Risks to ecological systems from hydraulic fracturing in the Nama Karoo, South Africa.

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ABSTRACT

This study focused on the potential impacts to biodiversity and ecosystem services that may occur in the event of hydraulic fracturing for shale gas materialising in the Nama-karoo biome in South Africa. Fracking has become a highly contested issue internationally and no less so in South Africa, where applications are being considered by the government to permit three international companies to proceed with shale gas extraction.

With no domestic experience of fracking in South Africa a literature research of data emanating from the USA was conducted to evaluate the extraction process. Documented environmental impacts and effects on biodiversity and ecosystem services in the USA have been used to provide insight into potential influences in the Nama-karoo.

A qualitative study method was applied to identify and evaluate existing biotic and abiotic systems within the biome. From the outset, hydraulic fracturing, will require that suitable infra-structure including roads and drill pads must be constructed that will necessitate habitat degradation and fragmentation with associated edge effects. The potential introduction of alien species, pollution of water resources and over utilisation of wildlife are also recognised as impacts that may affect prevailing biodiversity and existing ecosystems in the Nama-karoo.

Despite continuing attempts to value products and services derived from ecosystems, commonly accepted means to quantify ecosystem services remain vague. Utilising the identified sources of environmental impacts that may be introduced to the Nama-karoo, four ecosystem services, namely; provisioning, regulating, cultural and supporting services have been considered. Affected ecosystem services are not quantified or valued, however, suggestions are provided that will enable decision makers to appreciate the manner in which fracking may degrade existing ecosystem services to the detriment of current and future human well-being.

Keywords: **Hydraulic fracturing, shale gas, Nama-karoo, biodiversity, ecosystem services**

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Without the ongoing love and support that I have received from my beloved wife, Linda, this research report would never have materialised.

My children, Ross and Nicky, your youthful enthusiasm is infectious and inspiring.

Lynne Robinson, when times were difficult your well-considered words of advice were headed, and you introduced me to my mentor; Thomas Berry.

> *Our difficulty is that we have become autistic. We no longer listen to what the Earth, its landscape, its atmospheric phenomena and all its living forms, its mountains and valleys, the rain, the wind, and all the flora and fauna of the planet are telling us.*
>
> Thomas Berry

DECLARATION

I declare that the thesis which I hereby submit to the University of Pretoria for the degree of MPhil in Wildlife Management is my own work and have not been submitted before by me for a degree at another university.

Signature. Date.

(Mr. J.K.A. Arkert)

TABLE OF CONTENTS

List of figures

List of acronyms and abbreviations.

BETEX	benzene, toluene, ethylbenzene, and xylenes.
B.V	Besloten Vennootschap
ºC	degrees Celsius
^{14}C	carbon 14 isotope
CCA	Council of Canadian Academies
CO_2	carbon dioxide
CSIR	South African Council for Scientific and Industrial Research
CV	coefficient of variation
DEP	Department of Environment, Pennsylvania
DMR	Department of Mineral Resources, South Africa.
EIA	Energy Information Agency, USA
EMPR	Environmental Management Program
GSA	Geological Society of America
ha	hectare
HVHSF	high-volume horizontal slickwater fracturing
kl.	kilo litre
km^2	square kilometre
LSU	large stocking units
MA	Millennium Ecosystem Assessment
m	meter
mm	millimeter
m^3	cubic meter
masl	meters above sea level
mg/l	milligrams per litre
mPa	mega Pascal
mya	million years ago

$NaHCO_3$	Sodium bicarbonate
NH_4	Methane
NORM	Naturally Occurring Radioactive Materials
PetroSA	Petroleum, Oil and Gas Corporation of South Africa
SAfMA	Southern African Millennium Ecosystem Assessment
SEA	Strategic Environmental Assessment
SOEKOR	Southern Oil Exploration Corporation
SO_4	sulphate
tcf	trillion cubic feet
TKAG	Treasure the Karoo Action Group
UK	United Kingdom
USA	United States of America
WW II	Second World War

CHAPTER 1

1.1 INTRODUCTION.

In a world environment in which continued and unabated economic growth is perceived to be the sole means of improving the socio-economic circumstances of humanity, environmental considerations are often reduced to lower order priorities. Concomitant with growing economies is the continued reliance on energy, which for the past century has been dominated by the use of hydrocarbon based sources. Coal, oil and gas are the non-renewable fossil fuel resources that have traditionally been used to drive the growth of economic output. Growing populations and increasing commercialisation compounded by rapidly dwindling fossil fuel resources has compelled societies to apply greater technological innovation to enable exploitation of remaining energy reserves. Hydraulic fracturing is the combined application of drilling technology together with the ability to inject purpose designed fluids into impermeable rock formations to liberate methane gas. Fracking, which is the colloquial term for the highly industrialised mining process is currently applied in the USA, with significant direct economic benefit. The environmental costs however, are still to be determined and with application of relevant temporal and spatial scales, might prove to be considerable.

With the economic benefits recorded in the USA, many other nations, that are host to vast reserves of technically recoverable methane gas, have begun to review the potential of fracking potential gas bearing geological formations. In 2008, three companies submitted applications to the South African government for the rights to explore for shale gas in the Nama-karoo (Netshishivhe 2014). These applications and the subsequent outrage expressed by a variety of environmental organisations led to a plethora of opinions expressed and published, primarily in the popular media. Initial and oft quoted concerns referred to the potential risks to ground and surface water resources, which are obvious, given the arid climate of the Nama-karoo and the predominant reliance on agriculture in the area. This argument has largely been counteracted by the promise of job opportunities and regional economic growth (Econometrix 2012). Whilst negotiating between the concerns expressed by both extremes, the government is expected by its citizens to make an appropriate decisions with regard to fracking which is based on the best interest of its citizens; both present and future.

It is within the confines of this debate, which has been somewhat simplified, that another variable must be introduced. Economic growth and social improvement cannot proceed in a moribund and degraded natural environment. All life is beholden to functioning ecosystems, which include the abiotic and biotic parts of the biosphere (Van As *et al* 2012). The complexity of ecosystems, the time and spatial scales over which they operate, and the well-being that humanity derive from them is poorly understood. Whilst the mysteries of ecosystem functioning are continually being unravelled, humans continue to persevere with a single minded obsession of applying monetary values to tangible and intangible natural systems in order to add them to the list of national assets or liabilities.

It is upon the Nama-karoo, a semi-arid, biogeographical region located in south western South Africa, that it is proposed that fracking will be imposed. Chapter 1 provides an overview of the geology and associated groundwater conditions that prevail in this region and a description of the soils and the climate provides insight into the abiotic aspects of the Nama-karoo that create suitable habitats for a myriad of life forms; animal and plant.

Although the Nama-karoo is a rural area, with little economic activity other than pastoral agriculture, it is an area that has been affected by anthropogenic activities during the course of millennia. Over grazing, abuse of water resources, introduction of alien vegetation are amongst the activities that have resulted in environmental degradation and associated disruption to ecosystems (Milton & Dean 2010, Esler *et al* 2010, Eccard *et al* 2000, Dean *et al* 1995). Finally, some consideration is given to the concept of ecosystem services and the evaluation of such services. Reference is made to potential impacts that an extensive industrialised process, such as fracking, may have on already compromised ecosystem services in the Nama-karoo.

1.2 OVERVIEW AND AIM OF STUDY.

Hydraulic fracturing is the combined use of various technologies used to mine thermogenic methane gas contained within sedimentary rocks of low porosity. The so called fracking of unconventional gas sources is currently applied in the USA and in a number of other countries. This has not been without controversy, particularly from environmental and civic organisations. In South Africa anti-fracking activist from organisations such as Treasure the Karoo Action Group (TKAG) and others have been vocal in their opposition to the application by three international energy companies, namely Shell Exploration Company B.V, Falcon Oil and Gas and Sunset Energy to explore for gas in an area spanning some 130 000km^2 in the Karoo, with the intention of ultimately extracting gas by means of hydraulic fracturing. The extensive spatial and long temporal scale of fracking activities are regularly cited (TKAG 2015, FrackingSA.org 2015) by opponents as having potential impacts on the environment.

The economic advantages of exploiting shale gas has had a significant impact in the economy of the USA over the past decade and in particular in the recovery of the economy following the recession of 2008 (Rogers 2013). In light of perceived economic advantages of mining shale gas, the US Energy Information Administration (EIA) presented a report in 2011 (US EIA 2011) in which estimations of the potential volumes of shale gas world-wide was presented. It was estimated that South Africa has a volume of 485tcf of technically recoverable shale gas, confined within the Karoo Basin. Despite the revised EIA estimate in 2013 (US EIA 2013) of 390tcf, South Africa is considered to host the 8th largest reserves of shale gas in the world.

Faced with economic and social challenges, the government of South Africa have indicated a strong intention to pursue the exploitation of shale gas in the Karoo. In terms of the requirements of the Mineral and Petroleum Development Act 2002, it was required that applicants for a licence to conduct exploration must submit an environmental management plan (EMPR) to the DMR. Perusal of these reports (Golder and Associates 2011, Nsovo 2010) show that the environmental issues and concerns that they address are confined only to activities directly related to the proposed exploration activities. Little or no consideration is applied to the more wide ranging impacts on biodiversity and potential degradation to ecosystem services prevalent in the Karoo. Ultimately, making decisions that are based only on inappropriate and narrow economic reasoning, without appropriate consideration of ecological and associated sociological arguments, may have long term negative consequences.

A plethora of peer reviewed literature and data are available addressing the geology (Svensen *et al*. 2006, McCarthy and Rubidge 2005), groundwater (Steyl *et al.* 2012, Vermeulen 2012, De Wit 2011, Steyl, Van Tonder and Chevallier 2012, Van Tonder *et al.* 2012), biodiversity (Cowling and Hilton-Taylor 1999, Vernon 1999, Van Jaarsveld *et al.* 2005, Biggs *et al.* 2008, O'Farrell *et al.* 2010) and ecosystem services (Le Maitre *et al.* 2007, Le Maitre *et al.* 2009, Smith-Adao *et al.* 2011, O'Farrell *et al.* 2011) many environmental aspects of the Karoo are readily available. Similarly volumes of applicable information derived from the fracking experiences in North America also exists. It is therefore apparent that a broader assimilation of the literature is required to determine the potential impacts that the proposed industrial activities associated with hydraulic fracturing may have on biodiversity and ecosystem services in the Karoo.

1.3. METHODOLOGY.

This study followed a qualitative approach. Qualitative research is used to "*understand and also explain an argument, by using evidence from the data and from the literature, when the phenomenon or phenomena that we are studying are about"* (Henning *et al*. 2004).

The approach undertaken includes an exploratory and descriptive methodology in order to gain understanding of the process of shale gas development and hydraulic fracturing, followed by identifying and understanding the potential environmental impacts and the influences upon ecosystem services. Utilising the literature and research data available from the USA and elsewhere and in combination with the literature addressing the biophysical aspects of the Karoo in South Africa. The environmental impacts of hydraulic fracturing obtained from the literature have been considered in the context of the Karoo. Ecological patterns and processes have been taken into account in order to determine the shale gas extraction activities that may impact on the biotic and abiotic systems prevalent in the Karoo.

It is the aim of this study to investigate the premise that hydraulic fracturing will impact on biodiversity and will affect ecosystem services in the Karoo.

1.4. DELIMITATIONS OF THE STUDY.

The concept of hydraulic fracturing in South Africa has been largely centred on the Karoo, without any fixed perception of what makes up the area commonly referred to as the "Karoo". The Hydraulic Fracturing Task Team constituted by the Department of Mineral Resources (DMR 2012) define the Karoo in terms of the geological extent of the formations that are included in the Karoo Sequence of rocks as defined by the South African Committee for Stratigraphy (1980). Similarly Mkhacane (2012) makes reference to the Karoo Basin, while Mentor (2012) describes the area as the Great Karoo without a clear designation of the limits to the geographical area.

The Karoo is also referred to as the Great Karoo and the Little Karoo, which are political terms stemming from the colonial occupation in support of transhumance herding cycles

(Hoffman *et al*. 1999). The Nama-karoo and Succulent Karoo describe biomes that host a distinct assemblage of fauna and flora, which are constrained by abiotic conditions.

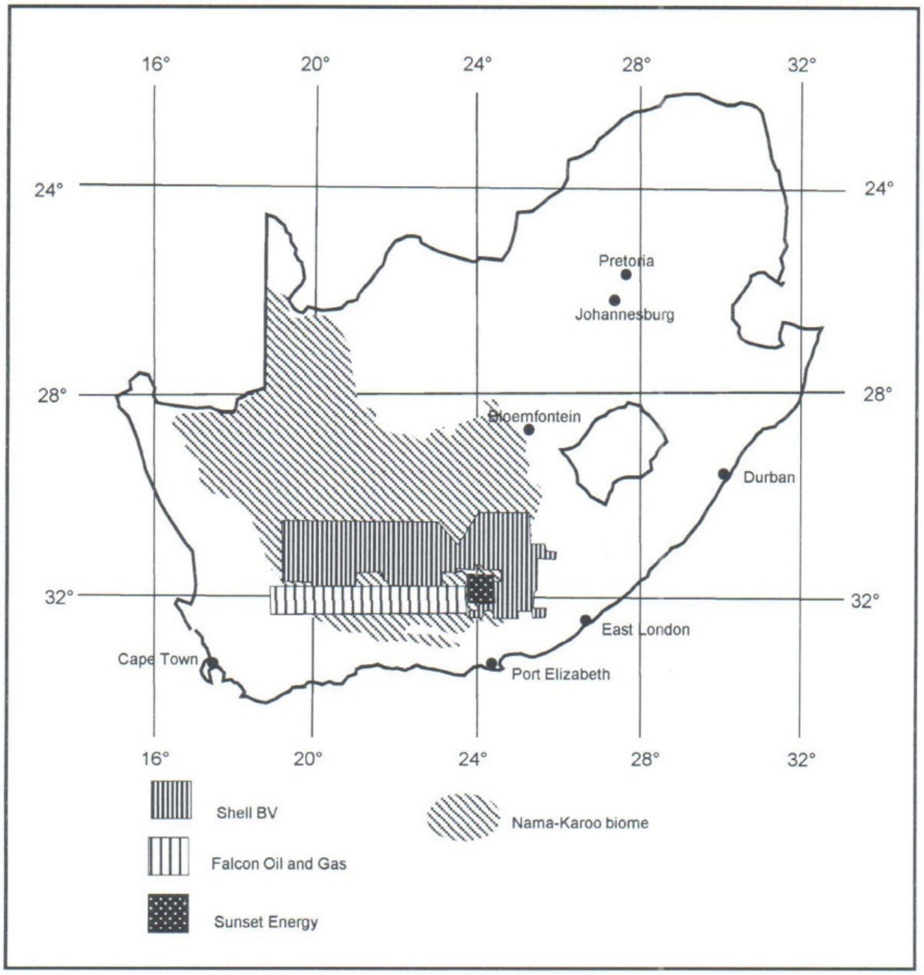

Figure 1.1 Map of the Nama-karoo biome and the three shale gas exploration areas.

Clearly the boundaries of the geological, biogeographical and political definitions of an area will not necessarily coincide and therefore for the purposes of this study the Karoo will be considered to be that area that is included within the biogeographical limitations of the Nama-karoo biome (Mucina and Rutherford 2006).

1.5 HYDRAULIC FRACTURING.

The use of explosives detonated in boreholes to fracture host rocks, thereby increasing the permeability was first used in the USA in 1865, and subsequently techniques were improved, using acid, gelled gasoline and a number of variations to the design of the fracking fluids. Following WW II, the oil and gas industry applied fracking techniques to stimulate the flow of hydrocarbons in wells and developed the technology to turn vertical boreholes and drill horizontally into oil and gas bearing reservoirs (GSA 2014) and the earliest application of fracking was used in reservoirs hosted in more permeable sandstone horizons. Slickwater hydraulic fracturing was first used in 1997 to extract methane gas from the low permeability Barnett Shale formation in Texas utilising a method developed by George P. Mitchell (Andrew *et al.* 2009). These early experimental methods proved that gas could be economically released from unconventional source rocks such as shale. Hydraulic fracturing which is colloquially referred to as fracking and in its modern context, is more correctly called high-volume horizontal slickwater fracturing (HVHSF) (Montgomery and Smith 2010).

Howarth and Ingraffea (2011) expressed the opinion that the combined utilisation of high-volumes of purpose designed fluids that are pumped under high pressure through a horizontally orientates borehole defines hydraulic fracturing as currently applied by the oil and gas industry in the USA and elsewhere.

Unconventional gas and oil extraction as applied to low permeability rock formations such as shale is a process in which a well is bored vertically to depth of up to 4000m. At a selected depth, the so called kick off point, the drill string is turned horizontally to intersect the targeted, gas bearing geological formation, which usually consists of shale. The horizontal section of the borehole may be up to 2500m in length (Kargbo *et al.* 2010, Kiviat 2013). Fracking fluids which typically includes 90% water, 9% sand or other propants and 1% chemical are introduced into the selected position along the horizontal leg of the well at pressures that exceed the confining stresses and inherent strength of the rock. The fractured rock releases the gas to flow along the induced and natural fractures of the host rock and is captured in the borehole. It is feasible to drill up to 32 wells from each surface platform with the advantage of reducing the foot print of the surface infrastructure. Arthur *et al.* (2008) provide an indication that each surface platform is able to extract gas from an area of approximately 64ha and the average economic lifespan of each well in the Barnett shale play in Texas is 7.5 years.

