A review of biophysical and socio-economic effects of unconventional oil and gas extraction - implications for South Africa

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ABSTRACT

The impacts associated with unconventional oil and gas (UOG) extraction will be cumulative in nature and will most likely occur on a regional scale, highlighting the importance of using strategic decision-making and management tools. Managing possible impacts responsibly is extremely important in a water scarce country such as South Africa, versus countries where more water may be available for UOG extraction activities. This review article explains the possible biophysical and socio-economic impacts associated with UOG extraction within the South African context and how these complex impacts interlink. Relevant policy and governance frameworks to manage these impacts are also highlighted.

Keywords: Review, unconventional oil and gas, fracking, impacts, South Africa

1. Introduction

Unconventional oil and gas (UOG) extraction by means of hydraulic fracturing (fracking), the sustainability of this activity and the management of its related impacts is a controversial issue worldwide, as more and more countries plan to extract this source of energy (Dernbach and May, 2016). This review outlines the first step that any country needs to take when considering such an activity, which is to develop an understanding of the extraction process and stimulation techniques that are used as well as the possible consequences related to UOG extraction. An understanding of possible impacts associated with the extraction process is also paramount to ensure a proper legal and regulatory framework and the effective regulation of this activity in order to ensure the protection of humans and the environment.

Various countries are in different phases of extracting UOG. For example in the United States, Canada and Australia, development of UOG resources is at an advanced stage, while in China and Poland these resources are still being explored. Other countries, such as Germany and South Africa, are considering the extraction of UOG and have not yet commenced with exploration or extraction of these resources (see Box 1 for a history of oil and gas in South Africa). The extent to which countries around the world are, to varying degrees, developing their UOG extraction resources, illustrates the importance of this novel oil and gas extraction technique for future energy security.

Box 1: Brief history of oil and gas in South Africa

In the 1960s the South African Oil Corporation (SOEKOR) explored for oil and gas and could only find low permeability gas deposits in the shales of the Karoo basin (De Wit, 2011). At that stage the technology to extract these resources did not yet exist, but with recent advances in technology (for example fracking) extraction of these gas resources has become more feasible. Since 2011, the South African government received various applications to extract UOG by means of hydraulic fracturing and other methods. If viable deposits of oil and gas are found, it could augment primary energy sources in South Africa and possibly displace energy imports.

Box 2: UOG resources defined

Oil and gas that occur in reservoirs with a low permeability (usually less than 1 milliDarcy) and which require fracking (or another stimulation technique) for the extraction of these resources are referred to as UOG resources.

Unconventional resources may include shale oil and gas, coalbed methane (CBM) and tight sand oil and gas deposits. Although fracking is the main technique used to extract oil and gas from shale gas and tight sand deposits, other stimulation techniques may also be used (e.g. acidizing). In coalbed methane reservoirs, depressurisation is usually used to extract the gas and may be used in conjunction with fracking.

Box 3: Fracking explained

High volume hydraulic fracturing (fracking) is a relatively recent stimulation technique that enables the extraction of oil and gas resources by enhancing the permeability of the target oil or gas reservoir. During hydraulic fracturing a water, proppant and chemicals are injected under high pressure into the reservoir to enhance reservoir permeability (Broomfield, 2012) and facilitate extraction of oil and gas from the reservoir.

Since this extraction technique is unprecedented in South Africa, this transdisciplinary group of authors from backgrounds in surface water quality, macro-invertebrates, fish, groundwater, vegetation, seismicity, legal and socio-economic experts performed research on this topic to understand what the extraction process entails and also to identify possible impacts that may emanate from this activity in the South African context.

Review articles that were surveyed focused on the technical aspects related to fracking such as fracturing fluid systems and factors influencing fracture propagation (Mahrer, 1999; Rahman and Rahman, 2010; Vatsa and Wang, 2013; Barati and Liang, 2014;) and the economic aspects of these oil and gas resources such as resource availability, estimates and productivity (Clarkson et al, 2012 and 2013; McGlade et al., 2013). These aspects are all important for the optimization of production from unconventional deposits. In recent years the linkages between environmental and socio-economic impacts in development have come to be considered paramount in ensuring sustainable human development (DSD 2015; Morton et al., 2009; O'Riordan, 2007; UNFPA 2012). The purpose of this review article is to elaborate on the impacts associated with the various phases of the UOG extraction process.

Such a review of possible impacts may assist governments in developing proper regulations that are based on credible scientific knowledge and ensure that cognisance is taken of the potential negative socio-economic and environmental impacts of UOG extraction in the interest of achieving sustainable human development.

2. UOG extraction – understanding the process

A background review on UOG resources (see Box 2) and its extraction is the first step towards understanding the complexities of this novel resource extraction process. A review could assist governments in developing the required regulatory policies and guidelines to manage and monitor UOG extraction and fracking effectively in a way that will protect human health and the environment and ensure sustainable use of resources such as water in water scarce countries. An important first step in the background review is to understand the process of UOG extraction – the different stimulation techniques used as well as ancillary activities - so that possible impacts that may emanate from such a process may be accurately anticipated. Apart from possible impacts associated with fracking (see Box 3 for an explanation of fracking); any of the related activities associated with unconventional gas extraction (water sourcing, wellsite establishment, road and pipeline construction) might have a serious impact on both the biophysical and socio-economic environments.

UOG extraction usually spans larger geographic areas than the extraction of conventional resources. This means that impacts usually occur on a larger spatial scale and are cumulative in nature, which complicates the management of this activity. In South Africa, UOG extraction will coincides with current land-uses such as astronomy and agriculture. UOG extraction is also performed in phases, which include the exploration phase (including firstly the identification of possible UOG reservoirs and secondly assessing the economic viability of extracting the gas in place, usually by means of hydraulic fracturing or fracking), the extraction phase (during which UOG is produced economically) and the post extraction phase (during which well decommissioning occurs in areas that are no longer productive). Chemicals that may be used in the fracking process could include biocides, breakers and friction reducers. Biophysical and socio-economic impacts are associated with all of these phases.

3. Possible impacts associated with UOG extraction

Apart from the possible positive impacts of UOG extraction (providing energy and employment, among others) (Wait and Rossouw, 2014, Warren, 2013) possible negative impacts may also occur in both the biophysical and socio-economic environments. There are multiple and reciprocal linkages between society and the environment, which necessitates research into the possible impacts of unconventional gas extraction on the biophysical and socio-economic spheres, and how these impacts interlink.

The possible negative social impacts resulting from UOG extraction need to be well understood and avoided where possible. These possible impacts include: disruption of social cohesion, competition over water between oil and gas companies and existing lawful water users in the Karoo; securing access to water and sanitation for previously disadvantaged communities in the face of competing demands presented by fracking operations; the potential health risks associated with lack of access to water and adequate sanitation in vulnerable communities; in-migration and higher population density in ecologically sensitive and water scarce areas (Beemster and Beemster, 2011; Broderick et al., 2011; Dolesh, 2011; Kargbo et al., 2010; Schafft et al., 2013 and Warren, 2013). Even a social-economic benefit such as job creation may be contentious as it is not guaranteed that jobs created in the oil and gas sector will offset job losses in other sectors such as the agricultural sector resulting in displacement of people (Dolesh, 2011; Kargbo et al., 2010; Schafft et al., 2013 and Warren, 2013). Therefore, the dynamic and multi-faceted socio-economic impacts of unconventional gas extraction in communities in areas where basic resources such as water are already under pressure should be identified and linked with wider developmental and environmental concerns.

Negative environmental impacts may also occur, which could include impacts on water resources (in terms of quality and quantity for both surface water and groundwater resources) (ANU, 2012; Broomfield, 2012; Rahm and Riha 2012; Herridge et al., 2012; Lechtenböhmer et al., 2011 and IEA, 2012), habitat fragmentation and loss (Jones and Pejchar, 2013; Northrup and Wittemyer, 2013) as well as possible increased seismicity associated with deep well wastewater injection as well as fracking operations (NRC, 2013). By identifying the possible impacts before extraction and development commences, some negative impacts during unconventional gas extraction may be minimised. The identification and description of impacts will also aid governments in the development of legislation and regulations to manage and minimize the possible impacts arising from UOG extraction.

Table 1 summarises possible impacts of UOG extraction on the biophysical and socio-economic environments during UOG exploration, table 2 the possible impacts during UOG extraction and table 3 the possible impacts after UOG extraction.

