -40

Values between -40 and -80 would imply that the possible impact should be considered as medium and it would probably necessitate additional assessment criteria and research. A Score value in bold white digits will then be displayed on a yellow background (Figure 43).

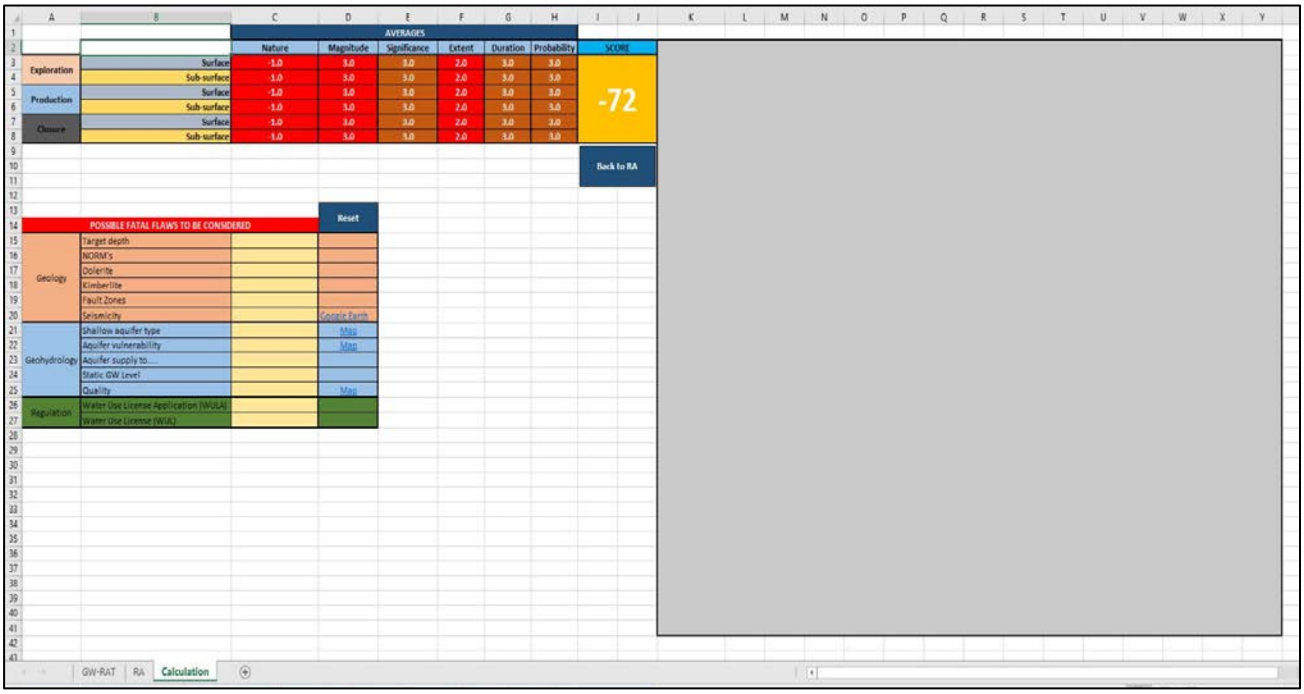

Figure 43: Calculation sheet indicating a scoring result between -40 and -80

If the sum of the scoring criteria averages at a value of between -80 and -120, a Score value in bold white digits will be displayed on a red background (Figure 44), which would indicate that no HF activities should be allowed.

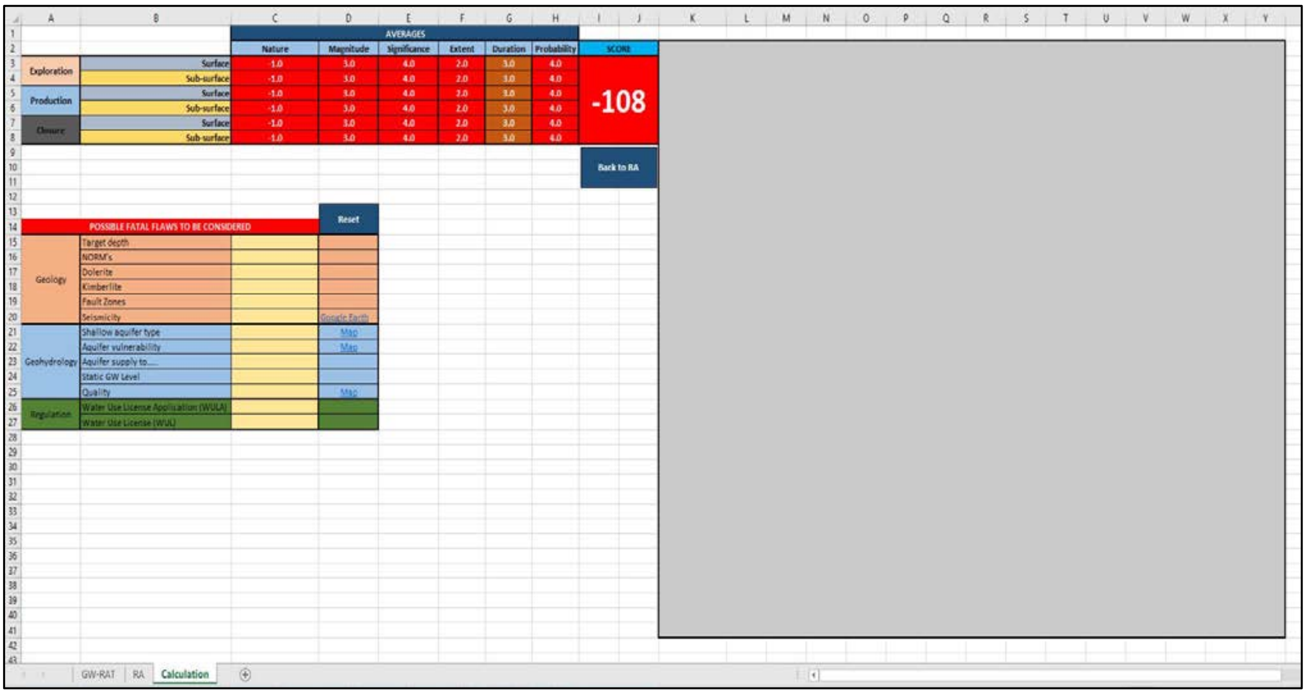

Figure 44: Calculation sheet indicating a scoring result between -80 and -120

7.4.3.2. Possible fatal flaw criteria

Section 7.3 in this chapter explains the thought process of including these criteria options in the risk assessment process.

The table dealing with this is also quite simple and requires the user to select options from a dropdown box. If one of the selections flag a warning comment in the grey area to the right (Figure 44), a message related to the selected option will appear and the grey area will become red. A Blue "Reset" button is available at the top right corner of the fatal flaw table and a "Back to RA" button, also in blue, just below the Score value.

Once again it must be noted that although this part of the risk assessment suggests "Fatal Flaws", this does not always mean that a project should not be allowed. A selection can be made based on limited information and the user/geohydrologist should then indicate it as such in their report and it would be the HF applicant's choice to either accept this decision and move to a next possible target location or do additional work to provide the missing information that might lead to a selection that does not raise a flag message. This is another supporting argument for a qualified geohydrologist with sufficient Karoo specific knowledge to be involved on every HF EIA investigation.

Some of the selections have hyperlinks to additional information to assist in making informed decisions. These links include:

- ❖ A Google Earth image with seismic events across the Karoo Basin, indicating year and magnitude of each event, is included as hyperlink to this flaw;
- ❖ "*Aquifer Classification of South Africa*", (DWS, 2012a);
- ❖ *Aquifer Vulnerability of South Africa"* (DWS, 2013b)
- ❖ *Groundwater Quality of South Africa*, (DWS, 2012b).

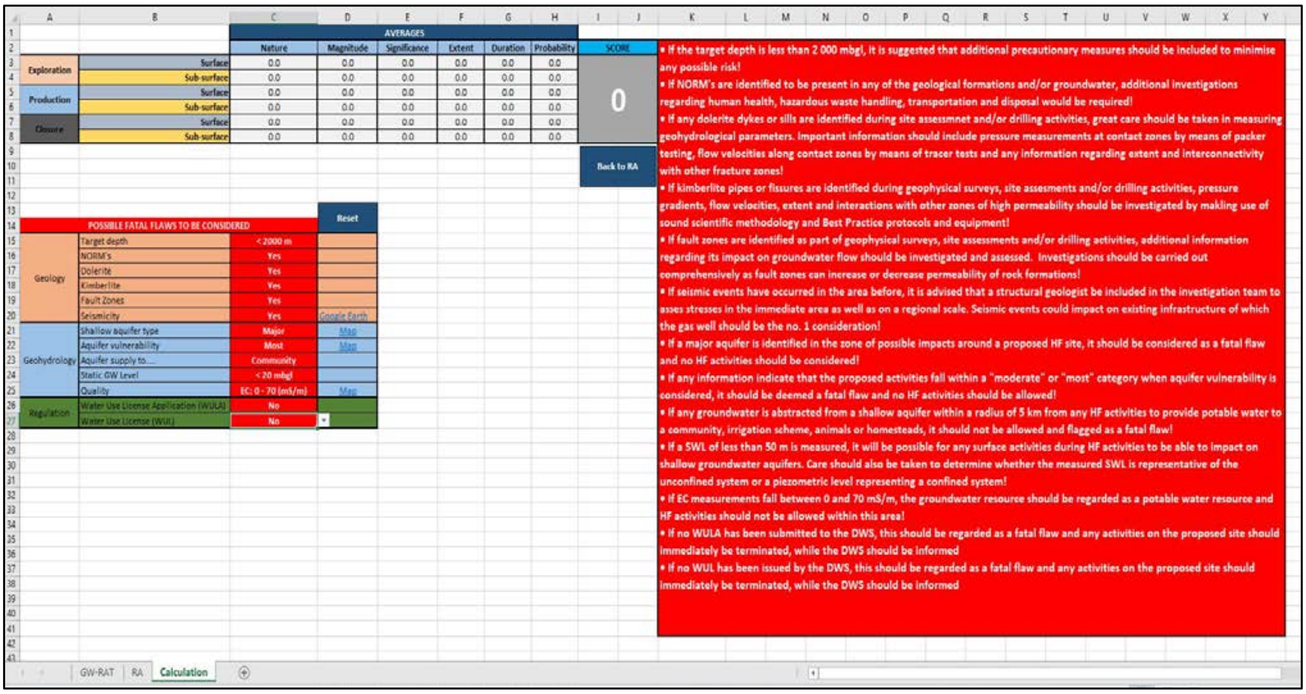

Figure 45: Calculation sheet with possible fatal flaws included

7.5. Conclusions

This chapter has described the development of an assessment tool and highlighted that to be able to assess possible risks to shallow groundwater aquifers the following is required:

- ❖ Sufficient information and accurate data should be made available to the user;
- ❖ Most of the data and information would have to be recorded by the HF applicant but it is recommended that an independent third party must be included as part of licence conditions to observe that all measurements and tests carried out are according to specifications; and
- ❖ The risk assessment should be carried out by an experienced and qualified geohydrologist familiar with the Karoo groundwater environment.