In order to mitigate the risks of ground water contamination associated with drilling and fracking, casing is installed into the wells simultaneously with the advance of the drilling. A single casing string is installed and grouted into place which extends to the bottom of the water table (Andrew *et al.* 2009) from where a smaller diameter borehole is continued into which a second casing tube is introduced and also cemented in place.

The surface casing and second order casing therefore prevent the inflow of groundwater into the borehole as well as protecting the aquifer from introduced drilling fluids and the migration of gas from intermediate geological horizons. A final or third order of casing, known as the production casing, is introduced to the borehole and extend to the full depth of the well. In a similar manner, this casing is also cemented into place prior to fracking occurring. Despite the precautions applied to prevent environmental contamination Ingraffea (2014) reported that in the order of 6% of well that were initiated between 2000 and 2012 were subject to cement and well casing failure in Pennsylvania, and the trend appears to be increasing.

1.5.1 Hydraulic fracturing in South Africa

Anglo America Corporation have applied limited fracking to extract methane from shallow coal beds in a pilot project conducted in the Waterberg Basin of Limpopo province (Koekemoer 2014) since 2007. Hydraulic fracturing as defined by Howarth and Ingraffea (2011) has however, not been applied in South Africa, and the resent increase in interest to apply the technology has been focused on the Karoo Basin.

Initial exploration for fossil fuels within the Karoo Basin occurred between 1965 and 1977 by Soekor, now called PetroSA (Vermuelen 2012) was centred largely on the area referred to as the Great Karoo. Twenty four deep vertical wells were drilled during the project and the basal Prince Albert shale formation and the upper Waterford and Fort Brown formations were of particular interest due to a total organic carbon content of 3-12% within these shale formations. Subsequently the Whitehill shale formation with an organic carbon content of 0.5-14.7% was also considered to be a potential reservoir for oil and gas (Steyl, Van Tonder and Chevallier 2012).

With the exception borehole C1/68 drilled on the farm Cranmere in the Pearston District in the Eastern Cape from which 1.8 million cubic feet of gas flowed per day for a short while (Vermuelen 2012) no economically viable sources of hydrocarbons were discovered and the exploration program was terminated.

Subsequent advances in drilling and fracking technology and the rapid expansion of shale gas exploration as well as the successful exploitation of the Barnett and Heynesville gas plays in Texas USA, other shale formations in the USA and worldwide were viewed as potential hosts of gas. The Karoo Sequence and in particular the Ecca Group of shale were once again targeted and during 2009 and 2010 three international energy companies, Shell Exploration Company B.V., Falcon Oil and Gas and Sunset Energy, submit applications to the South African government for exploration rights in Karoo. A total area of approximately 130 000km^2 was included in the exploration applications. Strong opposition, based largely on the grounds of concern for groundwater resources, environmental as well as socioeconomic interests, were lodged by civic and environmental organisations.

During April 2011 the South African government placed a moratorium on all fracking applications in order to enable the establishment of a task team to investigate the potential benefits and risks associated with fracking. Subsequently a report was issued to the South African government by the Department of Mineral Resources in July 2012 (DMR 2012). Despite not taking into account the potential impacts on ecosystem services, biodiversity, socioeconomic and other considerations, the report recommended that permits be awarded for the exploration of three lease areas in the Karoo (DMR 2012).

Based on the recommendations of the working group the South African government announced the lifting of the moratorium on hydraulic fracturing in September 2012, and began developing the regulations for hydraulic fracturing and a draft document was made available in October 2013 for public comment. During the State of the Nation address in February 2014, President Zuma referred to hydraulic fracturing in the Karoo as a “game changer” indicating the government’s commitment to proceed with hydraulic fracturing in South Africa. Consequently the DMR invited the original applicants for exploration licences to re-submit their applications in November 2014 with the condition applied that no hydraulic fracturing will be permitted during the exploration phase.

Strong arguments, both internationally and domestically have been presented in favour of fracking and many considered opinions have been used in opposition to this method of unconventional gas extraction. The responsibility rests with government to provide considered opinions based on independent research to make rational decisions that must be weighed up against moral, ethical and ultimately, legal scrutiny. In this context it is obvious that the social, economic and environmental needs and aspirations of society must be considered within the confines of the Bill of Rights. The fundamental environmental rights of society expressed in the South African Constitution are included in section 24 of Chapter 2, which states that everyone has the right;

a. to an environment that is not harmful to their health or well-being; and

b. to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that
    - i. prevent pollution and ecological degradation
    - ii. promote conservation; and
    - iii. secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development.

It is therefore clear that against this backdrop, decision makers are expected to consider the environmental rights of present as well as future requirements of society.

1.6. THE NAMA-KAROO ENVIRONMENT.

The Nama-karoo is a semi-arid biome covering an area of some 250 000 km^2 that is located within the south western portion of South Africa. The region straddles four provinces, namely Western Cape, Eastern Cape, Northern Cape and Free State, and the focus of this description will be on the biotic and abiotic aspects of the Nama-karoo biome.

1.6.1 Geology.

Within the geological assemblage of sedimentary rocks that make up the Karoo Supergroup is the basal Dwyka Formation which is overlain by sedimentary rocks that include the Ecca Group. These lithological units are in turn overlain by the Beaufort Group, which is capped by the sedimentary and volcanic rocks of the Stormberg Group (Catuneanu *et al.* 1998). Within the Permian aged (290-253mya) Ecca Group sedimentary rocks, shale formations of marine origin, containing appropriate proportions of organic matter have been targeted as potential sources oil and gas (Steyl *et al.* 2012).

The rocks of the Karoo Supergroup form an accumulation of sedimentary strata that were deposited from the late Carboniferous period 310 million years ago to the middle Jurassic Period 182 million years ago (McCarthy and Rubidge 2005). With an approximate thickness of up to 12km the Karoo Supergroup consists of layers of tillite, mudstone, shale and sandstone and intruded dolerite sills and dykes, with the entire sequence being capped by a layer of extruded basalt.

The basal unit of the Karoo Supergroup is the Dwyka formation deposited during the southern glaciation when Gondwanaland was located over the south-pole, approximately 310mya. With the gradual northward migration of the super continent the glacial sheets began to retreat and an assemblage of fine grained mud and coarser clastic fragments were deposited that formed the characteristically poorly sorted Dwyka tillite.

During the emplacement of the late Dwyka formation and early Ecca Group sediment, compressive tectonic stresses that caused folding within the rock formations of the Cape Supergroup resulted crustal subsidence (Catuneanu *et al.* 1998) north of the Cape Fold Mountains and gave rise to the Karoo Sea. Deposition of fine grained clastic material into the Karoo Sea gave rise to the Ecca Group of rocks.

Fine grained silt and clay particles eroded off the Cape Fold Mountains were transported into the distal parts of the sedimentary basin, where they were deposited in the calm deep-water marine environment. Associated with the fine grained particles was organic matter derived from algae, plants and animal remains which oxidised and dispersed rapidly into the deeper parts of the basin (de Witt 2011). Upon deposition in the anoxic environment the organic debris trapped within the fine grained mud metamorphosed into oil and gas under the influence of increasing temperature and pressure conditions. Included in the shale formations that were formed were the organic rich Prince Albert, Whitehill and Collingham formations, which are the current targets of shale gas exploration projects (Steyl *et al*. 2012).

With progressive sedimentation the Karoo Sea gradually became a small land locked, shallow lake into which coarser grained sand size and larger particles were deposited. These were derived from fluvial systems that meandered across the extensive flood plains that skirted the lake. The transition from a deep marine environment to a lacustrine and ultimately terrestrial environment is reflected in the rocks that make up the Beaufort Group (Johnson *et al.* 2006).

Increasingly arid conditions led to the formation of up to 4000m of sand that was derived from braided fluvial systems. The Beaufort Group is an assemblage of interbedded shale and sandstone that began forming 250 million years ago, and are host to the evolutionary transition of therapsid fauna (Mucina and Rutherford 2006). The Permian mass extinction event that led to the demise of approximately 96% of all species is recorded in the Beaufort Group (McCarthy and Rubidge 2009).

Subsequent hyper-arid conditions during which time sand, silt and clay derived from flood plain and ultimately large accumulations of aeolian sand dunes gave rise to the Stormberg Group (Eriksson 1981). This stratigraphic unit is recognised at the final phase of sedimentary deposition in the Karoo Basin which was terminated abruptly 182 million years ago.

As Gondwanaland began to fragment, the entire region was covered by basaltic lava and the resulting magma province is referred to as the Drakensburg Group. Several successions of outpouring of lava from fissures located in the vicinity of present day Lesotho resulted in an 800m thick horizon of basalt (Duncan and Marsh 2006). As lava accumulated and solidified on the surface of the earth, thus preventing further extrusion, later intrusive events forced magma into bedding planes and along fractures within the underlying sedimentary rocks. The intrusive bodies formed sills that are tens of kilometres in lateral extent and intersecting dyke swarms that occur extensively across large portions of the Karoo Basin (Steyl *et al.* 2012).

1.6.2. Geohydrology.

Most aquifers in South Africa are found in hard rock formations and 95% of all aquifers are located in the Karoo Supergroup (Steyl *et al.* 2012), and are described as being secondary in character (Vermeulen 2012). A secondary aquifer is one in which groundwater flows through openings that were developed after the rock was formed and the secondary opening form as a result of weathering, fracturing, faulting and dissolution in the host rock formations (DWAF 2015). Karoo aquifers, as stated by Vermeulen (2012), owe their storage and transmission characteristics to weathering, fracturing, faulting and the intrusion of dolerite bodies. In the Nama-karoo the saturated zone in which water that is used for domestic and agricultural purposes is located at a depth of 100 to 300m below surface. These shallow aquifers are recharged by rainfall at a rate of 1-5% of annual rainfall or alternatively expressed as 144m^3 per ha (Vermeulen 2012). The heterogeneous and anisotropic nature of the host rocks are further exacerbated by the ubiquitous presence of intruded dolerite dykes and sills (Steyl *et al.* 2012) and render the geohydrological modelling of the Nama-karoo aquifers imprecise. The intrusive bodies may behave as impermeable aquatards, while is other geological settings, the fractured contact zones adjacent to dikes and sills may provide preferential pathways for groundwater flow (van Tonder *et al.* 2014).

With the exception of the twenty boreholes drilled during the 1960's for the purposes of exploration for hydrocarbon's, few boreholes have been drilled beyond a depth of approximately 300m, and therefore geohydrological data beyond this depth is scant (Steyl *et al*. 2012). Little data exists on the water quality and geohydrological characteristic of the deeper saturated zones that exist from a depth beyond 1500m (Van Tonder *et al.* 2014)**.** The deep aquifers of the Karoo basin are confined by less permeable sedimentary rock formations both above and below the aquifers and are therefore under artesian and sub-artesian pressure (Van Tonder *et al.* 2014)**.** The existence of sixteen naturally occurring warm water springs within the main Karoo basin have provided evidence of natural connectivity between deep groundwater and surface (Van Tonder *et al.* 2014).This water is brackish and saline with total dissolved salt content in the order of 1390 to 10010mg/l and are characterised by high $NaHCO_3$ and SO_4 content (Kent 1949). Van Tonder *et al.* (2014) provided compelling arguments that preferential pathways for upward migration of groundwater is created by fault zones, intersecting dolerite dykes and sills as well as kimberlite pipes and associated breccia plugs, which are known to extend to depths in excess of 1000m. Drilling data provide from the SOEKOR boreholes indicate that vertical and sub-vertical fractures occur at depths in excess of 3000m.

Further evidence for the upward groundwater flow model postulated by Van Tonder and de Langa (2012) is provided by the chemical stratification and deteriorating groundwater quality observed in the Karoo basin. Fresh water is underlain by water that shows gradual increases in salinity to a depth of 1500m. They argue that low salinity of the upper aquifer is maintained by regular recharge by rainfall, while the deteriorating water quality between 300m and 1500m is a zone of dilution, in which the upward migrating brine merge with the over lying fresh water. A mathematical groundwater flow model provided by Van Tonder and de Langa (2012) indicate that flow velocities from a depth of 3000m may be as rapid as 5.5 days along continuous fractures with a width of 1mm, and 552 days where fracture width were assumed to be 0.1mm wide.

1.6.3. Soils.

The soils that cover the Nama-karoo are typical of an arid to semi-arid region and also represent the distribution of the underlying geology. Soil, being a combination of organic and inorganic particles, water and air represents the interface between the lithosphere and the atmosphere, and critically, is the zone upon which the biosphere is largely reliant for sustenance.

Physical and mechanical weathering processes are the dominant soil forming processes in the more arid western portions of South Africa, with chemical disintegration being secondary (Weinert 1980). The lack of leaching and chemical activity, compounded by the relative lack of organic activity in the soil horizon results in course grained inorganic orthic-A soils developing (Fey 2010).

Covering large portions of the central areas of the Nama-karoo are lithosols, which are derived from gradual soil formation processes and overly bedrock at shallow depth, usually less than 300mm (Mucina and Rutherford 2006). Being coarse grained skeletal soils with sharp property boundaries, these soils are susceptible to degradation and erosion.

In the western areas, in-situ weathering of tillite belonging to the Dwyka formation, have formed soil textures that include weakly structures sandy loam and sandy-clay loam (Watkeys 1999). The soils are usually calcareous throughout the soil horizon and are associated with dorbanks and hardpan calcrete.

Associated with these generalised soil descriptions are localised areas in which unique soil formation processes are active. In the vicinity of Die Vlakte, south east of Beaufort West, Quaternary aged transported soils have been deposited onto extensive alluvial fans, giving rise to deeper, unconsolidated, apedal, free draining soils (Watkeys 1999). Similarly, localised deposition of soils into pans has given rise to loamy topsoil with a high clay content. The chemical composition of these soils are enriched in potassium, calcium, magnesium and phosphorus, which together with greater water retention render these soils.

The abundant dolerite sills and dykes that exist within the central and northern portions of the Nama-karoo weather to form shallow to moderately deep sandy-clay loam which contain calcrete and calcareous horizons (Mucina and Rutherford 2006, Watkeys 1999). The presence of dykes and sills not only provide unique topographic features and affect groundwater flow and aquifers but also develop distinct soils.

It is therefore apparent that the soils in the Nama-karoo can be described as being shallow, free draining sand and gravel with limited organic activity. With localised exceptions the soils are lacking in essential nutrients and minerals such as nitrogen and phosphate that form poorly developed growth medium (Watkeys 1999).

1.6.4. Climate.

The climate of the Nama-karoo is continental, with marginal influence from the adjacent oceans (Mucina and Rutherford 2006), being dominated by a southern subtropical high pressure (anticyclonic) belt. Subsiding air gives rise to fine and clear conditions with little precipitation over the interior plateau (Desmet and Cowling 1999) that are considered to be the cause of the aridity of the region. Summer months are dominated by the presence of the high pressure belts, which move northwards during the winter, facilitating upper level low pressure systems to expand and to bear greater influence on winter weather patterns (Desmet and Cowling 1999).

A strongly developed rainfall gradient is apparent with reducing precipitation from east to west across the Nama-karoo. Similarly decreasing rainfall patterns are recorded from south to north, largely influenced by orographic precipitation along the Cape Fold Mountains and along the Great Escarpment (Desmet and Cowling 1999). Maximum annual precipitation varies from 70mm in the northwest to around 500mm in the southeast, with most rain falling in the late summer months from December to April (Mucina and Rutherford 2006). Although absolute measurements of rainfall are an important indicator of precipitation, it was argued by Fisher (1994) that rainfall variability expressed as co-efficient of variation (CV) is a metric that has important implications for the type of plant life history, plant community structure and dynamics prevalent in the Nama-karoo. Rainfall is unreliable with a CV of up to 40% in the Nama-karoo.

Albeit that biogeographic climate classifications of southern Africa identify rainfall as a primary variable (Rutherford and Westfall 1986), Schultze and McGee (1978) indicated that in addition to moisture availability, regional vegetation patterns are influenced by prevailing temperature regimes. High temperatures, low relative humidity and little or no cloud cover is characteristic of the Nama-karoo, with temperature ranges of -5°C in winter to 43°C in summer commonly experienced (McGinnis 1979). The entire region falls within a frost prone area with a 50% probability of receiving frost during winter, usually starting during the first half of May (Schultz 1997).

Desmet and Cowling (1999) recognised that the availability of water is considered to be the greatest limitation to plant growth and distribution, however, other climatic conditions such as extreme temperature ranges have significant impacts on ecosystems. Prolonged heat waves and desiccation are often associated with berg wind conditions that occur during pre-frontal divergence during winter and early spring that result in anomalously high temperatures causing severe stress to ecosystems if they persist. It is therefore apparent that the variability of precipitation and temperature patterns have an important influence on the biological processes that prevail in the Nama-karoo.

1.6.5. Vegetation.

The Nama-karoo is a complex of extensive plains that are dominated by dwarf shrubs that are intermixed with grasses and with succulents, geophytes and annual forbs occurring on rocky slopes. Trees are infrequent and occur preferentially along fluvial systems (Mucina and Rutherford 2006). Patterns in the distribution of the biotic components of the Nama-karoo are a function of the interaction between the biotic and abiotic ecological systems. The pristine plant composition of the Nama-karoo was considered by Lovegrove (1993) to consist of co-dominant species of chaemaphyte dwarf shrubs and hemicryptophyte grasses. The shrub dominated matrix which exists in Nama-karoo plant communities includes long lived individuals that are separated by competitive interaction. With the exception of short-lived grass component, the shrub matrix create stable long-lived plant communities that limit recruitment (Vorster 1999; Hoffman and Cowling 1990).