Table 1: Summary of possible impacts during the exploration phase

Aspects		Possible positives	Possible negatives
Biophysical	Surface water: Quality	• None indicated in the literature.	• Drilling fluids (diesel etc.) leaching into surface water *via* ground water or via overland flow from surface spillages [1] • Possible removal of sand from rivers. [2] • Possible increase in sediment load in rivers due to increased erosion from seismic exploration.
	Surface water: Aquatic Invertebrates	• None indicated in the literature.	• Vibration generated during seismic exploration may impact on invertebrates[3]. • Removal of sand may impact on biota in alluvial aquifer/hyporheic zone [4] • Increase of sediment in rivers could increase turbidity and limit habitat and food available to invertebrates [5, 6, 7, 8] • Diesel pollution reduces abundance and diversity of freshwater invertebrates [9,10]
	Surface water: Fish	• None indicated in the literature.	• Increased sediment delivery to river may impact critical fish habitats e.g. spawning habitat[11], cause turbidity and reduce visibility for predaceous fishes. • Loss of fish diversity and disruption of fish migration due to increased sedimentation, turbidity and fragmentation (from road crossings in rivers)[1]. • Reduction of stream flow in perennial rivers if water UOG extraction water is sourced from rivers and loss of critical refuge habitat during dry periods. • Loss of critical passage habitat lead to loss of mobility, reduced availability of food, fragmentation and isolation of fish assemblages. • Water quality changes in isolated pools from water abstraction, heat death of fishes in isolated pools[12], higher impact of contaminants on fish during periods of low stream discharge or isolation[11]. • Reduction in fish fitness and health due to increased predation, intra- & interspecific competition and crowdedness in isolated pools.
	Geohydrology	• Develop a better understanding of the deeper geology and geohydrology [13, 14, 3]	• Difficult to identify aquifers at risk for contamination since deeper geology and structures are unknown [3, 14]. • Artesian basin conditions [15, 16] in the Karoo geological basin may cause upward migration of formation water. • Possible shale instability with associated borehole problems such as hole collapse, stuck equipment, plastic flow, fracturing, circulation loss and poor well control may cause contamination [16, 17, 18, 19, 20] • Large quantities of saline water produced by CBM [21] and high possibility of aquifer contamination by CBM if aquifers and coalbed formations co-occur. [10,11] • Groundwater contamination if hydraulic fracturing is allowed [22, 23, 24] during the exploration phase, both for coalbed methane and shale gas formations.
	Seis-micity	• Not known	• Level of seismicity will increase. However the extent of this increase is uncertain. • Possibility to observe or induce and/or trigger a strong seismic event.
	Vegetation	• New species identified	• Woody vegetation removal (food and fibre), increased incidence of wild fires. • Surface spills of hazardous material [25] impacting on vegetation • Alien invasive species encroachment, biodiversity loss and habitat fragmentation due to vegetation clearance for drill site & road construction [26]
References		13 - De Wit, 2011; 14 - DMR, 2012; 15 - Steyl et al., 2012	1:- Lechtenböhmer et al., 2011; 2: Freyman, 2014; 3: McCauley et al., 2000; 4: Boulton et al., 1998; 5: DWAF, 1996; 6; Chutter, 1969; 7: Bishop, 2011; 8 :Vaughn, 2005; 9: Lytle and Peckarsky, 2001; 10: Wood et al., 2011; 11: Davis et al., 2006; 12: Mundahl, 1990; 14: DMR, 2012; 15: Steyl et al., 2012; 16: Woodford and Chevallier, 2002; 17: Manohar, 1999; 18: Khan et al., 2011; 19: Cabot, 2010; 20: Khodja et al., 2010; 21: USEPA, 2011b; 22: USEPA, 2011a; 23: Broomfield, 2012; 24: ANU, 2012; 25: Adams, 2011; 26: Milton and Dean, 2012

Table 1: Summary of possible impacts during the exploration phase (continued)

Aspects		Possible positives	Possible negatives
Socio-economic	Economic well-being	• Infrastructure development • Direct and indirect employment opportunities • Multiplier economic impacts [27, 28, 29, 30, 31]	• Decline in tourism potential [14, 27, 32, 33, 34] • Limited long term permanent employment opportunities • Potential jobs can take 10 years to materialise • Job losses in the agricultural and tourism sectors not offset by employment in unconventional gas industry [14, 27, 32, 33, 34]
	Health	• Improved access to health care services • Better nutritional status due to increased economic development [35, 36, 37, 38, 39]	• Negative impact of NORMs on the health of populations [29, 32, 33, 35, 27, 30, 40, 38, 41] • Increase in short term health complaints • Long term impacts on reproductive health • Risk of cancer and organ damage increases • Chronic conditions (i.e. asthma) worsen in vulnerable populations (children and elderly). • Increased incidence and prevalence of HIV/AIDS [46, 47, 48] • Higher incidence of motor vehicle accidents than normal [27, 29, 30, 32, 33, 35,38, 40, 41]
	Demo-graphic impacts	• Population increase [34, 42, 43, 36]	• Population increase [4, 36, 42, 43] • Distorted age structure • Gender imbalance [34, 36, 42, 43]
	Agriculture and food security	• None indicated in the literature.	• Long-term impacts from dust pollution, water shortages and quality on crop production are uncertain. [27, 33, 41, 44; 49; 50] • Loss of employment opportunities in the agricultural sector • Some chemicals used cause reproductive problems in animals • Rural livelihoods (wild food sources) affected by UOG impacts [27, 33, 41, 44, 45]
	Social well-being and living conditions	• Infrastructure development • Increased access to health and welfare services [39, 42]	• Psychological impacts, mining health risk fears, sense of loss of community, frustration and anxiety over traffic and noise nuisances • Local municipalities unable to deal with challenges (waste water management, unaffordable housing & rapid social change) • Increase in social ills (substance abuse, interpersonal violence, family disorganisation) • Higher costs associated with police and emergency services due to increased demand [27, 30, 31, 32, 34, 35, 42, 45]
	Astronomy	• None indicated in literature.	• Radio telecommunication and radio frequency emission may impact on radio telescopes. • Dust and pollutants associated with gas flaring generated during mining & related activities may impact on optical telescopes • Artificial lighting (for security and from vehicles) can produce light pollution, impacting negatively on optical observations.
	Air quality	• None that could be identified	• Dust release from vegetation clearance for seismic surveys impact on human health & environment. Emissions due to removal of carbon stocks. [60] • Toxic gasses released from venting, emissions (diesel) released by thumper trucks, equipment and construction activity. [35]
References		27 - Beemster and Beemster, 2011; 28 - Considine et al., 2011; 29 - Chung and Hoffnagle, 2011; 30 – Coburn et al., 2011; 31 - Williams, 2011; 35 - Broderick et al., 2011; 36 - Esteves, 2008; 37 - Larson et al., 2011; 38 - Marsa, 2011; 39 – Rolfe et al., 2007; 34 - Pelser et al., 2005; 42 - Weigle, 2011; 43 - Lockie et al., 2009	14: DMR, 2012; 27: Beemster and Beemster, 2011; 29: Chung and Hoffnagle, 2011; 30: Coburn et al., 2011; 31: Williams, 2011; 32: Dolesh, 2011; 33: Kargbo et al., 2010; 34: Pelser et al., 2005; 35: Broderick et al., 2011; 36 : Esteves, 2008; 38: Marsa, 2011; 40 - DSD 2010; 41: Pelser and Redelinghuys, 2006; 42: Weigle, 2011; 43: Lockie et al., 2009; 44: Williams et al., 2012; 45: Walsh, 2011; 46: DSD, 2010, 47: Heunis et al, 2012, 48: Pelser & Redelinghuys 2006; 49: Anderson and Theodori, 2009; 50: De Rijke, 2013 60: Forster & Perks, 2012.