The GW-RAT tool should be regarded as an initial attempt as a systematic approach to determine potential risks to shallow aquifers. It does not need to be confined to the HF industry and with minor changes this tool can be adapted for different scenarios across the whole EIA spectrum.

8. CONCLUSIONS

8.1. Introduction

Research for this theoretical analysis of possible impacts associated with HF on Karoo Basin geohydrology yielded various results. In some cases obvious impacts can be minimised by preventative and/or mitigation measures, while some other impacts that are more indirectly involved have been identified as more concerning.

From a technical perspective and available knowledge and skills within the South African geohydrological community, it is evident that we would be able to carry out site-specific investigations to generate enough information to conduct a comprehensive risk assessment with a high level of confidence.

The main concern that was identified was the issue of water governance and more specific groundwater governance in terms of implementation of rules and regulations. South Africa has one of the best water acts in the world, which has even won international recognition and awards. The question then is why we have so many issues with groundwater quantity and quality in our country. Our state department responsible for our water resources, DWS, is bankrupt and very little is done in terms of monitoring. A lot of paperwork is done and numerous management plans at different scales are developed but there are very few people out in the field actually implementing these plans. Some projects are initiated just to be postponed or terminated shortly afterwards, with a huge chunk of the budget being “paid” to service providers in advance with nothing to show in return.

The so-called “One Environmental System” (OES) has not been very efficient and inter-communication channels between state departments and regulators are not very well developed; in fact, they are mostly non-existent. Each entity makes its own decisions and develops its own guidelines based on its own research.

8.2. Groundwater governance

From the number of independent research projects that were initiated at the height of fracking mudslinging in South Africa, it is obvious that many concerns were identified but what became even more obvious was our lack of knowledge of what is happening at greater depths in our own backyard.

One positive realisation that came to light was that we have enough qualified, skilled, knowledgeable and creative individuals in the field of geohydrology that would be able to develop world-class criteria to assess possible impacts from HF on shallow groundwater aquifers.

Unfortunately the excitement and reassurance were of short duration when we realised that our groundwater governance capability over the past 22 years have dwindled down to anything between mediocre and non-existent. A severe drought period also did not do our citizens, and especially our farmers, any favours and more than 50% of Karoo communities are having to struggle with finding solutions to their water problems, of which sufficient volumes, are the least. A healthy slice of their water problem/issue-cake can be laid before the door of individuals, entities and regulators that are failing horrendously in their task of providing potable water to their constituents and/or areas of responsibility. A high percentage of water shortages is due to failing infrastructure and the concomitant losses, which in turn can be attributed to the absent maintenance of the aforementioned infrastructure.

If the four dimensions of water governance 1) Social, 2) Economic, 3) Political and 4) Environmental are considered, not one of them can be considered as healthy in the current South Africa. Social structures in the Karoo are falling apart in response of a system that rather provides meagre monthly social grants instead of focusing on job creation.

If our economy does not start to show an upward trend with a possibility of a growth percentage of more than 1, the final global rating agency, Moody's, will downgrade South Africa's credit rating to junk status. Two other global rating agencies, Standard and Poor and Fitch have already done this in 2017.

Political stability to establish an environment conducive to investment is not currently the case. Infighting between high ranking individuals and a definite division between two major camps have created too much uncertainty and the international community does not view South Africa as a country with a stable environment for investment. The current status quo where only an elite section of the governing party benefits from misadministration of state funds does not alleviate living conditions of the majority of our citizens living in squalor. It can be anticipated that any HF industry in South Africa will continue to benefit only a few high ranking officials with no benefit to the people whose livelihood can be influenced by negative impacts on their shallow groundwater resources.

One only has to look at current impacts by industry across South Africa e.g. Emalahleni, Middelburg and numerous other mining activities to realise that groundwater governance is highly inadequate and a lot of activities are allowed due to political interference and inappropriate, dishonest relationships between industry and regulators.

If there is one reason why HF should never be allowed in South Africa, it would be because of the non-existing groundwater governance at the moment. The inability of skilled individuals to go out and do their work is hampered by political appointments with no experienced technical input from experts.

8.3. International context

One of the main issues forthcoming from the international research papers and publications was the lack of baseline information that can be used as reference in cases where claims of shallow groundwater contamination due to HF activities were raised.

Prevention of the same situation should be addressed by means of initiating research to establish clear baseline criteria as well as protocols on a monitoring strategy to be able to identify any impacts the moment they occur.

Groundwater-related concerns from all international role-players include:

- Water volumes required during the HF process;
- Surface spills that affect surface as well as groundwater;
- Occurrences of subsurface pathways for contaminant migration along a gradient. This could allow contaminants to reach shallow aquifers supplying potable water to communities;
- Not only natural fractures should be considered as possible pathways but the gas well should also be viewed as a possibility if casing and cement jobs are not installed correctly;
- Inadequate monitoring;
- Transparency in the chemical content of fracking fluids; and
- A lack of credible data to base research on as well as differences of opinion when interpretation methodologies are selected.

South Africa's unique geological setting necessitate the development of Karoo-focussed research on possible impacts on shallow groundwater resources and regulators and government departments should be very careful in sourcing technical requirements and monitoring criteria and protocols from international documents.

8.4. South Africa – Unique situation

One of the most important questions on whether to allow a HF industry to be established in South Africa would be: Is there any shale gas within the Whitehill and Prince Albert Formations as assumed?

A lot of research has been focussed on possible impacts on the environment related to

HF activities. All research output and expenses would have been for nothing if it ends up where there are no resource that could be evaluated and estimated and become a reserve.

Recent research by the author yielded varying results across a large section of the Karoo, stretching from Murraysburg in the east to the Tankwa region in the west. Differences in groundwater levels, quality, recharge as well as uses occur across short distances in the same area.

What is important to note besides the scientific results is that most local farmers and communities are willing to participate in research projects as long as they perceive the research as being done independently without any funding from industry. This is why funding should be forthcoming from government institutions such as the WRC. The research project also showed that valuable data and information can be obtained by simple methodologies as well as acceptable budgets.

The possibility of a HF industry should be approached form a very conservative and information-intensive perspective otherwise risk assessments would be inadequate and shallow groundwater resources could be at risk. To be able to conduct a comprehensive risk assessment, accurate data and information obtained by sound scientific methodologies and techniques are required.

Although careful consideration should be given to possible risks, some allowance should be made, at least for some exploration, as it would be an opportunity to conduct research in a deep groundwater setting of which we know nothing.

8.5. Analytical, conceptual and numerical models

Research has proved that models can be useful in using field measurements and calculated or estimated data in an attempt to evaluate possible impacts on the groundwater system at any given location. The effectiveness of numerical models however, would be greatly dependent on skilled software operators and reliable and accurate data and information.

The requirement for a comprehensive and accurate conceptual model of any given HF site, should be a prerequisite to any applicant for a licence to produce shale gas. Not only in the Karoo but anywhere in the world. It should be populated with site-specific information from geological and geohydrological information. Input should be accurate from measurements, calculations and estimates from analytical solutions that are suitable for geohydrological conditions at the site.

An analytical solutions have indicated that travel times for pollutants can be quite rapid if an upward pressure gradient exists and a fracture or interconnected fractures with sufficient aperture width are present. This could put any pollutant in close proximity to shallow groundwater resources with only a sequenced combination of steel casing and cement jobs between the resource and pollutant. A single vertical fracture numerical model supports research by Atangana and van Tonder (2014), based on analytical solutions.

An additional, expanded model was constructed, which yielded another set of supporting results. In this case two prominent trends could be identified. One was that plume migration could occur primarily in fractures orientated vertical and secondly the zone in which stimulation/fracking of the formation is done should not be intersected by any dolerite intrusive structures.

8.6. Risk assessment

This chapter has described the development of an assessment tool and highlighted that to be able to assess possible risks to shallow groundwater aquifers the following is required:

- ❖ Sufficient information and accurate data should be made available to the user;
- ❖ Most of the data and information would have to be recorded by the HF applicant but it is recommended that an independent third party must be included as part of licence conditions to observe that all measurements and tests carried out are according to specifications; and
- ❖ The risk assessment should be carried out by an experienced and qualified geohydrologist familiar with the Karoo groundwater environment.

The GW-RAT tool should be regarded as an initial attempt as a systematic approach to determine potential risks to shallow aquifers. It does not need to be confined to the HF industry and with minor changes this tool can be adapted for different scenarios across the whole EIA spectrum.