Gibbs Russell (1987) provided an estimate of 2147 plant species present in the Nama-karoo which is approximately 30% of the number of species that occur in the succulent Karoo, with Asteraceae, Poaceae and Fabaceae the most frequently encountered families. Endemism is not high in the Nama-karoo, where 377 species, representing 17% of the total number of species being unique to the biome. In arid and semi-arid areas, Cowling and Hilton-Taylor (1999) reasoned that plant diversity increases with increasing rainfall up to 400mm per year after which diversity tappers off due to increasing competition for resources, thereby providing opportunities for niche separation. The relatively limited species diversity in the Nama-karoo in comparison to the succulent Karoo may therefore be attributed to the higher and more reliable precipitation in the latter. Despite the relatively low plant diversity, the Nama-karoo hosts a high diversity of growth forms which include ephemerals, annuals and geophytes that co-exist with C3 and C4 grasses, succulents, deciduous and evergreen chamaephytes and trees (Mucina and Rutherford 2006). The unstable and stochastic nature of climatic and disturbance events, including rainfall, which has been shown to have a high co-efficient of variability, may interact with factors such as grazing, fire, erosion and hailstorms to create the required heterogeneous conditions (Mucina and Rutherford 2006).

Working is limited site plots of 25m^2 in area, Milton (1990) showed that drainage lines supported twice as many species and a more diverse array of growth forms than plots located in the adjacent loamy plains, thus supporting the theory that regions that provide high heterogeneity of soil moisture conditions will support more growth forms than less heterogeneous areas.

Mapping of vegetation distribution patterns at the landscape level in the Nama-karoo biome have focused on using environmental variables such as elevation, rainfall and geology (Palmer and Hoffman 1997). The description that follows of the vegetation units will be confined to the landscape level and three vegetation units have been described by Mucina and Rutherford (2006) within the Nama-karoo.

The largest is Bushmanland and West Griqualand, with elevations ranging from 550 to 1300masl, rainfall range of 60mm to 200mm, with a CV of 75%. Annual maximum and minimum temperature range from 2°C to >35°C. The arid shrublands are dominated by such taxa as *Rhigozum trichotomum , Zygophyllum suffruticosum* and *Acacia mellifera* (Palmer *et al*. 1999). In undulating hilly and rocky terrain at elevations in excess of 1100masl, *Aloe dichotoma* and *Euphorbia avastamona* occur. Along the eastern and south eastern margins of the region plant communities include grassy dwarf shrubland, with the herbaceous vegetation being dominated by the grasses *Stipagrostis ciliate*, *S. obtuse* and *Enneapogon desvauxii*. The woody vegetation is dominated by *Rushia spinosa, Pentzia incana, Lycium prunus-spinosa, Pteronia* spp. and *Felicia* spp.

The second vegetation unit described by Mucina and Rutherford (2006) is referred to as the Upper Karoo. Elevations range from 900-1300masl and rainfall is in the range of 200 to 400mm with a co-efficient of variability of 40 to 50%. The arid montane grasslands occur on steeply sloping landforms and the dominant grasses include *Merxmuellera disticha, Cymbapogon plurinoidis* with *Themeda triandra* and *Tetrachne dregei* occurring in the mesic eastern portions of the region. Other important plant species that occur include *Lycium cinereum, Pentzia globose, Felicia filifolia, Elytropappus rhinocerotis* and *Nenax microphylla* (Palmer *et al*. 1999).

The Lower Karoo is the third of the vegetation units described by Mucina and Rutherford (2006), which occurs at elevations of between 550 and 1500masl. Winters are cold with frost and summers are hot with temperatures ranging from -4°C to 39°C and rainfall varies from 60 to 200mm with a CV of <50%. Large woody shrubs are supported and dwarf shrubs are replaced by grassland towards the east. The undulating plains in the western portions of this vegetation unit consist primarily of dwarf spiny shrubland that is dominated by *Chrysocoma ciliate, Eriocephalus ericoides,* and *Euclea undulata*. Drought resistant grasses include *Stipagrostis* spp. and *Aristida* spp. The eastern portions of this vegetation unit is characterised by low mountain ridges and hills with open grassy karroid dwarf shrubland with scattered low trees that include *Boscia* *oleodides, Pappea capensis* and *Schotia afra*. The dwarf shrubs include the species *Becium burchellianum* and *Chrysocoma ciliata* and typically the grasses include *Eragrostis obtusa, E. curvula Sporobolus fimbriatus* and *Cynodon incompletus*.

1.6.6. Animals.

The Nama-karoo is characterised by low rainfall that is erratic with long periods of drought that are punctuated by brief falls of rain (Venter *et al.* 1986). Whilst a stable environment permits individual animals to be sedentary and resident, seasonal events will compel individuals to react to changes, either through migration or dormancy (Vernon 1999). Individuals may also apply different feeding and foraging strategies, by altering their diet and foraging areas. Dean and Milton (1999) presented a few general principles that apply to animals feeding on seasonal resources such as the Nama-karoo.

- If the animal is resident, it should change its diet seasonally or be able to switch its diet.
- If a specialist feeder, it may store food and live for part of the year on food stores.
- The animal may only be active at those times of the year when resources are available.
- The animal may have a short lifespan, so that the life cycle is completed during the time when resources are available, or it needs a diapause phase in the life cycle.

Resources are temporally and spatially patchy and the xeric climate and stochastic nature of rainfall in the Nama-karoo are considered by Vernon (1999) to be contributing reasons for the relatively poor diversity of fauna and the few endemic species recorded.

1.6.6.1. *Invertebrates.*

Vernon (1999) expressed the opinion that invertebrates constitute possibly the most important but also the least studied of the faunal group in the Nama-karoo. Studies of termites in the Nama-karoo by Kok and Hewitt (1990); Milton and Dean (1993); Moore and Picker (1991), shared the opinion that in terms of biomass, termites constitute an important part of the energy cycle and a vital component of food to a number of animals. Twelve species of termite are known to occur in the biome of which *Hodotermes* *mossambicus* is the most widely distributed. The distribution of *Microhodotemes viator* overlaps into the Nama-karoo from the adjacent succulent Karoo, and following periods of poor rainfall *M. viator* increase in density and spread their foraging range (Coaton 1958).

Mima-like mounds referred to colloquially as *heuweltjies*, are created by *M. viator* (Moore and Picker 1991) and are distributed widely across the eastern and northern portions of the Nama-karoo. Using ^{14}C dating methods, Moore and Picker (1991) determined the age of some of these mounds to be approximately 4000 years old. The soil chemistry of the *heuweltjies* differ significantly from the adjacent soils and are enriched with Ca, Mg, P, Mn, and N, which have a significant impact on plant recruitment. Their high nutrient status is maintained by the burrowing activities of mammals and dung middens of antelope (Milton and Dean 1990).

Harvester ants *Messor capensis* create similar nest mounds on nutrient rich patches that occur along drainage lines and on nutrient poor soils on the plains of the Nama-karoo (Dean and Yeaton 1993a; Dean and Yeaton 1993b). Nutrients leached from nest mound soils have an influence on the nutrient status of the soils in the immediate vicinity of the mounds and Dean and Yeaton (1993a) concluded that nutrient rich patches such as the nests of *M. capensis* influence the types of plants that colonise them as well as enhancing the growth and reproductive output of certain plants.

Occasional irruptions of brown locusts *Locustana pardalina* cover extensive areas of the Nama-karoo, during which time the locusts are the most numerous animal in the biome (Vernon 1999; Mucina and Rutherford 2006). Following plant regrowth after periods of drought, populations of *L. pardalina* are rapidly stimulated to forage on the new growth, feeding only on photosynthetically active plants (Mucina and Rutherford 2006). Mimicking the patchy distribution of resources, major outbreaks of the locusts are usually confined to the central portions of the area (Erasmus 1988).

Vernon (1999), recorded that with the exception of caterpillars of the moth *Loxostege frustalis*, which constitutes a significant proportion of the biomass of the biome, Lepidoptera is poorly represented in the Nama-karoo. Only 33 of the 232 common species that are known to occur in South Africa, have been recorded in the Nama-karoo and three of these species are endemic (Migdoll 1987).

1.6.6.2 *Vertebrates.*

The degree of endemism of the order of Chelonii and Squamata including Serpentes and Sauria is poor in the Nama-karoo. Six species of tortoise of which three *Homopus* spp. are largely confined to the biome (Vernon 1999) and of the 100 species of snakes that occur in southern Africa, none are endemic to the Nama-karoo. Similarly the degree of endemism of the sub-order Sauria is also poor, with 47 species in 23 genera represented in the biome, of which three, namely; *Pachydactylus oculatus, P. serval* and *Typhlosaurus gariepensis* are endemic.

Over 400 species of birds have been recorded in the succulent and Nama-karoo (Dean 1995), and 10% of the bird species recorded showed a preference for these biomes. Eight of the species are considered to be endemic to the two karoo biomes and three of the species, namely karoo korhaan *Eupodotis vigorsii*, Sclater's lark *Spizocorys sclateri* and black-eared finchlark *Erempoterix australis* show a preference for the Nama-karoo. Boobyer (1989) offered the opinion that the karoo korhaan favours habitat with a diversity of shrubs and few succulents and little grass. It feeds on plants and animals and the omnivorous diet has evolved from perennial patchy resource availability and periods of ephemeral abundance of preferred food resources; conditions that characterise the Nama-karoo.

Opportunistic insectivores are a feature of the Nama-karoo, with large flocks of storks, bustards, kestrels and wattled starlings present following periodic outbreaks of insects (Visagie and Anderson 2006; Mucina et.al 2006). The Lesser Kestrel *Falco naumanni* is listed as *Vulnerable* by BirdLife International (2000), however, during periodic irruptions of brown locusts, 5000 to 6000 birds have been recorded at a single location on one day in the Nama-karoo (Visagie and Anderson 2006).

Due to habitat transformation and fragmentation of the grassland biome, the Blue Crane *Anthropoides paradiseus*, a southern African endemic and the national bird of South Africa, population declines by as much as 90% have been recorded in its historical range (McCann *et al.* 2007). With a habitat preference for short vegetation and good visibility the central Karoo accounts for some 42.4% of the population of Blue Cranes and approximately 42% of the stable core area falls within the Nama-karoo biome (McCann *et al.* 2007).

The majority of mammals that occur in the karoo are species with a widespread distribution and 83 species occur in the Nama-karoo. Three species are endemic and Vernon (1999) included; Grant's rock mouse *Aethomys grantii*, the Riverine rabbit

Bunolagus monticularis and Visagie's golden mole *Chrysochloris visagiei*, in the short list. The fossorial Visagie's golden mole is an isolated, relict population that is restricted by specific soil types that occurs in the central westerns portions of the Nama-karoo (Dean and Milton 1999). Contrary to savannah and forest moles that are insectivore desert and karoo golden moles utilise lizards as the main part of their diet.

Unproductive systems such as the Nama-karoo support solitary and territorial herbivores as opposed to gregarious grazers and it therefore favours vagile herbivores such as ostrich *Struthio camelus* and springbok *Antidorcas marsupialis*. . Nomadic and migratory behaviour has been recorded for springbok, in which herds numbering thousands gathered (Skinner 1993). Milton et.al (1994) suggest that the mobility of springbok between rainfall patches and their ability to select high quality forage enables these herbivores to survive in arid environments in such as the Nama-karoo.

In times past, large herbivores such as elephant *Loxodonta africana*, black rhinoceros *Diceros bicornis*, mountain zebra *Equus zebra*, quagga *E. quagga*, black wildebeest *Connochaetes gnou*, red hartebeest *Alcelaphus buselaphus*, gemsbok *Oryx gazelle* and eland *Taurotragus oryx* occurred periodically in the Nama-karoo (Dean and Milton 1999). During periods of high rainfall and above average production these large herbivores migrated into the karoo from the adjacent savanna and grassland biomes.

As a result of the physical factors that drive ecosystems in the Nama-karoo, a substantial proportion of the primary production takes place underground (Siegfried 1999). Predators have therefore adapted in the arid environment to prey on fossorial organisms that are readily available. Aardvark *Orycteropus afer* bat-eared fox *Otocyon megalostis* and aardwolf *Proteles cristatus* are termivores that are wide spread in the biome (Dean and Milton 1999). Diets may vary with availability and bat-eared foxes and aardvark will shift dietary preferences at certain times of the year.

Shifting from termites to ants and other insects or lizards, bat-eared foxes will seasonally utilise the available food (Mackie and Nel 1989). Bat-eared foxes are not strongly territorial and feed in small family groups in home ranges of about 1km^2 in extent (Mackie and Nel 1989). Similarly aardvark switch seasonally from feeding predominantly on termites to ants available within their home range, which in the Nama-karoo may be up to 3.5km^2 in extent (Van Aarde *et al*. 1992).

Aardwolf are obligate termivores, feeding on harvester termites *Trinervitermes trinervoides* that have limited nutritional value, which dictates the size of the home range. Richardson (1987) determined that the territory occupied by aardwolf must include about 3000 termitaria to satisfy their nutritional requirements and that the seasonal dearth of termites during winter affects the breading success of the species.

Larger carnivorous species such as lion *Panthero leo*, leopard *Panthera pardus*, African wild cat *Felis silvestris*, black-footed cat *Felis nigripes* and brown hyena *Parahyaena brunea*, occurred in the Nama-karoo in historical times (Skinner and Chimimba 2005), but anthropogenic encroachment and persecution have driven these predators from the biome. Despite continued persecution black-backed jackal *Canis mesomelas* caracal *Caracal caracal* remain widespread.

1.6.7. Human intervention.

Acheulean hand axes and other Early Stone Age artefacts found at various places in the Nama-karoo have provided evidence that the area was occupied by hominin's, thought to be *Homo erectus*, approximately 3 million years ago (Smith 1999), and no evidence exists that suggests habitation was ever interrupted. The evolutionary development of *H. erectus* to *H. sapiens* is considered to have occurred about 250 000 years ago and the transition is evident by the transformation observed in technology applied to the manufacture of stone implements. Smaller flake tools and blades that were hafted are indicative of the Middle Stone Age (Deacon and Deacon 2003). With the associated advances in weapons and tools *H. sapiens* replaced scavenging for meat with hunting. Rudimentary speech, social groups and cultural activities such as burial of the dead have been recorded, however the advances of *H. sapiens sapiens* approximately 40 000 years ago began to impact upon densities of mega fauna. Later Stone Age people were more effective at exploiting faunal resources than their Middle Stone Age predecessors (Klein 1979), and the emerging cultural adaptions are reflected in the archaeological record, in the Nama-karoo.

Further anthropogenically induced changes have been recorded in the Nama-karoo during the past millennium, due to the adoption of animal husbandry and crop farming. Migration of people, initially from western Africa into central, eastern, and ultimately southern Africa confronted indigenous Khoisan hunter gathers and Khoi-khoi pastoralists (Dean *et al*. 1995). Engaged in transhumance cycles, pastoral Khoi-khoi groups moved their herds of sheep and goats seasonally from grazing areas and watering points (Hoffman *et al.* 1999). Subsequent incursion of colonial patoralists during the eighteenth century who practiced similar nomadic agricultural practices, across seasonally variable rangeland, inevitably led to conflict. Limited availability to suitable grazing areas and water resources ultimately brought about sedentary pastoralism, with the subservience of Khoi-khoi by trek boers. (Penn 1986).

Dean *et al*. (1995) argue that there is little evidence to suggest changes to vegetation dynamic in the eastern Nama-karoo occurred due to the incursion of colonial farmers in the 18th and 19th century. It was suggested that the vegetation changes observed are due to the repeated use of campsites by Khoisan and Khoi-khoi herding practices prior to the arrival of trek boers. It was, however, indicated that excessively high stocking rates adopted following European occupation could explain the presence of the typical dwarf shrub land that currently characterises the Nama-karoo.

The introduction of fencing and technological advances which enabled boreholes to be drilled and windmills to extract subterranean water sources, together with land tenure policies, agricultural practices in the Nama-karoo began to impact upon ecological process at an accelerated rate (Archer 2010; Dean *et al.* 1995; Hoffman *et al.* 1999). Artificial watering points were created and stock animals were maintained in enclosed camps and during periods of drought supplementary feed was provided so that elevated stocking rates could be maintained to the detriment of the veld condition (Vorster 1999). Densities of up to 15 large stock units (LSU) per 100ha were retained from the mid-19th century dropping to 10LSU per 100ha by 1930 and subsequently reducing further to approximately 6LSU per 100ha by 1970 (Dean and Macdonald 1994). The reduction of more than 50% of the carrying capacity of the veld during a period of a century is considered to be due to the loss of suitable forage and veld degradation (Dean and Macdonald 1994)

Acock (1953) expressed the opinion that due to selective grazing pressure, the productive grasslands that occurred in the Nama-karoo prior to the advent of colonial farming practices, have reduced the biome to largely unpalatable shrub land. Continued poor veld management practices, Acock (1953) warned, will result in desertification of the Nama-karoo and will extend into the adjacent grassland biome in the east and northeast. Dean *et al.* (1995) however, argue that the term desertification is not appropriate terminology to describe the changing conditions recorded in the Nama-karoo, preferring instead to describe the process as dryland degradation.