Table 2: Summary of possible impacts during the extraction phase

Aspects		Possible positives	Possible negatives
Biophysical	Surface water: Quality	• None indicated in the literature.	• Possible removal of sand and water from rivers.[1] and water required may impact on the hydrology of the resources.[2] • Various sources of pollutants may impact on rivers.[3, 4, 5, 6]
	Surface water: Aquatic Invertebrates	• None indicated in the literature.	• Surface water abstraction lead to decrease in resource connectivity, invertebrate abundance & diversity, increase in pest species. [7, 8, 9] • Land use change could isolate rivers and pans resulting in genetic isolation and reduction in number of refugia[10, 11] • Increased sediment in rivers[12] or pollution of surface water by chemicals in fracking fluid influences invertebrates.[13, 14. 15, 16, 3, 17]
	Surface water: Fish	• None indicated in the literature.	• Groundwater abstraction lead to loss of baseflow to springs, loss of hyporheic flow, loss of refuge habitat, water quality & volume changes[18] • Contamination of surface water may lead to habitat quality impacts, reduced food sources and visibility, bioaccumulation of toxic substances, reduced fitness and health of fishes and resultant fish kills [,1,19,20,12,21] • Infrastructure construciton leads to fragmentation of habitat and reduced colonization and fish diversity [18] • Truck traffic accelerates erosion, leading to changes in sediment delivery to river, reduced habitat & visibility, lower fish productivity & fitness, lower levels of recruitment and possible effects on the food web. • Abstraction from rivers, pools & dams lead to loss of habitat, lower water levels in pools, loss of critical passage, changes in water quality, heat death of fish and higher impact of contaminants [18,22] • Discharge of wastewater into streams & pools could change flow regime, water chemistry & physico-chemical signature of stream or pool or degrade the natural habitat which could impact on fish hatch rate, survival rate, recruitment, vitality and fitness of fishes and fish behaviour and survival. [18, 19, 20, 12, 21, 22, 23, 24, 25,26, 27, 28]
	Geohydrology	• The use of safer chemicals is possible, e.g. gasses or plant based oils.[29, 7] • Green chemicals can be developed to use for fracking.[29, 30]	• Same as for exploration phase and: • Sourcing of water from local aquifers may induce aquifer connectivity, [31, 32] change groundwater levels, cause contamination and seismic activity.[33,34] • Shale drilling problems [35, 36, 37, 38,39] may cause contamination. • Surface activities contaminate aquifers via surface water-groundwater interaction.[40, 41, 42] • Wastewater poses serious challenges if not managed properly.[7, 43, 44, 45] • Poor well integrity may cause leakage of gas or fluids and groundwater contamination, also for CBM.[45, 7, 30,46 , 12, 47] • Various regulatory uncertainties may put groundwater resources at risk [48,49] • Extraction of water from CBM → geology and aquifer deformation, subsidence, decreased baseflow and reduced springflow.[40, 44]
	Seis-micity	• Not known	• Level of seismicity will increase. However the extent of this increase is uncertain. • Possibility to observe or induce and/or trigger a strong seismic event.
References		29 - Kargbo et al., 2010; 7 - Broomfield, 2012; 30 - IEA, 2012	1: Freyman, 2014; 2: Zorn et al., 2008; 3: Herridge et al., 2012; 4: Rahm and Riha 2012; 5: Lyons, 2012; 6: Scott et al., 2011; 7: Broomfield, 2012; 8: Grubert and Kitasei, 2010; 9: DMR, 2012; 10: Palmer, 1996; 11: Mead et al., 2011; 12: Bishop, 2011; 13: Wood et al., 2011; 14: Peterson et al., 2002; 15 Sumi, 2010; 16: CIEH, 2012; 3: Herridge et al. 2012; 17: Ramirez, 2005; 18: Davis et al., 2006; 19: Davis, 2008; 20: Lloyd-Smith and Senjen, 2011; 21: Bamberger and Oswald, 2012; 22: NRC, 2010; 23: Lind, 2004; 24: Skaar et al., 2004; 25: McBeth et al., 2003; 26: Johnson, 2007; 27: Kempema et al., 2011; 28: Rahm, 2011; 30: IEA, 2012; 31: Myers, 2012; 32: Warner et al., 2012; 33: Zoback et al., 2010; 34 NRC, 2012b; 35: Manohar, 1999; 36: Khan et al., 2011; 37: Cabot, 2010; 38: Khodja et al., 2011; 39: Sone and Zoback, 2011; 40: ANU, 2012; 41: Seaman et al., 2010; 42: Parsons, 2004; 43: USEPA, 2011a; 44: USEPA, 2011b; 45: Volz et al., 2011; 46: Steyl et al., 2012; 47: PA DEP, 2009; 48: Havemann et al., 2011; 49: Havemann, 2011

Table 2: Summary of possible impacts during the extraction phase (continued)

Aspects		Possible positives	Possible negatives
Bio-physical	Vegetation	• Possible new species identified	• Woody vegetation removal; scale of incidence of wild fires larger than during exploration. • Possible surface spills on larger scale than during exploration impacting on vegetation [50] • Alien invasive species encroachment, biodiversity loss and habitat fragmentation on a larger scale than during exploration[51]
Socio-economic	Economic well-being	• Infrastructure development • Employment opportunities • Multiplier economic impacts[52,53,54,55,56] • Potential tax benefits[52,53,54,55,56]	• Decline in tourism potential [9,52,57,29,58] • Limited long term permanent employment opportunities • • Job losses in the agricultural and tourism sectors not offset by employment in unconventional gas industry [9,29,52,57,58] • Economic inequality increases [70]
	Health	• Better access to health care services • Better nutritional status due to increased economic development[59,60,61,62,63]	Same as for the extraction phase, but on a larger scale [29,52,54,55,57,59 62 64,65,29, 52,54,55,57,59,62,64,65]
	Demo-graphic impacts	• Population increase on a larger scale [58,66,67,60]	• Population increase on a larger scale [58,60,66,67] • Distorted age structure • Gender imbalance[58,60,66,67]
	Agriculture and food security	• None indicated in the literature.	• Same as for extraction phase, but on a larger scale [29,52,65,68,69]
	Social well-being and living conditions	• Same as for the exploration phase, but on a larger scale [63,66]	• Same as for the exploration phase, but on a larger scale [52,55,56,57,58,59,66,69]
	Astronomy	• None indicated in literature.	• Same as for the exploration phase, but on a larger scale.
	Air quality	• Newer technologies may decrease air quality impacts	• High methane emissions contribute to greenhouse gasses [71,72], may negate gains of cleaner burning capability of UOG extraction and energy generation.[71,73] • Inadequate legislation and infrastructure cause uncontrolled flaring [30] • Poor air quality causes health impacts • Gas migration and built-up near structures may pose explosion risk.[47]
References		52: Beemster and Beemster, 2011; 53: Considine et al., 2011; 54: Chung and Hoffnagle, 2011; 55: Coburn et al., 2011; 56: Williams, 2011; 59: Broderick et al., 2011; 60: Esteves, 2008; 61: Larson et al., 2011; 62: Marsa, 2011; 63: Rolfe et al., 2007; 58: Pelser et al., 2005; 66: Weigle, 2011; 67: Lockie et al., 2009	9: DMR, 2012; 29: Kargbo et al., 2010; 52: Beemster and Beemster, 2011; 54: Chung and Hoffnagle, 2011; 55: Coburn et al., 2011; 56: Williams, 2011; 57: Dolesh, 2011; 58: Pelser et al., 2005; 59: Broderick et al., 2011; 60: Esteves, 2008; 62: Marsa, 2011; 64: DSD 2010; 65: Pelser and Redelinghuys, 2006; 66: Weigle, 2011; 67: Lockie et al., 2009; 68: Williams et al., 2012; 69: Walsh, 2011; 70: Deller & Schreiber, 2013; 71: Tollefson, 2012; 72: Forster and Perks, 2012; 73: Sovacool, 2008.