This page is reserved for a special mention of my brothers and sisters of 101 Battalion, Ondangwa, Namibia…..South-West Africa then. Extraordinary circumstances forged extraordinary bonds. Most of us survived and to this day we experience a devoted and loyal bond known by only a privileged few.

I want to single out one man amongst men, Chris Schutte, call sign 9F, Regimental Sergeant Major during my time with the unit, a hard but fair man, who led through example both in battle and in rest. Lessons of discipline, pride, respect, hard work and a no-quit attitude he instilled by various means in every NCO under his command. Respect Sir!!

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http://www.wri.org/applications/maps/aqueduct-atlas/ - Groundwater stress

APPENDIX A

Baseline survey – Field data

The hyperlinks below will open an Excel Workbook for each of the locations that includes a sheet for:

1. Hydrocensus;

2. Isotopic analysis results;

3. Hardness; and

4. Full chemical results.

00a_APPENDIX A_Murraysburg information.xls

00b_APPENDIX A_Nelspoort information.xls

00c_APPENDIX A_Nuweveld information.xls

00d_APPENDIX A_Koup No 4 information.xls

00e_APPENDIX A_Letjiesbos information.xls

00f_APPENDIX A_Merweville_information.xls

00g_APPENDIX A_Laingsburg information.xls

00h_APPENDIX A_Rietbron information.xls

00i_APPENDIX A_Tankwa information.xls

APPENDIX B

Vertical fracture model

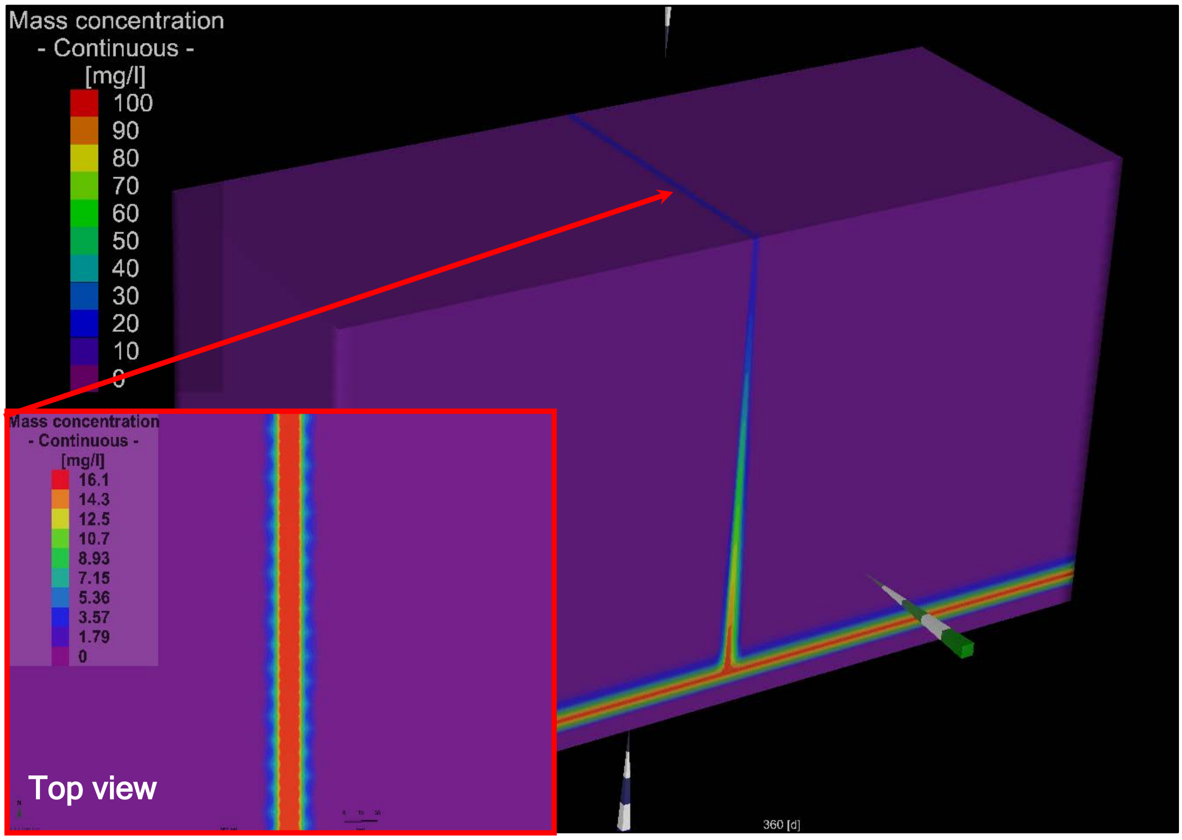

Figure 46: Potential pollutant migration after 360 days (1 year)

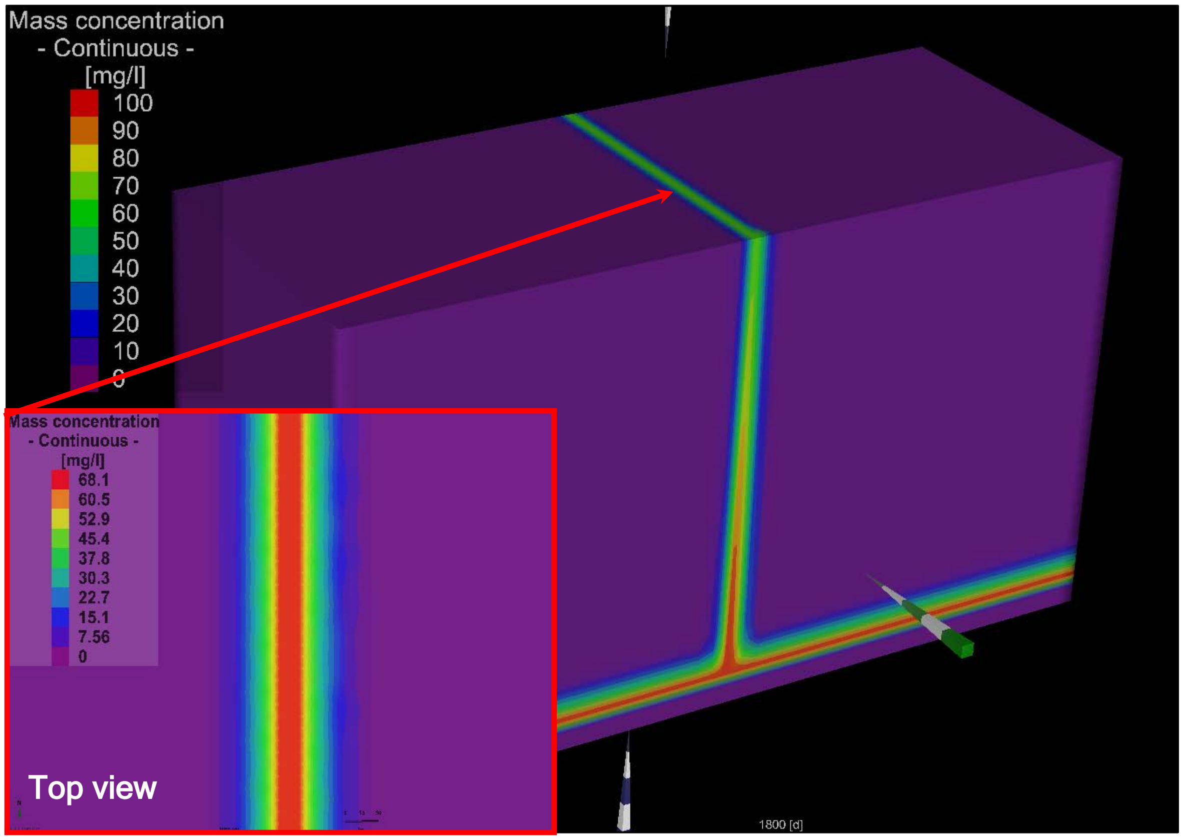

Figure 47: Potential pollutant migration after 1 800 days (5 years)

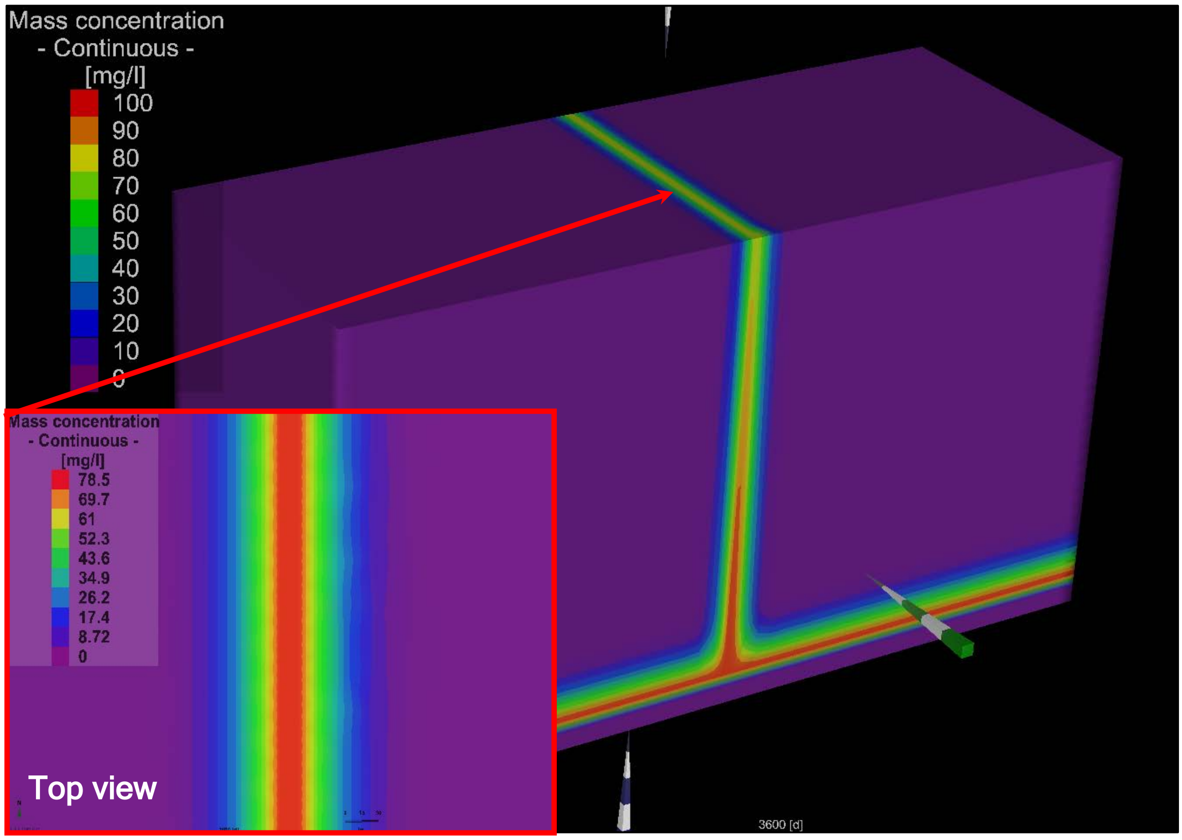

Figure 48: Potential pollutant migration after 3 600 days (10 years)