An early range succession model proposed by Clement (as cited in Connell and Slatyer 1977) suggested that plant dynamics were predictable and reversible, implying that a state of dynamic equilibrium exists. The perceived shortcomings of the rangeland succession model were studied by Westoby *et al.* (1989), and an alternative model called the state and transition model was proposed. Vegetation communities in a state of equilibrium affected by natural events such as fire, weather or man induced events will drive plant communities towards a new state. The changes to the state of the vegetation are not reversible once the cause of the perturbation has been removed and a threshold has been crossed, the community will be considered to be in a new position of successional equilibrium. (Westoby *et al*. 1989).

Applying the state and transition model, Roux and Vorster (1983) hypothesise that five stages of degradation of the Nama-karoo are identifiable should mismanagement continue and appropriate policies for intervention not be introduced. The initial stage consisted of the primary degradation that began during the 19th century and early 20th century. This was characterised by the loss of perennial grass due to the introduction of sedentary farming practices. A subsequent stage which continued from the early 1900's to the decade immediately following WW II, witnessed the continued over utilisation of available forage and palatable plant species that were exploited at a rate greater than regrowth. Government intervention through the Stock Reduction Scheme from 1969 to 1978 reduced animal numbers (Hoffman *et al.* 1999), however, plant communities were characterised by the appearance of unpalatable shrubs in greater densities.

The fourth stage proposed by Roux and Vorster (1983) is characterised by stable plant cover with areas dominated by unpalatable species. The final stage which was anticipated to occur from 2000 and beyond was identified as a stage of desertification due to changing climatic patterns and soil erosion.

1.7. ECOSYSTEM SERVICES.

Political and socio-economic decision-making often appears to be based on the assumption that humans, their development and their socio-economic processes are detached from the natural environment and ecological processes. Increasingly, however, human dependency on ecological systems and the anthropogenic degradation of such systems has been documented both in popular media as well as in peer reviewed academic journals. Daily (1997) expressed the opinion that ecosystem services are often not well understood, and may only be appreciated after they have been severely degraded or lost.

The Millennium Ecosystem Assessment (MA) Report (2005), ecosystem services, also referred to as natural capital (Daily & Matson 2008) and ecological economics (Becker

2006) are defined as the benefits provided by ecosystems and are the life support system of planet earth. In terms of macro-economic rational, the services and goods provided by ecological systems can be valued and used for the benefit of human well-being. Atmospheric cycling of gases including nitrogen, provided by nitrogen fixing bacteria, oxygen provided by decay and photosynthesis and by various bacteria approximately 1000 million years ago delivered the initial conditions for more complex life forms to evolve (McCarthy & Rubidge 2005). Thus it may be argued that ecological systems and the derived ecosystem services, sustain life on earth and therefore all economic activity and all human welfare can be attributed to ecosystem services

The concept of ecosystem services links ecology, economics and social theories from which the MA (2005) identified four groups of services, namely provisioning services (food, water, timber and genetic resources), regulating services (regulation of climate, floods, disease and water), cultural services (recreation, aesthetic enjoyment and spiritual fulfilment) and supporting services (soil formation, nutrient cycling and pollination). Nutrient cycling, photosynthesis and air quality regulation are included in a list of 24 ecosystem services presented the MA report (MA, 2005).

Valuation of ecosystem services to provide a rational comprehension and an awareness of the capital value of the natural assets available is a tool that can be used by decision makers (O'Farrel *et al*. 2011). This concept acknowledges, firstly, the benefits that are derived from ecosystems, without limiting services or goods to merely the end product of a process. Secondly, it recognises the relationship and integration between natural and social systems, potential changes in the one system possibly altering another. Thirdly, it recognises the usefulness of the concept of "value", but without limiting the concept of value to only monetary terms.

In an economically dominated world tied to the concept of maximising return on investments and profits, attempts have also been made to apply value to ecosystem services. From the initial attempts by Constanza *et al.* (1997) to determine the global value of all ecosystem services at a value of $33 trillion, which was a value in excess of the world total income at the time, multidisciplinary efforts have continued to place a monetary value (Boyd & Banzhaf 2007; Hein *et al.* 2006) to processes that are often poorly understood, and more often are poorly defined.

The metrics and time scales of the social and economic aspects of ecosystem services are well researched (Daly & Cobb 1989, Daily 1997, Daily & Matson 2008) and are universally applied. However, the spatial and temporal scales and generally acceptable metric standards to determine environmental well-being have not been developed. The difficulties associated with applying value to intangible goods and services and the complications associated with measuring the extent of human well-being derived from such services has resulted in no broadly accepted method of evaluation being available. Limitations to determining and measuring the extent of impacts to the environment renders the process of decision making, particularly with controversial projects such as hydraulic fracturing, difficult at best and perhaps impossible for managers and government officials.

In the same way that financial capital delivers financial benefits, so natural capital delivers benefits in the form of natural goods and services, but with the difference that humans do not need to pay to obtain these benefits. Natural goods and services only need to be paid for once they develop a scarcity value.

The valuation of natural phenomena and systems is a difficult and complex task, partially because value can be understood either as a subjective or objective quality. Conventional ways of economic valuation are not always appropriate to capture the true value of natural phenomena, therefore, regardless of the difficulty of the task, it is inevitable and it happens through decision-making on a daily basis. Valuation refers to *“the contribution of an item to meeting a specific goal or objective”,* in other words, it’s utility or instrumental value (Constanza *et al.* 1997). The instrumental value of natural phenomena, the utility worth or use of a natural good or service to humans, may be more intrinsic to the theory of ecosystem services than merely the generic definitions of value. McCauley (2006) expressed the view that while it appears to be arrogant and to some extent disrespectful to attempt to apply a monetary value to nature. In practice nature is often weighed against human welfare and financial opportunities and because the currency for comparing nature to such opportunities is in many instances incommensurable, the value of nature is often underestimated. Further arguments were expressed by Becker (2006), McCauley (2006) as well as Bina and Vaz (2011), who proposed that ethical arguments are not always considered in economical calculations and in these circumstances, principles such as equity and sustainability and intergenerational equity do not measure as strongly as fulfilling immediate social or economic demands and needs.

The MA (2005) asserted that the supply and resilience of ecosystem services are affected by changes in biodiversity. While biodiversity and ecosystem services are often addressed together in development strategies (Atkinson *et al*. 2012), some scientists have suggested that a high concordance between biodiversity and ecosystem services are unclear. Despite this need for a practical approach to valuation of nature, it may lead to the exclusion of valuation of certain natural processes and phenomenon on the basis that they are not of utility to humans. Even when certain species may seem redundant or unimportant to humans, they have a role and a place within ecosystems and therefore a reason for continued existence. Thus it may be argued that biodiversity plays a critical role in maintaining ecosystem functioning, and without ecosystem functionality, the delivery of ecosystem services to humans may be compromised (Naeem *et al.* 2012). In the event of a lack of information or a lack of understanding of biodiversity or the extent of an ecosystem, judgement errors may and do occur. As ecosystem services are the products of a system, these products and services should be regarded as greater than merely the sum of the parts. Due to the complexity of ecosystems, acknowledgement of the relationships between different parts of the systems is crucial for securing the delivery of ecosystem services. Valuing end products and services without recognition of the system which produced them may therefore be considered to be unwise. The calculation of the monetary worth of ecosystems will contribute to the commercialisation of ecological systems, but struggles to take into account the intangible cultural values (Infield 2001). Leopold (1949) expressed the opinion that eco-ethics may not be able to prevent the management and use of resources and therefore the concept of economic value, but strongly affirmed the right of ecological systems to exist in a natural state.

The Nama-karoo biome remains relatively neglected from an ecosystem services perspective and much of the literature on ecosystem services of the Karoo region has focused on segments of the little Karoo and the succulent Karoo (Le Maitre *et al,* 2007). In general, arid areas have received less attention from ecosystem services research initiatives than the higher rainfall regions in South Africa and given the possible changes in the Nama-karoo and the close dependence on the natural environment, the imperatives of safeguarding ecosystem services for current and future benefit becomes vital.

1.8. CONCLUSIONS.

The Nama-karoo is expected to face many new externally-driven intrusions, development and changes in the near future. Prospecting for uranium, phosphorus and shale gas, together with uncompromising agricultural practices, land-use changes and climate change, are expected to alter the landscape and ecosystems. These changes are expected to challenge the ability of communities and decision-makers to understand, respond, and adapt to transformations in ecosystems.

Hydraulic fracturing is a recent technological innovation developed to enable the exploitation of increasingly diminishing sources of fossil fuels. Employing the means to direct vertical boreholes to follow horizontally orientated geological horizons, fracking has the means to extract tightly held methane gas from unconventional sources. By injecting purpose designed fluids under pressured that overcome the confining stresses of the host formation, the rock is fractured, thus liberating the in-situ gases. This is a highly industrialised process that has been adopted in the USA, with considerable economic successes.

It was estimated by the EIA that some 390tcf of technically recoverable gas is contained within the Karoo Supergroup in South Africa, and the South African government is currently adjudicating the applications of three international energy companies to explore these resources. This has not been without considerable controversy and outcry from interest groups. In an attempt to balance the energy needs of the country, the socio-economic expectations of a growing population, and the constitution, the government is compelled to balance the potential economic benefits against the potential environmental costs of fracking in the Nama-karoo.

The Nama-karoo is one of South Africa’s nine recognised biomes, situated in the south western portion of the country. Underlain by the Karoo Supergroup the geology of the area is predominated by interbedded shale and sandstone formations that are both fractured and folded in the southern parts of the basin. Subsequent break up of Gondwanaland approximately 180mya caused the intrusion of spatially extensive dolerite sills and dykes. These intrusive features impact upon the geohydrological regime of the Nama-karoo, acting as barriers to ground water flow in some instances and a conduits to groundwater flux in others. The topographic morphology of the Karoo Basin is such that artesian groundwater condition exist which facilitate the upward migration of deeply located salt enriched water that are known to mix with potable groundwater that is located at a depth of approximately 300m. Considerable concern has been expressed by both environmental activists and the agricultural community about the potential contamination of ground water resources, due to shale gas extraction.

The climate of the Nama-karoo is hot and dry in the summer, and cold in the winter. Rainfall is irregular and poor, and the biome is subjected to frequent droughts. Climate, geology and topographical features of the Nama-karoo have been applied to divide the biome into three separate vegetative units, namely; Bushmanland and the Upper and Lower Karoo. Typical of semi-arid regions the soils are poor in nutrients and organic material, which dictate the primary productivity of the regions. Vegetation consists primarily of dwarf shrub land and grassland that occur in the north and east, with patches of more fertile soils associated with rivers and pans that support the heterogeneous distribution of plants.

Animal diversity is poorly represented in the Nama-karoo, which does not support a large number of endemic species. A significant proportion of the biomass of the biome is represented by invertebrates, of which ants and termites constitute the greater part, with the exception of periodic outbreaks of brown locust swarms that attract avian opportunistic feeders from the adjacent grassland and savannah biomes. Reptiles, amphibians and mammals are also poorly represented in the Nama-karoo, and only three endemic species of mammals are recorded.

Evidence of habitation by humans and their hominin ancestor's extent back for approximately 3 million years and in that time there is no suggestion that the Nama-karoo has not been occupied continuously by humans. Evidence of the late quaternary extinction of mega fauna is apparent in the Nama-karoo and subsequent impacts of the transient Khoisan hunter gathers and pastoral Khoi-khoi cultures are apparent. Later occupation by colonial era stock farmers led to the virtual elimination and demise of the indigenous cultural practices, and with the eventual introduction of wire fencing and boreholes, sedentary agricultural practices were adopted. Over stocking of sheep and goats that selectively browsed on palatable vegetation has caused degradation of Nama-karoo veld, with the associated environmental impacts of homogenisation of species, invasion of alien species and erosion. Whilst strongly debated in the literature, it is argued that the Nama-karoo is being subjected to desertification that is spreading toward the east.

It is upon this landscape that it is proposed that the spatially extensive, industrialised process of fracking will be imposed. Economic and financial benefits have been demonstrated in the USA, but the ecological costs have not been determined. Ecosystem services are considered to be a measure of the well-being that humans derive from ecosystems and is often expressed in monetary terms. Significant disagreement is evident in the literature about the concept of applying economic value to complex and often poorly understood ecosystems. Despite the moral and ethical debates, as well as the lack of a generally accepted metric system, it remains crucial that decision makers are provided with the means to determine the environmental costs of facilitating potentially detrimental land use changes. Appropriate attention must be applied to the spatial and temporal scale of impacts to ecological systems by decision makers, whilst balancing the needs of current and future societies.

CHAPTER 2

2.1 INTRODUCTION.

Fracking is a technological advancement that has been developed to enable extraction of methane gas held tightly in voids and fractures in shale rock. From the outset all fracking sites will require infrastructure to be constructed in rural areas to gain access to exploration sites and ultimately to production facilities. Roads will be required to gain access to drilling pads from which boreholes are initially drilled vertically to depths of up to 5000m and then turned horizontally and continue for up to 2500m. In order to overcome the confining pressures of the host rocks, high volumes of purpose designed frack fluids that include numerous chemical compounds are pumped into the boreholes. A proportion of the frack fluids return to the surface, combined with salt enriched brine that may contain elevated levels of radionuclides and organic compounds. These liquids are hazardous to both human health as well as to ecological systems (Vengosh *et al*. 2014, Karbgo *et al*. 2010, Rozell and Reaven 2011, Vidic *et al*. 2013). It is therefore required that liquid and solid waste products are removed for safe disposal or treatment prior to being discharged into the environment.

Much of the debate both in popular media and academic literature surrounds the potential migration of frack fluids, brine and methane gas into shallow aquifers (Howarth *et al.* 2011, Myers 2012, Vengosh *et al.* 2014, CCA 2014) as well as the potential pollution of surface water resources as a result of inappropriate disposal of waste liquids. To date, fracking has not occurred in the study area, and therefore no primary data is available to evaluate and determine the impact of fracking in the Nama-karoo. Appropriate peer reviewed resources emanating from the USA have therefore been perused to examine published research data from that country. With the limited applicable geohydrological information available from the Nama-karoo, potential risks and impacts associated with fracking have been considered.

Whilst considerable focus has been applied to the potential risks to the integrity ground and surface water resources, considerably less attention has been extended towards the potential impacts on biodiversity. The Nama-karoo is a semi-arid region in which stock farming is currently the primary economic activity. The intrusion of an extensive industrial process such as fracking upon a rural and poorly developed region will alter the landscape on an extensive temporal and spatial scale.

Habitat degradation, introduction of alien species, utilisation and destruction of species and increased environmental pollution are some of the factors that Sala *et al.* (2000), identified as presenting direct threats to global biodiversity. Shale gas mining has the potential of exacerbating existing environmental problems in the Nama-karoo and to introduce additional conditions that will further negatively impact on ecological processes. The Millennium Ecosystem Assessment (MA 2005) recognised the direct benefits that human beings derive from ecosystem services and the benefits of conserving ecosystem services for the well-being of humanity. This therefore implies that values must be applied to tangible and intangible resources in order to enable society to determine whether they are indeed an asset or liability. Attempting to place a monetary value to complex natural processes has the advantage of assisting decision makers, to reach rational conclusions regarding the social, environmental and economic development. This is particularly relevant to the current proposal to frack in the Nama-karoo.

Chapter 2 therefore presents some detail of the methods that are applied to hydraulic fracturing and considers the scale of the infra structure that may be required to facilitate the process. Consideration is given to the potential risks of pollution to regional water resources and the potential impacts on biodiversity due to habitat degradation and fragmentation. Similarly, abiotic aspects of ecosystems are also addressed, recognising that fugitive methane gas emissions from fracking activities may exacerbate atmospheric greenhouse gas concentrations. Recognition is also given to potential soil erosion and sedimentation as well as diminished water quality.

On the basis of the argument that biodiversity constitutes an integral component of healthy and functioning ecosystems (MA 2005, Van Jaarsveld *et al.* 2005) the reasoning is extended to illustrate the potential impacts that fracking may have on ecosystem services and by extension, on current and future human well-being.

2.2. HYDRAULIC FRACTURING.

A combination of improved drilling technology and the ability to pump purpose designed fluids under sufficiently high pressures that have been developed in the USA over the past two decades, has enabled methane gas trapped within low permeability shale formations to be mined. Drilling several wells from a single pad, the ability to direct the drill string horizontally and drill long laterals of up to 2500m in length and then to pump purpose designed fluids into the borehole at well head pressures in excess of 50mPa

(Ritzel 2013, Andrew *et al.* 2009) in order to fracture the host shale and liberate the associated gas, is referred to as high-volume horizontal slickwater fracturing (HVHSF), more commonly known as fracking. Typical hydraulic fracturing operation in the USA, require that well pads are placed at a density of 1 well pad per 2.6km^2 and Vermeulen (2012) provided an indication that well pads in the Nama-karoo will be placed at a density of 1 drill pad per 4-5km^2. The location of each well pad is primarily dictated by the underlying geology and resource reserves and therefore concerns such as environmental, topographic and sociological become secondary. Well pads occupy a surface area in the order of 3.5ha (Kiviat 2013) and are required to accommodate the drilling machines, control centre, waste water ponds, water storage facilities for up to 20 000kl and chemical and sand storage facilities. Often deep cuts and high fills on steep sided inclines are required to accommodate well pads (Kiviat 2013) and similarly, road and pipeline networks may be required to follow tortuous routes over undulating terrain. Suitable roads are required to be constructed to enable the transport of all equipment, water, chemicals and propants. Upon completion of fracking all the waste products including flow back water (returned fracking fluids) and produce water (brine and water pumped to surface during production phase) must be removed to appropriate treatment facilities.