Table 3: Summary of possible impacts during the post extraction phase

Aspects		Possible positives	Possible negatives
Biophysical	Surface water: Quality	• Risk of surface water contamination lowers.	• Not all chemicals used in fracturing fluids are known, therefore unknown chemical impacts is an uncertainty. • Various sources of pollutants may impact on rivers.[1, 2, 3, 4]
	Surface water: Aquatic Invertebrates	• None indicated in the literature.	• Possible contamination due to possible groundwater contamination as they are interconnected[5]
	Surface water: Fish	• None indicated in the literature.	• The impact specific chemicals could have on individual endemic species or the community as a whole is unknown. • Reduced habitat quality due to exposure to toxic substances. • Reduced fitness and health of fishes. • Fish kills[6, 7]. • Reduction in the availability of food sources e.g. invertebrates. • Bioaccumulation of toxic substances in fish tissue – effect on food web.
	Geohydrology	• Pollution risk in the area where fracking is ceased, lowers.	• Aquifer pollution from deep shale layers may only surface years after a pollution incident. • The extent of possible long-term contamination in freshwater aquifers could not be predicted at this stage. • South Africa not able to rehabilitate contaminated aquifers in complex geology (physically and economically) [8] • Well abandonment and long term monitoring may be problematic [9,10] • Oil and gas well casing failure and leakage may pose long term legacy issues and lead to inevitable groundwater contamination [6,10,11,12]
	Seismicity	• Not known	• Level of seismicity will increase. However the extent of this increase is uncertain. • Possibility to observe or induce and/or trigger a strong seismic event.
	Vegetation	• None that could be identified in the literature	• Migration of polluted ground-and/or surface water pollution to the rooting zone – vegetation die-back[13] • Success of rehabilitation uncertain. • Continued habitat fragmentation[14,15] due to poor upkeep of existing infrastructure, roads or alien invasive control • Continued loss of plant biodiversity due to a continued loss of ecosystem services and possible alien invasive species[16,17] • Continued trade of e.g. succulents due to access roads[17]
Socio-economic	Economic well-being	• None that could be identified in the literature	• Severe economic downturns experienced in local communities • Unemployment rises • Poverty increases [18,19,20,21,22]
	Health	• Decline in the prevalence of short term health impacts.	• Lingering ill health • Birth defects as a result of exposure to mutagenic chemicals • Decreased access to health care • Lingering impacts of an increase in HIV [19,20,21,23,24,25,26,27]
References			1: Herridge et al., 2012; 2: Rahm and Riha 2012; 3: Lyons, 2012; 4: Scott et al., 2011; 5: Graham and Butts, 2005; 6: Bishop, 2011; 7: Bamberger and Oswald, 2012; 8: GAO, 2010; 9: Broomfield, 2012; 10: ANU, 2012; 11: Dusseault et al., 2000; 12: Dusseault et al., 2001; 13- Steyl et al., 2012; 14: O'Connor and Kuyler, 2006; 15: Van Wilgen et al., 2008; 16: Northrup and Wittemyer, 2013; 17: Lovegrove, 1993; 18: DMR, 2012; 19: Beemster and Beemster, 2011; 20 :Dolesh, 2011; 21: Kargbo et al., 2010; 22: Pelser et al., 2005; 23: Coburn et al., 2011; 24: DSD 2010; 25: Marsa, 2011; 26: Pelser and Redelinghuys, 2006; 27: Chung and Hoffnagle, 2011

Table 3: Summary of possible impacts during the post extraction phase (continued)

Aspects		Possible positives	Possible negatives
Socio-economic	Demo-graphic impacts	• Population decline [22,28,29,30]	• Population decline • Distorted age structure[22,28,29,30]
	Agriculture and food security	• None indicated in the literature.	• Land that is unsuitable for farming after gas is depleted [31,19,25,21,32]
	Social well-being and living conditions	• None that could be identified in the literature.	• Sense of fatalism, loss, deprivation and perceived deterioration in socio-economic well-being[21,19,23,33,20,22,32,28]
	Astronomy	• None indicated in literature.	• None indicated in literature.
	Air Quality	• Air quality emissions in the region of previous UOG extraction lowers.	• Pollution still emitted at waste disposal sites, compressors, condensate tanks and in flow back.[34,35] • Gas migration and built-up near structures due to poor well sealing may pose explosion risk. [36]
References		22 - Pelser et al., 2005; 28 - Weigle, 2011; 29 - Lockie et al., 2009; 30 - Esteves, 2008;	19: Beemster and Beemster, 2011; 20: Dolesh, 2011; 21: Kargbo et al., 2010; 22: Pelser et al., 2005; 23: Coburn et al., 2011; 25: Pelser and Redelinghuys, 2006; 28: Weigle, 2011; 29: Lockie et al., 2009; 30: Esteves, 2008; 31: Williams et al., 201; 32: Walsh, 2011; 32: Walsh, 2011; 33: Williams, 2011; 34: Broderick et al., 2011; 35: Tollefson, 2012; 36: PA DEP.

Table 1, table 2 and table 3 describe possible impacts on the biophysical and socio-economic environments. The activities which may pose some of the largest risks for South Africa, are the sourcing of water to be used in large scale hydraulic fracturing operations, water contamination that may be associated with transport of chemicals as well as migration of fracking fluids, and the as yet unaddressed problem of how wastewater from UOG extraction operations and brines resulting from wastewater treatment should be managed, which may impact negatively on water quality.

In terms of water availability, South Africa is classified as a water-stressed country (Siebrits & Winter, 2013), meaning that people have access to less than 1700 m^3/person/annum; and it will probably be facing water scarcity (<1000 m^3/person/annum) by 2025 (DWA, 2011). In 2010, 80% of its surface water resources and 40% of its groundwater resources were already allocated to water users (DWA, 2010). Withdrawals of large quantities of water from surface water resources (e.g. streams) may not only have significant impacts on water availability for users in the catchment, but also on the hydrology and hydrodynamics of these resources. Such withdrawals from streams can alter the flow regime by changing their flow depth, velocity, and temperature (Zorn et al., 2008) and reduce the dilution effect. Furthermore, it is important to recognise that groundwater and surface water are hydraulically connected (Parsons, 2004 and Winter et al., 1998); any changes in the quantity and quality of the surface water will affect groundwater and vice versa. Road construction and stream crossings could cause erosion, sediment transport and an increase in salinity, which impacts the receiving rivers (Rahm and Riha, 2012). The removal of sand (if the type is suitable) from riverbeds in the Karoo for use as proppant could have a negative impact on the alluvial aquifers present in some of these rivers. The removal and processing of sand for use as proppant is also particularly water-intensive and would be of particular concern for the semi-arid Karoo environment with its temporary waters.

Air quality impacts may also be significant, and relates to dust released during seismic surveys, carbon dioxide and diesel fumes that may be released during drilling as well as methane emissions during fracking (Broderick et al., 2011 and Field et al, 2014). Regional scale UOG extraction may have significant impacts in terms of biodiversity fragmentation and competition with existing water and land uses. In terms of land use, the area where UOG is to be extracted in South Africa, also coincides with astronomy development areas, specifically the Square Kilometre Array (SKA) and the Southern African Large Telescope (SALT), both of which are very important development ventures in South Africa.

The tables describing possible impacts of UOG extraction clearly illustrate that impacts on the social and biophysical environment can be complex and are interrelated across the different biophysical and socio-economic aspects and across the different phases of UOG extraction. Possible impacts on the biophysical and socio-economic environments may interlink. For example, while UOG exploration and extraction may drive socio-economic development in certain areas, worker migration may impact negatively on municipal service levels, while impacts on the environment (water contamination, seismicity) may impact on community health and safety. The complex inter-linkage of impacts necessitates that inter- and intra-institutional cooperation and communication be optimized in order to effectively manage and minimise possible impacts related to UOG extraction. The governance of UOG extraction should be handled as a whole and linkages between the biophysical and socio-economic environments should be researched, understood and managed in an integrated way.

The impacts listed in Table 1 may not occur on a very large scale during the exploration phase, since the footprint that companies explore in, may be limited. However, as UOG resources are proven, the geographic areas that are targeted for UOG extraction may expand significantly (IEA, 2012). The impacts for the biophysical sphere differ between the exploration and extraction phases in some instances, but are similar for the socio-economic sphere. Although the type of impacts are the same for the socio-economic sphere during the exploration and extraction phases, the extent and scale of these impacts may be much larger during the extraction phase.

In South Africa, different UOG companies applied for licences to explore and extract UOG in different geographic areas, making the possible impacts that may emanate from UOG, regional and cumulative. These regional scale cumulative impacts make the minimization of negative consequences difficult for governments with limited human or financial resources to manage and monitor these activities. During the post extraction phase (Table 3), negative impacts may be significantly less, but the long term management and maintenance of decommissioned oil and gas boreholes and the long term monitoring of groundwater quality, becomes problematic. The above challenges can be exacerbated by complex legal systems where different government departments have specific mandates and where legislation is fragmented, especially in view of the fact that the environmental and social impacts of UOG extraction are interrelated.

4. Conclusion: Implications for South Africa

The impacts associated with UOG extraction will be cumulative in nature and will most likely occur on a regional scale, highlighting the importance of using strategic decision-making and management tools, such as strategic environmental assessments in addition to environmental impact assessments. UOG operations will cumulatively add to impacts associated with current land and water use activities. This means that the impact assessments for different areas or different oil and gas companies cannot be considered in isolation during decision-making processes. It is also vital that the regulation of UOG exploration and extraction is undertaken with a holistic approach. This should consider environmental integrity on an ecosystem basis and should extend the regulation of UOG to possible incidental impacts and impacts associated with ancillary activities. Managing possible impacts in the correct way is extremely important in a water scarce country such as South Africa, versus countries where more water may be available for UOG extraction activities.