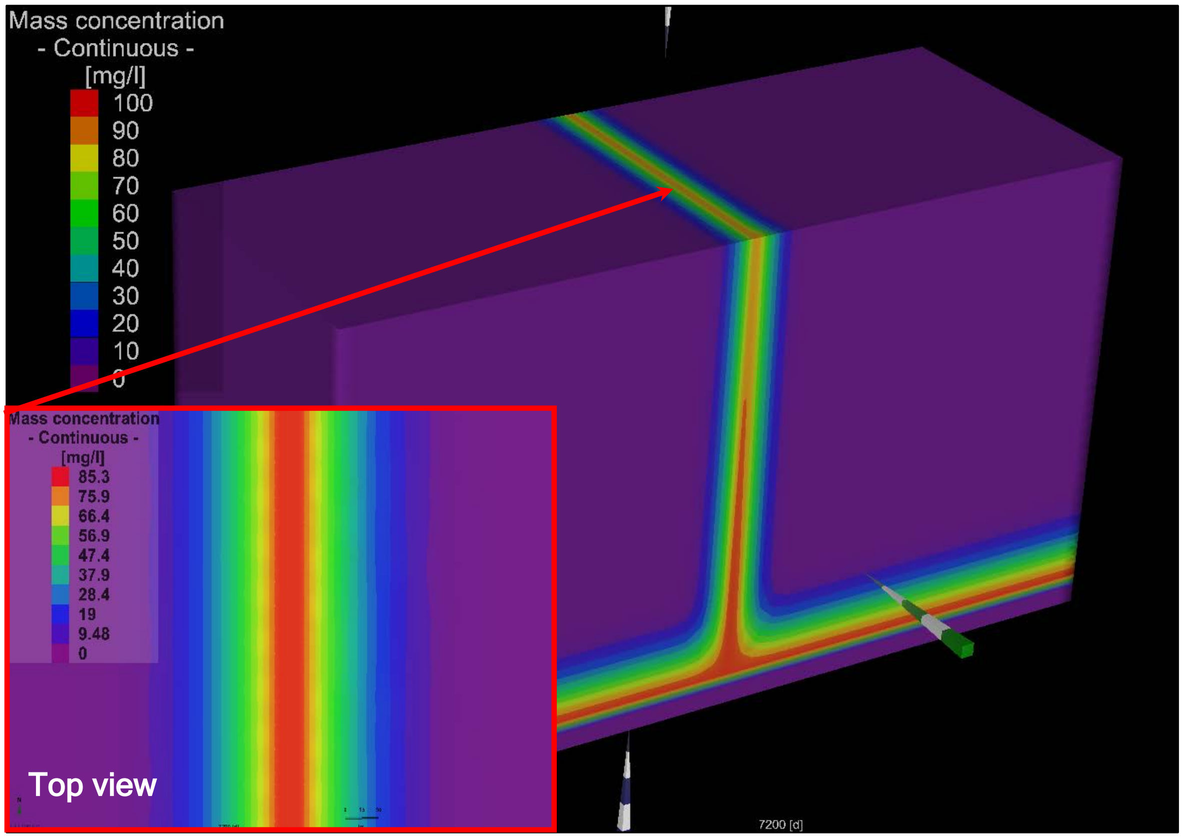

Figure 49: Potential pollutant migration after 7 200 days (20 years)

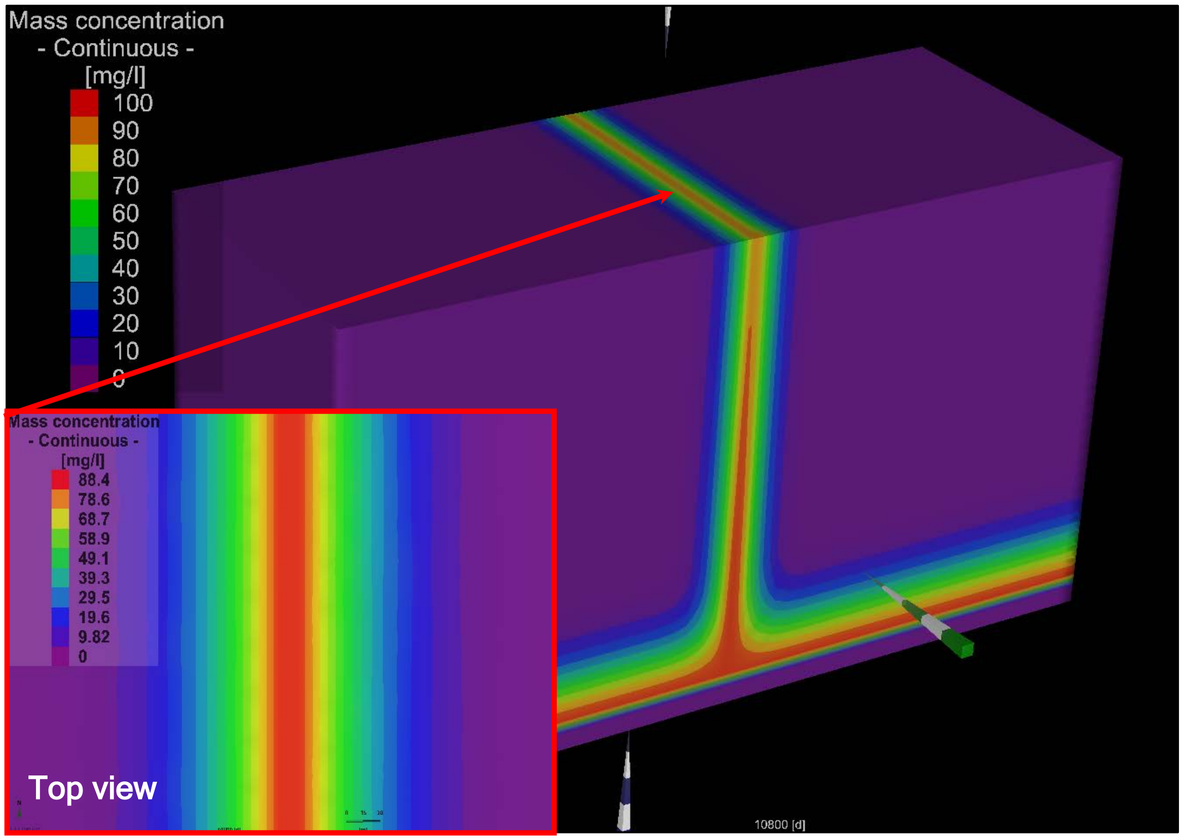

Figure 50: Potential pollutant migration after 10 800 days (30 years)

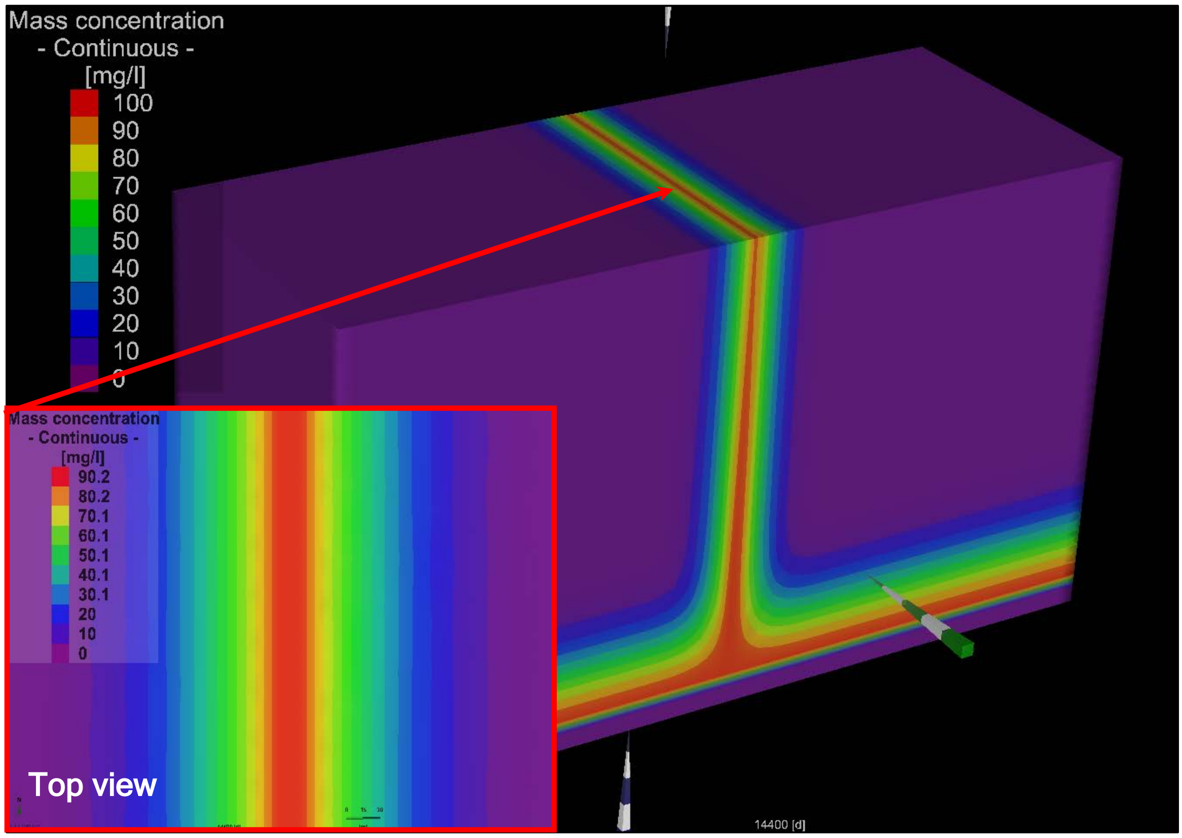

Figure 51: Potential pollutant migration after 14 400 days (40 years)