Data derived from an economic feasibility report commissioned by Shell Exploration Company BV (Econometrix 2012), was used to determine the anticipated scale of the fracking operations proposed within the Shell lease area of the Karoo. It is anticipated that 600 to 700 well pads will host approximately 10 500 wells that will be drilled to recover an assumed volume of 50tcf of methane gas.

The volume of water required for each fracking event will be determined by unique geological conditions in each well and figures ranging from between 2 000kl to 38 000kl per fracking event are quoted in the literature (Kiviat 2013; Kargbo *et al.* 2010; Arthur *et al.* 2008). The volume of fluid required is also dependant on the depth of the borehole and the confining stresses within the rockmass that vary considerably in the Karoo (de Witt 2011). Approximately 90% of the fracking fluid consists of water and the balance is made up of 9% fine silica sand or similar material that is used as a propant and 1% includes a selection of chemicals (Andrew *et al*. 2009). The chemicals include acid, friction reducers, biocide, corrosion inhibitors, oxygen scavenger, scale inhibitor and surfacants (Kargbo *et al.* 2010; Walton and Woocay 2013; Arthur *et al*. 2008).

In the USA, more than 750 synthetic chemicals have been used in fracking fluids and include methanol, naphthalene, xylene, acetic acid, ammonia and diesel (Rozell &

Reaven 2011). Following the injection of fracking fluids, the proportion that flows back to surface varies from 9 to 100% and the return fluids include connate water, that contain salts and chemical compounds derived from the host shale and include sodium chloride, bromide, arsenic, barium, other heavy metals, organic compounds and radionuclides (Kiviat 2013). The South African government Regulations for Petroleum Exploration and Production published in June 2015 (DMR 2015) preclude the storage of flow back and produce water in open storage ponds and also forbid the use of deep well injection, a waste management method applied extensively in the USA (Entrekin *et al*. 2011). This therefore implies that in the South African context, all waste water must either be transported away from the site or recycled for re-use on site.

Karbgo *et al*. (2010) was of the opinion that the 2005 exemption of the energy industry to complying with the Safe Drinking Water Act in the USA, that precluded the industry from disclosing the contents of hydraulic fracturing fluids has significantly complicated waste water treatment efforts. Arguing that public waste water treatment plants in the USA are not designed to handle hydraulic fracturing waste water, Rozell and Reaven (2011) and Vidic *et al.* (2013), indicated that elevated levels of salinity and dissolved solids found in Appalachian rivers are associated with the inadequate treatment of fracking wastewater.

2.3 POTENTIAL ENVIRONMENTAL RISKS IN THE NAMA-KAROO.

Applications to explore for shale gas in the Nama-karoo have been submitted by three international energy companies to the Department of Mineral Resources in South Africa, covering an area of 125 000km^2, and with the exception of a limited area in the west, all three areas fall within the biogeographical limits of the Nama-karoo biome.

Following unsuccessful exploration efforts by SOEKOR for hydrocarbons during the 1960’s and 1970’s it was recognised that methane, contained within organic rich shale did exist within the Karoo Supergroup. Only the Whitehill, Collingham and Prince Albert shale formations that form the base of the Ecca Group contain 3 to 12 percent total organic carbon that is comparable with other shale formations that are currently producing gas elsewhere in the world (Steyl *et al*. 2012). These shale formations are buried to a depth of between 5 and 6km and fall within the dry gas window in which methane gas is produced (Steyl *et al.* 2012) and therefore only the shale formations of the lower Ecca Group that are located south of 29°S are the subject of the proposed shale gas exploration efforts.

Rendering the geology of the Karoo basin unique and more complex are the presence of dolerite intrusions of Jurassic age. The majority of dykes vary in width from 3m to 15m and may extend for 500km to 800km in length (Steyl *et al.* 2012). Similarly, horizontal intrusive bodies, concordant with the bedding orientation of the sedimentary rocks also occur extensively in the Karoo basin north of approximately latitude 32°30'S (Svensen *et al.* 2007). The absence of intruded dolerite in the Karoo Basin south of this approximate line of latitude is due to compressional tectonic forces within the rockmass associated with the Cape Fold Mountains. Steyl *et al.* (2012), Van Tonder *et al.* (2014), de Witt (2011) and Vermeulen (2012) all made reference to the presence of groundwater contained within fractured rock formations that are in proximity to dolerite intrusions and expressed the opinions that the dolerite intrusions in the Karoo may be regarded as preferential pathways for the migration of groundwater.

2.3.1 Groundwater impacts.

Potential contamination and pollution of groundwater resources due to the impact of unconventional shale gas mining has been addressed in popular media, academic journals (Howarth *et al.* 2011, Myers 2012, Vengosh *et al*. 2014) and state initiated research initiatives (CCA 2014; DMR 2012) and much of the rhetoric has focused on the potential migration of fracking fluids into groundwater aquifers as a direct result of unconventional gas mining.

It is anticipated that the fracking technology applied in the USA and other areas of the world where fracking currently occurs, will be adopted in South Africa, there remain many geological and environmental differences that potentially set the Nama-karoo apart. Tucker and van Tonder (2013) succinctly listed six water related concerns that are particular to the Nama-karoo, (i) the arid climate. (ii) effects on available water resources. (iii) potentially severe impact water pollution may have on ecosystems in an arid area. (iv) the potential for migration of pollutants due to dykes, sills and natural fractures. (v) potential upward movement due to deep fault systems in the south western portion of the Nama-karoo. (vi) upward migration of fracking fluids due to the artesian structure of the Karoo basin.

Considering the concerns expressed by Tucker and van Tonder (2013), well documented case studies and research emanating from the USA have been perused to determine the potential pollutant flow paths and risks associated with fracking.

Myers (2012) reasoned that potential pathways along which frack fluid may migrate include adventive transport through sedimentary rock, fractures and faults as well as abandoned wells and open boreholes. Poor well construction and faulty cement seals around the casing annulus accounted for 3.4% of the 6466 notices of violation issued by the Pennsylvania Department of Environmental Protection (DEP) during the period 2008 to March 2013 (Vidic *et al*. 2013). Groundwater flow models tend to simplify and homogenise complex multi variable geological characteristics and are therefore fraught with conjecture. Myers (2012) concluded that adventive transport within sedimentary rocks would require tens of thousands of years to move contaminant from an assumed depth of 1500m. In the presence of the high pressure regime required to fracture shale, Myers (2012) argued that the pressure gradient is sufficient to induce upward migration. In the event of fracking out of formation (fractures developing beyond the target formation) and in the presence of faults and fractures the travel time of contaminants to the surface may be reduced to tens or hundreds of years.

Working specifically in Germany, Kissinger *et al.* (2013) developed a qualitative evaluation of certain scenarios to determine the potential hazards posed by migrating fluids as a result of hydraulic fracturing. Hydraulic flow models were developed to examining three scenario that cover potential fluid migration. Scenario 1 explored the short term migration of fracture fluids and brine into the overburden under the influence of an induce pressure gradient. The results indicate that a maximum vertical migration of 50m is anticipated. The second scenario explored the long term horizontal and vertical movement of fracking fluid and brine in the presence of a fully penetrating and permeable vertical fault zone. Indications are that fluids will reach surface, albeit, at concentrations reduced by a factor of 4000. No temporal scale was provided for the vertical flow and a lateral flow rate in the range of tens of meters per year was offered. The final scenario studied the amount of methane that may migrate to shallow groundwater aquifers, using the assumption of an induced pressure gradient and the presence of a fully penetrating fault zone. It was recorded that between 20% and 60% by mass of methane will reach shallow layers and surface under both assumed conditions.

Whilst much of the fracking debate in public forums continues to revolve around the potential contamination of groundwater due to hydraulic fracturing, the energy industry's position is that no evidence of contamination of ground water due to fracking operations has been determined. This assertion is refuted by the empirical evidence published by Warner *et al.* (2012) in which the presence of cross-formational flow paths that enable deep hypersaline brine to migrate into shallow fresh water aquifers in western Texas.

Similarly the presence of elevated salinity in groundwater detected in Pennsylvania suggest the existence of cross formational pathways within the Marcellus shale formations and deeper geological formations. Muelenbachs and Olmstead (2014) and Vengosh et al. (2014) pointed out that the migration of heavier and less mobile contaminants such as frack fluids and brine are more likely to be detected, given appropriate temporal scales. The low molecular weight and viscosity of methane ensures that the gas is more likely to be detected in shallow groundwater sooner than heavier elements and molecules that are included in frack fluids and brine. Jackson *et al.* (2013) and Vengosh *et al*. (2014) suggested that the presence of elevated methane concentrations in groundwater is likely to occur through leaking well casings and along the cemented annulus in gas wells. The origin of the fugitive methane may be from the targeted shale horizon and in many instances is considered to be derived from non-targeted intermediate horizons (CCA 2014). Rozell and Reaven (2011) stated that given appropriate time scales following drilling, fracking and production of a well, the initial indications of casing and cement failure would be provided by the presence of elevated methane concentrations in the areas surrounding the wells Considering the dearth of scientific understanding of fluid flow through geological formations, Rozell and Reavon (2011) are of the opinion that it is likely that fracking fluids and brine will affect shallow groundwater sources with time.

Many publication, (Vengosh *et al*. 2014; Rozell and Reaven 2011; Muelenbachs & Olmstead 2014; Andrew *et al*. 2009; Warner *et al*. 2012; Jackson *et al.* 2013) provide evidence that indicate the presence of elevated thermogenic methane in groundwater sources. With a saturation level of 28mg/l of methane in shallow groundwater aquifers, the US Department of the Interior has recommended that water containing in excess of 10mg/l must be monitored and that immediate action must be taken when methane concentration reached 28mg/l. The oxidisation of methane by bacteria can lead to oxygen depletion, than may result in increased solubility of such elements as arsenic and iron (Vidic *et al.* 2013). Furthermore, Vidic *et al.* (2013) also reported that anaerobic bacteria that exist in the deoxygenated environments may reduce sulphate to sulphide, with associated environmental issues, similar to acid mine drainage.

2.3.2. Surface water impacts.

The process of unconventional shale exploitation requires large volumes of water, both during the drilling process and during hydraulic fracturing of the shale. Quantities of water requires depend on the underlying geological conditions, but quantities ranging from 2000kl (Arthur *et al.* 2008) to 38 000kl per fracking event (Kiviat 2013; Kargbo *et al.* 2010) have been reported. Following individual hydraulic fracturing event in each well between 9% and 100% of the injected fluid return to the surface as flow back, the balance of the fluids remains within the fractures and pores of the rock formation, and are probably release over time (Rozell & Reaven 2011). The flow back period of injected water may last for up to 30 days, with the greatest flow volumes occurring during the initial 7 to 10 days following fracking. Due to the inclusion of a host of chemicals and other agents, flow back water is considered to be a hazardous waste and in the USA must be confined in lined waste ponds, either to be transported to suitable waste treatment facilities, or deep well injection disposal facilities or treated and reused on site (Vengosh *et al.* 2014; Rozell & Reaven 2011; Kiviat 2013).

Similarly, during the gas production phase, produce water is generated, which is water that occurs together with the gas and is contained within the voids in the shale. Together with the liberation of the gas by fracking, connate water or brine also flows to the surface. Brine may be hypersaline with total dissolved salts contents of approximately 25 000mg/l (similar to seawater) to as much as 180 000mg/l (Vengosh *et al.* 2014). The concentration of toxic elements such as barium, strontium and radioactive radium is positively correlated with the salinity. Samples of produce water derived from the Marcellus shale in the USA that were tested for radium 226 indicated the levels that were as high as 267 times the safe disposal limits set by New York Department of Environmental Conservation (Kargbo *et al.* 2010). The elevated levels of naturally occurring radionuclides (NORM) that are recorded in the Marcellus shale in the USA are also likely to be encountered in the Nama-karoo where uranium is present within the sandstone formations of the Adelaide subgroup that occurs above the target shale formations (Cole 1998). The mobilisation of radium from uranium rich source rocks into liquid phase under high salinity and reducing conditions will potentially elevate the level of NORM present in produce water generated during gas extraction in the Karoo.

The South Africa regulations for petroleum exploration and production (DMR 2015) clause 118 (3) and (4) state that the storage of flow back and produce water in waste ponds will not be permitted and all untreated fluids must be removed from site within 60 days after completion of hydraulic fracturing. Furthermore clause 124 (3) requires that liquid waste must be disposed of at an approved waste treatment facility, while clause 124 (5) explicitly forbids the disposal of waste water in deep injection wells. These regulations for the management and disposal of waste appear to consider both human health concerns and environmental pollution, however, the appropriate treatment of waste water have not been addressed.

Rozell and Reaven (2011) identified three means by which surface water resources may potentially be contaminated by waste water generated from shale gas extraction processes. These include accidental spillage during transportation, leaks and spillage at drill sites and inadequate treatment at waste water treatment plants. By assessing transportation risks including accident frequencies and inadvertent spillage Rozell and Reaven (2011) expressed the opinion that the risks of spillage due to transportation failure is low with a worst case scenario 50th percentile contamination volume of 0.3m^3 per well in a typical Marcellus shale gas well. Considering the alternative potential surface water contamination pathways, drill site spillages was deemed to contribute 3m^3 per well and ineffective waste treatment potentially contributed 13 500m^3 contamination to surface water resources per typical Marcellus shale gas well. Entrekin *et al.* (2011) drew similar conclusions and stated that ineffective or inappropriate waste water treatment constitutes the highest risk to environmental pollution. These findings are borne out by Vengosh *et al*. (2014) who identified elevated levels of salinity of up to 120 000mg/l, strontium, barium and radioactive elements as well as organic compounds such as benzene and toluene in the discharge from public water treatment plants in Pennsylvania. Bromide was enriched by up to 12 000 fold at the discharge point and 2km downstream of the discharge position, after dilution, levels were 16 times greater than background levels. Entrekin *et al.* (2011) clearly stated that domestic waste water treatment plants in Pennsylvania are not capable of treating high total dissolved solids, neither are they designed to remove organic compounds such as benzene, toluene, ethylbenzine and xylene (BTEX) and NORM, indicating that water treatment options are limited. With accumulations of radium detected on stream sediments downstream of treatment plants, Vengosh *et al.* (2014) were of the opinion that the cumulative impact of discharging large volumes of water into natural water courses will cause a build-up of radium, thus causing substantial environmental harm.

At the current preliminary phase of shale gas exploration in South Africa, the proposed source of water for fracking have not been disclosed. Three potential sources of water have been considered, and these include the use of local groundwater, transporting of water from the Orange River and the possible use of sea water. Vengosh *et al.* (2014) warned against the use of groundwater resources in arid areas stating that local water shortages may occur. Water withdrawals for fracking from small streams in the Appalachian Basin and in areas of southern Alberta in Canada (CCA 2014) were shown to exceed the natural flows. Similar observations were recorded by Nicot and Scanlon (2012) in Texas USA, where variable precipitation (mean annual varies from 740mm/year in the south to 1320mm/year in the northeast), wet and drought periods as well as conflicting land use, primarily agriculture, apply stresses to depleting groundwater resources. The Nama-karoo is a water stressed environment where annual precipitation ranges from 70mm in the west to 500mm in the northeast and there are no perennial surface water recourses in the area, a situation more dire than that described by Nicot and Scanlon (2012) in Texas, where competing interests for water in the Eagle Ford gas play has reduced groundwater levels by up to 60m, resulting in the disappearance of springs, and rivers becoming influent as opposed to effluent.

An assessment completed on the Gouritz River in the Klein Karoo by Le Maitre *et al.* (2009) and Smith-Adoa *et al.* (2011) recognised that the catchment area of the river included a substantial portion of the Nama Karoo. The sub-catchments of the Gouritz river include the Touws, Buffels, Dwyka and Gamka rivers, all of which rise in the Nama Karoo and experience low volumes of runoff with high coefficients of variability (CV). Furthermore the quality of the water in rivers draining the Nama-karoo are considered to have high suspension loads and elevated salt content, due partially to run off from existing agricultural activities but also due to naturally saline groundwater (Le Maitre *et al.* 2009). The Touws River is considered to have a high groundwater-surface water interaction and a portion of the base flow is fed by groundwater. Groundwater contribution to the Buffels, Dwyka and Gamka rivers is minimal and are therefore considered to be more susceptible to surface activities such as agriculture and potentially from fracking (Smith-Adoa *et al.* 2011). Rivers in semi-arid and arid areas such as the catchment area of the Gouritz River are heavily utilised and water demand in the year 2000 exceeded the available supply by 10%. Le Maitre *et al*. (2009) warned that water resources in the Klein Karoo are unsustainable with an imbalance between growing population demands and ecological requirements. The projected increase in demand of between 23% and 150% is anticipated by 2025. These projections were made prior to 2009 when applications for shale gas exploration permits were initially mooted, and therefore have not taken into account the additional burden that fracking activities may place on the already constrained water supply. Smit-Adao *et al.* (2011) warned of the ecological consequences of maintaining consistent groundwater recharge into river systems in arid areas to sustain base flow during low rainfall periods, particularly the maintenance of river pools, wetlands and riparian vegetation. Smit-Adao *et al.* (2011) also determined that 50% of the rivers systems in the Gouritz catchment area can be described as being degraded with minimal options available for the conservation of natural systems.