In South Africa there is insufficient information on the potential health risks associated with UOG exploration and extraction (Havemann et al., 2011). The unacceptable risk of losing biodiversity and jeopardising ecological integrity together with the possible impact on social well-being necessitates the timely identification of all potential risks and impacts before exploration commences. In the light of significant uncertainties there is a need to take a risk-averse and cautious approach (Glazewski and Plit, 2015).

The governance of UOG extraction should be handled as a whole and linkages between the biophysical and socio-economic environments should be researched, understood and managed in an integrated way (Esterhuyse et al., 2016). The quasi-federal constitutional framework comprising of national, provincial and local spheres of government each with their own spheres of jurisdiction needs to be taken cognisance of. The *National Environmental Management Act* (107 of 1998) *(NEMA)* principles which significantly apply to all organs of state acknowledge the interdependence of socio-economic and biophysical systems and one of the key principles of the *NEMA* requires that all developments be socially, economically and environmentally sustainable. Sustainable socio-economic development can only be achieved if it is underpinned by both socio-economic and environmental considerations as envisaged in the environmental right contained in the South African Constitution. In South Africa, where water demand will exceed water supply in the near future, unsustainable use of water resources will result in increasingly limited water resources for future health and well-being as well as for sustained socio-economic development. Society in general, and specifically the residents in the Karoo where access to water is already limited, needs to be assured of the sustainable use of the water resources for health and wellbeing by understanding and, where possible, avoiding the negative social impacts resulting from unconventional gas extraction by means of hydraulic fracturing.

The Report on Investigation of Hydraulic Fracturing in the Karoo Basin of South Africa (DMR, 2012) recommended that the current regulatory framework be complemented by establishing appropriate regulations, controls and co-ordination systems. To this end, the Department of Mineral Resources published the “Regulations for Petroleum Exploration and Production” under the *Mineral and Petroleum Resources Development Act 28 of 2002 (MPRDA)* in June 2015.The then Department of Water Affairs published their notice of intent to declare “ The exploration for and or production of onshore unconventional oil or gas resources and any activities incidental thereto including but not limited to hydraulic fracturing as a controlled activity” under the *National Water Act 36 of 1998 (NWA)* in August 2013. The proposed UOG extraction activities and its related impacts will straddle the competencies of various national, provincial and local government agencies departments, amongst others the Departments of Mineral Resources, Water and Sanitation, Environmental Affairs and Science and Technology. This may require that regulations be promulgated not only under the *MPRDA* and *NWA*, but also under the *NEMA*, the *National Environmental Management Waste Act 59 of 2008 (NEMWA)* and the *National Environmental Management Air Quality Act 20 of 2014 (NEMAQA)* but in the interests of co-operative government a multi-agency regulatory framework could be considered. It will be vital for industry and government to recognise the complexity of the challenges posed by these possible impacts. However, the impacts can be minimised where an effective regulatory system and best monitoring practice are in place and can be remediated where they do occur. If the oil and gas industry is to earn and retain the social licence to operate, it is a matter of urgency to have a transparent, adaptive and effective regulatory system in place that is implemented and backed by best practice monitoring, in addition to credible and high quality baseline surveys. A major coordinated programme of research to address the various uncertainties and knowledge gaps should be initiated at an early stage to ensure that South Africa is ready for UOG exploration and extraction.

Vulnerability mapping, determining safe zones and identifying vulnerable areas that should be avoided during UOG extraction, is a step that could be used to assist decision-makers and other practitioners by providing information on the vulnerability to unconventional gas extraction of the specified mapping themes on a regional scale. In addition, performing monitoring of various entities of the biophysical and socio-economic spheres before exploration, during exploration, during extraction and after extraction is important to assess possible changes in these entities due to the unconventional gas extraction process. Whereas this review illustrates various possible impacts of concern, active monitoring of certain entities can address some of these concerns and identify possible problems timeously. It is especially important for South Africa to perform baseline monitoring before exploration starts to ensure that we will have reference conditions in order to identify what impact UOG extraction activities has on the biophysical and socio-economic environments. Without such a baseline, determining impacts would not be possible. It is also important that monitoring occur during UOG exploration and extraction (to address impacts as they occur in order to minimise and/or mitigate the effects of these impacts) as well as post extraction, since some of the impacts may only be observed long after wells in a certain area have been decommissioned and after the oil and gas companies have moved on to another part of the oil and gas reservoir.

A background review of possible UOG-related impacts and the development of specific regulations to manage and minimize such impacts, would also be important for other countries that must still embark on UOG extraction. These activities resort under the precautionary approach with the aim to pre-emptively protect natural resources during economic development activities.

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References

Adams, M.B. (2011). Land application of hydrofracturing fluids damages a deciduous forest stand in West Virginia. *Journal of Environmental Quality*, *40*(4), 1340-1344. doi:10.2134/jeq2010.0504

Anderson, B.J., & Theodori, G.L. (2009). Local leaders' perceptions of energy development in the Barnett Shale. *Southern Rural Sociology*, *24*(1), 113-129.

ANU (Australian National University). (2012). *Unconventional gas production and water resources: Lessons from the United States on better governance – A workshop for Australian government officials*. Canberra: Crawford School of Public Policy.

Bamberger, M., & Oswald, R.E. (2012). Impacts of gas drilling on human and animal health. *New solutions: a journal of environmental and occupational health policy*, *22*(1), 51-77. doi:10.2190/NS.22.1.e

Barati, R., & Liang, J.T. (2014). A review of fracturing fluid systems used for hydraulic fracturing of oil and gas wells. *Journal of Applied Polymer Science*, *131*(16). doi:10.1002/app.40735

Beemster, B., & Beemster, R. (2011). *Report on the effects of shale gas extraction by means of hydraulic fracturing in the Republic of Ireland* (2^{nd} ed.). Sligo: Fracking Research and Information Centre.

Bishop, R.E. (2011). *Chemical and Biological Risk Assessment for Natural Gas Extraction in New York (Draft Report).* Chemistry and Biochemistry Department State University of New York, College at Oneonta.

Brasier, K.J., Filteau, M. R., McLaughlin, D.K., Jacquet, J., Stedman, R.C., Kelsey, T.W., & Goetz, S.J. (2011). Residents' perceptions of community and environmental impacts from development of natural gas in the Marcellus Shale: A comparison of Pennsylvania and New York cases. *Journal of Rural Social Sciences, 26*(1), 32-61.

Broderick, J., Anderson, K., Wood, R., Gilbert, P., & Sharmina, M. (2011). *Shale gas: An updated assessment of environmental and climate change impacts*. A report commissions by the Co-operative and undertaken by researchers at the Tyndall Centre, University of Manchester. Retrieved from Tyndall Centre: http://www.tyndall.ac.uk/sites/default/files/coop_shale_gas_report_update_v3.10.pdf

Broomfield, M. (2012). *Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe* (Report No. ED57281-17c). European Commission DG Environment. Retrieved from http://ec.europa.eu/environment/integration/energy/pdf/fracking%20study.pdf

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H., & Valett, H.M. (1998). The functional significance of the hyporheic zone in streams and rivers. *Annual Review of Ecology and Systematics*, *29*, 59-81.

Cabot. (2010). *Compatibilities and interactions, Section B11, Compatibility with shale*. Cabot Corporation, USA.

CIEH (Chartered Institute of Environmental Health). (2012). Hydraulic fracturing impacts on the environment and health. The Center for Rural Pennsylvania – A legislative agency of the Pennsylvania General Assembly. Briefing note. Retrieved from http://www.cieh.org/assets/0/72/1126/1212/1216/1218/08316171-c668-41d1-8d85-8af09f3d2193.pdf

Chung, H., & Hoffnagle, G. (2011). The risks of hydrofracking. *Risk Management, 58*(5), 32-34.