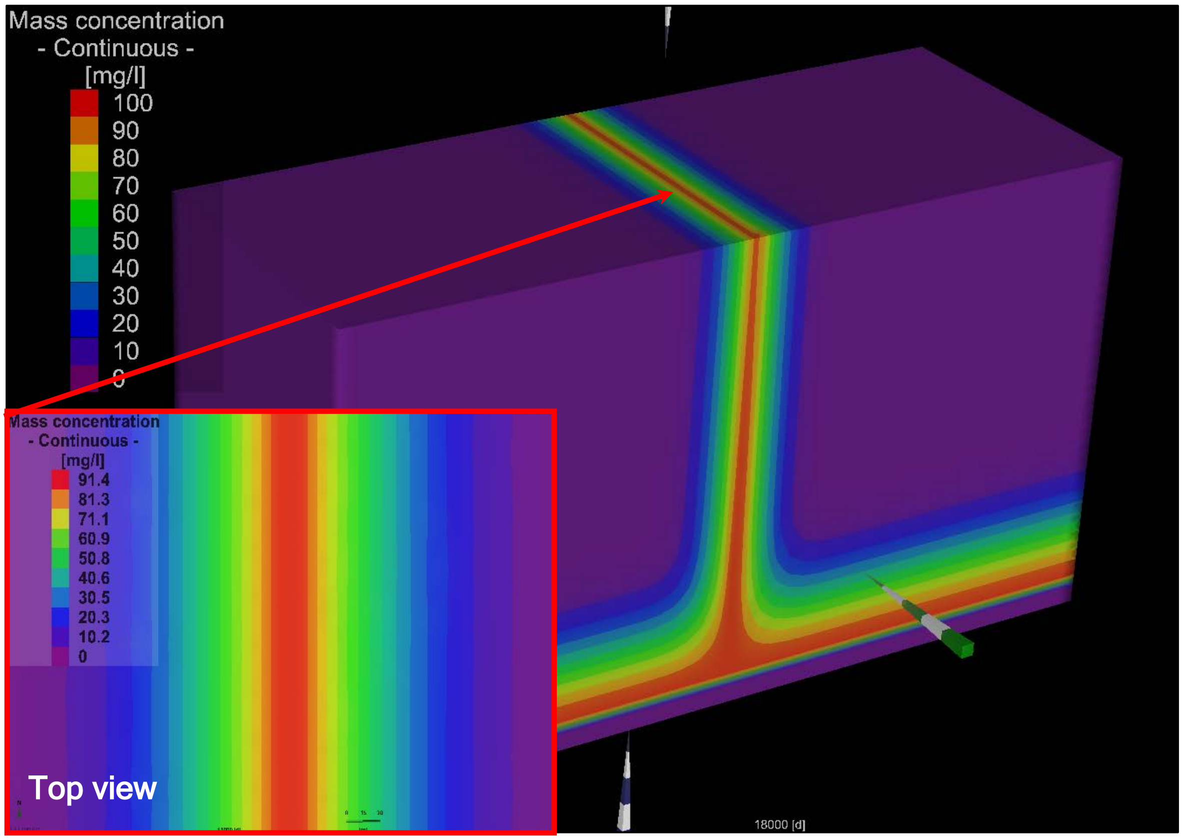

Figure 52: Potential pollutant migration after 18 000 days (50 years)

Karoo Groundwater Atlas model

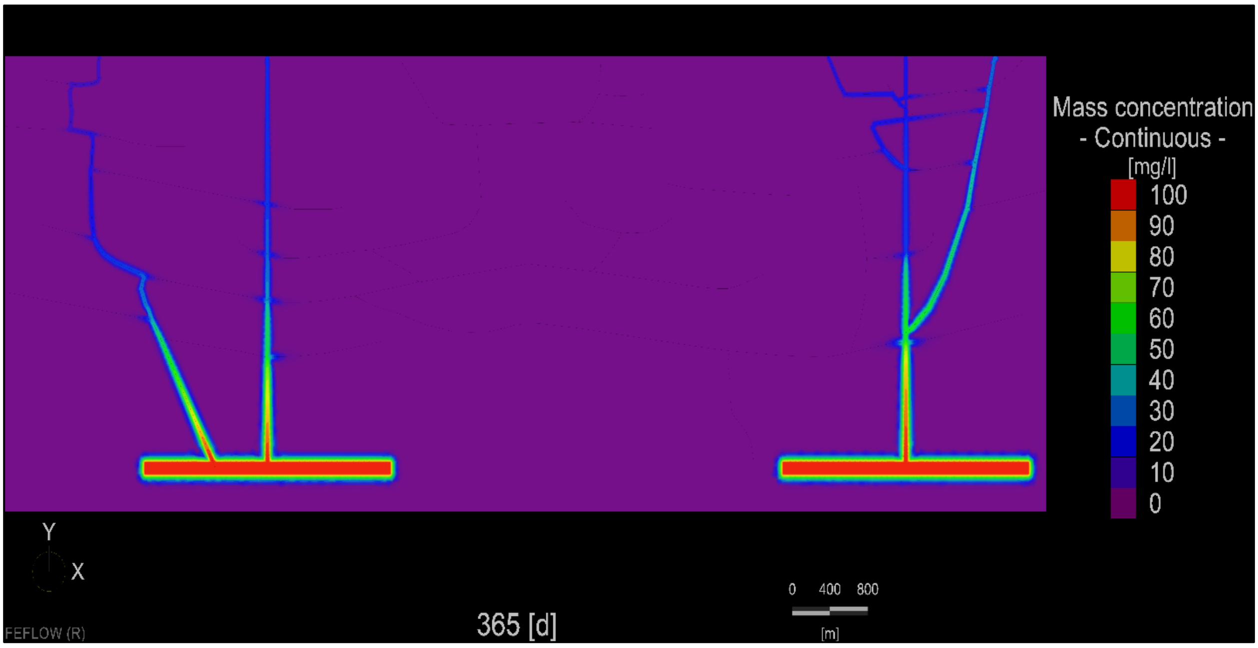

Figure 53: Potential pollutant migration after 365 days (1 year)

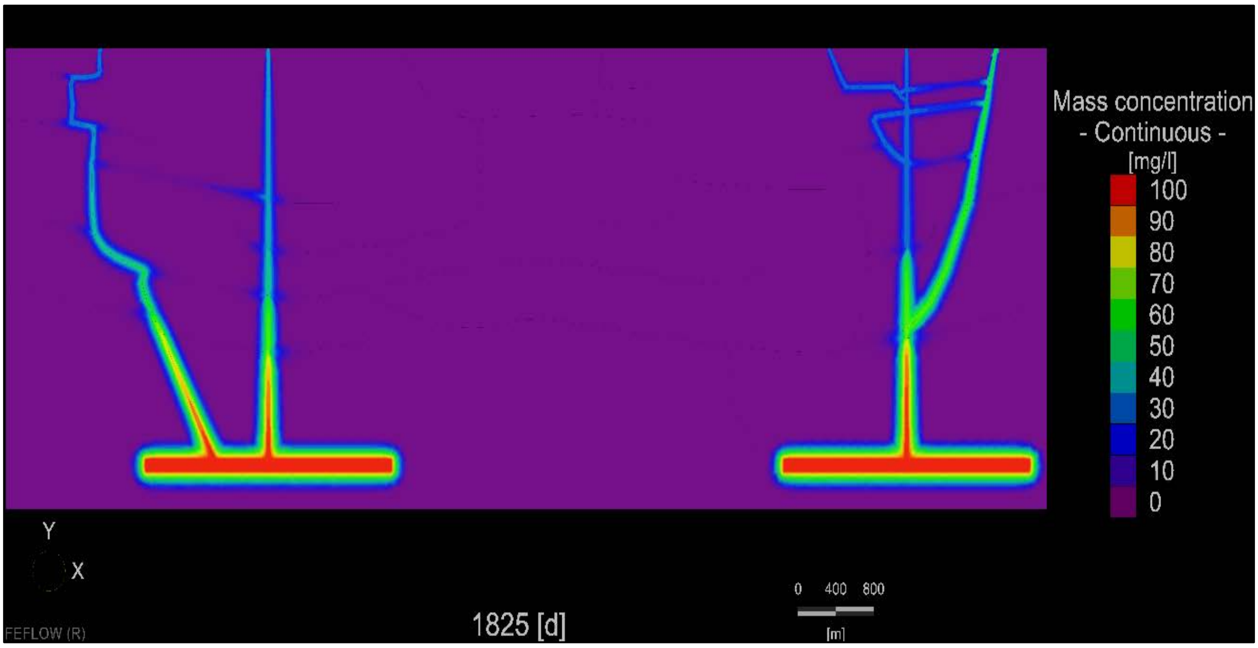

Figure 54: Potential pollutant migration after 1 825 days (5 years)