In a proposed keynote address to a CSIR conference that Turton (2008) was forbidden to present, he presents a bleak picture of South Africa’s water and sanitation requirements. Arguing that South African rivers have lost their dilution capacity, leading to reduced water quality, increased eutrophication, increased impact due to acid mine drainage and increased concentrations of endocrine disrupting chemicals. There is no reason to exclude rivers and water resources in the Nama-karoo from this general description. The implications are therefore are that waste treatment facilities must treat waste water to increasingly elevated standards before being discharged into river systems to prevent cumulative pollution downstream, a scenario investigated by Rahm and Riha (2012) in the Susquehanna River Bain in New York. Increased effluent loading from water treatment works dealing with shale gas waste water as well as competing demands for water was shown to have significant cumulative impacts on the ecological functioning of the river system downstream.

It is therefore apparent that growing demands for water that have been driven by growing populations and increased economic growth have placed increasing burdens on existing surface and groundwater resources. This, in the opinion of Smit-Adao *et al.* (2011) is evidence that fresh water ecosystems are among the most endangered ecosystems worldwide. The Millennium Assessment (2005) similarly indicated that the continued degradation of freshwater ecosystems leads to loss of biodiversity and the unavoidable loss of ecosystem services.

2.3.3. Habitat loss and fragmentation.

The industrialisation of the Nama-karoo will require construction of infra-structure to support the extraction of shale gas. The ability to drill multiple wells from a single drilling platform is an advantage of fracking over conventional gas extraction. Despite the reduced density of wells on the surface, fracking is spatially extensive and it has been estimated by Vermeulen (2012) that in the Nama-karoo well pads will be placed at a density of approximately 1 well pad per 4 - 5km^2, and in the USA each well pad occupies approximately 1.5 to 3.0ha of land (Entrekin *et al.* 2011). Considering the limited infra-structure development available in the Nama-karoo it is evident that connecting roads and pipeline will be required to be constructed across the landscape. Kiviat (2013) provided an indication that approximately 6800 truck trips are required to frack a single well and with up to 32 wells being located on a single platform, roads will have to be constructed to a standard that can support the anticipated traffic volumes. The South African Committee of State Road Authorities (CSRA 1990) design specifications for gravel roads carrying more than 200 vehicles per day require a minimum width of 9m. A conservative assumption that in the order of 900 well pads may be developed within the three lease areas of the Nama-karoo that will require approximately 4500km of roads to be constructed. These assumptions have not included pipeline servitudes. With the removal of vegetation, organic and mineral enriched topsoil and the compaction of soils, the development of the fracking related infra-structure will degrade an estimated 6000 to 7000ha of existing habitat in the Nama-karoo.

Among the several factors that impact upon global biodiversity, Sala *et al*. (2000) identified land use changes as the greatest single contributor to the loss of species in desert environments. Similarly Fischer and Lindenmayer (2007) lamented the impacts of habitat degradation and fragmentation, observing that with increasing human intrusion into landscapes, loss of biodiversity has been recorded due to perforation, dissection, sub-division and erosion of indigenous vegetation. Similar observations were recorded by Penas *et al.* (2011), working in arid zones in south eastern Spain.

Habitat degradation and habitat fragmentation, in the opinion of Fahrig (2003) have different effects on biodiversity, stating that fragmentation has a weaker effect on biodiversity, than habitat degradation. It is therefore appropriate to consider a definition presented by Hobbs *et al.* (2008) in which habitat fragmentation is described as being the dissection of the earth's surface into spatially isolated parts that rearranges the structure of ecosystems and shapes their function worldwide. In a similar vein, Fischer and Lindenmayer (2007) described habitat degradation as the gradual deterioration of habitat quality, in which species may decline, occur at lower density and may not breed. In terms of the definitions provided the effects of industrialisation of the Nama-karoo will cause both fragmentation and degradation of the existing habitats with concomitant risks to the prevailing diversity of species in the biome.

Processes that induce habitat fragmentation and degradation typically occur simultaneously and the effects of both were studied by Fahrig (1997), using simulation models. Despite the evident negative effects on biodiversity as a result of habitat fragmentation, Fahrig (1997) concluded that habitat degradation constitutes a greater threat. Arguing that the effects of fragmentation on species breeding habitats are mitigated by the provision of movement corridors, Fahrig (1997), indicated that a minimum of 20% of the intact landscape is sufficient to ensure species survival. Fahrig (1997), did however, recognise that the effects on habitat specialist, sedentary and sessile species is significant. Fischer and Lindenmayer (2007), however, suggested that a minimum 30% threshold of intact landscape is required to prevent increased loss of species.

Fischer and Lindenmayer (2007) identified that habitat alteration may limit species access to resources and dispersal, thus resulting in negative impacts on metapopulations. These factors affect the biology, breeding behaviour and interaction of species with consequences to inter and intra specific competition, predation, parasitism and mutualism. With increasing fragmentation smaller patches of suitable habitat, isolated by larger areas of unsuitable matrix areas are created and Fahrig (2003) suggested that populations of species trapped within isolated and reducing patches of the landscape diminish in size and become susceptible to stochastic events. Fischer and Lindenmayer (2007) described both exogenous events such as climate change, weather phenomena and fire, as well as endogenous threats such as reproductive success and genetic drift that provide a definite threat to small and isolated populations.

Edge effects along the boundaries of fragmented habitat change the physical and biological conditions of ecosystems boundaries and effect the reproductive and breeding success of species (Fischer and Lindenmayer (2007). Abiotic effects include changing moisture conditions, temperature fluctuations, radiation exposure and varying soil nutrient content, while biotic edge effects include species composition and competition. Fahrig (2003) suggested that with increasing fragmentation more edges are created for a given amount of habitat, increasing the probability of species leaving the habitat or sedentary species being confined to unsuitable habitat. Increasing exposure to the matrix areas reduces fecundity and increases mortality, with associated reduction in population viability.

Arguing that the number of individual species that a landscape can support is in function of the spatial extent of appropriate habitat, Fahrig (2003), indicated that the relationship is, however, not linear. A minimum suitable habitat level is achieved beyond which populations are unsustainable and an extinction threshold is reached. Changes in spatial distribution and deterioration of vegetation structure can cause fundamental alterations to ecosystem functioning and the loss of individual keystone species may induce an extinction cascade (Fischer and Lindenmayer 2007).

2.3.4. Impacts of roads.

The construction of road and pipeline networks, linking well pads together will be required to facilitate fracking in the Nama-karoo. Absence of a suitable road network within the area in which shale gas exploration and production is proposed, and with the predicted traffic volumes, roads will have to be designed and constructed to appropriate national standards. The lower order roads that are likely to be constructed are anticipated to be narrow; in the order of 9m wide, unsurfaced, gravel roads that will be remote and traversed primarily by fracking related traffic. As such the anticipated ecological effects of the roads will be (a) habitat loss by road construction, (b) altered water routing and downstream peak flows, (c) soil erosion and sedimentation of streams and rivers, (d) altered species patterns and (e) human access and disturbance in remote areas (Forman and Alexander 1998).

2.3.4.1. *Barriers.*

Pastoral agricultural practices dominate the current economic activities in the Nama-karoo and rotational feeding in grazing camps is the principal farming practice adopted (Tainton 1999). The spatial extent of camps depend on the management policies applied and are subject to the number of animals maintained, the vegetation and terrain conditions, number and types of ecotopes and the availability of water. Fencing is used extensively to manage the movement of domestic stock as well as retaining tenure over land and animals. Road construction for the purposes of fracking will therefore have to take cognisance of current land management practices applied in the Nama-karoo, and it is therefore a reasonable assumption that fences will have to be constructed or either side of all roads and pipeline servitudes, thus creating barriers to movement of larger wildlife.

Linear infra-structure systems such as roads, pipelines and railway lines have the effect of fragmenting habitat by creating distinct boundaries between contrasting habitats and form barriers to movement by sedentary and specialist species. Andrews (1990) noted that gradational changes that occur in ecotones do not exist adjacent to roads, which create sharply contrasting habitats. The sharply defined ecological edges created by roads are considered by (Huiser and Clevenger 2006) to be key components of the ecological trap hypothesis in which fauna choose edge habitats but are exposed to higher rates of mortality. Andrews (1990) also expressed the opinion that edge effect of roads are a function of the length of the road and not the width. Forman and Alexander (1998) however, were of the opinion that road width and traffic volumes are the most significant factors affecting biodiversity adjacent to roads, while road surfacing constitutes a minor factor.

Roads also have the effect of impeding the movement of small mammals, reptiles, amphibians and arthropods and disrupting the social organisation of species and effect population dynamics in a manner similar to habitat fragmentation, described previously by Forman and Alexander (1998). Andrews (1990) provided evidence that barriers need not be impermeable structures and small mammals are less likely to crossing clearings that are in excess of 30m wide. A study by Swihart and Slade (1984) in Kansas USA, provided evidence that roads of less than 3m in width inhibited the movement of prairie voles *Microtus ochrogaster* and cotton rats *Sigmodon hispidus.*

The use of roads and adjacent reserves as movement corridors have been studied and Adams and Geis (1983) indicated that species that are less habitat specific are more likely to use these areas. Forman and Alexander (1998) reported that in general, roads, road reserves and areas immediately adjacent to roads are rarely used as movement corridors. Exceptions were recorded where foraging animals intersect roads and may move along roads for a short distance, as well as carrion feeders and predators at night (Coffin 2007). The barrier effects of roads and limited movement adjacent to or along roads therefore tend to divide large continuous populations into smaller sub-populations, creating metapopulations that are more susceptible to stochastic events and declining population dynamics (Forman and Alexander (1998).

The land immediately adjacent to roads potentially create high quality habitat with more abundant and better quality forage. Access to run-off water from road surfaces and nitrogen from vehicle exhausts and access to light provide resources for vegetation growth (Huiser and Clevenger 2006). Herbivores foraging within the fenced boundaries of road reserves are susceptible to collision with vehicles. Similarly, predators preying on small mammals found within these habitats, fall victim to vehicle collisions. Huiser and Clevenger (2006) describe roads and adjacent road reserves as a population sink in which breeder mortality may exceed production of offspring.

2.3.4.2. *Road mortality*.

Animal related road accidents were studied by Eloff and van Niekerk (2005) in the Eastern Cape along a 226km length of road between Uitenhage and Graaff-Reinet. The most common herbivore victims documented were kudu *Tragelaphus strepsiceros*, steenbok *Raphicerus campestris* and common duiker *Sylvicapra grimmia* that are attracted to palatable forage growing within the road reserve. The study concluded that the presence of game–proof fencing on both sides of the road significantly reduced the probability of collisions.

In a study of avian mortality conducted by Dean and Milton (2003) it was concluded that Southern Pale Chanting Goshawk *Melierax canorus*, Yellow-billed Kite *Milvus migrans parasitucus* and Jackal Buzzard *Buteo rufofuscus* were the most frequent victims of road kills in the Nama-karoo. A similar survey was conducted by Visagie and Anderson (2006) in the eastern Karoo in which it was determined that the number of dead Lesser Kestrels *Falco naumanni* observed constituted 3.1% of the total population of birds recorded. A total of 0.4 dead Lesser Kestrel's were recorded per kilometre of road travelled, while 12.5 live birds were observed per kilometre travelled.

Although the survey completed by Bullock *et al.* (2011) was conducted in the southern Kalahari in the Northern Cape; an area that straddles the boundaries between the Nama-karoo biome and the adjacent Savanna biome, factors that cause mammal and bird road mortalities are common to both bioregions. Roads bisecting habitats, territories and home ranges and separation from resources such as food, water and shelter, were considered to be among the reasons for the road mortalities observed. Bat eared foxes *Otocyon megalotis* were the most common mammal victims recorded and Bullock *et al.* (2011) reported mortality rates of 5.4 mammals per 100 kilometres which is considerably higher than 1.38 mammal deaths per 100 kilometres recorded by Dean and Milton (2003). Spotted Eagle owl *Bubo africanus* and Southern Pale Chanting Goshawk *Melierax canorus* were the most common avian victims recorded by Bullock *et al*. (2011).

2.3.4.3. *Invasive species*.

Habitat disturbance associated with road construction is considered to facilitate the invasion of non-native plant species (Huiser and Clevenger 2006). The creation of suitable linear habitat stimulates the spread of generalist species that are able to exploit variable ecological conditions that exist along roadsides. Coffin (2007) offered the opinion that many exotic plants fit into the category of generalist and roadside environments facilitate the spread of these plants into the adjacent landscapes. Propagules and seeds of exotic plants are spread by air turbulence caused by passing traffic, and Huiser and Clevenger (2006) described the increased recruitment of *Acaia* species due to anthropogenic disturbance from roadworks in Australia. Black wattle *Acacia mearnsii*, is a declared invasive alien plant originating from Australian that is common in the Nama-karoo, and is prevalent in disturbed areas along river course, in wetlands and along roads (Esler *et al.* 2010). Further ecological disturbance caused by construction activities will further exacerbate the spread of *A. mearnsii* and other non-native plant species such as *Populus* sp, *Prosopis* sp and *Arundo donax*.

2.3.4.4. *Soil erosion*.

Construction of roads, pipelines and drilling pads will alter abiotic aspects of the ecosystem in the Nama-karoo. Any disturbance of the land increases the likelihood of soil erosion with subsequent increased sedimentation of rivers and wetlands (Burton *et al*. 2014). Activities such as clearing, grading and excavation will be necessary to create the infra-structure required. Sediment yield from roads are a function of the road geometry, slope lengths, width and surfacing, as well as the topography which determines the extent of cut and fill slopes. Increased storm-water runoff from exposed surfaces will increase the hydrological flow and sediment transport into natural drainage facilities. Run-off from impervious surfaces and concentration of storm-water flow and escalation the energy of stream systems will lead to channel erosion and scouring that alter sedimentation and deposition processes (Coffin 2007).

Accelerated erosion of organic enriched topsoil and underlying regolith is greatest in semi-arid environments where the vegetation cover is not complete and rainfall is sufficient to cause sediment loss. Continuing decline of basal cover of large parts of the Nama-karoo due to increased age structure of plants following recurring drought events has escalated the rate of sediment loss (Snyman 1999). Due to continuing degradation and poor veld condition over large areas of the Nama-karoo, Roux and Opperman (1986) predicted that run-off rates and sedimentation will progressively increase. Placing inappropriately designed and maintained infra-structure in areas that are already subjected to degradation will exacerbated the impacts of erosion and sedimentation

Non-perennial streams that exist in semi-arid environments such as the Nama-karoo are subjected to sudden flood events following short intense rain storms. During high flow occasions accumulated sediments are flushed from streams and deposited into larger water bodies such as seasonal pools and wetlands (Forman and Alexander 1998). Fine sediment increases the turbidity of the water and disrupts stream ecosystems by impeding the growth of aquatic fauna and flora. Low flow events are characterised by deposition of fine sediment onto gravel beds and pools which further limit the functioning of aquatic ecosytems by raising water temperature and reduced light penetration and reducing photosynthesis (Coffin 2007).

2.3.4.5. *Chemical pollution*.

Gillen and Kiviat (2012) describe the impacts on wildlife as a result of chemical spills adjacent to roads in the USA. Increased salinization and elevated concentrations of heavy metals in polluted streams and other water bodies were recorded in Pennsylvania, affecting salt sensitive organisms and fish. A wide array of chemicals that are associated with roads are introduced into the environment, and are usually distributed via stormwater run-off (Coffin 2007). Emissions including carbon monoxide (CO), nitrogen oxides (NO_x) volatile organic compounds, sulphur dioxide (SO_2), lead (Pb), methane (CH_4) as well as benzene, butadiene and formaldehyde were reported by Coffin (2007).

Pollutants alter soil chemistry and may alter the soil pH and be absorbed by plants and enter into stream systems. Changes to plant species composition as a result of exhaust emissions that act as fertilizers was studied in Hampshire, UK by Angold (1997). The observed trends in altered plant composition was correlated with distance from each side of the road, and edge effects of up to 200m were recorded with a strong relationship between traffic volumes. Roads with low traffic volumes of less than 800 axle pairs per 12 hour cycle were determined to have pollutant induced effects on the vegetation that extended for 20 to 30m on either side of the road (Angold 1997).

Dust covering leaves and surfaces of plants located in the immediate vicinity of gravel roads may affect photosynthesis, respiration and transpiration (Farmer 1993) thereby reducing productivity. The enhanced ability for plants to adsorb volatile compounds through dust covered surfaces was described by Coffin (2007), suggesting that phytotoxic pollutants enter plant tissue. Subsequent ingestion of the plant material by animals and humans may lead to respiratory ailments. Forman and Alexander (1998) suggested that the lateral extent of areas affected by fugitive dust emission to be less than 10 to 20m, but may extend to as much as 200m downwind.

Gillies *et al.* (2005) used a range of vehicle sizes to study the factors contributing to airborne PM_{10} dust particle emissions in a semi-arid environment in Texas, USA. Passing traffic has a pulverizing effect of gravel road surfaces and together with the shearing forces of the wheels and air turbulence, soil particles are ejected from the road.

Dust emission rates were shown by Gillies *et al.* (2005) to depend on the clay and silt content of the road surface, the moisture content, vehicle weight and the speed at which vehicles travel. The spatial extent of the distribution of PM_{10} dust particles over the adjacent landscape was determined to be related to the height of the dust plume and the prevailing atmospheric conditions. Under stable atmospheric conditions the extent of the vertical mixing is limited by particle buoyancy, enabling dust particles to remain closer to the ground for a longer time. The removal rate of dust plumes within 1000m of the road were approximately within 2 orders of magnitude greater under stable atmospheric conditions when compared to unstable conditions (Gillies *et al.* 2005).