Chutter, F.M. (1969). The distribution of some stream invertebrates in relation to current speed. *Internationale Revue der Gesamten Hydrobiologie und Hydrographie*, *54*(3), 413-422. doi:10.1002/iroh.19690540305

Clarkson, C.R., Nobakht, M., Kaviani, D., & Ertekin, T. (2012). Production analysis of tight-gas and shale-gas reservoirs using the dynamic-slippage concept. *Spe Journal*, *17*(01), 230-242. SPE-144317-PA. doi:10.2118/144317-PA

Clarkson, C.R., Solano, N., Bustin, R.M., Bustin, A.M.M., Chalmers, G.R.L., He, L., Melnichenko, Y.B., Radlinski, A,P., & Blach, T.P. (2013). Pore structure characterization of North American shale gas reservoirs using USANS/SANS, gas adsorption, and mercury intrusion. *Fuel*, *103*, 606-616. doi:10.1016/j.fuel.2012.06.119

Coburn, M., Kozikowski, T., Lloyd, N., Meredith, B., Parnes, D., Reed, J., & Shah, R. (2011). *Positives, negatives, uncertainty, and opinions on hydrofracturing in the Marcellus Shale*. USA Mountain Ridge AP Environmental Science.

Considine, T.M., Watson, R. W., & Considine, N.B. (2011). *The economic opportunities of shale energy development* (Energy Policy & the Environment Report, No. 9, June). The Manhattan Institute for Policy Research. Retrieved from http://www.manhattan-institute.org/html/eper_09.htm

Davis, W.N. (2008). *Effects of Coalbed Natural Gas Development on Fish Assemblages in Tributary Streams in the Powder River Basin, Montana and Wyoming* (Unpublished master's thesis). Montana State University, Bozeman, MO. EPA-HQ-OW-2008-0517, DCN 07229.

Davis, W.N., Bramblett, R.G., & Zale, A.V. (2006). *The effects of coalbed natural gas activities on fish assemblages: a review of the literature*. Report prepared by the Montana Cooperative Fishery Research Unit, Department of Ecology, Montana State University, Bozeman, Montana for the United States Department of the Interior, Bureau of Land Management, Miles City, Montana.

De Wit, M.J. (2011). The great shale debate in the Karoo. *South African Journal of Science*, *107*(7-8), 02-10. doi:10.4102/sajs.v107i7/8.791

Deller, S.C., & Schreiber, A. (2012). Mining and community economic growth. *The Review of Regional Studies: Journal of the Southern Regional Sciences Association*, *42*, 121-141.

Dernbach, J.C., & May, J.R. (eds.). (2016). *Shale gas and the future of energy: Law and policy for sustainability*. Edward Elgar Publishing.

DMR (Department of Mineral Resources). (2012). *Report on investigation of hydraulic fracturing in the Karoo Basin of South Africa*. Department of Mineral Resources, South Africa.

Dolesh, R.J. (2011). Fractured parks. *Parks & Recreation*, *June 2011,* 56–61. Retrieved from http://ezine.parksandrecreation.org/HTML5/NRPA-Parks-Recreation-Magazine-June-2011

DSD (Department of Social Development). (2010). *Progress review of the implementation of: the White Paper on Population Policy for South Africa (1998) and the ICPD Programme of Action (1994).* Pretoria: South African Department of Social Development.

DSD (Department of Social Development). (2015). *Fifteen Year Progress Review of the Implementation of the Population Policy for South Africa (1998) and the International Conference on Population and Development (ICPD) Programme of Action (1994) @20 (RP 264/2015).* Pretoria: DSD.

Dusseault, M.B., Bruno, M.S., & Barrera, J. (2001). Casing shear: Causes, cases, cures. *SPE Drilling & Completion*, *16*(02), 98-107. Retrieved from http://www.geomechanicstech.com/article/spe72060.pdf doi:10.2118/48864-MS

Dusseault, M.B., Gray, M.N., & Nawrocki, P. (2000). *Why oil wells leak: cement behaviour and long-term consequences*. Paper presented at Society of Petroleum Engineers International Oil and Gas Conference and Exhibition, Beijing, China, 7-10 November 2000.

DWA (Department of Water Affairs). (2010). *Groundwater Strategy 2010.* Department of Water Affairs, Pretoria, pp. 64.

DWA, (2011). Directorate Water Resource Planning Systems: Water Quality Planning. *Resource Directed Management of Water Quality. Planning Level Review of Water Quality in South Africa*. Sub-series No. WQP 2.0. Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry). (1996). *South African Water Quality Guidelines Volume 1: Domestic Use* (2nd ed., 1st issue).

Esterhuyse, S., Redelinghuys, N, Kemp, M. (2016). Unconventional oil and gas extraction in South Africa: water linkages within the population-environment-development nexus and its policy implications. *Water International special edition - Out of Mines, Out of Site: The water legacies of conventional mining*, 41(3):409-425. doi:10.1080/02508060.2016.1129725

Esteves, A.M. (2008). Mining and social development: Refocusing community investment using multi-criteria decision analysis. *Resources Policy*, *33*(1), 39-47. doi:10.1016/j.resourpol.2008.01.002

Field, R. A., Soltis, J., & Murphy, S. (2014). Air quality concerns of unconventional oil and natural gas production. *Environmental Science Processes & Impacts*, 16(5), 954–969. http://doi.org/10.1039/c4em00081a

Freyman, M. (2014). *Hydraulic fracturing and water stress: water demand by the numbers*. Retrieved from http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers

Forster, D., Perks, J. (2012). Climate impact of potential shale gas production in the EU. Retrieved from http://doi.org/AEA/R/ED57412.

GAO (General Accounting Office). (2010). *Superfund EPA's estimated costs to remediate existing sites exceed current funding levels, and more sites are expected to be added to the national priorities list*. Commissioned report to USA Congress. Retrieved from http://www.gao.gov/products/GAO-10-380.

Glazewski, J., & Plit, L. (2015). Towards the application of the precautionary principle in South African law. *Stellenbosch Law Review = Stellenbosch Regstydskrif*, *26*(1), 190-219.

Graham, D.N., & Butts, M.D. (2005). Flexible, integrated watershed modelling with MIKE SHE. In V.P. Singh, & D.K. Frevert (Eds.). *Watershed Models*. (pp. 245-272). CRC Press.

Grubert, E., & Kitasei, S. (2010). *How energy choices affect fresh water supplies: A comparison of U.S. coal and natural gas*. Worldwatch Institute. Retrieved from http://www.worldwatch.org/system/files/BP2.pdf

Havemann, L. (2011, November). A South African regulatory framework for fracking: Is the cart being put before the horse? *Mining prospectus, 1*, 54-58.

Havemann, L., Glazewski, J., & Brownlie, S. (2011). A critical review of the application for a Karoo Gas Exploration Right by Shell Exploration Company BV. *Cape Town: Havemann Inc*. Specialist Energy Attorneys.

Heunis, J.C., Wouters, E., & Kigozi, N.G. (2012). HIV, AIDS and tuberculosis in South Africa: Trends, challengs and responses. In H.C.J. Van Rensburg (Ed.). *Health and Health Care in South Africa* (2nd ed.) (pp. 294-350). Pretoria: Van Schaik.

Herridge, A., Kerwin, T., Lestarjette, T., Schmidt, M., & Wohlgemuth, L. (2012). The Consequences of Hydraulic Fracturing. Retrieved from https://shalegasespana.files.wordpress.com/2012/10/the-consequences-of-hf.pdf

IEA (International Energy Agency). (2012). *Golden rules for a golden age of gas: World energy outlook special report on unconventional gas*. Paris: OECD/IEA. Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/2012/goldenrules/weo2012_goldenrulesreport.pdf

Johnson, L.A. (2007). *Longitudinal changes in potential toxicity of coalbed natural gas produced water along Beaver Creek in the Powder River Basin, Wyoming* (Unpublished Master's dissertation). University of Wyoming, Laramie, Wyoming.

Jones, N.F., & Pejchar, L. (2013). Comparing the ecological impacts of wind and oil & gas development: A landscape scale assessment. *PloS one*, *8*(11), e81391. doi:10.1371/journal.pone.0081391

Kargbo, D.M., Wilhelm, R.G., & Campbell, D.J. (2010). Natural gas plays in the Marcellus shale: Challenges and potential opportunities. *Environmental science & technology*, *44*(15), 5679-5684. doi:10.1021/es903811p

Kempema, E.W., Ettema, R., & Stiver, J.J. (2011). *Effects of CBM discharge on winter fluvial and ice processes in Powder River Basin, Wyoming*. Paper presented at CGU HS Committee on River Ice Processes and the Environment, 16th Workshop on River Ice, Winnipeg, Manitoba, 18-22 September 2011.