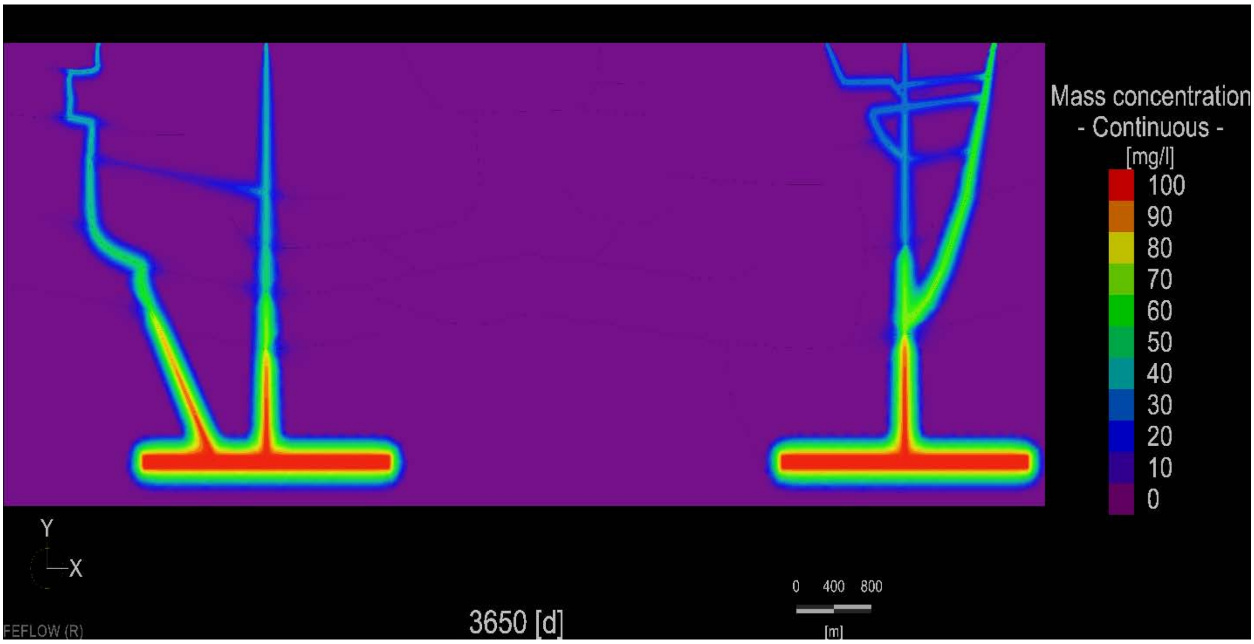

Figure 55: Potential pollutant migration after 3 650 days (10 years)

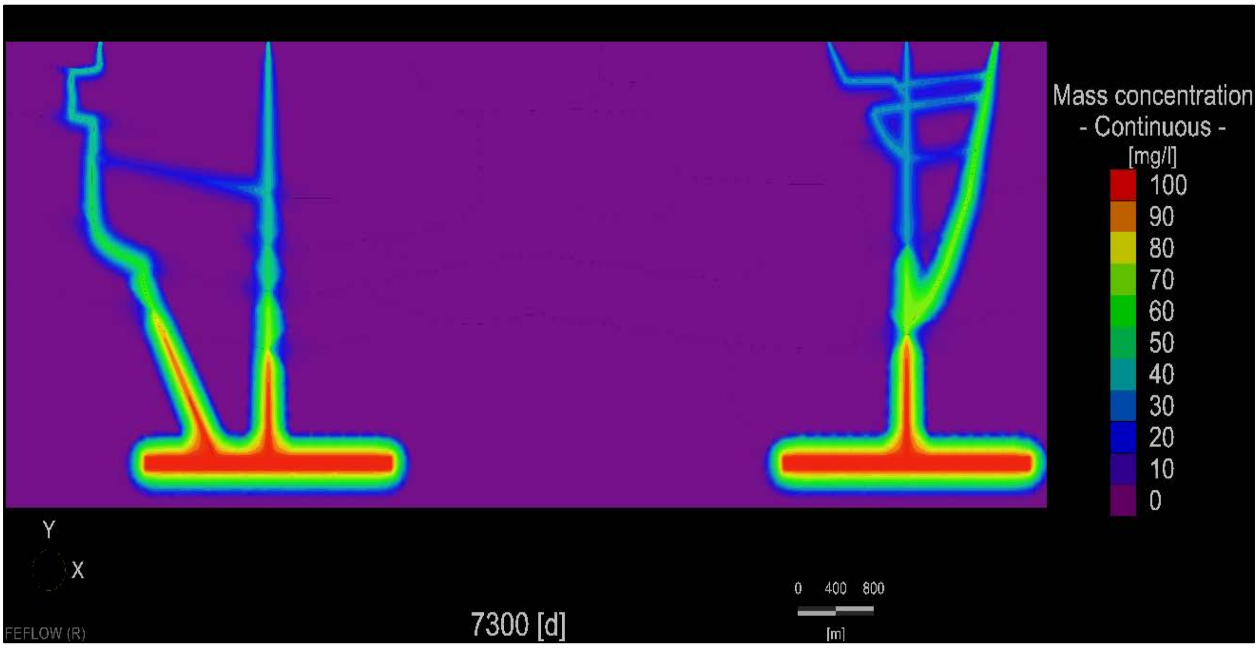

Figure 56: Potential pollutant migration after 7 300 days (20 years)

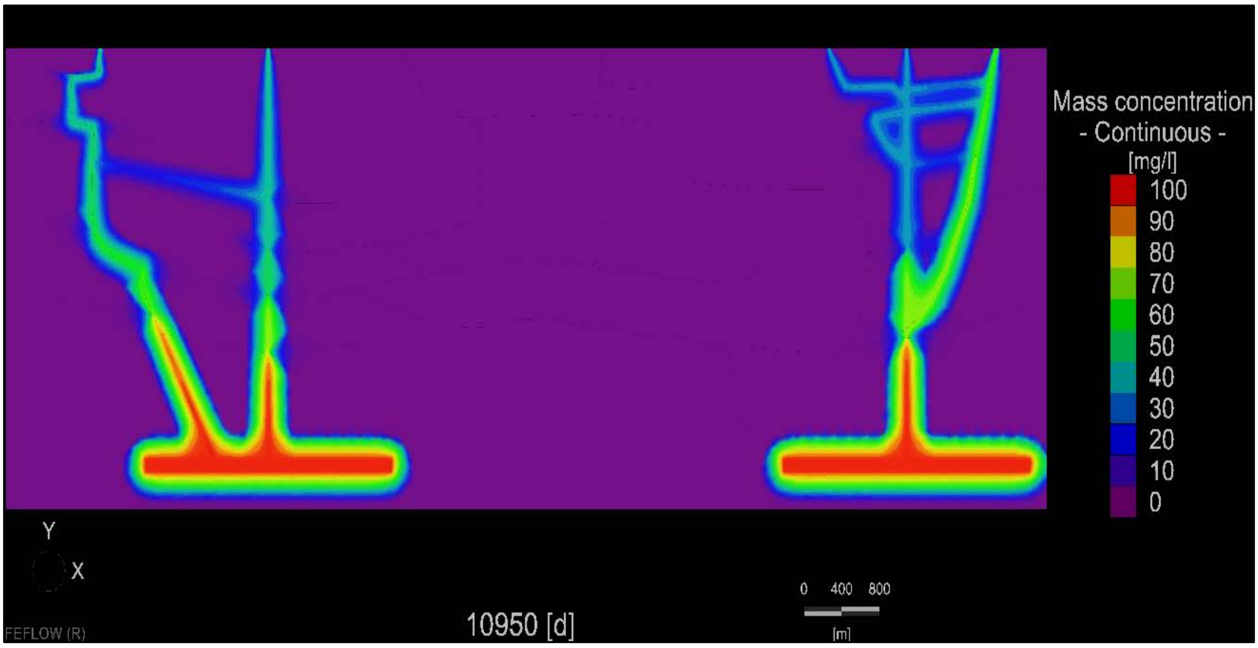

Figure 57: Potential pollutant migration after 10 950 days (30 years)

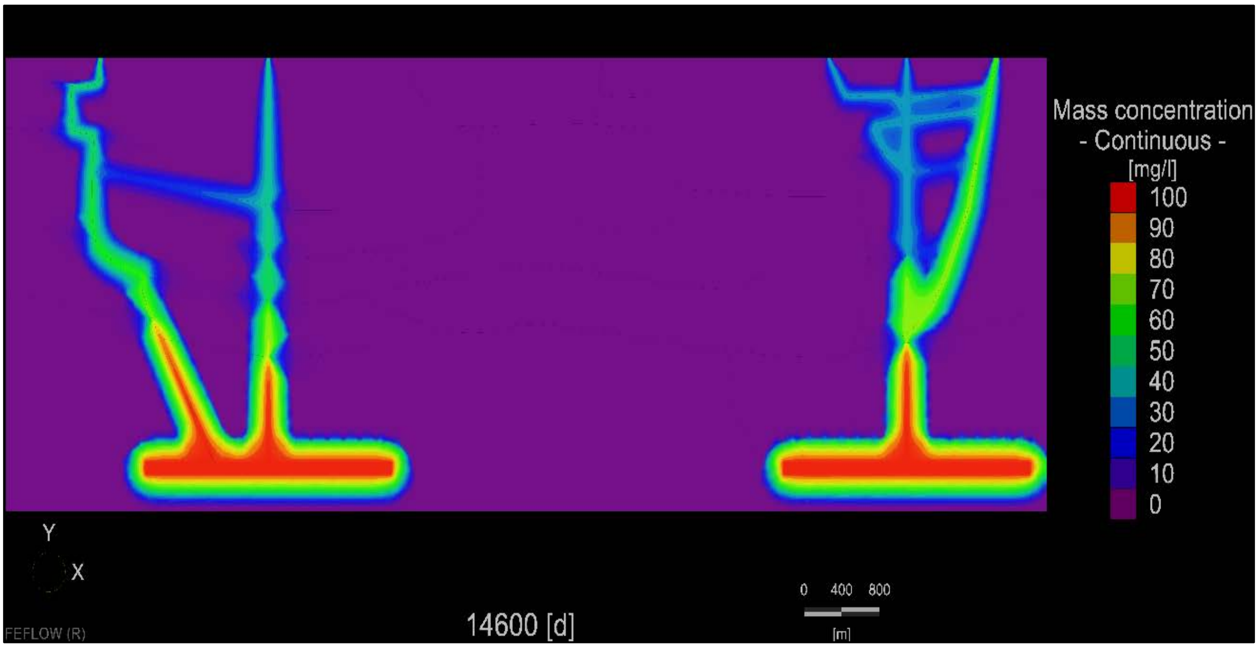

Figure 58: Potential pollutant migration after 14 600 days (40 years)