Habitat destruction, habitat fragmentation, barrier effects on populations of species, and the less apparent effects of erosion and distribution of pollutants are negative impacts that roads apply to ecosystems. The spatial extent of the effects of roads vary widely and are subject to many biotic and abiotic variable that have been described (figure 2.1). The intrusion of road networks, pipelines and drilling pads onto the landscape will potentially exacerbating existing environmental problems in the Nama-karoo and will have the effect of introducing additional environmental stressors that will further negatively impact on ecological processes.

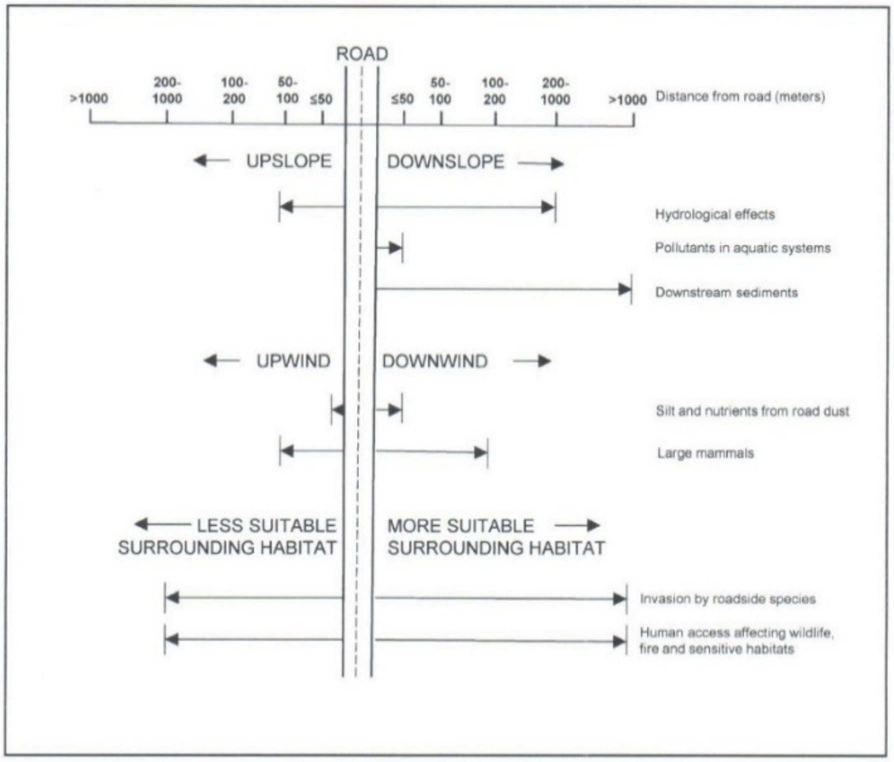

Figure 2.1 Spatial impacts on biotic and abiotic aspects of ecosystems adjacent to roads. Adopted from Forman and Alexander (1998).

2.4. ECOSYSTEM SERVICES.

It may well be argued that all economic activity can only occur due to the provision of ecosystem services. Without nutrient cycling, air quality regulation, water purification and cycling, soil fertilisation and pollination, amongst other ecosystem services, human life might not be able to exist and by extension, without life there cannot be any economic activity. Although this argument is somewhat futile and bears little relevance to the current social dynamics of human activity, it may bear some relevance whilst considering the potential impacts on ecosystem services in the Nama-karoo due to shale gas exploitation.

The benefits of conserving ecosystem services for the well-being of humanity; a definition proposed by the Millennium Ecosystem Assessment (MA 2005), must off set the disadvantages, failing which alternative use will be sought for the land and natural ecological systems that occur on that land. This therefore implies that values must be applied to tangible and intangible resources in order to enable society to determine whether they are indeed an asset or liability. Attempting to place a monetary value to complex natural processes has the advantage of assisting unqualified decision makers, to reach rational conclusions regarding the social, environmental and economic development.

In the often morally stunted environment of world economics and politics it is an unfortunate reality that a value must be applied to ecological systems. Pearce and Turner (1990) for example determined that the total economic value of a wildlife resource is the sum of the use value and the non-use value. Use value is the sum of direct use value, indirect use value and quasi option value, while the non-use value is the existence value. The concept of existence value is intangible and is defined as the value not arising from use (Attfield 1998). Attfield (1998) also argues in his paper that existence value and intrinsic value, which is usually defined as value that depends solely on the nature of the thing in question, or if it is good "in and of itself" are separate value items. A further intangible non-use value that must be considered is instrumental value, which is dependent on the relation of the thing in question to the good of something else (Attfield 1998). Instrumental value can have both use value and non-use value, such as a wetland, in which the use value might be manifested in the direct use of water or fertile ground. The non-use value of the same environment might be reflected in the breeding ground of several species. The ambiguity of instrumental value may also be reflected in wildlife, where the presence of a particular animal may have non-use value in its ability to attract photographic safaris, while hunting safaris would derive direct use value from that same animal.

The consideration of ethical attitudes may further complicate the evaluation of the value of ecosystems. Many of the value items that must be considered by evaluators are subjective and cannot easily be placed into objective pigeon holes. Economists consider that the amorphous mass, known as “the market”, when suitably regulated will provide sufficient social values with which to determine the value of ecosystem. A contrary argument is presented by Jenkins (1998) in which it is stated that the regulation of the markets attempt to perfect and humanise nature. The technical manipulation of economic value of ecological resources also has a moral aspect in which human society is morally preferable and as Jenkins (1998) succinctly stated that “*cultivated gardens are preferable to purposeless and imperfect nature”*. Similar powerfully worded arguments have been presented by other authors, Becker (2006), made a strong philosophical argument that human beings are moving beyond the narrow and self-serving economically dominated society inhabited by *Homo economicus* and will evolve into a society in which a relationship is developed between man and nature. *Homo ecologicus* is defined by three characteristics; (i) its relation with nature is based on sympathy and respect, (ii) it orientates its creativity upon nature and (iii) its relationship with nature is especially based on personal experiences and encounters (Becker 2006). Similar values are espoused by Thomas Berry (1999) in his seminal book, The Great Work, in which repeated references are made to man’s relationship with the community of life on planet earth. McCauley (2006) presented a paper that followed a similar argument in which he argued that stronger and more lasting impacts will be made on people by instilling a love for the environment as opposed to commodifying and selling out on nature.

Identifying appropriate solutions to the evaluation of ecosystems cannot be left to the almost polarised disciplines of ecology and economics, which currently appear to dominate the debate. Bina and Vaz (2011) describe the conflicting material and utilitarian values of economically motivated society as being driven by self-interest. The perception of man not being dependent on nature and the ability to create substitutes to natural processes motivates market driven forces that dictate price and value. There is therefore a desperate need for sociological contribution to the debate in which society is displayed in all of its complexities that include, cultural, economic, religious and ethical differences. Despite the philosophical and ethical arguments that question the morality of placing a value to ecosystem services, there can be no doubt that within a world of burgeoning human numbers and the need for socio-economic development, that appropriate systems of gauging the benefits humans derive from ecosystem services is required. Particularly within the realm of under developed and developing nations, the needs for suitable development must be evaluated against the potential impacts on ecological systems.

In a synthesis of published research compiled on ecosystem services in South Africa, Le Maitre *et al.* (2007b) gathered a limited contribution of 18 papers on the subject. The majority of the papers dealt with water related services and policy formulation, while the next most commonly studied aspect of ecosystem services related to provisioning services. The MA (2005) listed four primary categories of ecosystem services that contribute to human well-being, and these include (i) provisioning services such as food, fibre and fresh water, (ii) regulating services that include climate regulation, water regulation, erosion and pest regulation amongst others, (iii) cultural services includes, but are not confined to, social relations, knowledge systems, spiritual values and recreation, and the fourth group (iv) supporting services that include soil formation, primary production, nutrient and water cycling. Le Maitre *et al.* (2007a) also indicated that the majority of the papers perused did not provide estimates of economic value and in the cases where some attempts were made to apply an economic value to the consequences of change to ecosystem services, no standardised method of evaluation was applied and results could therefore not be compared; an observation that concurred with O'Farrell *et al.* (2011). Under these circumstances the usefulness of providing incomparable data, recommendations and conclusions that are specific to a single ecosystem service in a limited context must be questioned, and in the words of Le Maitre *et al.* (2007b), *"Ecosystem service research will not contribute effectively to sustainable development if it continues to be just a subject for ecological research."* However flawed the process, efforts must continue to use multi-disciplinary research processes to better evaluate ecosystem services and the continued reliance on placing a monetary value may be replaced by a universally accepted index value system.

In order to prevent so called "double accounting" that may over estimate the value of ecosystem services, only the end product or output are valued (Atkinson *et al.* 2012). The inclusion of the value of biodiversity, which is considered by some (Turner *et al.* 2007) to be a driver of ecosystems and not the end result, have therefore been excluded from ecosystem service valuation methods that only consider the end result. Atkinson *et al.* (2012) draw attention to the exclusion of biodiversity from eco-accounting system with the emphasis being placed on the end product of ecosystem services, therefore ignoring, or at best, devaluing the existence of biodiversity. The term "ecosystems" was coined by Tansley (1935) in an attempt to explain the co-existence of organisms with their environment, thus forming a single physical system; the ecosystem. It is therefore apparent that ecosystems by definition include both biotic and abiotic processes. Van Jaarsveld *et al.* (2005) made the observation that all ecosystems, to some degree, require the presence of living organisms and in the collation of the Southern African Millennium Ecosystem Assessment (SAfMA), identified that the inclusion of biodiversity was integral to regulating services. Van Jaarsveld *et al.* (2005) presented an example that greater diversity of food plants grown in more diverse environments are more likely to ensure reliable crop success, particularly during drought conditions or in the presence of pest out breaks.

In the realm of cultural services, biodiversity, in particular mega-fauna, comprise a large and measurable service to the well-being of humans in southern African, where tourism to the many and diverse conservation areas, accounts for a substantial proportion of the region's gross domestic product. The role and significance of biodiversity in ecosystem services was also recognised in the MA (2005) in which biodiversity was considered to be the basis of cultural, supporting and regulating services such as carbon sequestration, soil nutrition and nutrient cycling.

Within the limitations identified in applying standardised evaluation methods to ecosystem services, it remains imperative that consideration must be given to the potential impacts that an industrialised process such as fracking may have on a relatively pristine environment such as the Nama-karoo. The entire process of shale gas exploitation, from the initial exploration phase, development, production and ultimate closure are anthropogenic activities that will apply stresses to prevailing ecosystems. Potential risks to ground and surface water resources in the Nama-karoo and further afield have been considered, and the potential impacts of habitat degradation and fragmentation, as well as the influences of a widely developed road network have been discussed.

Ecosystems may operate on a small spatial scale of centimetre's to meters and on temporal scales of days to decades that are driven by vegetative processes that determine plant growth and soil structure (Risser 1995). Intermediate processes that may operate over areas that extend for hundreds of meters to hundreds of kilometres and on time scales of years to decades are dominated by disturbance events such as fire, insect outbreaks, plant disease and the availability of water. A third and very long and broad scale includes geomorphic and edaphic structure that operate on spatial scales of thousands of kilometres and over time scales that span centuries and millennia. Risser (1995) goes on to argue that ecosystems are variable over time and space and interact on large scales, in which the state of one ecosystem affects others. This inherent complexity therefore leads to conflicting advice being provided to policy makers about ecosystem functioning and the value of associated ecosystem services.

Shell BV. commissioned a study to determine the economic benefits that may be derived from the exploitation of the shale gas within the proposed 95 000km^2 lease area, and a report was presented by Econometrix in January 2012 (Econometrix 2012). Indications of substantial financial profits and benefits, accruing both to the state and to the energy company were determined, however, no account was made of potential impacts on prevailing ecosystem services and the associated costs resulting from the diminishing efficiency or complete loss of such services. Continued growth and development of human welfare must be balanced against the needs and requirements of biodiversity and the maintenance of viable ecosystem services. The challenges of applying direct monetary valuation to ecosystem services have been addressed, but the exclusion of potential environmental costs from an economic study of an industrial activity as intensive and extensive as shale gas mining, does not provide all the facts and information that would enable policy makers to make appropriate and rational decisions.

2.4.1. Provisioning services.

The four categories of ecosystem services that were identified in the Millennium Ecosystem Assessment (MA 2005) are all applicable to the Nama-karoo. The ability of ecosystems to provide arable land, clean water, energy and genetic resources for the benefit of human well-being are termed provisioning services. The value of end products provided by provisioning services are generally determined by the surface area of productive agricultural land or volumes of clean water that are typically easy to quantify and can be expressed in monetary terms. In the Nama-karoo, the direct loss of land currently used for agricultural purposes, the potential loss of water through direct competition with shale mining and the loss of genetic diversity due to habitat transformation and introduction of non-native species all have direct implications for the continued quality of provisioning ecosystem services (figure 2.2). Removal of vegetation and the associated reduction of leaf litter and organic material, including animal waste from the uppers soil horizons will limit the introduction of nitrogen, organic carbon and phosphorus and hence the fertility of the soils that are already considered to be nutrient deficient (Eccard *et a*l. 2000). .

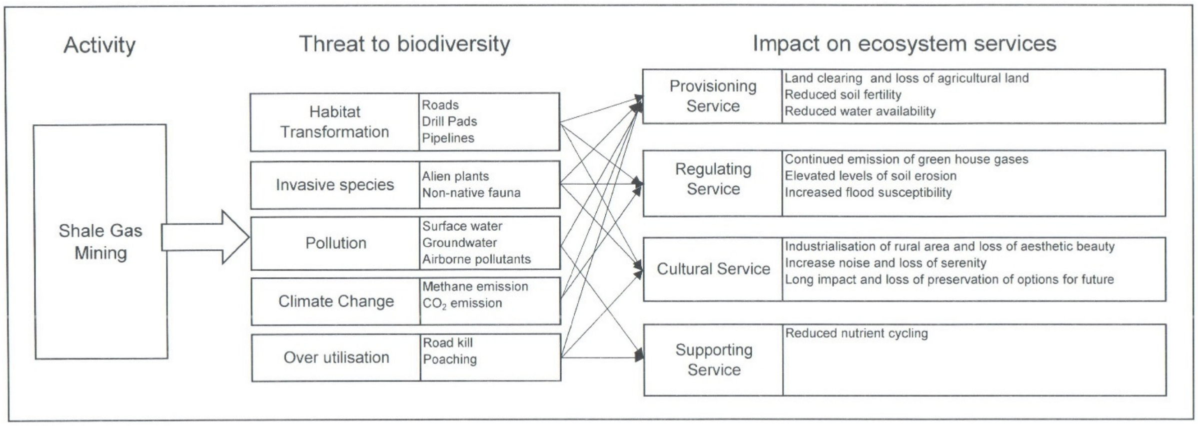

Figure 2.2. Relationships displayed of the impact of shale gas mining, potential threats to biodiversity and impacts to existing ecosystem services in the Nama-karoo. Adapted from MA (2005).

2.4.2. Regulating services.

Regulating services prevalent in the Nama-karoo include, but are not confined to, the stabilisation and regulation of the hydrological cycle, erosion control and air quality. The spatial extent, as well as the temporal scales over which regulating services operate, are such that the ecosystem services described as regulation services are subject to considerable anthropocentric abuse. In a modern display of the tragedy of the commons, (Hardin 1968), upstream exploitation of regulating services such as the discharge of pollutants into a natural water system that may provide financial benefit to a few, could result in deprivation or direct financial implications to many downstream users.

As has been shown, shale gas mining in the Nama-karoo will introduce a widely distributed industrial process to the region in which extensive linear infra-structure will be required and large volumes of water may potentially be made unavailable to alternative use. The extent of roads, pipelines and drilling pads that will be developed will require approximately 6000 to 7000ha of land to be cleared of vegetation, which will exacerbate the rate of removal of topsoil from the area due to increased stormwater run-off. Concentrated run-off of water from un-vegetated and unprotected surfaces will reduce water infiltration into the soil horizon and will reduce groundwater recharge, thereby increasing the severity of periodic flood event. Head ward extension of erosion gullies and rills due to increased flow velocity will cause loss of viable land and deterioration of water quality (Tainton 1999) which can be translated as a reduced quality of a viable ecosystem service.

Rehabilitation and revegetation of land in arid and semi-arid areas is a gradual process requiring time; decades and even centuries (Van Den Berg and Kellner 2005). Initial exploration, production and subsequent closure of gas mining activities are anticipated to span a period of 25 years (Econometix 2012) during which time it is assumed that maintenance will be provided to limit and control soil erosion, however, it is more probable that low level of supervision and maintenance will be applied following closure. The impacts of deposition of sediment will be extensive, expanding beyond the initial foot print area. Similarly the gradual deposition of infertile sediment with low nutrient content as a thin capping layer over large depositional areas following sheet wash will reduce plant recruitment and also reduce the viability of fossorial meso and macro fauna and flora.