Khan, S., Ansari, S., Han, H., & Khosravi, N. (2011). *Importance of Shale Anisotropy in Estimating In-Situ Stresses and Wellbore Stability Analysis in Horn River Basin*. Paper presented at Canadian Unconventional Resources Conference, Alberta, Canada, 15-17 November 2011. Published in Society of Petroleum Engineers. doi:10.2118/149433-MS

Khodja, M., Canselier, J.P., Bergaya, F., Fourar, K., Khodja, M., Cohaut, N., & Benmounah, A. (2010). *Shale problems and waterbased drilling fluid optimisation in the Hassi Messaoud Algerian Oil field*. Applied Clay Science, *49*(4), 383-393. doi:10.1016/j.clay.2010.06.008

Larson, D., Breech, R., Hendricks, J., Chernaik, M., Mall, A., Smith, F., Joswick, J., & Eisenfeld, M. (2011). *Gassed! Citizen investigation of toxic air pollution from natural gas development*. California: GCMonitor. Retrieved from http://www.marcellusprotest.org/sites/marcellusprotest.org/files/GASSED!%20FINAL_0.pdf

Lechtenböhmer, S., Altmann, M., Capito, S., Matra, Z., Weindrorf, W., & Zittel, W. (2011). *Impacts of shale gas and shale oil extraction on the environment and on human health*. Committee on Environment Public Health and Food Safety. Retrieved from http://www.europarl.europa.eu/document/activities/cont/201107/20110715ATT24183/20110715ATT24183EN.pdf

Lind, K. (2004). *Powder River biological survey and implications for coalbed methane development*. Report prepared by Confluence Consulting Inc. for Powder River Basin Resource Council, Sheridan, Wyoming.

Lloyd-Smith, M., & Senjen, R. (2011). *Hydraulic fracturing in coal seam gas mining: the risks to our health, communities, environment and climate*. Report prepared for National Toxics Network, Bangalow, Australia.

Lockie, S., Franettovich, M., Petkova-Timmer, V., Rolfe, J., & Ivanova, G. (2009). Coal mining and the resources community cycle: A longitudinal assessment of the social impacts of the Coppabella coal mine*. Environmental Impact Assessment Review, 29*, 330-339. doi:10.1016/j.eiar.2009.01.008

Lovegrove, B. (1993). *The living deserts of Southern Africa*. Fernwood Press, Vlaeberg, South Africa.

Lyons, B. J. (2012). *Fuelling America and the energy water nexus*. *How and why it impacts the nexus and what next.* A Report from the Atlantic Council's Energy Water Nexus Initiative. Retrieved from http://www.atlanticcouncil.org/images/files/EnergyEnvironment/062212_EEP_FuelingAmericaEnergyWaterNexus.pdf

Lytle, D. A., & Peckarsky, B. L. (2001). Spatial and temporal impacts of a diesel fuel spill on stream invertebrates. *Freshwater Biology, 46*, 693–704. doi:10.1046/j.1365-2427.2001.00695.x

Mahrer, K.D. (1999). A review and perspective on far-field hydraulic fracture geometry studies. *Journal of Petroleum Science and Engineering*, *44*(1), 13-28. doi:10.1016/S0920-4105(99)00020-0

Manohar, L. (1999). *Shale Stability: Drilling Fluid Interaction and Shale Strength*. Present at SPE Latin American and Caribbean Petroleum Engineering Conference held in Caracas, Venezuela, 21-23 April 1999. Published in Society of Petroleum Engineers.

Marsa, L. (2011). Fracking nation. *Discover*, *32*(4), 62-70.

McBeth, I.H., Reddy, K.J., & Skinner, Q.D. (2003). Coalbed Methane Product Water Chemistry in Three Wyoming Watersheds. *Journal of the American Water Resources Association*, *39*, 575-585. doi:10.1111/j.1752-1688.2003.tb03676.x

McCauley, R.D., Fewtrell, J., Duncan, A. J., Jenner, C., Jenner, M.N., Penrose, J.D., Prince, R.I.T., Adhiyta, A., Murdoch, J., & McCabe, K. (2000). Marine seismic surveys – A study of environmental implications. *APPEA Journal, 40*, 692–706.

McGlade, C., Speirs, J., & Sorrell, S. (2013). Unconventional gas — a review of regional and global resource estimates*. Energy, 55*, 571–84. doi:10.1016/j.energy.2013.01.048

Mead, J.V., Anderson, F., Velinsky, D., & Horwitz, R. (2011). *Current findings on the impact of mining gas from Marcellus shale formation on surface waters: Balancing gas mining with impacts to surface water quality*. Patrick Center for Environmental Research. Academy of Natural Sciences.

Milton, S.J. and Dean, W.R.J. 2012. *Potential environmental risks and impacts of mining in the Karoo*. Paper presented at the Karoo Development Conference, Beaufort West, October 2012.

Morton, S.R., Hoegh-Guldberg, O., Lindenmayer, D.B., Olson, M.H., Hughes, L., McCulloch, M.T., McIntyre, S., Nix, H.A., Prober, S.M., Saunders, D.A. and Andersen, A.N., 2009. The big ecological questions inhibiting effective environmental management in Australia. *Austral Ecology*, *34*(1), pp.1-9.

Mundahl, N.D. (1990). Heat death of fish in shrinking stream pools. *American Midland Naturalist, 123*(1), 40-46. doi: 10.2307/2425758

Myers, T. (2012). Potential contaminant pathways from hydraulically fractured shale to aquifers. *Ground Water*, *50*(6), 872-882. doi: 10.1111/j.1745-6584.2012.00933.x

Northrup, J.M., & G, Wittemyer. (2013). Characterizing the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecology Letters*, *16*(1), 112-125. doi: 10.1111/ele.12009

NRC (National Research Council). (2010). *Management and effects of coalbed methane produced water in the western United States*. Committee on Management and Effects of Coalbed Methane Development and Produced Water in the Western United States, Committee on Earth Resources and National Research Council. The National Academies Press, Washington D.C.

NRC. (2012). A*lternatives for managing the nation's complex contaminated groundwater sites*. Committee on Future Options for Management in the Nation's Subsurface Remediation Effort, Water Science and Technology Board, Division on Earth and Life Studies, National Research Council. The National Academies Press, Washington D.C.

NRC. (2013). *Induced seismicity potential in energy technologies*. National Research Council. Washington,DC: The National Academies Press.

O'Connor, T., & Kuyler, P. (2006). National Grasslands Initiative: Identification of compatible land uses for maintaining biodiversity integrity*: Mining Addendum*. 1 March 2006. Report for South African National Biodiversity Institute, Pretoria.

O'Riordan, T. 2007. Faces of the sustainability transition. In J. Pretty, A. Ball, T. Benton, J. Guivant, D. R. Lee, D. Orr, M. Pfeffer, & H. Ward (Eds.). *The SAGE handbook of environment and society* (pp. 325-334). London: SAGE.

PA DEP (Pennsylvania Department of Environmental Protection). (2009). *Stray natural gas migration associated with oil and gas wells*. Bureau of Oil and Gas Management. Department of Environmental Protection, Harrisburg, PA.

Palmer, R.W. (1996). *Invertebrates in the Orange River, with emphasis on conservation and management*. Southern African Journal of Aquatic Sciences 22(1/2):3-51. doi:10.1080/10183469.1996.9631371

Parsons, R. (2004). *Surface water – Groundwater interaction in a Southern African context*. WRC Report TT 218/03, Water Research Commission, Pretoria.

Pelser, A.J., Botes, L.J.S., Marais, L., Redelinghuys, N., & Benseler, A. (2005). *Application for a new mining right for De Beers Consolidated Mines Limited (Koffiefontein Mine): Social Impact Assessment report.* Centre for Development Support, University of the Free State, Bloemfontein.

Pelser, A.J., & Redelinghuys, N. (2006). Mining migration and misery: Exploring the HIV/AIDS nexus in the Free State Goldfields of South Africa. *Journal for Contemporary History, 31*(1), 29-48.