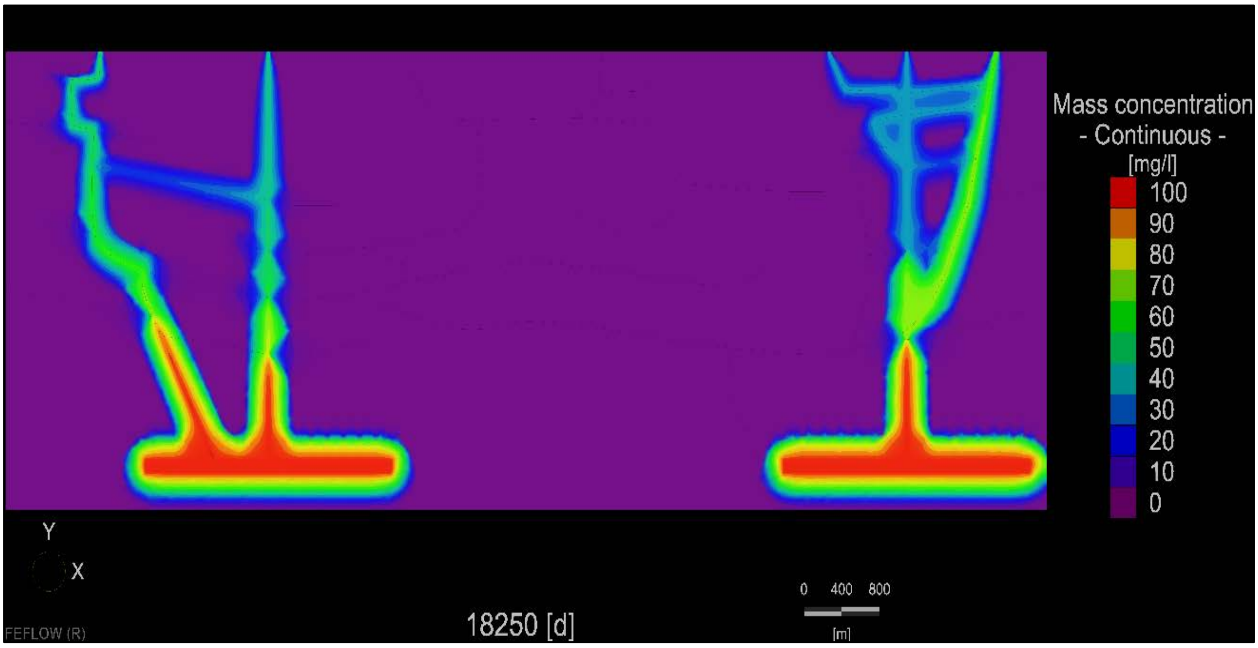

Figure 59: Potential pollutant migration after 18 250 days (50 years)