The deleterious impacts on a regulating ecosystem service due to the homogenisation of plant species and the impacts of abiotic components of an ecosystem are illustrated by the effects of introduced non-native flora. Recruitment of invasive plants adjacent to the road and pipeline network as a result of the distribution of viable seeds by passing traffic has been described by Huiser and Clevenger, (2006) and Coffin (2007). Seeds of non-native vegetation that propagate along roads and pipelines are transported by storm water drainage facilities that discharge into local river system. Elser *et al.* 2010 describe the prevalence of exotic growth of *Acacia mearnsii* and other non-native plant species such as *Populus* sp, *Prosopis* sp and *Arundo donax* that prevail along degraded Nama-karoo water courses. Loss of river bank soil stability provided by indigenous woody and herbaceous plant matter, particularly following drought, exacerbating the erosional effects of periodic floods.

Shale gas mining will perpetuate the continued use of hydrocarbons for energy. It is broadly appreciated that methane (NH_4) has lower carbon dioxide (CO_2) emission levels that tradition fossil fuels such as coal and oil. Howard *et al.* (2011) presented a study that argued that when account is taken of the volumes of fugitive gas emissions derived from shale gas mining, the carbon equivalent of methane as a greenhouse gas is greater than traditional fossil fuels in the short term and equivalent in the long term. The conclusions presented by Howard *et al.* (2011) have been disputed by Cathles *et al.* (2012), citing procedural errors and inappropriate assumptions applied to their research methodology. Irrespective of the credibility or otherwise of the research, it remains that methane is a fossil fuel that will continue to contribute to greenhouse gas concentrations in the atmosphere, which are acknowledged to be a driving force behind global climate change (Hannah *et al.* 2002). The universal impacts of global climate change on biodiversity are provided in the Millennium Ecosytem Assessment (MA 2005), while a regional synthesis of the impacts are discussed by (Biggs and Scholes 2002), while (Von Maltitz and Scholes 2006; Biggs *et al.* 2002; Midgley *et al.* 2002) offer a review of the national impacts of climate change.

The temperature gradient will increase from east to west across southern Africa together with progressive xeric conditions extending across the sub-continent and the geographical locations of suitable habitat for species will shift towards the east. Suitable bioclimatic conditions are also predicted to move toward more temperate climatic zones as well as altitudinal shifts. In South Africa changes of bioclimatic zones are projected to move towards the south east causing an expansion of the Nama-karoo biome into the adjacent savanna and grassland (Joubert 2006). Sedentary and specialist species, unable to spread propagules beyond geological and topographic boundaries are less likely to adapt to rapidly changing biotic and abiotic conditions and suitable habitat will diminish in extent or disappear altogether. Co-evolutionary symbiotic relationships between species will be affected by the climatic changes, resulting in the demise of biodiversity due to the loss of one or more of the species dependant on such relationships.

The anticipated effects of climate change on biodiversity and the demise of ecosystems will directly affect the ecosystem services that provide well-being to populations inhabiting the Nama-karoo and further afield.

2.4.3. Cultural services.

Cultural services are intangible human benefits derived from ecosystems that include spiritual and creative inspiration, a sense of aesthetic fulfilment as well as present and future scientific discovery. Further cultural ecosystem services are the preservation of ecosystems for future generations to apply options that may not be considered by current generations (Daily 1997). The evaluation of cultural aspects of ecosystem services are often reduced to determining the value of tourism (Le Maitre 2007b). From economic principles, tourism is based on the value that individual are prepared to pay for the service. This cannot be a reasonable reflection of the full value of a region as permanent residents and inhabitants are not included in the value derived from tourism and neither are the associated spiritual and aesthetic values that are derived by transient movement of people through the area. Similarly the present and future scientific option value of the Nama-karoo cannot be determined but are also relevant to the cultural value of ecosystem services.

Shale gas mining in the Nama-karoo will convert the current rural ambiance of the region to a more intensively used and industrialised area. The visual intrusion of gas mining infra structure, such as roads, drill rigs, gas flares, pipelines and compressor stations will reduce the aesthetic allure and serenity of the areas affected. Furthermore, the potential reduction of biodiversity and degradation of traditional, cultural and historical sites may impact on the existing socio economic well-being of indigenous populations (Mentor 2012).

2.4.4. Supporting services.

Nutrient cycling is among the many supporting services that are provided in the Nama-karoo. Illustration of aspects of nutrition cycling may be demonstrated by the ecological role of aardvark *Orycteropus afer*. Aardvark are widely distributed, but uncommon, solitary and nocturnal animals that occur throughout the Nama-karoo (Skinner and Chimimba 2005). Feeding almost exclusively on ants and termites, aardvark are uniquely adapted to detection, locating and consuming formicid ants and termite. Equipped with acute olfactory and auditory senses, aardvark are able to locate subterranean prey and with powerful forefeet that are armed with long claws are able to dig out termite and ant colonies. Home ranges extent for 2.1 to 4.6km^2 (Skinner and Chimimba 2005) and they may cover up to 8.43km in a single night of foraging (van Aarde *et al.* 1992). During nocturnal foraging events, Dean and Milton (1991) recorded an average of 94±14 aardvark diggings per hectare in the Nama-karoo. The burrows and prospecting scrapes created provide suitable habitat for other animal species, and also become microsites in which plant seeds, detritus and water accumulate, thus creating patches in which plant diversity is increased (Dean and Milton 1991).

The distribution of nests of the harvester ant *Messor capensis* are closely associated with mima like mounts, known as heuweltjies, created by harvester termites *Microhodotermes viator* (Moore and Picker 1990), particularly along the southern and western limits of the Nama-karoo. Nests of *M. capensis* are evenly spread over the landscape at a density of about 2.1 per hectare (Dean and Yeaton 1993a) and have been shown to be enriched with organic matter and contain elevated concentrations of phosphorus, potassium and nitrogen, when compared to inter-mound areas (Dean and

Yeaton 1993b). The raised concentrations of nutrients within the *M. capensis* nest sites are attributed to the granivorous ants accumulating plant matter and seeds in cells within nests. High ratio (40 to 60%) of the seed are viable and are able to return to the seed bank (Milton and Dean 1993). Whilst exposing the nests of *M. capensis*, aardvark disturb viable seeds contained in the nest by re-distributing them into the disturbed soil (Dean and Yeaton 1992a) and other seeds are unintentionally ingested while feeding on ants. The seeds remain viable and are distributed widely in the faeces of aardvark (Milton and Dean 2001).

Selective grazing by livestock of more palatable perennial plants in the Nama-karoo has altered the abundance of seed availability of palatable plant species (Milton 1995). In a landscape already subjected to anthropogenic homogenisation of plant and animal species, the transfer of nutrients and plant matter by aardvark, thus creating a patchwork of plant diversity that was considered by Dean and Milton (1993) to be vital for the stability and diversity of the Nama-karoo, both in the short and long term.

Habitat degradation and fragmentation, barriers and edge effects, introduction of invasive species and potential increase of mortality by road accidents and poaching are activities that may be introduced to the Nama-karoo by shale gas mining. Viability of existing populations of aardvark, a species of which the population dynamics is poorly researched, may be affected by all of the species limiting factors listed. The associated reduction of nutrient distribution as a result of the demise of aardvark populations and the potential increase in populations of harvester ants and termites may result in the further homogenisation of vegetation in the Nama-karoo.

2.5. CONCLUSIONS.

Shale gas production, which includes the highly technological process of hydraulic fracturing, is both spatially extensive and the remnants of the operations will leave long term temporal impacts. Infra-structure associated with the mining activities include the development of approximately 4500km of roads as well as unknown lengths of pipelines and drilling pads. Approximately 6000 to 7000ha of land will be denuded of vegetation and the uppers nutrient rich soils may be subjected to compaction and erosion. The inclusion of chemicals and organic compounds into the fracking fluids, of which varying proportions return to surface following fracking, renders the water a hazardous waste product. Elevated concentrations of NORM and volatile organic compounds contained in the connate water that is flushed to the surface during production further compound the difficulties associated with disposal. Potential migration of fracking fluids and hyper-saline brine into groundwater resources in the Nama-karoo may be exacerbated by the ubiquitous presence of geological faults and intruded igneous dolerite dykes and sills.

Habitat degradation and fragmentation have known undesirable consequences on plant and animal population dynamics. Migration and recruitment of species are affected by roads that effectively become barriers to habitat specialists and sedentary species. Exacerbated by edge effects due to dust, road pollution and storm water runoff, the spatial extent of fracking may impact on the viability of species well beyond the immediate area of industrialisation.

Although the Nama-karoo is not a biome enriched by a high prevalence of plant or animal endemism, extensive gas mining operations will effect biodiversity, and therefore by extension, the ongoing sustainability of ecosystems. It is recognised that of the four categories of ecosystem services included in the Millennium Ecosystem Assessment (MA 2005) aspects of provisioning services, regulating services cultural services and supporting services will each be affected by fracking in the Nama-karoo. Considerable debate around the moral and ethical relevance of applying monetary value to ecosystem services as well as the lack of universally accepted methods to determine the value does not render the process of considering the impact on ecosystem services meaningless.

The recognition that fracking in the Nama-karoo will have an impact upon several ecosystem services should be sufficient for decision makers to identify the need to proceed with caution. Reflection on all aspects of human well-being as well as the intrinsic option that future generations must be allowed to derive benefits from intact and functioning ecosystems must be respected.

CHAPTER 3

3.1 DISCUSSION AND CONCLUSIONS.

Shale gas mining in the Nama-karoo will introduce alternative land use practices to a region that is already considered to be degraded (Reyers *et al.* 2009). The impacts on biodiversity in the Nama-karoo due to fracking are anticipated to be similar to those demonstrated in the USA and also from experiences derived from other mining and industrial activities. Effects on ecosystem and biodiversity are expected to be compounded by the large geographical extent over which fracking will occur and will leave a long term legacy that will remain long after production has ceased.

The extent of potential chemical pollutants introduced to ground water and surface water resources due to the fracturing of shale bearing formations cannot be determined within the limited time frames available. Intensive fracking activities in the USA, utilising the current technology, is little more than a decade old, and data obtained indicate that contamination of water resources due to the flux of more viscous fluids may only be detected in the future (Muelenbachs and Olmstead 2014, Vengosh *et al.* 2014).

Pumping fracking fluids that contain a cocktail of chemical compounds, of which approximately 750 different chemicals and components have been used (Vidic *et al.* 2013), into the ground introduces contaminants to the environment. Approximately 9 to 100% of the fracking fluid returns to the surface as flow back, usually within 10 days post fracking and a proportion returns together with the produce water during the production phase, however a quantity remains in the ground, from where it may migrate with time. Myer (2012) indicated that migration along cross cutting faults will occur within decades to centuries. Studies of geohydrological characteristics of the Nama-karoo by Van Tonder and de Lange (2012), Steyl *et al.* (2012) and van Tonder *et al.* (2014) all agreed that the artesian groundwater conditions in the Karoo Basin, which are rendered more complex by deep fault systems, dolerite dykes and sill, will complicate ground water modelling and may enable rapid upward migration of fracking fluids and brine.

A study of well defects conducted by Ingraffea *et al.* (2014) indicated the need to apply appropriate time scales to the studies of well design, integrity and performance. Data obtained from Pennsylvania USA during the period from 2000 to 2012 indicate that compromised cement and casing integrity failures were reported in 0.7 to 9.1% of active wells during the study period, with an increasing trend. Possible reasons forwarded for the apparent increase in well defects observed was that regulation authorities are more vigilant in performing their tasks, and the increasing age of wells inspected, thus time related defects such as corrosion were more apparent. Potential distortion of well casings and failure of the cement annulus due to latent tensile and compressive stress regimes in the host rock may induce micro fractures in the outer cement annulus that isolates the borehole casing from host rock formations (CCA 2014). Migration of corrosive fluids along fractures may result in the deterioration and ultimate failure of steel casing and the inner cement annulus of wells. With sufficient time, remnant gases and fracking fluids as well as hypersaline connate water may migrate along patent flow paths provided by the well, thus creating hydraulic connectivity with shallow ground water aquifers.

Kiviat (2013) expressed the opinion that the biodiversity impacts of fracking may be mitigated by a zero-loss management policy that would remove the risk of chemical, waste water and pollutants entering the environment. Whilst the opinion has merit, it is somewhat idealistic and given the extensive and intensive nature of shale gas mining it is unlikely that the energy industry would be capable of achieving such goals. Furthermore, the potential risks to the environment are not only confined to ground water contamination; the effects of habitat degradation and fragmentation, which are acknowledged as being one of the drivers of biodiversity loss cannot be mitigated (Reyers *et al.* 2009). The total extent of surface infra structure required to facilitate shale gas mining may be reduced by extending the horizontal portions of the wells, thereby reducing the number of drill pads required as well as the density of roads and pipelines (Kiviat 2013). But the imposition of industrial land use requirements on a rural landscape will compromise the integrity of existing habitats, with the associated implications for biodiversity and ecosystems.

The economic benefits of fracking have been demonstrated in the USA, however ecosystem changes have long term and potentially costly consequences for current and future societies. Reyers *et al.* (2009) expressed the opinion that in order to understand the consequences and potential cost implications of impacts to ecosystems, awareness is required of the links between ecosystems, biodiversity and human well-being. The interconnected make-up of ecosystems are such that over exploitation of an ecosystem service might influence the ability of a linked ecosystem service to function effectively. Reyers *et al.* (2009) cited the example of poorly managed food cultivation, a production service, impairing the regulatory service of soil erosion control and water quality. Similar linked and co-existing ecosystem services exist in the Nama-karoo that will be impacted upon by the proposal to mine for shale gas in the biome.

Natural capital, which is defined by Daly and Cobb (1989) as the renewable and non-renewable resources that occur independently of human action or fabrication, is in the view of Milton *et al*. (2003) eroded due to over exploitation of forage, invasion of alien species and surface mining amongst other reasons. Shale gas mining is a process of extracting a non-renewable resource, whilst severely depleting renewable natural capital. By stripping vegetation over large areas, destroying the biological soil crust and mixing surface and subsurface soils within the foot print area of drill pads and along lines of linear infra-structure, fracking will degrade the land (Milton *et al.* 2003). Severely degraded land was described by Reyers *et al.* (2009) as being land that is vegetated by totally altered plant communities, having no biological crust and that are subjected to severe soil loss, and they suggested that such areas require restoration to re-establish communities and ecosystem functions. In the opinion of Milton *et al*. (2003) vegetation recovery in arid areas may take many decades and the costs of restoration increase exponentially as the scale of degradation increasingly affects vegetation cover and ecosystem processes.

Natural ecosystem processes in the Nama-karoo perform a vital function in reducing soil losses and safeguarding surface water quality and ensuring recharge to ground water resources. The maintenance of viable communities of species, that are an integral component to the functioning of ecosystems, will ensure continued value being derived from ecosystem services. The degree of impact on the degradation of ecosystem services will manifest on temporal and spatial scales that will vary, but cannot be predicted, and will have negative influences on the benefits that human society derive from them. The loss of aesthetic value that a place of significance may have on an individual cannot be compared to the potential loss of adequate water resources that may affect entire towns or farming communities, yet the impact to ecosystems may be of similar magnitude.

Cornell (2011) provided a comment that the increasing interest applied to the concept of ecosystem services is indicative of societies shift towards viewing the environment as a life support system. The focus on “what nature does for us” as opposed to what “nature does” is a fundamental shift that society must embrace. Better management of ecosystems will therefore provide improved ecosystem services, for the benefit of human well-being. Sustained benefits obtained from ecosystem services are, in the opinion of Cornell (2011), dependent on the healthy functioning of the whole system with the whole being greater than the sum of the parts.

Protection of ecosystem services must become an integral component of government policy. Milton and Dean (2010) argued that integrated planning is required in order to ensure sustainable development, which in rural areas include, amongst others, the provision of biodiversity corridors and sites of scientific and cultural significance. The control of alien vegetation and fire management through various government initiatives must be expanded to include rehabilitation and remediation programs that will provide direct employment and initiate a process of veld restoration. Whilst immediate and direct intervention is required, policy must be based on the best information available that can be applied to ensure sustainable ecosystem services for current and future generations. Science as a simple research process that provides solutions must change, in the opinion of Knight *et al*. (2008) science must be inclusive of social processes that answers problems though shared learning and participation with interested parties. This is a sentiment that is not dissimilar to that expressed by Van Jaarsveld *et al*. (2005) in which they made the point that the over emphasis of research into the observation and measurement of biodiversity patterns will be unlikely to convince civil society and policy makers of the urgency with which issues of ecosystem management is required. Greater efforts to embrace all stakeholders is more likely to result in inclusive decision making that will result in policy implementation that will be supported by society. The Strategic Environmental Assessment (SEA) process initiated by the South African government in June 2015, is such a process that includes the interest of government, industry, academia and civic society.

Finding appropriate solutions to the divide that exists between the “what nature does for us” mind set of economist and policy makers and the “what nature does” conditioning of the scientific community must be bridged. The greater inclusion of the social science disciplines in the debate may provide valuation systems that move away from a monetary system or from the emphasis on quantifying loss of biodiversity to a more inclusive indexing system in which the financial aspects, environmental conditions and human welfare are included into a single metric that determines and tracks the state of ecosystem services. The development of a universally accepted metric to measure the costs and potential impacts on ecosystem service will enable decision makers, investors and society to make rational choices about hosting industrialised processes such as fracking within their communities.

Ill-considered decisions to permit shale gas mining in the Nama-karoo will have the potential to severely impact upon ecosystem services that have already been compromised. Further degradation of biodiversity and ecosystems will affect the well-being of communities in areas well beyond the boundaries of the biome and on temporal scales that are impossible to determine.

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