Peterson, M.J., Smith, J.G., Southworth, G.R., Ryon, M.G., & Eddlemon, G.K. (2002). Trace element contamination in benthic macro-invertebrates from a small stream near a Uranium mill tailings site. *Environmental Monitoring and Assessment, 74*(2), 193-208. doi: 10.1023/A:1013872103460

Rahm, D. (2011). Regulating hydraulic fracturing in shale gas plays: The case of Texas. *Energy Policy*, *39*(5), 2974-2981. doi:10.1016/j.enpol.2011.03.009

Rahm, B.G., Bates, J.T., Bertoia, L.R., Galford, A.E., Yoxtheimer, D.A., & Riha, S.J. (2013). Wastewater management and Marcellus Shale gas development: trends, drivers, and planning implications. *Journal of environmental management*, *120*, 105-113. doi:10.1016/j.jenvman.2013.02.029

Rahm, B.G., & Riha, S.J. (2012). Toward strategic management of shale gas development: Regional, collective impacts on water resources. *Environmental Science & Policy*, *17*, 12-23. doi:10.1016/j.envsci.2011.12.004

Rahman, M.M., & Rahman, M.K. (2010). A review of hydraulic fracture models and development of an improved pseudo-3D model for stimulating tight oil/gas sand. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *32*(15)1416-1436. doi:0.1080/15567030903060523

Ramirez, P. (2005). *Assessment of contaminants associated with coal bed methane – Produced water and its suitability for wetland creation or enhancement projects*. Contaminant Report Number: R6/721C/05. U.S. Fish and Wildlife Service, Region 6. EPA-HQ-OW-2006-0771-0928.

Rijke, K. (2013). The Agri-gas fields of Australia: Black soil, food, and unconventional gas. *Culture, Agriculture, Food and Environment*, *35*(1), 41-53. doi:10.1111/cuag.12004

Rolfe, J., Miles, B., Lockie, S., & Ivanova, G. (2007). Lessons from the social and economic impacts of the mining boom in the Bowen Basin 2004-2006. *Australasian Journal of Regional Studies*, *13*(2), 134-153.

Schafft, K.A., Borlu, Y., & Glenna, L. 2013. The relationship between Marcellus Shale gas development in Pennsylvania and local perceptions of risk and opportunity. *Rural Sociology, 78*(2),143-166. doi:10.1111/ruso.12004

Scott, C. A., Pierce, S. A., Pasqualetti, M. J., Jones, A. L., Montz, B. E., & Hoover, J. H. (2011). Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, *39*(10), 6622-6630. doi:10.1016/j.enpol.2011.08.013

Seaman, M.T., Avenant, M.F., Watson, M., King, J., Armour, J., Barker, C.H., Dollar, E., Du Preez, P. J., Hughes, D., Rossouw, L., & van Tonder, G. (2010). *Developing a method for determining the environmental water requirements for non-perennial systems*. Report to the Water Research Commission by Centre for Environmental Management, University of the Free State. WRC Report No. TT 459/10, Pretoria.

Siebrits, R., & Winter, K. (2013). *Identifying and prioritising water research questions for South Africa. Water Research Commission* (Report no. 2170/1/13). Retrieved from http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/2170-1-13.pdf

Skaar, D., Morris, B., & Farag, A. (2004). *National pollution discharge elimination system. Toxicity of the major salt (sodium bicarbonate) from coalbed natural gas production on fish in the Tongue and Powder River drainages in Montana*. Progress report prepared for US Environmental Protection Agency, Helena.

Sone, H., & Zoback, M.D. (2011). *Visco-plastic properties of shale gas reservoir rocks*. Paper presented at the 5th U.S. Rock Mechanics / Geomechanics Symposium, San Francisco, California, 26-29 June 2011. Conference Paper published by the American Rock Mechanics Association.

Sovacool, B.K. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy* 36:2940-2953.

Steyl, G., Van Tonder, G. J., & Chevalier, L. (2012). *State of the art: Fracking for shale gas exploration in South Africa and the impact on water resources*. WRC Report. KV 294-11. Water Research Commission, Pretoria.

Sumi, L. (2010). *Environmental concerns and regulatory initiatives related to hydraulic fracturing in shale gas formations: potential implications for North American Gas Supply*. Report prepared for the Council of Canadians.

Tollefson, J. (2012). Air sampling reveals high emissions from gas field. News in focus. *Nature* 482:139-140.

UNFPA (United Nations Population Fund). 2012. *Population Matters for Sustainable Development.* New York: UNFPA.

USEPA (United States Environmental Protection Agency). (2011a). *Draft plan to study the potential impacts of hydraulic fracturing on drinking water resources*. Ref: EPA/600/D-11/001/February 2011/www.epa.gov/research. Retrieved from http://water.epa.gov/type/groundwater/uic/class2/hydraulicfracturing/upload/hf_study_plan_110211_final_508.pdf

USEPA (United States Environmental Protection Agency). (2011b). Coalbed methane extraction: Detailed study report. U.S. Environmental Protection Agency Office of Water (4303T).

Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M., & Schonegevel, L. (2008). A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *Journal of Environmental Management*, *89*(4), 336-349. doi:10.1016/j.jenvman.2007.06.015

Vatsa, T., & Wang, J. Y. (2013). Fracture height containment in the stimulation of Oriskany Formation. *Journal of Energy Resources Technology*, *135*(2), 022902. doi:10.1115/1.4023169

Vaughn, C.C. (2005). *Freshwater mussel populations in Southeastern Oklahoma: Population trends and ecosystem services*. Proceedings of Oklahoma Water. Tulsa. OK.

Volz, C.D., Ferrar, K., Michanowicz, D., Christen, C., Kearney, S., Kelso, M., & Malone, S. (2011). *Contaminant characterization of effluent from Pennsylvania Brine Treatment Inc., Josephine Facility: Implications for disposal of oil and gas flowback fluids from brine treatment plants*. EPA Hydraulic Fracturing Study Technical Workshop 3, Fate and Transport. March 28-29, 2011, EPA Potomac Yards Conference Facility.

Wait, R., & Rossouw, R. (2014). A Comparative assessment of the economic benefits from shale gas extraction in the Karoo, South Africa. *Southern African Business Review, 18*(2), 1-34.

Walsh, B. (2011). The Gas dilemma. *Time, 177*(14), 40-48.

Warner, N.R., Jackson, R.B., Darrah, T.H., Osborn, S.G., Down, A., White, A., Vengosh, A., & Zhao, K. (2012). Geochemical evidence for possible natural migration of Marcellus Formation brine to shallow aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences*, *109*(30), 11961-11966. doi: 0.1073/pnas.1121181109

Warren, C.H. (2013). Shale gas in South Africa: Toward an understanding of the security implications. *African Security Review*, *22*(1), 67-73. doi:10108010246029.2013.766443

Weigle, J.L. (2011). *Resilience, community, and perceptions of Marcellus Shale development in the Pennsylvania wilds: Reframing the discussion*. Sociological Viewpoints. Retrieved from http://www.readperiodicals.com/201110/2645624801.html

Williams, J., Stubbs, T., & Milligan, A. (2012). *An analysis of coal seam gas production and natural resource management in Australia*. A report prepared for the Australian Council of Environmental Deans and Directors by John Williams Scientific Services Pty Ltd. Canberra, Australia.

Williams, S. (2011). *Discovering shale gas: an investor guide to hydraulic fracturing*. USA: IRRC Institute.

Winter, T.C., Harvey, J.W., Franke, O.L., & Alley, W.M. (1998). *Ground water and surface water: A single resource*. *US Geological Survey Circular 1139*. Denver, Colorado.

Wood, R., Gilbert, P., Sharmina, M., Anderson, K., Footitt, A., Glynn, S., & Nicholls, F. (2011). *Shale gas: A provisional assessment of climate change and environmental impacts*. Tyndall Centre Technical Reports.

Woodford, A.C., & Chevallier, L. (2002). *Hydrogeology of the main Karoo basin: Current knowledge and future research needs*. WRC Report TT 179/02. Water Research Commission, Pretoria.

Zoback, M., Kitasei, S., & Copithorne, B. (2010). *Addressing the Environmental Risks from Shale Gas Development (briefing paper 1)*. Worldwatch Institute. Washington, DC.

Zorn, T.G., Seelbach, P.W., Rutherford, E.S., Wills, T.C., Cheng, S., & Wiley, M.J. (2008). *A regional-scale habitat suitability model to assess the effects of flow reduction on fish assemblages in Michigan streams.* Fisheries Division Research Report 2089. Lansing, MI: State of Michigan Department of Natural Resources. Retrieved from http://www.michigandnr.com/PUBLICATIONS/PDFS/ifr/ifrlibra/Research/reports/2089/RR2089.pdf