APPENDIX C

GW-RAT: Possible fatal flaws - Hyperlinks

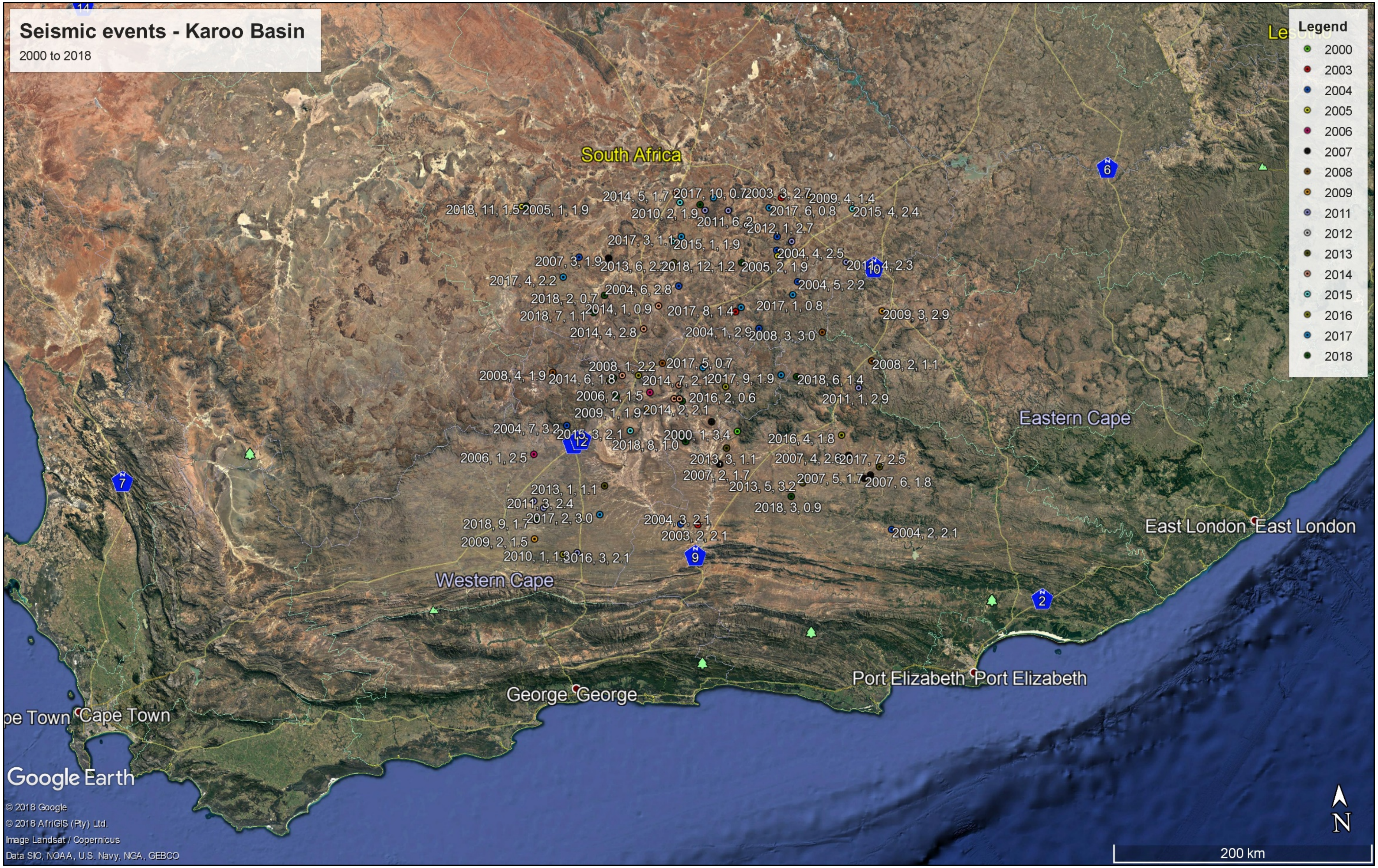

Figure 60: Seismic events across the Karoo Basin – 2000 to 2018

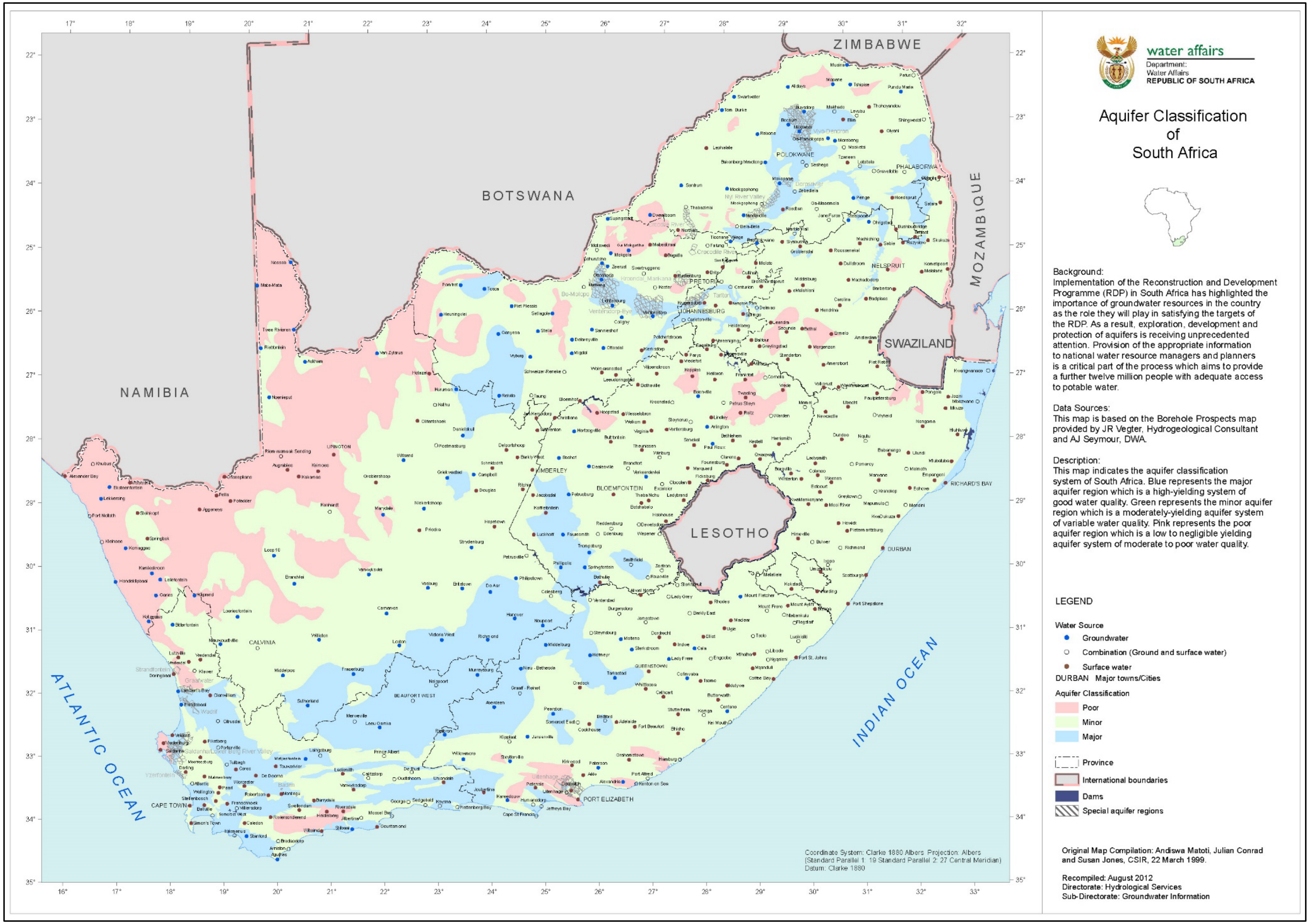

Figure 61: Aquifer Classification of South Africa (DWS, 2012a)

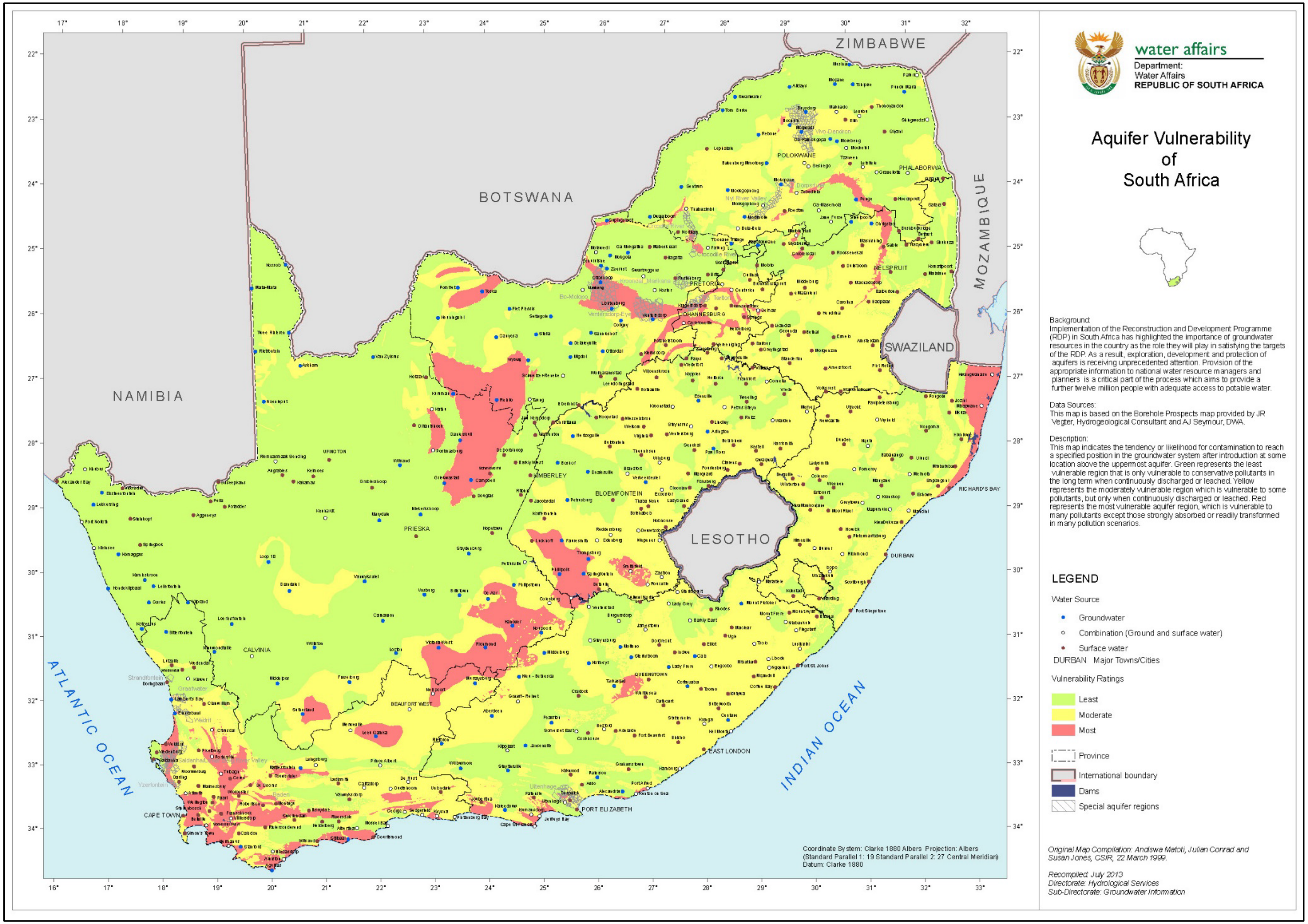

Figure 62: Aquifer Vulnerability of South Africa (DWS, 2013b)

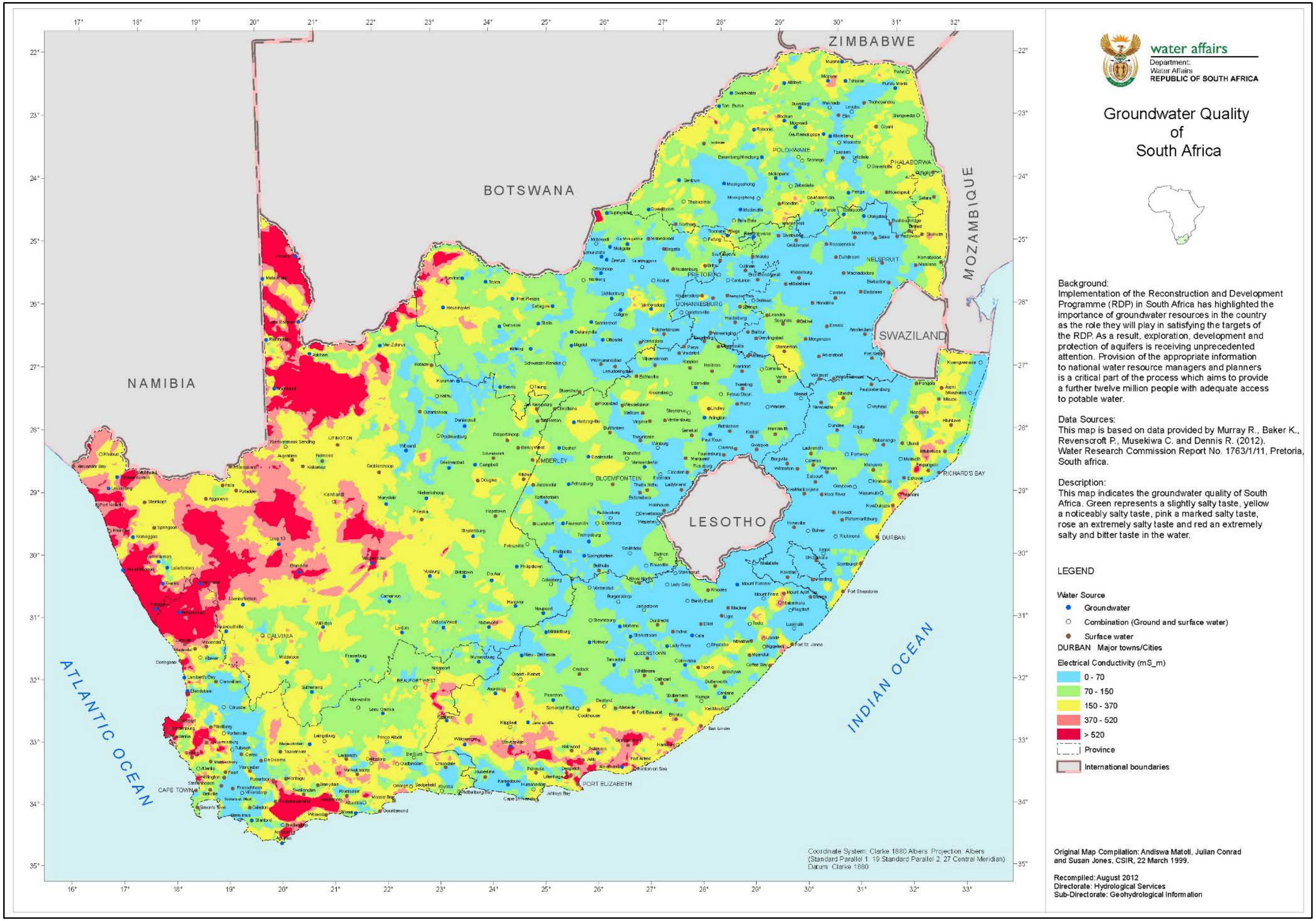

Figure 63: Groundwater Quality of South Africa (DWS, 2012b)